MODEL REPRESENTING THE RELATIONSHIP BETWEEN THE SOIL ATTRIBUTES AND THE PRODUCTION OF SUGARCANE USING STRUCTURAL EQUATIONS

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- *ABSTRACT:* The sugarcane is the main source of renewable energy in Brazil and it is considered that this crop has an economically as well as environmentally promising future around the world. This fact justifies the researches regarding the comprehension of its behaviour in the soil-plant system. This study aimed to explain the productivity of the sugarcane crop through latent factors formed from chemical and physical attributes of an Ultisol with a medium/clayey texture using the technique of structural equations modelling. In order to collect the data of the plant as well as the soil, we defined 118 sampled points of a regular grid in the depths of 0 to 0.20 m and from 0.20 to 0.40 m. The first three factors composed the chemical, physical and production attributes explaining around 60% of the data variability. The technological and production components of the sugarcane were negatively influenced by the physical attributes factor from 0 to 0.20 m. However, there was a positive influence of the chemical attributes factor associated with the acidity in the layer from 0.20 to 0.40 m.

- *KEYWORDS:* Factors; biomass; yield; Ultisol.

1 Introduction

The growing global concern about the environment raises questions regarding the use of fossil fuels, which are mainly responsible for the emission of polluting gases into the atmosphere. Several countries have sought to reduce the use of these fuels to reduce the

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pollution load, making the non-fossil fuels an alternative source, such as biofuels, derived from renewable biomass (MAULE *et al*., 2001; VAKKILAINEN *et al*., 2013).

In this scenario, the sugarcane is the most important primary crop as the primary source of energy in Brazil, standing among the best options of renewable energy sources, having great importance in the Brazilian agricultural setting as well as a promising future in the global setting (EPE, 2008; MARTINS *et al*., 2015).

According to Ololade *et al*. (2010), the agricultural yield is a complex interaction among the environmental variables, the soil attributes and the nutrient's dynamics in the soil-plant system. Therefore, additional studies regarding the productive potential of the sugarcane crop in Brazilian soils are necessary.

It is difficult to evaluate the weakening of soil fertility, including nutrient depletion (a decrease in pH and/or an increase of exchangeable aluminium), loss of the content of the soil organic matter and the increase of the contents of toxic elements because most of the chemical attributes of the soil change very slowly or have large seasonal fluctuations. In this regard, the pH is perhaps the most important attribute attached to the efficient use of fertilizers, wherein the availability of macronutrients may change from low (acidic soil) to high (pH 6.0 to 7.0); however, the availability of iron, copper, manganese and zinc is higher under acidic conditions, decreasing as the pH increases (LOPES and GUILHERME, 2000; HARTEMINK, 2006).

Attributes that can also influence the growth and development of the plant are aeration, the amount of water in the soil, soil temperature, soil resistance to compaction, and these, in turn, are altered by changes in the overall porosity, in the aggregate stability as well as in the bulk density (SILVA *et al*., 2002; BRAUNACK, 1991).

According to Maule *et al*. (2001), studying the crop in its developmental environment can generate a huge amount of information to suit the best management as well as to farm the specific environments (soil and climate). This makes it possible to best exploit the production site to promote a better crop return and, consequently, higher productivity and greater competitiveness for the agricultural industries of sugarcane. In this context, the soil is one of the components of a complex set of factors that influence the production of the crop, notable for its important role of providing physical support, water and nutrients needed for good crop growth. Therefore, knowledge of the attributes inherent to each soil, the so-called soil factors, is important to judge the agricultural production potential (LEPSCH, 1987).

Several studies have used the geostatistical tool, correlations and regressions, in order to study the spatial variability of the physical, chemical and biological attributes of the soil, the productivity of crops as well as to evaluate the relationship between them. For this we can cite Dias (1999), Gioia (2011) and Soria (2014). In addition, structural equations modelling/analysis (SEM) has been indicated and employed in soil studies (NAZMI, 2013; PÉRÈS *et al*., 2013; EISENHAUER *et al*., 2015, ZHU *et al*., 2016, WILLIAMS *et al*., 2016).

The application of SEM as an alternative to the traditional methods is justified by providing the researcher the ability to accommodate multiple interrelated dependency relationships in a single model (HAIR *et al*., 2009). The SEM makes it possible to purge the errors in the variables by means of measurement models and structural model, which cleanse the variables (BOLLEN, 1989), something that does not happen in the classic models, causing damages in the parameters estimation. Nazmi (2013) used multiple linear regression models and structural equations analysis in order to relate latent factors (unobservable factors in the field associated to observed attributes in the field, which are related) and the amount of influence of these physical and chemical attributes on wheat yield. He noted that measurements of physical and chemical attributes were statistically significant in predicting and understanding of the components of wheat yield through the regression model as well as the structural model.

Freitas *et al*. (2014) benefited from multivariate techniques in order to evaluate comparatively the physical and chemical attributes regarding the textural classes in depths from 0 to 0.10 m and 0.10 to 0.20 m under a continuous cultivation of sugarcane. The use of multivariate analysis techniques was efficient to verify the similarities and/or differences of the studied areas with different textural gradients.

Before this context, the goal of this study was to explain the crop productivity of the sugarcane by latent factors, formed from chemical and physical properties of the soil at different depths of assessment. Therefore, a variety of methods were used: analysis of the main components and factor analysis to reduce the dimensionality of the data, as well as to assist in the formation of each factor; and application of structural equations analysis in order to obtain a better characterization of the performance components of the sugarcane crop associated with the soil properties.

2 Material and methods

2.1 Experimental area

The experiment was conducted in a commercial planting area of sugarcane of 10.5 ha, located in the municipality of Suzanápolis, SP, Brazil, with the coordinate 20°29'54" S, 51°01'38" W, with an elevation of 350 m above sea level (Figure 1). The climate classification, according to Köppen, is Aw, characterized as tropical humid with a rainy summer and a dry winter, typical of the Brazilian Cerrado region, with an average annual temperature of 24.5°C and a total annual average rainfall of 1400 mm. According to the Thornthwaite System, the climate classification region was C_2rA'a' (ROLIM et al., 2007).

For the installation of the crop, the RB855453 variety of the sugarcane was used. The preparation of the soil was done through a heavy harrow with two medium harrows. The distribution haul of 2.0 t ha-1 of dolomitic limestone embedded with a mouldboard plow followed by a light harrowing was done. The planting was done in June 2009, through a trencher of two rows, with a space of 1.50 m with a planting fertilizer dose of 500 kg ha-1 of the formula 6-30-24 and for covering of billets in the planting furrow. After the first cut, there was the application of 1 t ha^{-1} of gypsum. Data collection was performed in the third cut of the crop (05/24/2014). The harvesting was performed in mechanized way.

To collect the plant and soil data, 118 sampling points were defined, distributed evenly in the area, featuring a georeferenced grid with a distance of 34 m between the sampling points of the large grid and 17 m in grid refinement in order to cover the selected area of the plot (Figure 1). The attributes of the plant (production and technological components) that were studied were: plant population (POP), expressed in pl m^{-2}; ton of sugarcane per hectare (TSH), expressed in t ha^{-1}; total recoverable sugars (TRS), expressed in kg t^{-1}; total soluble solids (TSS); sucrose in the juice (POL); apparent purity (PUR); and fibre (F), all expressed in % (BIDOIA, 2008; CONSECANA, 2006).

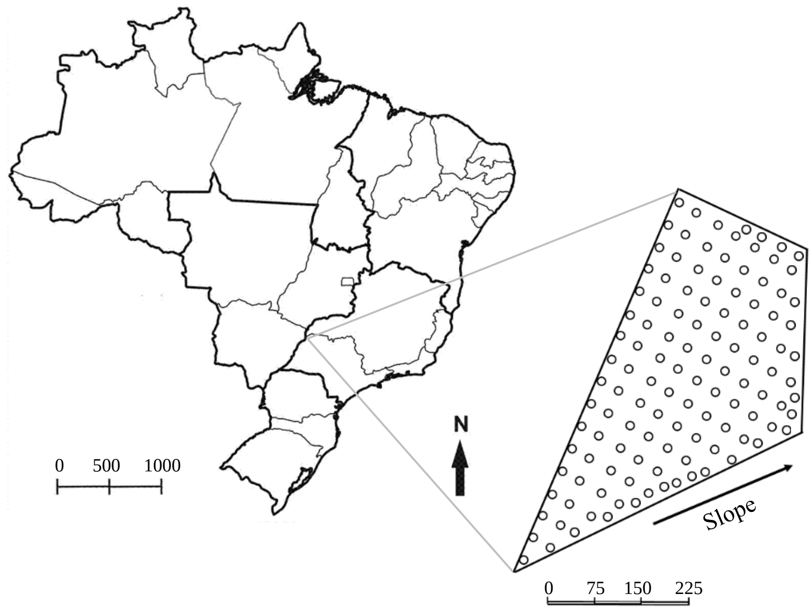

Figure 1 – Schematic map of the experimental area of 10.5 ha and the distribution of 118 sampling points in the sugarcane area in the city of Suzanápolis, SP, Brazil.

In order to obtain the physical attributes of the soil (05/29/2014), the following variables were determined: soil density (BD) (kg dm^{-3}), penetration resistance of the soil (RP) (MPa), gravimetric soil moisture (UG) (kg kg^{-1}), volumetric soil moisture (UV) (m^3 m^{-3}), soil macro-porosity (MA) (m^3 m^{-3}), soil micro-porosity (MI) (m^3 m^{-3}) and total porosity of the soil (TPV) (m^3 m^{-3}) (Kiehl, 1979; Stolf, 1991; EMBRAPA, 1997; Montanari, 2009). The chemical soil properties that were evaluated were: organic carbon (OC) (t ha^{-1}), the pH in water (pHw), the pH in calcium chloride (pHCa) and the pH in potassium chloride (pHK) (Raij et al., 2001; EMBRAPA, 2009). All samples were collected in 1 (0-0.20 m) and 2 (0.20-0.40 m) depths. The measurements of the soil properties were conducted in the Laboratórios de Fertilidade do solo e Análises Físicas do Solo da Faculdade de Engenharia de Ilha Solteira – UNESP.

2.2 Data analysis

In the first part of the data analysis procedure, the behavior of each attribute was verified through the descriptive analysis of the data as well as the existence of outliers (multivariate outliers), the evaluation of multivariate normality hypothesis. Subsequently, it was performed application of multivariate statistical methods: principal component analysis (PCA) and robust factor analysis (RFA) in the two studied depths. In order to verify the existence of multivariate outliers, it was used the two-dimensional graph Q-Q plot, based on the Mahalanobis robust distance (FILZMOSER *et al*., 2005).

The PCA method (Eq. 1) consists of a rigid rotation in the system of original coordinate axes so that the new axes were in the direction of greater variability of the data

(FERREIRA, 2011), wherein the coefficients of the new axes are the eigenvectors of the matrix of the sample covariance data. In the factor analysis (Eq.3), it is explained the covariance between the set of attributes of the study, limited in terms of unobservable factors. For added strength, we used the MCD (Minimum Covariance Determinant) to estimate the matrix of the sample covariance, whose goal was to find a subset *h* of observations that makes the determinant of the classical covariance matrix minimum, being the average local estimator h of these points, while the estimator of its scale covariance matrix. The estimation method was the main factor (PISON et al., 2003).

For a better interpretation of the RFA results, we used the oblique rotation method (*oblimin*) since it was alleged the existence of an association between the factors. The numbers of components and factors PCA and RFA, respectively, were determined by Kaiser's criteria (1958), factors with an eigenvalue greater than or equal to 1 (one) of the parallel analysis of Horn (1965), the average values of the generated eigenvalues by simulation compared to real eigenvalues. Additionally, for the selected components and factors on PCA and RFA, we considered only the attributes associated with these components with coefficients higher than 0.35 and factors with factor loadings greater than 0.4 (LATTIN et al., 2011). As the adequacy of data was evaluated by the Kaiser criteria - Meyer - Olkin (KMO): we take into account the inverse of the close correlation matrix of a diagonal matrix; the closer to 1 (one), the greater the suitability.

Being $X=[X_1, X_{2,...,}X_p]^T$ an aleatory vector with *p* attributes, the sample covariance matrix S_{pxp} with eigenvalues $\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_p \geq 0$. The Eq.1 describes the PCA model in its matrix form

$$\begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_p \end{bmatrix} = \begin{bmatrix} e_{11} & e_{12} & \cdots & e_{1p} \\ e_{21} & e_{22} & \cdots & e_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ e_{p1} & e_{p2} & \cdots & e_{pp} \end{bmatrix}^T \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_p \end{bmatrix} \Rightarrow Y = O^T.X\ , \qquad (1)$$

where $e_i^T = (e_{i1}, e_{i2} ..., e_{ip})$ is an eigenvector with a dimension of 1*xp* with $e_i^T \cdot e_i = 1$, e $e_i^T \cdot e_j = 0$ being $i \neq j$ for the last condition and *i* and *j* varying from 1 to *p* for both conditions.

Being μ the mean vector of X_{px1}, the matrix of variance and covariance sample S_{pxp} and a vector of common latent factors not observable F_{mx1}; according to Mingoti (2005) and Hair *et al*. (2009), the factor analysis model can be described by the Eq. 2:

$$\begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_p \end{bmatrix}_{px1} = \begin{bmatrix} \mu_1 \\ \mu_2 \\ \vdots \\ \mu_p \end{bmatrix}_{px1} + \begin{bmatrix} l_{11} & l_{12} & \cdots & l_{1m} \\ l_{21} & l_{22} & \cdots & l_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ l_{p1} & l_{p2} & \cdots & l_{pm} \end{bmatrix}_{pxm} \begin{bmatrix} F_1 \\ F_2 \\ \vdots \\ F_m \end{bmatrix}_{mx1} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_p \end{bmatrix}_{px1}, \quad (2)$$

where l_{ij} are the factorial loads, F_j are the common factors and ε_i are the random mistakes or specific factors, in which $j = 1,..,m$ and $i = 1,..., p$.

Therefore, it can be rewritten as (Eq. 3)

$$X = \mu + LF + \varepsilon \quad \Rightarrow \quad X - \mu = LF + \varepsilon, \quad (3)$$

where the matrix L_{pxm} is the matrix of factorial loads associated to the variable i-eth X_i and to the j-eth the factor F_j .

In the second part of the analysis, the structural equations model (SEM) was constructed considering two aspects: First, the existing relationships between attributes of the soil and the components of sugarcane production, obtained through previous studies such as Silva *et al.* (2002), Hartemink (2006), Braunack (1991), Lopes and Guilherme (2000). Second, the application of PCA and RFA techniques in the formation of latent factors (latent variables or variables not observable in the field), according to (BRAHIM *et al.*, 2011).

The general model of structural equations analysis is composed of the measurement models, which interrelate the attributes observed in the field with their respective latent factors, and, a structural regression model that represents the relationships between the latent factors. The structural regression model with r dependent latent factors $\eta^T = (\eta_1, \eta_2, \ldots, \eta_r)$, with a coefficients matrix of η of the structural model $B_{r\times r}$, s independent latent variables $\xi = (\xi_1, \xi_2, \ldots, \xi_s)$, with coefficients matrix of ξ of the structural model $\Gamma_{r\times s}$ and $\zeta^T = (\zeta_1, \zeta_2, \ldots, \zeta_r)$ the measurement errors of the structural model, is described according to Bollen (1989) by the equation (Eq.4)

$$\eta = B\eta + \Gamma\xi + \zeta \,. \quad (4)$$

The SEM is a generalized modeling technique, with had as its goal to test and validate theoretical models that define causal and hypothetical relationships between variables studied. Such relationships were measured by the model parameters that represent the effect size of the independent attributes over the dependent attributes (MARÔCO, 2010; SCHUMACKER and LOMAX, 2010). In Figure 2 we have the application procedures of the SEM.

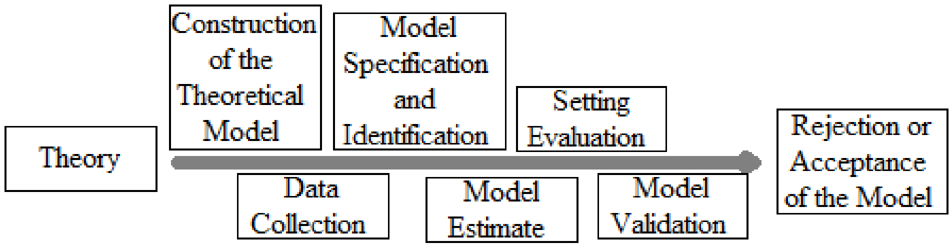

Figure 2 – Steps of the analysis of the structural equations. (Source: Marôco (2010).

To avoid problems of multivariate normality deviations, we used the estimation method of maximum likelihood with a correction or adjustment of the statistic χ^2, as well as robust standard errors, calculated based on multivariate kurtosis (SATORRA; BENTLER, 1988, 2001). The measures used to assess the quality of model fit were: chi-squared value of the overall adjustment test (χ^2), ratio between the chi-square value of the overall adjustment test and the degrees of the freedom of the model (χ^2/gl), comparative fit index (*CFI*), setting quality index (*GFI*), Tucker-Lewis index (*TLI*), parsimony adjustment quality index (*PGFI*) and root of the mean square error of approximation (*RMSEA*).

Data analyzes were conducted for the layers from 0.0 to 0.20 m and from 0.20 to 0.40 m, separately, in order to compare the results between the soil layers. All analyzes were done using the statistical software R version 3.1.1 (R CORE TEAM, 2017), and, for the adjustments of the structural equations models, the function *sem* from the *lavaan* package was utilized.

3 Results and discussion

3.1 Preliminary analysis

Initially, the data was analyzed in terms of their descriptive statistics (Table 1). It can be seen that asymmetry and kurtosis values of the attributes in depth from 0 to 0.20 m were near 0.00 and 3.00, respectively. In other words, the probability distribution of the attributes approached or have a normal distribution. The only exception is for the OC attribute, which showed skewness of 0.29 and kurtosis 2.37, which indicates a probability distribution with right asymmetry (0.29> 0.00) as well as a more flattened shape of distribution or platykurtic (2.37 <3.00), which shows a deviation from normality.

Regarding the depth 0.20 to 0.40 m (Table 1), it was noted atypical asymmetry values and kurtosis together for pHCa and OC variables with an asymmetry of 0.32 and 0.62, respectively, and kurtosis of 2.58 and 3.89, respectively. This indicates a distribution with a slight asymmetry in the right (0.32> 0) and flattened or platykurtic (2.58 <3.00). For the pHCa a distribution with an asymmetry to the right (0.62> 0) and leptokurtic (3.89> 3.00) for the OC, allowing us to say that these two attributes have some deviation from normality.

Cruz et al. (2010) found a similar behavior in the distribution of organic carbon measurements when studying spatial analysis of physical attributes and organic carbon in a red-yellow Ultisol cultivated with sugarcane in the depth from 0 to 0.20 m, with an asymmetric curve to the right (0.12) and with a flattened shape or platykurtic.

The chemical properties (Table 1) showed higher measurements in the layer from 0.20 to 0.40 m than in the 0 to 0.20 m, for pHCa, pHK and pHw. These results corroborate with the ones from Freitas *et al*. (2010) when they evaluated the physical and chemical properties of a red Ultisol in the sugarcane reform for the production of Oilseeds, pH values in water were 6.3 in the 0 to 0.10 m layer; 6.2 in the layer from 0.10 to 0.26 m and 6.7 in the layer of 0.26 to 0.42 m, showing a pH increase of surface layers for the subsurface layer.

In Carvalho *et al.* (2013), it was studied the productivity of ratoon cane as a function of gypsum and vinasse use, in a dystrophic, medium texture, red-yellow latosol, in a production system without burning. It was observed an increase of 0.4 units of the pH of calcium chloride (increasing from 4.3 to 4.7) in the layer from 0.20 to 0.40, being compared with and without the application of gypsum. This value is considered the ideal value for the cultivation of sugarcane, which according to the authors, would be in the range from 4.5 to 5.0. The fact reinforces the importance of gypsum in reducing soil acidity in the subsurface soil layers.

With regard to physical attributes (Table 1), we observed mean values of soil density equal to 1.56 kg dm^{-3} from 0 to 0.20 m and 1.63 kg dm^{-3} for the layer from 0.20 to 0.40 m, with higher standard deviation for the surface layer. The soil macro-porosity was less than 0.10 in both depths, the minimum amount required for the development of the root system. Oliveira Filho *et al*. (2015) found significant differences in the evaluation of soil physical properties in different years of sugarcane cultivation, with soil density values above 1.5 kg dm^{-3} and macro porosity below 0.10, where it was detected a higher compression over the years. Mechanized harvesting of sugarcane, even held in friability zone, may cause additional soil compression (SEVERIANO *et al*., 2010).

The water content in the depth from 0 to 0.20 m was 0.14 m^3 m^{-3}, while from 0.20 to 0.40 m the corresponding value was 0.09 $m^3.m^{-3}$. It is noted a decrease in the volumetric moisture of the surface layer to the subsurface layer, agreeing with Rodrigues (2014) when he studied the spatial variability of physical, chemical and biological attributes of an eutrophic red latosol, clayey texture and the cane productivity sugar.

Finally, with an average ratio of plant attributes (Table 1), it was noted a production of 89.51 $t.ha^{-1}$, TRS equal to 136 $kg.t^{-1}$, TSS (19.59%) and corresponding purity of 85.48%, lower than those found by Alves et al. (2014), with an average productivity of 112.12 $t.ha^{-1}$, TRS equal to 160.68 $kg.t^{-1}$, TSS (22.52%) and purity measured at 86.60%. Looking at Figure 3, it was detected 11 observations candidate for multivariate outliers by the Mahalanobis Robusta distance (*QQ Plot*), but considering the size of the sample (118 observations), we chose to not take such observations and work with robust estimation methods (PISON et al., 2003).

Table 1 - Descriptive statistics for the attributes of plant and soil in the experiment, on both depths.

Variable	Depth from 0.00-0.20 m						Depth from 0.20-0.40 m					
	Average	Median	Standard Deviation	CV	Asymmetry	Kurtosis	Average	Median	Standard Deviation	CV	Asymmetry	Kurtosis
TSH (t ha^{-1})	89.51	90.34	20.62	23.04	0.14	3.02	89.51	90.34	20.62	23.04	0.14	3.02
POP (pl m^{-2})	6.58	6.56	1.37	20.89	0.05	3.68	6.58	6.56	1.37	20.88	0.05	3.68
TRS (kg t^{-1})	136.00	136.65	16.18	11.90	- 0.46	3.14	136.00	136.65	16.18	11.90	- 0.46	3.15
TSS (%)	19.59	19.38	2.21	11.26	0.17	3.11	19.59	19.38	2.21	11.26	0.17	3.11
PUR (%)	85.48	85.68	3.22	3.77	- 0.44	2.71	85.48	85.69	3.22	3.77	-0.44	2.71
BD (kg dm^{-3})	1.56	1.58	0.09	5.93	-0.24	2.35	1.63	1.62	0.07	4.54	0.24	2.68
UV ($m^3.m^{-3}$)	0.14	0.14	0.03	23.23	0.01	2.67	0.09	0.09	0.02	23.91	0.21	3.01
MA (m^3 m^{-3})	0.09	0.08	0.04	43.18	0.49	2.71	0.06	0.06	0.02	34.95	0.46	2.83
TPV (m^3 m^{-3})	0.36	0.36	0.34	8.65	-0.26	3.49	0.35	0.35	0.03	9.73	0.08	3.63
pHw	5.87	5.90	0.25	4.21	0.24	3.04	6.01	6.00	0.24	3.99	0.08	2.85
pHK	4.82	4.85	0.26	5.32	0.05	2.49	4.97	4.90	0.28	5.67	0.17	2.61
pHCa	4.64	4.70	0.23	5.01	-0.02	2.64	4.75	4.70	0.25	5.25	0.32	2.58
OC (t ha^{-1})	16.77	16.24	1.88	11.21	0.29	2.37	15.25	15.0	1.96	12.86	0.62	3.89

TSH = ton of sugarcane per hectare, POP = plant population, TRS = total recoverable sugar, TSS = total soluble solids, PUR = purity, BD = soil density, UV = volumetric soil moisture, MA = soil macro-porosity, TPV = total porosity of the soil, pHw = hidrogenionic potential in the water, pHK = hidrogenionic potential in potassium, pHCa = hidrogenionic potential in calcium, OC = organic carbon.

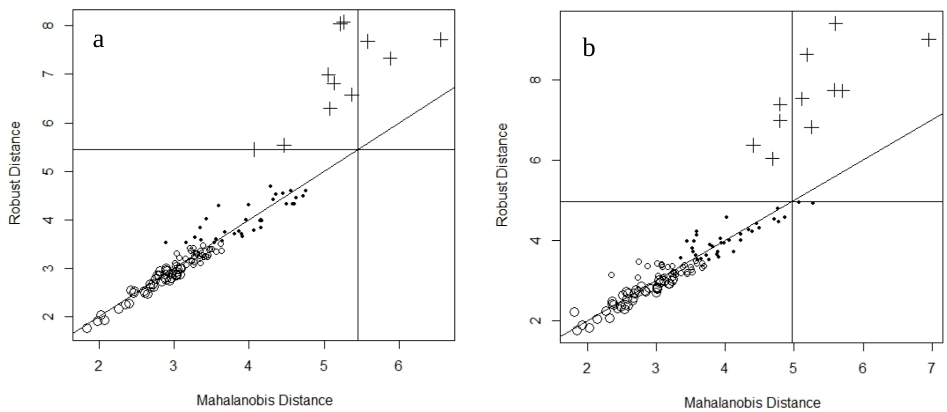

Figure 3 – Graph for the verification of discrepant values (multivariate outliers) for the depths: a) 0.00-0.20 m and b) 0.20-0.40 m.

3.2 Factorial analysis and principal component analysis

The number of the main factors and components in the two depths were determined by the parallel analysis and by the Kaiser method, overlapping in a scree plot (Figure 4). The results suggest the use of 4 components and factors for the depth from 0 to 0.20 m. For a more parsimonious model, we chose to work with 4 components and factors instead of 5 in the depth from 0.20 to 0.40 m. In addition, the sample correlation matrix of the data, in the two depths, is presented in Table 2.

In order to assist in the formation of latent factors in the analysis of structural equations, there were performed analyses of the main components as well as robust factor analysis (Brahim *et al*., 2011). The results of the two techniques were similar to the depths 1 and 2, whereas the coefficients of the main components greater than 0.35 and the factor loadings of factors greater than 0.40.

Figure 5 shows the results of the factor analysis. It can be seen that for the depth of 0 to 0.20 m, factor 1 retained the physical attributes BD, MA and TPV; Factor 2 referred to the chemical attributes pHw, pHK and pHCa; For factor 3, the components were related to yield and technology of sugarcane, TRS, TSS and PUR. Finally, factor 4 referred to the production attributes TSH and POP as well as the chemical attribute OC. Regarding the depth 0.20 to 0.40 m, factor 1 referred to the chemical attributes (pHw, pHK, pHCa), factor 2 to the physical attributes (BD, MA and TPV), factor 3 composed the components of production and technology of sugarcane (TRS, TSS and PUR) and factor 4 referred to the TSH production attribute as well as UV and OC attributes.

Table 2 – Pearson´s correlation coefficients between the attributes of plant and soil of the experiment, on both depths

	POP	TRS	TSS	PUR	BD	UV	MA	TPV	pHw	pHK	pHCa	OC
						Depth from 0.00-0.20 m						
TSH	0.39	-0.03	-0.07	-0.03	0.11	-0.09	-0.02	-0.04	-0.02	0.03	0.07	0.30
POP		-0.18	-0.14	-0.15	0.06	0.00	-0.06	-0.11	0.12	0.07	0.13	0.17
TRS			0.90	0.46	-0.14	-0.23	0.02	0.04	-0.09	-0.12	-0.10	0.05
TSS				0.24	-0.10	-0.25	-0.04	-0.03	-0.13	-0.14	-0.12	0.00
PUR					-0.24	-0.07	0.20	0.19	-0.02	-0.06	-0.05	0.11
BD						0.30	-0.74	-0.74	0.01	-0.02	-0.01	-0.18
UV							-0.19	-0.32	-0.05	-0.08	-0.15	-0.29
MA								0.76	-0.12	-0.08	-0.05	0.09
TPV									-0.09	-0.06	-0.03	0.18
pHaw										0.78	0.72	-0.19
pHK											0.90	0.02
pHCa												0.05
						Depth from 0.20-0.40 m						
TSH	0.39	-0.03	-0.07	-0.03	0.06	-0.17	0.04	-0.08	-0.01	0.13	0.18	0.22
POP		-0.18	-0.14	-0.15	0.01	0.00	-0.04	0.02	0.24	0.23	0.23	0.04
TRS			0.90	0.46	-0.13	-0.14	-0.02	-0.11	-0.21	-0.22	-0.15	0.01
TSS				0.24	0.00	-0.16	-0.10	-0.12	-0.23	-0.23	-0.18	0.04
PUR					-0.22	0.05	0.08	-0.05	-0.11	-0.16	-0.12	-0.07
BD						-0.16	-0.49	-0.56	-0.07	-0.06	-0.04	0.09
UV							0.01	0.34	0.12	0.03	-0.05	-0.33
MA								0.51	0.00	0.11	0.05	-0.10
TPV									0.09	0.12	0.02	-0.28
pHw										0.82	0.79	-0.28
pHK											0.93	0.02
pHCa												0.08

TSH = ton of sugarcane per hectare, POP = plant population, TRS = total recoverable sugars, TSS = total soluble solids, PUR = purity, BD = soil density, UV = volumetric soil moisture, MA = soil macro-porosity, TPV = total porosity of the soil, pHw = hidrogenionic potential in the water, pHK = hidrogenionic potential in potassium, pHCa = hidrogenionic potential in calcium, OC = organic carbon.

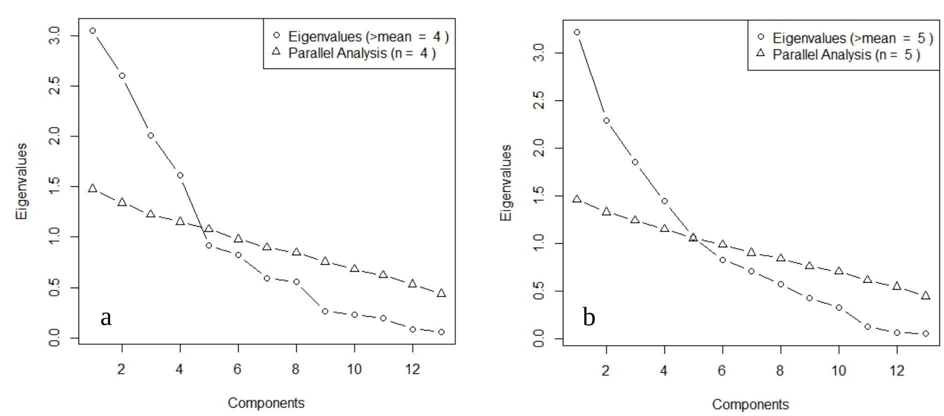

Figure 4 – Scree plots of the analysis of the main components for all the attributes studied in the depths: a) 0.00-0.20 m and b) 0.20-0.40 m.

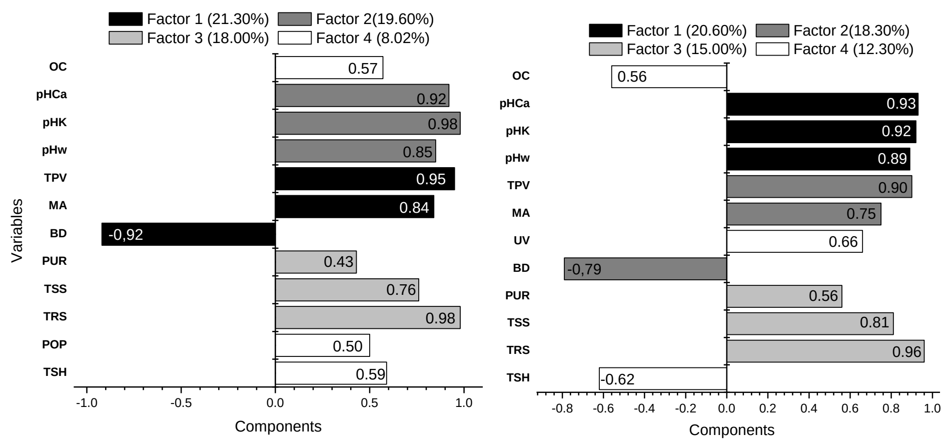

Figure 5 – Factor analysis presented the factor loadings between the variable and the factor. The reference values to the percentage of variation in the original data set retained by the factor in the depths: a) from 0.00-0.20 m and b) 0.20-0.40 m. TSH = ton of sugarcane per hectare, POP = plant population, TRS = total recoverable sugars, TSS = total soluble solids, PUR = purity, BD = soil density, UV = volumetric soil moisture, MA = soil macro-porosity, TPV = total porosity of the soil, pHw = hidrogenionic potential in the water, pHK = hidrogenionic potential in potassium, pHCa = hidrogenionic potential in calcium, OC = organic carbon.

In the two depths, the first three factors explained most of the variation in the original data (around 60%), so that the four factors explain 66% of the data variability in the depth from 0 to 0.20 m as well as 67% in the depth from 0.20 to 0.40 m. It should be noted that in depth from 0 to 0.20 m, Factor 1, corresponding to the physical attributes of the soil, was responsible for the largest proportion of variance explained (21.3%), while in the depth from 0.20 to 0.40 m most of the variance explained (20.6%) was corresponded to factor 1, which represents the soil chemical properties. The suitability of the KMO model measures for depths of 1 and 2 were 0.62 and 0.60, respectively, which may be considered sufficient for the factors so that they could explain the variation in the sample data (CORRAR et al., 2009).

Actually, it has physical attributes related in the greater variability direction in the surface layer, whose measurements indicate incidence of compaction due to machine traffic and its sandier texture (Argisol); and chemical attributes related toward greater variability in the subsurface layer, whose pH values are in the range considered suitable for the cultivation of sugarcane, which may be associated with the effect of the gypsum applied after the first cut (CARVALHO *et al*., 2013). Brahim *et al.* (2011) evaluated the effect of the latent factors in the carbon dynamics of an Ultisol. The latent factors were constructed using as a basis the literature review as well as the factorial analysis with oblique rotation. The chemical properties pH, organic matter, nitrogen and the physical density of the soil attribute composed the first latent factor that explained 38.422% of the variation of the data, while clay, silt and sand physical attributes made up the second latent factor, which explained 28.955% of the variance of the data; whose accumulated explained variance was 67.377%.

3.3 Analysis of structural equations

Based on the results shown in Figure 5 as well as the importance of the physical and chemical attributes to the components of the production culture, three latent factors were formed for each depth. In the depth 0 to 0.20 m, the first latent factor (F1) was formed by the physical attributes: soil density (BD), total porosity of the soil (TPV) and soil macro-porosity (MA). The second latent factor (F2) was formed by the chemical attributes pHK, pHCa and pHw. The third latent factor (F3) was formed by the components of production and technology of the sugarcane, total recoverable sugars (TRS), purity (PUR) and plant population (POP), setting up thus model measures.

For the depth of 0.20 to 0.40 m, the first latent factor (F1) was formed by the chemical attributes pHK, pHCa and pHw. The second latent factor (F2) was based on the physical attributes of soil density (BD), total porosity of the soil (TPV) and soil macro-porosity (MA). The third latent factor (F3) was formed by the components of production and technological culture, total recoverable sugars (TRS), purity (PUR) and plant population (POP), configuring thus the models of measures for that depth.

On both depths, the structural model was constructed to equate the three latent factors, in both being tested the influence of physical and chemical attributes factors on the latent factor response components of production and technology of sugarcane. Figure 6 and 7 shows the paths of diagrams with the estimates of standard parameters. The model parameters were estimated by maximum likelihood robust method.

Both models were well-adjusted to the data, which was what indicated the χ^2 test adjustment (p-values> 0.05) and the adjustment of quality indicators (Table 3) It is worth highlighting that in structural equations modeling the validity of the models is tested (χ^2 test adjustment) under the null hypothesis that the conceptual models explain the "causal" relationships established, being appropriate a model with p-value > 0.05. The evaluation of the adjustment, as well as the adjustment indices were shown in Table 3. According to the reference values of statistics and adjustment of quality indicators of SEM models cited in Marôco (2010), it was concluded that the adjusted models for the depths from 0 to 0.20 as well as 0.20 to 0.40 m provide an acceptable explanation for the observed data.

It is possible to observe that the relative indexes CFI e TLI, which evaluate the quality of the model under analysis in regards to the worst adjusted model and the best adjusted model, were, respectively 0.998 and 1.000 for the model in the depth 0.00 – 0.20 m, and respectively 0.979 and 0.969 for the model in the depth 0.20 – 0.40 m, which indicates a very good adjustment according to Marôco (2010); being the same criterion for the absolut index GFI, corresponding to 1.000 for the two models. Lastly, the population discrepancy index RMSEA measures the disarrange of nested models, and they were equal to 0.01 and 0.056, for the models in the depth 0.00 – 0.20 m and 0.20 – 0.40 m, respectively (Table 3), such index must have value less than or equal to 0.10, according to Marôco (2010).

Table 3 – Statistics and indexes of the adjustment quality of the models of analysis of the production and technological components of the sugarcane in structural equations

Statistics	Depth 0.00 – 0.20 m	Depth 0.20 – 0.40 m
χ^2	20.264 (p = 0.682)	33.005 (p = 0.104)
χ^2/gl	0.840	1.375
CFI	0.998	0.979
GFI	1.000	1.000
TLI	1.000	0.969
PGFI	0.610	0.600
RMSEA	0.010	0.056

χ^2 = chi-squared value of the adjustment test, χ^2/gl = rate between the chi-squared value of adjustment test and the degrees of freedom of the model , CFI = comparative fit index, GFI = goodness fit index, TLI = Tucker-Lewis index, PGFI = parsimony GFI, RMSEA = rot mean square error of approximation.

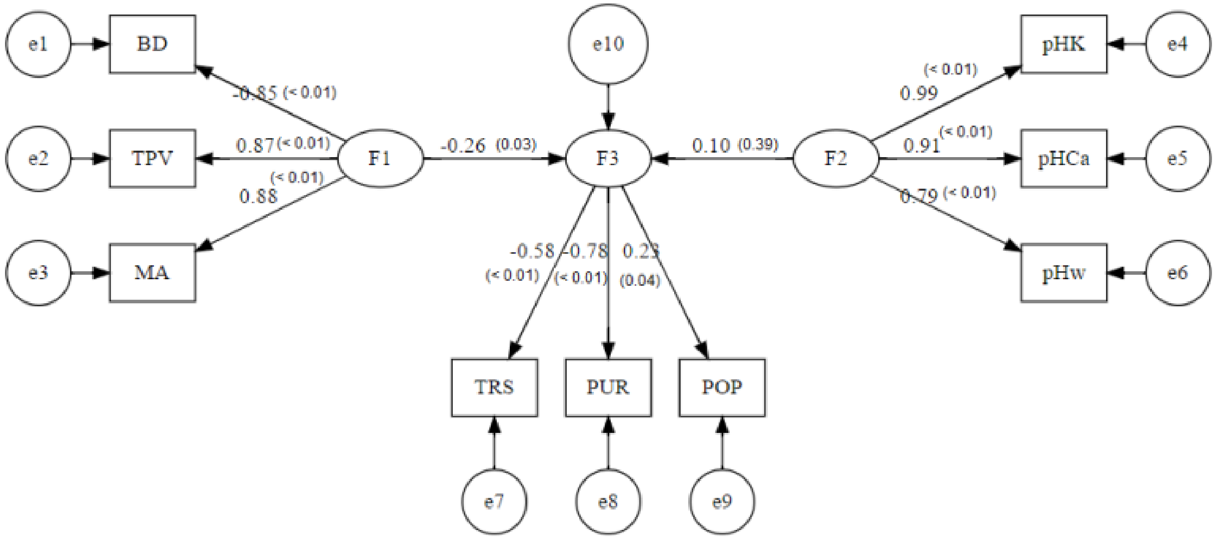

Figure 6 – Diagram of the paths and statistical significances of the of the structural equations analysis for the depths of 0.00-0.20 m.

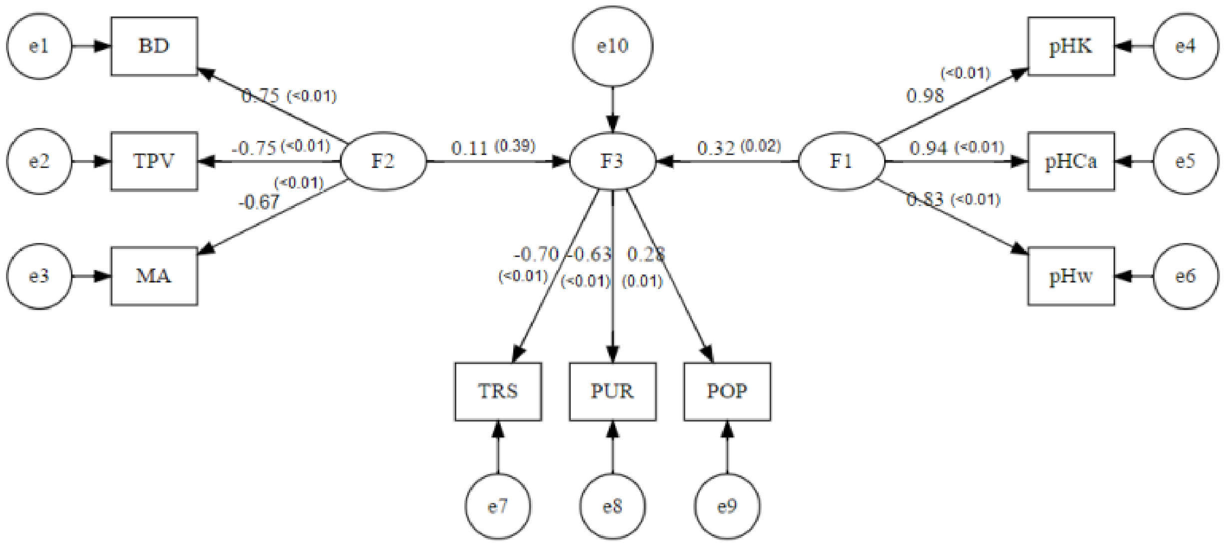

Figure 7 – Diagram of the paths and statistical significances of the of the structural equations analysis for the depths of 0.20-0.40 m.

All parameters for both models are statistically significant at the level of 5% probability (Table 4). For the depth from 0 to 0.20 m, all the attributes were influenced by the corresponding latent factor to the soil physical properties (BD, TPV e MA), and, similarly, all chemical attributes (pHCa, pHK and pHw) were influenced by the latent factor corresponding to the chemical attributes (Figure 6). Regarding the latent factor production and technological components of the sugarcane, this manifested itself strongly in the attributes total reduced sugars and purity (Figure 6).

Regarding the depth from 0.20 to 0.40 m, the latent factor chemical attributes of the soil strongly manifested itself in all its attributes: pHCa, pHK and pHw; and, similarly, all the physical properties (BD, TPV e MA) were strongly influenced by the physical attributes latent factor (Figure 7). Finally, the latent factor production and technological components of the sugarcane manifested itself with greater effect in the attributes total recoverable sugars and purity (Figure 7).

Table 4 – Summary of the results of the adjustments of the Analysis of Structural Equations model

Latent Variables	Depth 0.00 – 0.20 m				Latent Variable	Depth 0.20 – 0.40 m			
	Est.	SE	Value Z	P Value		Est.	SE	Value Z	P Value
F1					F1				
BD	-0.85	0.06	13.92	<0.01	pHk	0.88	0.02	61.39	<0.01
TPV	0.87	0.04	19.68	<0.01	pHCa	0.94	0.02	60.96	<0.01
MA	0.88	0.03	27.62	<0.01	pHw	0.83	0.03	32.33	<0.01
F2					F2				
pHK	0.99	0.01	69.88	<0.01	BD	0.75	0.08	8.82	<0.01
pHCa	0.91	0.03	30.90	<0.01	TPV	-0.75	0.10	-7.95	<0.01
pHw	0.79	0.04	21.53	<0.01	MA	-0.67	0.08	-8.52	<0.01
F3					F3				
TRS	-0.58	0.14	-4.08	<0.01	TRS	-0.70	0.14	-5.00	<0.01
PUR	-0.78	0.16	-4.99	<0.01	PUR	-0.63	0.12	-5.32	<0.01
POP	0.23	0.11	2.04	0.04	POP	0.28	0.11	2.53	0.01
Regression					Regression				
F3					F3				
F1	-0.26	0.12	-2.15	0.03	F1	0.32	0.13	2.36	0.02
F2	0.10	0.12	0.87	0.39	F2	0.11	0.12	0.85	0.39

Est. = Estimate, SE = Standard Error, POP = plant population, TRS = total recoverable sugars, PUR = purity, BD = soil density, MA = soil macro-porosity, TPV = total porosity of the soil, pHw = hidrogenionic potential in water, pHK = hidrogenionic potential in potassium, pHCa = hidrogenionic potential in calcium, F1 = Factor 1, F2 = Factor 2, F3 = Factor 3, Value Z = Value of the statistic Z, P Value = level described.

Regarding structural models for the first depth, the latent factor components of production and technology of the crop, suffered significant negative influence only on the latent factor physical attributes (Table 4), in order of 2.6 (module) times higher than the latent factor chemical properties (Figure 6), which was not statistically significant. On the other hand, for the second depth, only the latent factor chemical attributes (pHCa, pHK and pHw) influenced positively and significantly the latent factor components of production and technology of the sugarcane (Table 4), in order of about 3 times higher than the physical attributes, which were not statistically significant (Figure 7).

Nazmi (2013) applied the analysis of structural equations in order to relate latent factors and the size of the influence of the physical, chemical and yield of wheat. The results showed that the factor chemical attributes of the soil influenced wheat yield components more than the factor physical attributes of the soil, especially for the factors organic carbon of the soil, pH and the equivalent calcium carbonate.

In Williams *et al*. (2016), conceptual models of structural equations were established to evaluate the effects of climatic and edaphic factors on the risk of descent in maize production in four states of the United States of America: Illinois, Michigan, Minnesota and Pennsylvania, in the period 2000 to 2014. The researchers pointed out negative effect of the climate (high temperatures in the summer) upon the stability of maize production, this effect can be strongly mediated by the soil attributes responsive to the agronomic management Alameda *et al.* (2012), applied structural equation modeling (SEM) to describe the causal relationships between the types of treetops, the attributes related to soil compaction and herbaceous production. The results indicated that the treetop affects the attributes of soil compaction and their effects in herbaceous production are produced primarily by a positive effect of the organic matter (with a depth of 2 – 7 cm) and a negative effect of the penetration resistance (with a depth of 9 – 14 cm).

In this study, the reason the physical attributes factor influence significantly and negatively the factor components of production and technology of sugarcane, in the 0 to 0.20 m depth, is associated with soil compaction due to machine traffic (SEVERIANO *et al*., 2010). According to Souza *et al*. (2012) and Carvalho *et al*. (2014), sugarcane areas in highly mechanized systems can modify the physical properties of the soil, which may cause soil compaction; and the reform of the sugarcane plantation after the fifth cut (depending of the variety and/or productivity), represents a crucial stage in the longevity of the sugarcane agricultural crop. On the other hand, in the layer from 0.20 to 0.40 m, chemical attribute factor significantly and positively influenced the factor components of production and technological of the sugarcane. It is important to note the gypsum was applied after the first cut, correcting soil acidity in this subsurface (CARVALHO and RAIJ, 1997; CAIRES *et al*., 1999; FOLTRAN, 2008).

Therefore, it is possible to say that the structural equations models provided an adequate explanation for the simultaneous interaction between the soil attributes and the components of sugarcane production. These models may also be useful for studies of the components of other agricultural crops production, when it is desired to obtain interactions with the soil attributes.

Conclusions

The models of factorial analysis and the principal component analysis were adequate to reduce the dimensionality of the data of soil depths studied, as well as to describe the structure of variance and covariance of these through components and factors associated with the attributes studied. The theoretical models of the structural equations analysis for the depths from 0 to 0.20 m and 0.20 to 0.40 m were adjusted. Such models provided an adequate explanation for the simultaneous interaction between the soil attributes and the components of sugarcane production.

According to the proposed structural equation model, it was found that the depth from 0 to 0.20 m, the factor components of yield and technology of the sugarcane showed a negative and significant influence of the factor soil physical properties, showing the effect of compaction due to machine traffic (3rd cut).

In the depth of 0.20 to 0.40 m, the factor components of production and technology of the sugarcane was influenced positively and significantly by the soil chemical attributes factor associated with soil acidity; a beneficial effect of gypsum application after the first cut was suggested to explain this positive effect.

Finally, the conceptual models of structural equations analysis constructed in this study can be considered as base models in studies in the agricultural area, including other soil classes, when the purpose is to model agricultural crops performance data, to better understand their relationship with the group of physical and chemical attributes of the soil.

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ARAÚJO. E. G., CARVALHO, M. P., MONTANARI, R., ANDREOTTI, M. CARDOZO, N. P., PANOSSO, A. R. Modelagem das relações entre os atributos do solo e a produção de cana-de-açúcar com uso de equações estruturais. *Rev. Bras. Biom*., Lavras, v.36, n.2, p.489-511, 2018.

- *RESUMO: A cana-de-açúcar é a principal fonte de energia renovável no Brasil e com um futuro promissor em todo o mundo, tanto na questão econômica quanto na ambiental, o que justifica cada vez mais as pesquisas sobre o entendimento do seu comportamento no sistema solo-planta. Objetivou-se explicar a produtividade da cultura da cana-de-açúcar por meio de fatores latentes formados a partir de atributos químicos e físicos de um Argissolo Vermelho Distrófico abrúptico textura média/argilosa, simultaneamente, utilizando a técnica de modelagem de equações estruturais. Para a coleta de dados da planta e do solo, foram definidos 118 pontos amostrais de uma grade regular, nas profundidades 0 a 0,20 m e 0,20 a 0,40 m. Os três primeiros fatores compuseram os atributos químicos, físicos e de produção com explicação em torno de 60 % da variabilidade dos dados. Os componentes de produção e tecnológicos da cana-de-açúcar foram influenciados significativamente e negativamente pelo fator latente atributos físicos na camada de 0 a 0,20. Entretanto, houve influência significativa e positiva do fator latente atributos químicos associados à acidez, na camada de 0,20 a 0,40 m*.

- *PALAVRAS-CHAVE: Fatores; modelos; biomassa; Argissolo.*

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