

Modeling the amount of mineralized carbon from swine manure and wheat straw

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Abstract

A method capable of reducing the environmental damage caused by swine manure and the soil enrichment with nutrients is based on the use of these residues together with the crops straw in soils for agricultural production. Through the use of carbon mineralization curves, it is possible to determine the best intervals for the use of organic matter from manure to better adapt the use of soil and crops. Dynamics of carbon present in manure can help in the selection of the best management. The objective of this study was to compare the fit of three nonlinear models that describe the carbon mineralization in soil over time, in addition to assessing the carbon stock of wheat straw alone and combined with swine manure. The experiment was carried out in a randomized block design, with four replications and eight treatments. The following treatments were tested: T1 – soil (S), T2 – soil + straw on the surface (SSUR), T3 – soil + incorporated straw (INCS), T4 – soil + manure on the surface (MSUR), T5 – soil + incorporated manure (INCM), T6 – soil + incorporated manure + straw on the surface (INCMSSUR), T7 – soil + incorporated manure + incorporated straw (INCMINCS), T8 – soil + straw on the surface + manure on the surface (SSURMSUR). Soil samples were incubated for 95 days, and ten observations were made throughout time. Carbon mineralization was described using nonlinear models Cabrera, Stanford and Smith and Juma, considering the autoregressive error structure AR (1), when necessary. The comparison of fit of models was made using the Akaike Information Criterion (AIC). The description of carbon mineralization of wheat straw and swine manure carried out by nonlinear models was satisfactory. The Cabrera model was the most appropriate to describe all treatments. The Stanford and Smith model, most used in the literature to describe the mineralization of organic waste in soil, did not achieve better results in relation to the other nonlinear models for the treatments under study. In general, the treatments with straw on the surface resulted in a larger carbon stock in the soil, and with the addition of manure to the wheat

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straw, the carbon stock was lower, so it is interesting for producers to evaluate, according to their production targets, which is the best strategy to be adopted for the use of waste.

Keywords: Organic waste. Stanford and Smith model. Cabrera model. Juma model.

Introduction

Pig farming is an important agricultural activity that contributes significantly to the Brazilian economy, generating employment and income for producers and providing meat for domestic supply and for export. The participation of pig farming in agribusiness is relevant, considering that Brazil is the 4th largest pig producer in the world (EMBRAPA, 2018). In 2019, Brazilian pig production was expected to exceed 4 million tons, with exports of approximately 700 thousand tons (CONAB, 2019). Due to the high demand for pork, new farmers have appeared in different regions of Brazil. However, not all of them use the proper management for the disposal of residues generated by the animals, and as a consequence these residues are often the cause of river pollution. Several problems may arise from contamination of water courses. The high load of nutrients in water bodies, for example, can lead to eutrophication, mainly by the P and N present in the chemical composition of the material (CADONÁ, 2017). However, due to these problems, means were developed for the correct use of residues generated by pigs, representing an alternative to take advantage of the nutritional quality of liquid manure, mainly N, and use it as an organic fertilizer in agriculture. A practice that is becoming very common in Southern Brazil is the use of organic residues on the straw of winter crops, such as wheat, in no-till system for the production of corn and beans (LUZ, 2007).

No-till is a production system that brings various benefits to agriculture, providing several improvements in crops planting, in which straw has important functions, such as to protect the soil surface against direct action of the sun, increase soil organic matter content and reduce the impact of raindrops. For these reasons, it is important to conduct studies related to the decomposition of straw and liquid waste to seek improvements in the management of the system, since the speed of straw decomposition is important regarding whether the soil is bare or covered.

There is a colossal and varied number of microorganisms in soil, which are benefited from the input of organic matter through manure and straw, so that both carbon mineralization and immobilization can occur in soil, and this can vary depending on the relationship of several aspects of this material, such as: pH, chemical composition, C:N ratio, quantity, quality and incorporation or not of the added material. Nevertheless, decomposition also depends on several other factors present around the material to be decomposed, such as: the types of microorganisms in the area, the type of soil, the vegetation, that is, the entire soil ecosystem influences directly or indirectly on the decomposition of the material (MOREIRA et al., 2013).

The material to be decomposed contains labile compounds in its chemical composition, which are mineralized at the beginning of the decomposition, since they represent the most soluble fraction of the material used, and as this fraction decomposes, mineralization tends to become slower because microorganisms have more difficulties in mineralizing the resistant fraction of the remaining compounds (GIACOMINI et al., 2008; PULROLNIK, 2009). The behavior of the mineralization curve can be described by mathematical functions that constitute nonlinear regression models (FERNANDES et al., 2011; SILVA et al., 2019b; ZEVIANI et al., 2012; SOUZA et al., 2010; SILVA et al. 2020).

The Stanford and Smith nonlinear model is the most used to describe the mineralization of organic matter in soil (FERNANDES et al., 2011; BARRETO et al., 2010; MARTINES et al., 2006; ANDRADE et al., 2013; ANDRADE et al., 2015; NUNES et al., 2016; PAULA et al., 2013).

When the decomposition has two phases of mineralization, due to chemical composition, the Cabrera model has shown a good fit (SILVA et al., 2019b; 2019c).

Therefore, given the direct importance of soil management more favorable to the production of agricultural crops, it becomes relevant the understanding of the dynamics that involves the decomposition of organic residues in soil, and for this it is important to know the carbon mineralization curves over time.

In order to improve the productive capacity of the soil, it is necessary to understand the carbon dynamics during the decomposition of crop residues. The goal of this study was to compare the fit of three nonlinear models – Stanford and Smith, Cabrera and Juma – to describe the carbon mineralization in soil with wheat straw and swine manure over time, as well as to evaluate C mineralization of wheat straw alone and in combination with swine manure.

Material and methods

Data used for fitting the models were extracted from Luz (2007), and correspond to the results in means of an experiment that evaluated carbon mineralization in different treatments involving doses of swine manure in soil and wheat straw. The experiment was carried out in Santa Maria, state of Rio Grande do Sul, in the Soil and Environment Microbiology Laboratory, Soil Department, University of Santa Maria.

The soil used is classified as arenic dystrophic red argisol, and was collected in the 0-10 cm layer on July 1, 2006. The area in which the soil was collected had been grown with corn since 1998, in no-till system. After removing the crop residues remaining on the soil surface, soil was collected and transported to the laboratory for homogenization and sieving through 4.0 mm mesh, remaining stored moist in plastic bags, at room temperature, until incubation. The contents of C and N were determined by dry combustion, and the excess ^{13}C , by mass spectrometry. Values of the contents of C and N were: 42.7% and 0.65% (C/N = 65) respectively, and the excess ^{13}C , 2.016%. There was determination of the nitrate content ($\text{NO}_3\text{-N}$) of the water-soluble fraction of straw, by colorimetry, representing 16.2% total nitrogen content. Liquid swine manure was collected from a farm in the city of Restinga Seca, state of Rio Grande do Sul. The levels of organic C, total N, ammonia N, dry matter and pH values of swine manure were determined according to the methodology described in Tedesco et al. (1995).

The experiment was a randomized block design with four replications and the following treatments: T1 – soil (S), T2 – soil + straw on the surface (SSUR), T3 – soil + incorporated straw (INCS), T4 – soil + manure on the surface (MSUR), T5 – soil + incorporated manure (INCM), T6 – soil + incorporated manure + straw on the surface (INCMSSUR), T7 – soil + incorporated manure + incorporated straw (INCMINCS), T8 – soil + straw on the surface + manure on the surface (SSURMSUR). The amount of mineralized carbon was evaluated at 2, 4, 6, 9, 15, 25, 40, 60, 80, 95 days of incubation, totaling 10 observations.

In addition to these treatments, three flasks containing the NaOH solution (blank) were incubated to capture the C-CO₂ from the internal atmosphere of the flasks of all treatments. Thirty-two experimental units were set up (8 treatments and 4 replications), consisting of acrylic containers, 5.0 cm high and 5.0 cm diameter, with a capacity of 110.0 mL, added with soil of each treatment. To each acrylic container was added 131.0 g soil with 15.0 % moisture, equivalent to 117.8 g soil dried at 105 °C. Moisture was maintained at field capacity.

The C-CO₂ released in each treatment was captured in 10.0 mL of a 1 mol L⁻¹ NaOH solution placed in a 37.0 mL glass vial, suspended on the top of each flask. The excess NaOH in each sampling interval was titrated with a solution of 1 mol L⁻¹ HCl, after precipitation of carbonate with a solution of 1 mol L⁻¹ BaCl₂.

Nonlinear models evaluated are: Cabrera (1), Juma (2) and Stanford and Smith (3) with the following equations:

$$y_i = C_1(1 - \exp(-k_1 t_i)) + k_0 t_i + u_i \quad (1)$$

$$y_i = C_0 t_i / (v + t_i) + u_i \quad (2)$$

$$y_i = C_0(1 - \exp(-kt_i)) + u_i \quad (3)$$

at which:

$u_i = \phi_1 u_{i-1} + \dots + \phi_p u_{i-p} + \varepsilon_i$, with $i = 1, 2, \dots, n$ and n is the number of times measurements were taken;

u_i is the residual of the fit in the i -th time;

ϕ_1 is the autoregressive parameter of order 1;

u_{i-1} is the residual of the fit of time immediately before the i -th measurement;

ϕ_p is the autoregressive parameter of order p ;

u_{i-p} is the residual of the fit in p times before the i -th measurement;

ϕ_i is the blank residue, with normal distribution, $N(0, \sigma^2)$.

In the models, when the residuals are independent, the parameters ϕ_i will be null, and consequently $u_i = \varepsilon_i$ (MAZZINI et al., 2003; GUEDES et al., 2004).

In equations (1), (2) and (3), y_i defines the average value of the mineralized carbon amount in times t_i in days; C_0 indicates the value of the potentially mineralizable carbon amount; C_1 is the easily mineralizable carbon amount; k , k_1 , k_0 are mineralization rates; v is half-life; t_i refers to the time of the i -th measurement, expressed in days (PEREIRA et al., 2005). In addition, the Cabrera model considers two carbon fractions, one that is easily mineralizable (C_1) and the other, resistant (k_0). The Stanford and Smith and Juma models consider only a fraction of carbon that is potentially mineralizable (C_0). The half-life time (v) of the potentially mineralizable carbon for the Stanford and Smith model was estimated by the equation:

$$v = \ln(2)/k. \quad (4)$$

The estimation of the parameters C_0 , C_1 , k , k_1 , k_0 and v of the models was done by the least squares method, through which the nonlinear normal equations system is obtained. In the case of nonlinear models, the system does not present a direct solution, requiring the use of iterative numerical algorithms to obtain the parameter estimates (DRAPER; SMITH, 2014). Several iterative processes are described in the literature, and the algorithm used in the present study was the Gauss-Newton one. This algorithm considers the Taylor series expansion to approximate the nonlinear regression model with linear terms and then apply the method of ordinary least squares to estimate the parameters (MUIANGA et al., 2016; MUNIZ et al., 2017; FERNANDES et al., 2017; RIBEIRO et al., 2018a; RIBEIRO et al., 2018b; SOUSA et al., 2014; SILVA et al., 2019a; OLIVEIRA et al., 2013; PEREIRA et al., 2005; PEREIRA et al., 2009). Calculations of estimates for the sample data, as well as the graphic adjustments and all the computational part involved in the elaboration of this study were obtained using the statistical software R (R DEVELOPMENT CORE TEAM, 2016).

Assuming the normality of residuals, the confidence intervals for parameter estimates were also obtained. According to Draper and Smith (2014), the 95% confidence interval for the β_i parameter is defined as:

$$IC(\beta_i) : b_i \pm t(v;0;0.25) \quad (5)$$

at which:

b_i is the estimate for the parameter (β_i);

$S(b_i)$ is the standard error of the estimate;

$t(v;0;0.25)$ is the upper quantile of the Student's t distribution, considering $\alpha = 5\%$ and the degree of freedom $v = n - d$, where d is the number of parameters of the model.

The Durbin Watson test allowed to verify the presence of residual dependence between the measures, evaluating whether the residual of an observation can be associated with the residual of adjacent observations (HOFFMANN AND VIEIRA, 1998). The Breusch-Pagan test was applied to check the homogeneity of the residuals and the Shapiro-Wilk test, to check normality.

Models were compared as to the goodness of fit and it was indicated which model was the most appropriate to describe the mineralization curve as a function of time. The following criteria were used:

- i. Coeficiente de determinação ajustado, R^2_{aj} :

$$R^2_{aj} = 1 - \frac{(1-R^2)(n-1)}{(n-d)}; \quad (6)$$

at which

R^2 is the coefficient of determination;

n is the number of observations; and

d is the model number of parameters. One model should be preferred over the other if it has a higher R^2_{aj} .

- ii. Akaike Information Criterion, AIC

$$AIC = 2\log L(\tilde{\theta}) + 2p \quad (7)$$

at which

$L(\tilde{\theta})$ is the maximum of the likelihood function;

p is the number of parameters in the model; and

\log is the natural logarithm operator. Between two models, the lower the AIC value, the better the model fits the data.

- iii. Residual standard deviation, RSD

$$RSD = \sqrt{MSE} \quad (8)$$

at which

MSE is the mean squared error.

RSD is proportional to the mean squared error, so lower values indicate better fits.

Carbon mineralization of wheat straw was calculated based on the C_0 estimates of the Stanford and Smith and Juma models. Carbon mineralization for treatments using straw alone was calculated based on the equation:

$$MC = \left(\frac{C_{O\text{ straw}} - C_{O\text{ soil}}}{C_{\text{added}}} \right) 100 \quad (9)$$

And for treatments with the use of straw combined with manure, based on the equation:

$$MC = \left(\frac{C_{O\text{ straw+manure}} - C_{O\text{ manure}}}{C_{\text{added}}} \right) 100 \quad (10)$$

at which

MC is carbon mineralization of the straw (% added carbon);

$C_{O\text{ straw}}$ is the estimate of the potentially mineralizable carbon of the straw by the Stanford and Smith or Juma models.

$C_{O\text{ soil}}$ is the estimate of the potentially mineralizable carbon of the soil by the Stanford and Smith or Juma models.

$C_{O\text{ straw+manure}}$ is the estimate of the potentially mineralizable carbon of the treatments with straw + manure by the Stanford and Smith or Juma models.

$C_{O\text{ manure}}$ is the estimate of the potentially mineralizable carbon of manure by the Stanford and Smith or Juma models.

C_{added} is the added carbon (Mg kg⁻¹) with the straw, which was 2,135 Mg kg⁻¹ dry soil.

Results and discussion

The Shapiro-Wilk, Breusch-Pagan and Durbin-Watson tests were applied to analyze the experimental errors (Table 1). According to the results of the Shapiro-Wilk test, there was residual normality for all models and all treatments. Also, there was residual homogeneity in all models and treatments by the Breusch-Pagan test ($p > 0.05$). In the Durbin-Watson test, there was a correlation in all models and treatments, except for the INCS, MSUR and INCM treatments in the Cabrera model, and for the S treatment in all models. In the treatments in which there was a correlation, fits with first order autoregressive errors AR (1) were used to elucidate the dependence of residuals of these treatments. Since these measurements were performed on the same plot over time, this correlation in errors was expected. Silveira et al. (2018) also reported a correlation in the errors in the fit of the nonlinear model of the cumulative biogas production from swine manure. Paula et al. (2020) also found a correlation in the fit of nonlinear models in data on carbon mineralization of swine manure in the soil.

Table 1 – P-values of the Shapiro-Wilk (SW), Durbin-Watson (DW) and Breusch-Pagan (BP) tests applied to errors of models for mineralized carbon, in mg CO₂/kg, of the analyzed treatments.

Treatments	Model	SW p-value	BP p-value	DW p-value
S	Stanford and Smith	0.2369	0.0722	0.1900
S	Cabrera	0.7060	0.1035	0.7460
S	Juma	0.2684	0.0717	0.1980
SSUR	Stanford and Smith	0.4431	0.2497	0.0380
SSUR	Cabrera	0.5229	0.4271	0.0020
SSUR	Juma	0.2953	0.2483	0.0240
INCS	Stanford and Smith	0.2015	0.5981	0.0020
INCS	Cabrera	0.6539	0.3160	0.0820
INCS	Juma	0.1124	0.7140	0.0020
MSUR	Stanford and Smith	0.1377	0.4170	0.0000
MSUR	Cabrera	0.1595	0.9598	0.1140
MSUR	Juma	0.1321	0.4239	0.0000

(continue...)

Table 1 – Continuation

Treatments	Model	SW p-value	BP p-value	DW p-value
INCM	Stanford and Smith	0.2532	0.1365	0.0040
INCM	Cabrera	0.5405	0.4089	0.3720
INCM	Juma	0.0337	0.0689	0.0060
INCMSSUR	Stanford and Smith	0.6424	0.4077	0.0140
INCMSSUR	Cabrera	0.8138	0.5319	0.0000
INCMSSUR	Juma	0.2244	0.6440	0.0060
INCMINCS	Stanford and Smith	0.4786	0.2684	0.0020
INCMINCS	Cabrera	0.2239	0.5670	0.0460
INCMINCS	Juma	0.2398	0.6673	0.0100
SSURMSUR	Stanford and Smith	0.8461	0.3763	0.0020
SSURMSUR	Cabrera	0.8076	0.6870	0.0320
SSURMSUR	Juma	0.4351	0.3500	0.0200

Source: Elaborated by the authors (2019).

Tables 2, 3 and 4 list the estimates of the model parameters with their respective 95% confidence intervals.

Table 2 – Estimates for the Stanford and Smith model parameters and their respective asymptotic 95% confidence intervals (LL - lower limit and UL - upper limit) in the fit of mineralized C, in mg of CO₂ kg⁻¹, of the analyzed treatments.

Stanford and Smith Model							
S				SSUR			
	LL	Estimates	UL		LL	Estimates	UL
C ₀	452.9373	619.7000	1192.4610	C ₀	1232.7100	1455.4100	1678.1100
k	0.0035	0.0079	0.0126	k	0.0152	0.0235	0.0318
v	55.0116	87.7401	198.0420	v	21.7970	29.4956	45.6017
				φ		0.5430	
INCS				MSUR			
	LL	Estimates	UL		LL	Estimates	UL
C ₀	1572.7470	1763.0000	2028.8900	C ₀	233.4000	423.1000	612.9000
k	0.02432	0.0345	0.04727	k	0.0208	0.0269	0.0746
v	14.6635	20.0912	28.5011	v	9.2915	25.7675	33.3243
				φ		0.8073	
INCM				INCMSSUR			
	LL	Estimates	UL		LL	Estimates	UL
C ₀	281.4854	323.6000	387.8470	C ₀	1422.5470	1631.7418	1840.9360
k	0.0228	0.0360	0.0536	k	0.0180	0.0266	0.0351
v	12.9318	19.2540	30.4011	v	19.7477	26.0581	38.5081
				φ		0.6268	

(continue...)

Table 2 – Continuation

	INCMINCS				SSURMSUR		
	LL	Estimates	UL		LL	Estimates	UL
C_0	1406.6100	1608.8496	18110.8400	C_0	1556.9400	1732.8700	1908.8100
k	0.0322	0.0519	0.0714	k	0.0293	0.0416	0.0539
v	9.7079	13.3554	21.5263	v	12.8598	16.6621	23.6569
ϕ		0.6577		ϕ		0.6453	

Source: Elaborated by the authors (2019).

Table 3 – Estimates for the Cabrera model parameters and their respective asymptotic 95% confidence intervals (LL - lower limit and UL - upper limit) in the fit of mineralized C, in mg of CO_2 , kg^{-1} , of the treatments analyzed.

Cabrera Model							
	S				SSUR		
	LL	Estimates	UL		LL	Estimates	UL
C_1	18.1347	33.5663	48.9980	C_1	223.9000	547.4000	870.9000
k_1	0.0074	0.14886	0.2899	k_1	0.0017	0.0728	0.1439
k_0	2.9612	3.1938	3.4266	k_0	4.3787	8.3028	12.2269
v	2.3909	4.6551	93.6685	v	4.8168	9.5212	407.7336
				ϕ		0.4940	

	INCS				MSUR		
	LL	Estimates	UL		LL	Estimates	UL
C_1	631.6181	761.3340	938.36b87	C_1	117.3150	142.1310	173.5589
k_1	0.0739	0.1052	0.1506	k_1	0.1719	0.3051	0.6565
k_0	8.8246	11.1677	13.0359	k_0	2.4332	2.9236	3.3481
v	4.6025	6.5885	9.3795	v	1.0558	2.2718	4.0322

	INCM				INCMSSUR		
	LL	Estimates	UL		LL	Estimates	UL
C_1	116.2500	132.1170	150.8641	C_1	498.8000	708.0000	917.3000
k_1	0.1002	0.1288	0.1671	k_1	0.0411	0.0752	0.0140
k_0	1.9303	2.1962	2.4334	k_0	6.1881	8.8165	11.4449
v	4.1480	5.3815	6.9176	v			
				ϕ		0.22829	

	INCMINCS				SSURMSUR		
	LL	Estimates	UL		LL	Estimates	UL
C_1	847.6240	955.2640	1062.9000	C_1	865.2448	1024.4400	1183.6400
k_1	0.1000	0.1290	0.1572	k_1	0.0676	0.0913	0.1148
k_0	6.4020	7.9541	9.5060	k_0	5.8002	7.9247	10.0491
v	4.4093	5.3732	6.9314	v	6.0378	7.5919	10.2536
ϕ		0.1615		ϕ		0.2062	

Source: Elaborated by the authors (2019).

Table 4 – Estimates for the Juma model parameters, and their respective asymptotic 95% confidence intervals (LL - lower limit and UL - upper limit) in the fit of mineralized C, in mg of CO₂ kg⁻¹, of the treatments analyzed.

Juma Model							
S				SSUR			
	LL	Estimates	UL		LL	Estimates	UL
C ₀	718.8202	1041.8700	2049.2070	C ₀	1637.8318	1973.8859	2309.9400
v	121.2930	206.2100	476.3200	V	30.2050	48.9256	67.6456
				φ		0.5006	
INCS				MSUR			
	LL	Estimates	UL		LL	Estimates	UL
C ₀	2111.3563	2485.1280	2858.9008	C ₀	247.3000	479.7000	712.1000
v	23.4403	38.9656	54.4908	V	-10.2374	22.3519	54.9411
φ		0.7673		φ		0.6609	
INCM				INCMSSUR			
	LL	Estimates	UL		LL	Estimates	UL
C ₀	365.9460	461.5983	557.2490	C ₀	1867.6131	2140.1080	2412.6040
v	17.1430	37.7030	58.2630	V	27.4885	39.9532	52.4170
φ		0.7152		φ		0.5417	
INCMINCS				SSURMSUR			
	LL	Estimates	UL		LL	Estimates	UL
C ₀	1724.0700	1900.0640	2076.0500	C ₀	1952.0700	2119.2298	2286.3800
v	10.9190	15.7996	20.6790	V	16.6654	21.8408	27.0160
φ		0.5455		φ		0.5005	

Source: Elaborated by the authors (2019).

Considering the confidence intervals for the estimate of parameter (C₀) in the Stanford and Smith model, there was an overlap in the confidence intervals of the treatments SSUR, INCMSSUR, INCMINCS and SSURMSUR, indicating that all treatments had the same amount of potentially mineralizable carbon, which were higher than the amount in treatments S, INCS, MSUR and INCM. These results occur due to the increase in the carbon content from straw and/or manure available to microorganisms, thus stimulating the mineralization of the added carbon, as well as the degradation of soil organic matter (FERNANDES et al. 2011).

In the Cabrera model, considering the confidence intervals for the estimation of parameter (C₁), the amount of easily mineralizable carbon followed the order: S<MSUR=INCM<SSUR=INCS=INCMSSUR=INCMINCS=SSURMSUR. Taking into account the parameter (k₀), there was an overlap between the confidence intervals of the MSUR and INCM treatments, thus, they had the same mineralization rate as the resistant carbon. The INCS, SSUR, INCMSSUR, INCMINCS and SSURMSUR treatments had the highest rate of resistant carbon mineralization in relation to the other treatments.

In the Juma model, considering parameter (C₀), the SSUR and INCS treatments had the same amount of potentially mineralizable carbon, as there was an overlap in the confidence intervals. The same occurred in the INCMSSUR and INCMINCS treatments, as well as in the MSUR and INCM treatments, that showed the same amount of potentially mineralizable carbon. According to Silva et al. (2019b) and Giacomini et al. (2008), the result presented shows that there is a fraction of C in the

residues that is difficult to decompose, regardless of whether they are incorporated into the soil or on the surface, whether they are in greater contact with the microorganisms.

Considering the confidence intervals for the estimation of parameter (v), half-life, in the Stanford and Smith model, there was no difference between the time spent to mineralize half of the potentially mineralizable carbon between the SSURMSUR and INCMINCS treatments. The S treatment in relation to the SSUR, INCMSSUR, INCMINCS and SSURMSUR treatments took longer to mineralize half of the potentially mineralizable carbon (PMC), this happens because there were no nitrogen supplied by manure and straw to the soil and, consequently, the growth and development of microorganisms were not stimulated (SAVIOZZI et al. 1997).

In the Cabrera model, taking into account the confidence intervals for the estimation of the half-life, there was a difference between the INCM and MSUR treatments, in which manure on the surface spent less time compared to the incorporated residues for half of the (C_1) to be mineralized.

In the Juma model, considering the confidence intervals for the estimation of parameter (v), treatment S spent more time than the others to mineralize half of (PMC), due to the lack of nitrogen from manure and straw (SAVIOZZI et al. 1997).

All models had excellent fits in all treatments, since the values of the adjusted coefficient of determination (R^2_{aj}) were above 95%, as can be seen in Table 5. In addition, for each treatment, similar values were obtained for the residual standard deviation of the models (Table 5). In the fit of nonlinear models, Stanford and Smith and Cabrera, for carbon mineralization of swine manure and oat straw in soil, Silva et al. (2019b) obtained values of R^2_{aj} greater than 0.97, indicating that the models adequately describe the data.

For all treatments, the most suitable model was the Cabrera one, as it presented the lowest AIC values and the highest R^2_{aj} values compared to the Stanford and Smith and Juma models; thus, these treatments present mineralizable carbon fractions with exponential behavior and more resistant fractions, with constant mineralization. The fit of the Cabrera model to the treatments can be seen in Figures 1 and 2.

In the literature, the Stanford and Smith model is widely used to describe the carbon mineralization in soil (FERNANDES et al., 2011; BARRETO et al., 2010; MARTINES et al., 2006). However, in the present study, this model did not obtain a better fit in the treatments under study, in relation to the Juma and Cabrera models.

Table 5 – Estimates of the selection criteria: adjusted coefficient of determination (R^2_{aj}), Akaike Information criterion (AIC) and residual standard deviation (RSD) for the models fit in the description of mineralized carbon, in $\text{mg CO}_2 \text{ kg}^{-1}$, of the treatments analyzed.

Treatment	Model	Selection criteria		
		R^2_{aj}	AIC	RSD
S	Stanford and Smith	0.9935	78.0287	9.91
	Cabrera	0.9987	70.2000	6.48
	Juma	0.9938	77.3315	9.57
	Stanford and Smith	0.9855	112.3871	58.51
SSUR	Cabrera	0.9985	103.4000	117.77
	Juma	0.9902	108.3809	46.61
	Stanford and Smith	0.9976	114.3000	93.10

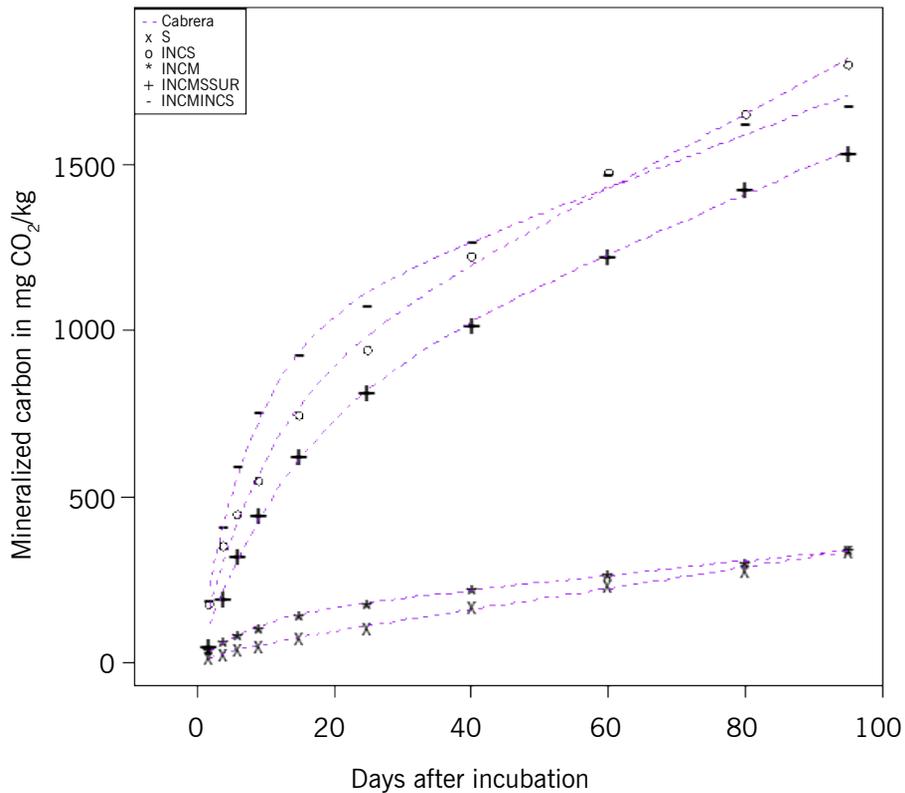
(continue...)

Table 5 – Continuation

Treatment	Model	Selection criteria		
INCS	Cabrera	0.9963	104.1344	35.38
	Juma	0.9872	111.2599	70.49
	Stanford and Smith	0.9875	101.9000	40.75
MSUR	Cabrera	0.9885	83.4880	12.60
	Juma	0.9909	98.9000	32.12
	Stanford and Smith	0.9980	79.2000	21.60
INCM	Cabrera	0.9976	65.7400	5.18
	Juma	0.9805	85.2416	17.76
	Stanford and Smith	0.9858	113.4718	66.07
INCMSSUR	Cabrera	0.9991	101.9000	119.90
	Juma	0.9927	107.7196	46.29
	Stanford and Smith	0.9665	122.9191	109.2511
INCMINCS	Cabrera	0.9946	106.7994	37.01
	Juma	0.9865	113.3056	61.36
	Stanford and Smith	0.9813	118.1900	85.18
SSURMSUR	Cabrera	0.9951	107.9176	39.44
	Juma	0.9933	108.9506	47.94

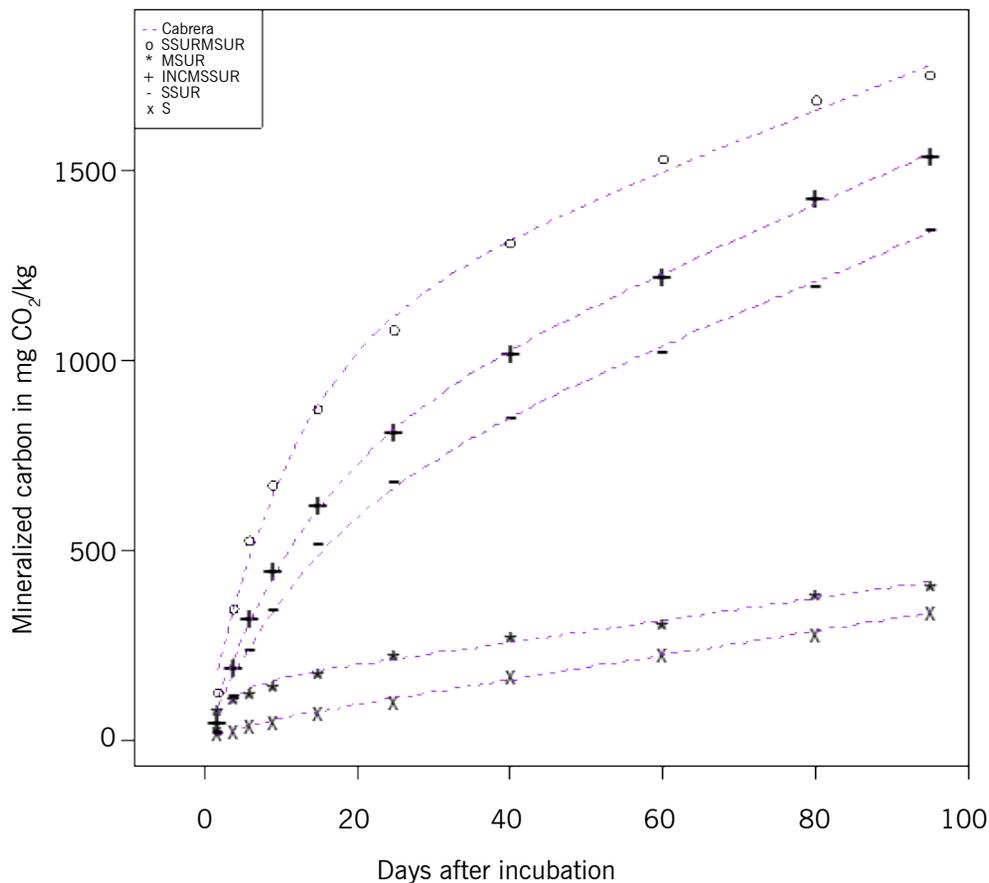
Source: Elaborated by the authors (2019).

Figure 1 – Cabrera model fit to carbon mineralization, in mg of CO₂.kg⁻¹, of the residues incorporated in soil according to incubation time.



Source: Elaborated by the authors (2019).

Figure 2 – Cabrera model fit to carbon mineralization, in mg of CO₂.kg⁻¹, of the residues on the surface in soil according to incubation time.



Source: Elaborated by the authors (2019).

Table 6 lists the percentages of carbon mineralization (CM) of wheat straw alone and combined with swine manure. Based on the Stanford and Smith model, the carbon percentage of straw on the surface was approximately 39.0 %, and straw incorporated into the soil was approximately 53.0 %. Adding manure, straw mineralized approximately 60.0 %, indicating that the manure favored mineralization of the carbon of the straw, regardless of whether the straw is incorporated or on the soil surface. This increase in mineralization of straw incorporated in relation to straw on the surface may be related to the fact that microorganisms have a greater facility to decompose the materials incorporated into the soil (FERNANDES et al. 2011). In cases where the farmer decides to perform straw management and maintain this carbon stock as a soil cover in the area, it is interesting that the straw is not easily decomposed, and according to the results presented, in this case it is more feasible to use straw on the surface of the soil without using manure, as it would increase carbon mineralization of the straw, which could hinder management and leave the soil more exposed because of the consumption of carbon stock. On the other hand, the addition of manure to wheat straw can benefit the crop present in the area, as pig manure contains several nutrients in its composition, in addition to a large amount of nitrogen, that is quite required by most agricultural crops.

Table 6 – Carbon mineralization (CM) of wheat straw (% added carbon).

Treatment	Stanford and Smith	Juma
SSUR	39.14%	43.65%
INCS	53.55%	67.60%
INCMSSUR	61.27%	78.61%
INCMINCS	60.19%	67.37%
SSURMSUR	61.34%	76.79%

Source: Elaborated by the authors (2019).

Based on the Juma model, straw on the surface mineralized approximately 43.0 % added carbon; and the incorporated straw, approximately 67.0 %, which was expected, as the incorporation may have stimulated microorganisms to decompose the straw. With the addition of manure to the straw, carbon mineralization of straw was on average 77.0 %, regardless of whether the manure was incorporated or on the surface. This shows once again that the addition of manure to the straw increases carbon mineralization and the release of nutrients and, consequently, decreases the carbon stock that could be used as soil protection against weathering and invasive plants. Another noteworthy point is that the mineralization of straw in these treatments, with an average of 77%, obtained high rates of mineralization, and from an environmental point of view this is not good, as it causes an environmental impact due to the amount of CO₂ released into the atmosphere. On the other hand, with manure and straw incorporated into the soil, the percentage of mineralization was approximately 67.0 %.

In general, the treatments in which the straw was incorporated into the soil showed a higher percentage of mineralized carbon than the straw on the surface, thus leaving a smaller amount of carbon stock in soil. When pig manure was added to wheat straw, the percentage of mineralized carbon of the straw increased further, so the carbon stock of the straw decreased considerably because of mineralization. This is an interesting point for the farmer to consider in relation to the management of these residues, as the choice of whether or not to add manure to the straw will depend a lot on the production and management system the farmer wants to implant, because with the addition of manure, the soil becomes richer in nutrients over time; however, on the other hand, straw decomposition increased by the addition of manure may not be beneficial to the producer, as there may be an increase in the release of CO₂ into the environment, resulting in environmental impact. Moreover, straw on the soil has functions that are most often beneficial for soil conservation and crop production, such as controlling soil temperature, retaining water, increasing organic matter and controlling weeds.

Conclusions

The description of carbon mineralization of wheat straw and swine manure by nonlinear models was satisfactory.

The Cabrera model was the most suitable to describe the carbon mineralization of all treatments, since these treatments present mineralizable carbon fractions with exponential behavior and more resistant fractions, with constant mineralization.

The Stanford and Smith model, despite being widely used in the literature, did not achieve better results compared to the other nonlinear models evaluated in this study.

The treatments in which the straw was incorporated into the soil showed a higher percentage of mineralized carbon than the ones in which the straw was on the surface, thus leaving a smaller amount of carbon stock in soil. When swine manure was added to wheat straw, the percentage of mineralized carbon of the straw increased even further, so carbon stock of the straw decreased considerably because of mineralization.

Uso de modelagem da quantidade de carbono mineralizado de resíduos de dejetos de suínos e palha de trigo

Resumo

Um método capaz de reduzir os efeitos ambientais provocados por dejetos de suínos e de enriquecer o solo com nutrientes baseia-se na utilização desses resíduos com a palha de resíduos culturais em solos para produções agrícolas. Por meio da utilização de curvas de mineralização de carbono, é possível determinar os melhores intervalos para a utilização da matéria orgânica oriunda dos dejetos de modo a adequar melhor o uso do solo e das culturas agrícolas. A dinâmica do carbono presente nos dejetos pode ajudar na escolha do melhor manejo. Objetivou-se com este estudo comparar o ajuste de três modelos não lineares que descrevem a mineralização de carbono no solo ao longo do tempo, além de avaliar o estoque de carbono da palha de trigo isolada e conjuntamente com dejetos de suínos. O experimento foi realizado usando o delineamento em blocos casualizados, com quatro repetições e oito tratamentos. Foram utilizados os seguintes tratamentos: T1 – solo (S), T2 – solo + palha na superfície (PSUP), T3 – solo + palha incorporada (PINC), T4 – solo + dejetos em superfície (DSUP), T5 – solo + dejetos incorporados (DINC), T6 – solo + dejetos incorporados + palha em superfície (DINCPSUP), T7 – solo + dejetos incorporados + palha incorporada (DINCPINC), T8 – solo + palha em superfície + dejetos em superfície (PSUPDSUP). As amostras de solo coletadas foram incubadas por 95 dias e foram feitas 10 observações ao longo do tempo. A descrição da mineralização do carbono foi realizada por meio dos modelos não lineares Cabrera, Juma e Stanford e Smith, considerando estrutura de erros autorregressivos AR (1) quando necessário. A comparação dos ajustes dos modelos foi feita por meio do critério de informação Akaike (AIC). A descrição da mineralização do carbono da palha de trigo e dos dejetos de suínos realizada pelos modelos não lineares foi satisfatória. O modelo Cabrera foi o mais adequado para descrever todos os tratamentos. O modelo Stanford e Smith, mais utilizado na literatura para descrever a mineralização de resíduo orgânico no solo, não atingiu melhores resultados em relação aos outros modelos não lineares para os tratamentos em estudo. Em geral, os tratamentos com palha na superfície deixaram maior estoque de carbono no solo; na adição de dejetos à palha de trigo, o estoque de carbono foi menor, sendo assim, torna-se interessante aos produtores avaliarem a melhor estratégia a ser usada no uso dos resíduos de acordo com seus objetivos de produção.

Palavras-chave: Resíduo orgânico. Modelo Stanford e Smith. Modelo Cabrera. Modelo Juma.

Referências

ANDRADE, C. A.; SILVA, L. F. M.; PIRES, A. M. M.; COSCIONE, A. R. Mineralização do carbono e do nitrogênio no solo após sucessivas aplicações de lodo de esgoto. **Pesquisa Agropecuária Brasileira**, v. 48, p. 536-544, 2013. Doi:10.1590/S0100-204X2013000500010. Disponível em: <http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0100-204X2013000500010&lng=en&nrm=iso>. Acesso em: 14 jan. 2019.

ANDRADE, C. A.; BIBAR, M. P. S.; COSCIONE, A. R.; PIRES, A. M. M.; SOARES, A. G. Mineralização e efeitos de biocarvão de cama de frango sobre a capacidade de troca catiônica do solo. **Pesquisa Agropecuária Brasileira**, v. 50, p. 407-416, 2015. doi:10.1590/S0100-204X2015000500008. Disponível em: <http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0100-204X2015000500407&lng=en&nrm=iso>. Acesso em: 14 jan. 2019.

BARRETO, P. A. B.; RODRIGUES, E. F. G.; RODRIGUES, A. C. G.; BARROS, N. F.; ALVES, B. J. R.; FONSECA, S. Mineralização de nitrogênio e carbono em solos sob plantações de eucalipto, em uma sequência de idades. **Revista Brasileira de Ciência do Solo**, Viçosa, v. 34, n. 3, p. 735-745, jun. 2010. Disponível em: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0100-06832010000300015&lng=en&nrm=iso. Acesso em: 14 jan. 2019.

CANODÁ, E. A. **Contaminação da água pelo uso agrícola de dejetos de suínos na bacia hidrográfica rio coruja/bonito, braço do Norte/SC**. 2017. 127 p. Dissertação (Mestrado). Universidade Federal de Santa Catarina, Florianópolis.

Companhia Nacional de Abastecimento - CONAB. **Indicadores da agropecuária**, v. 38, n. 7, julho/2019.

DRAPER, N. R.; SMITH, H. **Applied regression analysis**. 3rd ed., reprint. New York: J. Wiley; 2014.

Empresa Brasileira de Pesquisa Agropecuária - EMBRAPA. Estatística/Desempenho da produção. Central de inteligência de aves e suínos, 2018.

FERNANDES, A. H. B. M.; CARDOSO, M. A.; SOUZA, R. A. C.; FERNANDES, F. A.; SOARES, M. T. S.; CRISPIM, S. M. A.; GALVANI, F.; LISITA, F.O. **Nitrificação e Mineralização de Carbono em Solos Tratados com Dejetos de Suínos Biodigeridos**. Corumbá: Embrapa Pantanal, 2011.

FERNANDES, T. J.; PEREIRA, A. A.; MUNIZ, J. A. Double sigmoidal models describing the growth of coffee berries. **Ciência Rural**, v. 47, p. 1-7, 2017. Disponível em: <http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0103-84782017000800401&lng=en&nrm=iso>. Acesso em: 29 jan. 2019.

GIACOMINI, S. J.; AITA, C.; MIOLA, E. C.C.; RECOUS, S. Mineralização do carbono da palha de aveia e dejetos de suínos aplicados na superfície ou incorporados ao solo. **Revista Brasileira de Ciência do Solo**, v. 32, p. 2661-2668, 2008. Disponível em: <http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0100-06832015000501428&lng=en&nrm=iso>. Acesso em: 29 jan. 2019.

GUEDES, M. H. P.; MUNIZ, J. A.; PEREZ, J. R. O.; SILVA, F. F.; AQUINO, L. H.; SANTOS, C. L. Estudo das curvas de crescimento de cordeiros das raças Santa Inês e Bergamácia considerando Heterogeneidade de variâncias. **Ciência e Agrotecnologia**, Lavras, v. 28, n. 2, p. 381-388, mar./abr. 2004. Disponível em <http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1413-70542004000200019&lng=en&nrm=iso>. Acesso em: 15 jan. 2019.

HOFFMANN, R.; VIEIRA, S. **Análise de regressão: uma introdução a econometria**. 3. ed. São Paulo: Hucitec, 1998. 379 p.

LUZ, L. P. **Dinâmica do carbono durante a decomposição de palha de trigo marcada com ¹³C e dejetos líquidos de suínos**. 2007. 61 p. Dissertação (Mestrado). Universidade Federal de Santa Maria, Santa Maria.

MARTINES, A. M.; ANDRADE, C. A.; CARDOSO, E. J. B. N. Mineralização do carbono orgânico em solos tratados com lodo de curtume. **Pesquisa Agropecuária Brasileira**, Brasília, v. 41, n. 7, p. 1149-1155, jul. 2006. Disponível em: <http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0100-204X2006000700011&lng=en&nrm=iso>. Acesso em: 14 jan. 2019.

MAZZINI, A. R. A.; MUNIZ, J. A.; SILVA, F. F.; AQUINO, L. H.; SILVA, F. F. Análise da curva de crescimento de machos hereford. **Ciência e Agrotecnologia**, v. 27, n. 5, p. 1105-1112, 2003. Disponível em: <http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1413-70542003000500019&lng=en&nrm=iso>. Acesso em: 15 jan. 2019.

MOREIRA, F. M. S.; CARES, J. E.; ZANETTI, R.; STÜMER, S. L. **O ecossistema solo: componentes, relações ecológicas e efeitos na produção vegetal**. Lavras: UFLA, 2013.

MUIANGA, C. A.; MUNIZ, J. A.; NASCIMENTO, M. S.; FERNANDES, T. J.; SAVIAN, T. V. Descrição da curva de crescimento de frutos do cajueiro por modelos não lineares. **Revista Brasileira de Fruticultura**, v. 38, n. 1, p. 22-32, 2016. Disponível em: <http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0100-29452016000100022&lng=en&nrm=iso>. Acesso em: 15 jan. 2019.

MUNIZ, J. A.; NASCIMENTO, M. S.; FERNANDES, T. J. Nonlinear models for description of cacao fruit growth with assumption violation. **Revista Caatinga**, v. 30, n. 1, p. 250 – 257, 2017. Disponível em: <http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1983-21252017000100250&lng=en&nrm=iso>. Acesso em: 15 jan. 2019.

NUNES, D. A. D.; RODRIGUES, E. F. G.; BARRETO, P. A. B.; RODRIGUES, A. C. G.; MONROE, P. H. M. Carbon and nitrogen mineralization in soil of leguminous trees in a degraded pasture in northern Rio de Janeiro, Brazil. **Journal of Forest Research**, v. 27, p. 91-99, 2016. Disponível em: <<https://link.springer.com/article/10.1007/s11676-015-0164-3>>. Acesso em 15 jan. 2019.

OLIVEIRA, W. J.; SILVA, C. A.; MUNIZ, J. A.; SAVIAN, T. V. Mineralização de nitrogênio em latossolos adubados com resíduos orgânicos. **Revista Brasileira de Ciência do Solo**, v. 37, p. 715-725, 2013. Disponível em <http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0100-06832013000300018&lng=en&nrm=iso>. Acesso em: 19 jan. 2019. DOI: <http://dx.doi.org/10.1590/S0100-06832013000300018>.

PAULA, G. S.; SILVA, E. M.; FURTADO, T. D. R.; FRÜHAUF, A. C.; MUNIZ, J. A. Comparação de modelos não lineares na descrição da mineralização do carbono no solo tratado com dejetos de suínos. **Revista Agrogeoambiental**, Pouso Alegre, v. 12, n. 1, 2020. DOI: <http://dx.doi.org/10.18406/2316-1817v11n420191412>.

PAULA, J. R.; MATOS, A. T.; MATOS, M. P.; PEREIRA, M. S.; ANDRADE, C. A. Mineralização do carbono e nitrogênio de resíduos aplicados ao solo em campo. **Revista Brasileira de Ciência do Solo**, v. 37, p. 1729-1741, 2013. Disponível em: <http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0100-06832013000600029&lng=en&nrm=iso>. Acesso em 12 nov. 2019.

PEREIRA, J. M.; MUNIZ, J. A.; SILVA, C. A. Nonlinear models to predict nitrogen mineralization in an Oxisol. **Scientia Agricola**, Piracicaba, v. 62, n. 4, p. 395-400, ago. 2005. Disponível em: <http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0103-90162005000400014&lng=en&nrm=iso>. Acesso em: 15 jan. 2019.

PEREIRA, J. M.; MUNIZ, J. A.; SÁFADI, T.; SILVA, C. A. Comparação entre modelos para predição do nitrogênio mineralizado: uma abordagem bayesiana. **Ciência e Agrotecnologia**. v. 33, Edição Especial, p. 1792-1797, 2009. Disponível em: <http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1413-70542009000700016&lng=en&nrm=iso>. Acesso em: 15 jan. 2019. DOI: <http://dx.doi.org/10.1590/S1413-70542009000700016>.

PULROLNIK, K. **Transformações do carbono no solo**. Planaltina, DF: Embrapa Cerrados; 2009.

R CORE TEAM. **R: a language and environment for statistical computing**. R Foundation for Statistical Computing Viena: 2019. Disponível em: <http://www.r-project.org>. Acesso em: 15 dez. 2019.

RIBEIRO, T. D.; MATTOS, R. W. P.; MORAIS, A. R.; MUNIZ, J. A. Description of the growth of pequi fruits by nonlinear models. **Revista Brasileira de Fruticultura**. v. 40, n. 4, p. 1-11, 2018a. Disponível em: <http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0100-29452018000400705>. Acesso em: 20 dez. 2018.

RIBEIRO, T. D.; SAVIAN, T. V.; FERNANDES, T. J.; MUNIZ, J. A. The use of the nonlinear models in the growth of pears of 'Shinseiki' cultivar. **Ciência Rural**, v. 48, n. 1, p. 1-7, 2018b. Disponível em: <http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0103-84782018000100202&lng=en&nrm=iso>. Acesso em: 15 jan. 2019.

SAVIOZZI, A.; LEVI-MINZI, R.; CARDELLI, R. RIFFALDI, R. The Influence of Heavy Metals on Carbon Dioxide Evolution from a Typic Xerochrept Soil. **Water Air and Soil Pollution**. v. 93, p. 409-417, 1997. Disponível em: <https://link.springer.com/article/10.1007/BF02404770>. Acesso em: 15 jan. 2019.

SILVA, E. M.; FRÜHAUF, A. C.; FERNANDES, F. A.; PAULA, G. S.; MUNIZ, J. A.; FERNANDES, T. J. Método de Newton e Gauss-Newton na estimação dos parâmetros de modelo de regressão não linear. **Sigmae**, v. 8, n. 2, p. 728-734, 2019a. Disponível em: <<https://publicacoes.unifal-mg.edu.br/revistas/index.php/sigmae/article/view/946/692>>. Acesso em: 15 jan. 2019.

SILVA, E. M.; FURTADO, T. D. R.; FRÜHAUF, A. C.; MUNIZ, J. A.; FERNANDES, T. J. Bayesian approach to the zinc extraction curve of soil with sewage sludge. **Acta Scientiarum. Technology**, v. 42 p. 1-9, 2020. Disponível em: <<http://periodicos.uem.br/ojs/index.php/ActaSciTechnol/article/view/46893/751375149043>>. Acesso em: 15 jan. 2020.

SILVA, E. M.; RIBEIRO, T. D.; FERNANDES, J. G.; MUNIZ, J. A. Descrição da mineralização do carbono de dejetos de suíno e palha de aveia no solo por modelos não lineares. **Revista Agrogeoambiental**, Pouso Alegre, v. 11, p. 210-225, 2019b. Disponível em: <https://agrogeoambiental.ifsuldeminas.edu.br/index.php/Agrogeoambiental/article/view/1299/pdf_1>. Acesso em: 15 out. 2019.

SILVA, E. M.; SILVEIRA, S. C.; RIBEIRO, T. D.; MUNIZ, J. A. Descrição da decomposição do lodo de esgoto e palha de aveia por modelos não lineares. **Revista Agrogeoambiental**, Pouso Alegre, v. 11, p. 153-164, 2019c. Disponível em: <https://agrogeoambiental.ifsuldeminas.edu.br/index.php/Agrogeoambiental/article/view/1287/pdf_1>. Acesso em: 15 out. 2019.

SILVEIRA, S. C. MUNIZ, J. A. SOUSA, F. A. CAMPOS, A. T. Modelos não lineares ajustados à produção acumulada de biogás provenientes de camas sobrepostas de suínos. **Revista Agrogeoambiental**, Pouso Alegre, v. 10, n. 3, p. 91-103, jul./set. 2018. Disponível em: <<https://agrogeoambiental.ifsuldeminas.edu.br/index.php/Agrogeoambiental/article/view/1168>>. Acesso em: 14 jan. 2019. DOI: <http://dx.doi.org/10.18406/2316-1817v10n320181168>.

SOUSA, I. F.; NETO, J. E. K.; MUNIZ, J. A.; GUIMARÃES, R. M.; SAVIAN, T. V.; MUNIZ, F. R. Fitting nonlinear autoregressive models to describe coffee seed germination. **Ciência Rural**, v. 44, n. 11, p. 2016-2021, 2014. Doi:10.1590/0103-8478cr20131341. Disponível em: <http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0103-84782014001102016>. Acesso em: 15 jan. 2019.

SOUZA, E. M.; MUNIZ, J. A.; MARCHI, G.; GUILHERME, L. R. G. Non-linear modeling of zinc extracted from a sewage sludge – treated. **Acta Scientiarum Technology**, v. 32, p. 193–199, 2010. Disponível em: <https://www.researchgate.net/publication/233800672_Non-linear_modeling_of_zinc_extracted_from_a_sewage_sludge-treated_soil>. Acesso em: 15 jan. 2019.

TEDESCO, M. J.; GIANELLO, C.; BISSANI, C. A.; BOHNEN, H.; VOLKWEISS, S. J. Análise de solo, plantas e outros materiais. **Boletim Técnico de Solos**, 5, 2. ed. 174p., Porto Alegre, Departamento de Solos da Universidade Federal do Rio Grande do Sul. 1995.

ZEVIANI, W. M.; SILVA, C. A.; CARNEIRO, W. J. O.; MUNIZ, J. A. Modelos não lineares para a liberação de potássio de esterco animal em latossolos. **Ciência Rural**, Santa Maria, v. 42, n. 10, p. 1789-1796, out, 2012. Disponível em: <<http://www.scielo.br/pdf/cr/v42n10/a28712cr3006.pdf>>. Acesso em: 15 jan. 2019.

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