

Mathematical model to describe litter decomposition rate in semiarid regions

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ABSTRACT: Although semiarid regions present a poor rainfall distribution throughout the year, the most frequently used mathematical model describing the litter decomposition rate (LDR) predicts the same behavior of crop residues behavior in dry and rainy seasons. The aim of this study was to design a mathematical model to describe the LDR by a means of piecewise continuous function depending on the rainfall quantity. A field experiment was conducted from October 2009 to September 2010 at Brejo Paraibano, Paraíba, Brazil. The experimental design was completely randomized in a 6 x 12 factorial arrangement, with six plant residues, brachiaria (*Brachiaria decumbens* Stapf), corn (*Zea mays* L.), sorghum (*Sorghum bicolor* (L.) Moench), jack bean (*Canavalia ensiformis* L.), pigeonpea (*Cajanus cajan* (L.) Hunth), and leucaena (*Leucaena leucocephala* Lam.), and 12 collection periods. Using data obtained from an experimental field, a mathematical model was developed. The proposed model is based on the concept of infinite series. It was verified that in dry seasons the LDR can be well described by a linear function whereas in rainy ones an exponential function describes it better. Statistical analysis showed good agreement between the experimental data and the theoretical model. For the model, the decomposition coefficients for each culture and each period are proposed.

Key words: crop residues; grasses; legumes; theoretical model

Modelo matemático para descrever a taxa de decomposição de resíduos em regiões semiáridas

RESUMO: Apesar de regiões de clima semi-árido apresentarem uma má distribuição de chuva ao longo do ano, o modelo matemático descrevendo a taxa de decomposição de serrapilheira (TDS) mais utilizado prevê o mesmo comportamento de resíduos de culturas em estações secas e chuvosas. O objetivo deste trabalho foi propor um modelo matemático para descrever TDS por uma função contínua por partes, considerando as variações de precipitação. Conduziu-se um experimento em campo entre outubro de 2009 e setembro de 2010 no brejo Paraibano, Paraíba, Brasil. Seguiu-se um delineamento experimental inteiramente casualizado, formando um fatorial 6 x 12, com resíduos vegetais formados por diferentes espécies: brachiaria (*Brachiaria decumbens* Stapf), milho (*Zea mays* L.), sorgo (*Sorghum bicolor* (L.) Moench), feijão de porco (*Canavalia ensiformis* L.), guandu (*Cajanus cajan* (L.) Hunth) e leucena (*Leucaena leucocephala* Lam.); e, 12 períodos de coletas. O modelo matemático foi desenvolvido com base nos dados obtidos no experimento de campo, sendo baseado no conceito de séries infinitas. Verificou-se que em estações secas, TDS pode ser descrito por uma função linear, enquanto em estação chuvosa TDS é melhor descrito por uma função exponencial. As análises estatísticas indicaram um bom ajuste do modelo proposto aos dados obtidos em campo. Para uso do modelo, foram propostos coeficientes de decomposição para cada cultura nos períodos secos e chuvosos.

Palavras-chave: resíduo de culturas; gramíneas; leguminosas; modelo teórico

Introduction

Litter decomposition is an important ecological process in global carbon and nutrient cycling in terrestrial ecosystems (Berg & Laskowski, 2006) and involves physical, chemical, and biological processes by which dead plant material is transformed and nutrients are cycled through the environment (Berg & McClaugherty, 2014). The arid and semi-arid drylands of the world are increasingly recognized for their role in the terrestrial net carbon dioxide uptake, which depends largely on plant litter decomposition (Gliksman et al., 2017). Environmental conditions have been found to be closely related to litter decomposition, and thus affect soil nutrients contents (Zhang et al., 2018). In particular, the Northeast of Brazil (NB) consists of a region with a semiarid climate, with poor rainfall distribution and a long dry season. This poor rainfall distribution leads to a small production of biomass (Melo et al., 2013).

Because of the low humidity in NB dry seasons, the litter decomposition rate (LDR) is very low, presenting an increase during the rainy seasons when high humidity and temperatures occur (Nunes et al., 2010; Melo et al., 2013; Mendonça et al., 2015). This behavior is noted in LDR analyses for other world regions with same climatic conditions, e.g., the Judean Desert (Hamadi et al., 2000) and the semiarid Loess Plateau (Zhang et al., 2016). In a three-years study, Kemp et al. (2003) showed that the graphic representation of the LDR shows a step-like behavior, in which rainy seasons present a high LDR whereas in dry seasons the LDR is low. Thus, the implementation of the no-till system in semiarid regions faces a major obstacle: the low accumulation of phytomass on the soil surface due to the high LDR in the rainy seasons. Thus, in order to select coverages that can remain longer on the soil surface and provide promising results in the implementation of the no-till system, the study and understanding of the LDR of different plant residues in different seasons are important (Hamadi et al., 2000; Silva et al., 2011; Mendonça et al., 2015; Zhang et al., 2016).

In agronomic systems, tillage of crop residues after harvest results in increased nutrient release into the soil (Ruhland et al., 2018). The nutrients may be maintained or enhanced by certain management practices. For example, long-term no-till is usually recommended as an improved management system that may increase soil organic matter and associated nutrients (Sarker et al., 2018). Thus, an assessment of the substrate quality and decomposition dynamics of litter can provide a framework for expounding the nutrient feedback processes in a plant-soil system and the nutrient balance of ecosystems (García-Palacios et al., 2016; Horodecki & Jagodziński, 2017).

From the theoretical point of view, a widely used mathematical model to describe the LDR is defined by the exponential equation, $P = P_0 e^{-kt}$, derived by Thomas & Asakawa (1993), here called Thomas and Asakawa's model (TAM). In this theoretical model, P is the litter percentage after time t , P_0 is the initial litter percentage, and k is the litter

decomposition constant, which depends on the considered crop residue. Torres et al. (2005) successfully adopted TAM to describe the litter decomposition in the Brazilian Cerrado, in which the rain is well distributed along the year. However, because it uses only one decomposition constant to describe the LDR for the entire year, TAM is not a good model to describe the LDR in semiarid reality. Indeed, it has been observed, in many experiments conducted in regions with a semiarid climate that, despite the accordance between experimental and theoretical data in the rainy periods, there is an evident difference between theoretical predictions and experimental results in the dry seasons (Hamadi et al., 2000; Melo et al., 2013; Zhang et al., 2016). Another theoretical proposition to describe LDR can be given by a quadratic function. However, in some cases the calculated coefficients generate an increase in the initial litter quantity (Nunes et al., 2010), in evident disagreement with the real data.

Based on the above ideas, the aim of this study was to provide a mathematical model to describe the LDR by means of a piecewise continuous function, depending on the rainfall quantity.

Material and Methods

Description of the experiment

The experiment was conducted from October, 2009 to September, 2010 at *Chã do Jardim*, of the *Centro de Ciências Agrárias* of the Federal University of Paraíba (UFPB), municipality of Areia, Brejo Paraibano, Paraíba, Brazil. The climate is of the type As in the Köppen climate classification, characterized as hot and humid, with rainy seasons occurring in the autumn-winter (from March to August). The local soil is classified as Latossolo Amarelo (Embrapa, 2013).

The experimental area was 12.0 m × 11.5 m, that is 138 m². The experiment was conducted in a completely randomized plot in a 6 × 12 factorial arrangement, with 6 plant residues and 12 collection periods relating to the 6 repetitions, totaling 432 plots. The plant residues were represented by three grass litter *brachiaria* (*Brachiaria decumbens* Stapf), corn (*Zea mays* L.), sorghum (*Sorghum bicolor* (L.) Moench), jack bean (*Canavalia ensiformis* L.), pigeonpea (*Cajanus cajan* (L.) Hunth) and leucaena (*Leucaena leucocephala* Lam.). The plants were cut during the flowering stage at the beginning of fruiting stage, except the corn and sorghum, which were cut after the grain production. The litter of all plants was ground in a fodder machine in order to obtain litter particles varying from 0.01 m to 0.04 m in length. After a shadow dry, the litter was put in nylon bags and deposited in the experimental field.

The main factor is the plant residues and the second factor is the evaluated months. In each plot, residues of each treatment were deposited. The bags were made of nylon with holes of two different diameters, 1 mm and 4 mm. A 1-mm mesh was placed at the bottom the bags to avoid loss of material. The 4-mm mesh of was placed at the top to allow tiny insects to enter in the bag, simulating a real crop

situation. The bags measured 0.20 m wide × 0.30 m long and were spaced 0.20 m apart. The space between the bags was covered with residues of the evaluated crop. The amount of residue in each bag was 60 g, corresponding to 10 mg of dry matter per hectare, equivalent to the average litter production found in experiments on tillage (Nunes et al., 2010).

The experiment was initiated on Oct 10, 2009, because at this time the litter is left on the soil after harvest. The bags were collected monthly on the 21st day of each month. On Apr 21, 2010, the weeds were hoed, and the residues were used as ground cover. The corn was planted at a spacing of 1.0 x 0.20 m, exemplifying a customary crop in the considered region. On Oct 21, 2010, the final bag collection in the experimental area was performed.

The rainfall was measured daily by means of a rain gauge installed near the test area. Moreover, we performed soil temperature measurements weekly at a depth of 0.00-0.05 m, using a soil thermometer. Soil samples were collected for determining soil moisture, the values of which are shown in Figure 1.

In each month, one bag was collected per plot for quantifying the percentage of residue remaining. After collection, the plant materials were cleaned and put in an oven to dry with forced air circulation at 65 °C during 72 h, and then, weighed on a precision balance. Samples of litter from each plant were sent to a Laboratory of Chemistry and Soil Fertility and Plant Tissue for evaluation of their chemical composition. The results are provided in Table 1. In order to calculate the LDR, the formula

$$\text{Remaining} = \frac{\text{Final mass}}{\text{Initial mass}} \times 100 \tag{1}$$

was used.

Mathematical model

The proposed mathematical model to describe the LDR is based on the concept of infinite series, which originates in the possibility of writing a function as an infinite series of functions. That is, given a function $f(x)$, one can write it as an expansion of the type

$$f(x) = \sum_{n=0}^{\infty} a_n(x) \tag{2}$$

where $a_n(x)$ is a function, the form of which depends on the type of series expansion adopted. A particular and interesting representation of a function is the Taylor expansion (TE), in which the function $f(x)$ is expanded into an infinite series of powers of a variable x or into a finite series plus a remainder term. The determination of the coefficients of successive terms of this expansion involves successive derivatives of the function $f(x)$. The explicit form of TE can be obtained by the integration of the n^{th} derivative of $f(x)$ n times (Arfken & Weber, 2005). This procedure leads to

$$f(x) = \sum_{n=1}^{\infty} \frac{(x-a)^n}{n!} f^{(n)}(a) \tag{3}$$

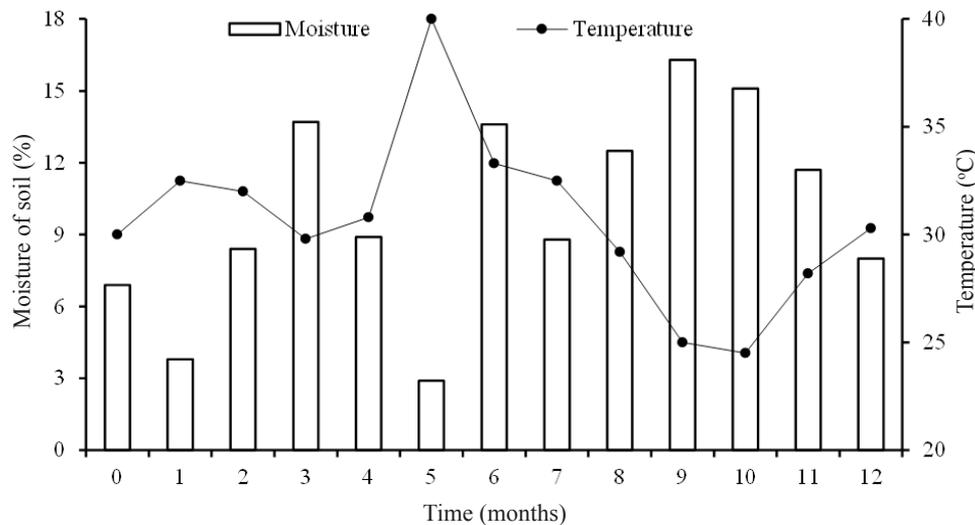


Figure 1. Soil temperature and moisture along the evaluated months (October 2009 – October 2010).

Table 1. Dry matter, nitrogen (N), carbon (C), cellulose, lignin, C/N ratio, and lignin/N ratio in the grass and legume plant weights used in the experiment.

Crop residue	Dry matter	N	C	Cellulose	Lignin	C/N ratio	Lignin/N ratio
Brachiaria	860.7	11.83	473.14	469.7	108.0	40.0	0.91
Corn	844.7	9.03	499.24	452.5	90.1	55.3	1
Sorghum	859.8	13.41	452.86	458.7	175.4	33.8	1.31
Jack bean	818.1	25.48	452.63	303.7	87.5	17.8	0.34
Pigeonpea	851.3	23.21	421.53	464.4	234.2	18.2	1.01
Leucaena	826.5	45.08	498.57	305.5	342.3	11.1	0.76

where $f^{(n)}$ denotes the n^{th} derivative of the function $f(x)$ in relation to x and a is the point at which the expansion is being considered. If the function is expanded about the origin ($a=0$), Eq. (2) is evaluated as

$$f(x) = \sum_{n=1}^{\infty} \frac{f^{(n)}(0)}{n!} x^n \quad (4)$$

which is known as a Maclaurin's series. In particular, for $f(x)=e^x$, the n^{th} derivative is well known, given by $f^{(n)}(x)=e^x$. Then, $f^{(n)}(0)=1$ for all positive integer n . Thus, by expanding the exponential function in a Maclaurin's series, we obtain

$$e^x = 1 + x + \frac{x^2}{2} + \frac{x^3}{3!} + \dots = \sum_{n=0}^{\infty} \frac{x^n}{n!} \quad (5)$$

Aiming to describe the LDR, Thomas & Asakawa (1993) proposed a model in which the litter percentage, after a time t , is given by an exponential function, written in the form

$$P(t) = P_0 e^{-kt} \quad (6)$$

where $P(t)$ is the fraction of the initial litter quantity at time t . P_0 is the potentially disposable proportion of the litter and $k > 0$ is the litter decomposition constant, used to calculate the litter half-life time (HL). By using Equation (4), one can rewrite Equation (5) as

$$P(t) = P_0 \sum_{n=0}^{\infty} \frac{(-kt)^n}{n!} = P_0 \left[1 - kt + \frac{(kt)^2}{2} - \frac{(kt)^3}{3!} + \dots \right] \quad (7)$$

If one considers $k \ll 1$, the above expansion is simplified to

$$P(t) = P_0 \left[1 - kt + (kt)^2 \right] \quad (8)$$

where $O(kt^2)$ is a terms of order ≥ 2 , which can be neglected. However, for large k , the terms of order greater or equal to two become important and cannot be neglected in the calculation of $P(t)$.

Now, Equation (5) can be used to calculate the value of k , being evaluated to give

$$k = \frac{1}{t} \ln \left[\frac{P(t)}{P_0} \right] \quad (9)$$

and the HL, defined as the time needed for half of the initial quantity of the litter to decompose, is evaluated to give

$$t_{hl} = \frac{1}{k} \ln(2) \quad (10)$$

Now, proceeding with the representation of the logarithmic function in a TE, Equation (8) yields

$$k = \frac{1}{t} \sum_{n=0}^{\infty} \frac{(-1)^n}{n} \left[\frac{P(t)}{P_0} - 1 \right]^n \quad (11)$$

It can be noted from the analyses performed in several studies dedicated to investigating the plant residue decomposition in several climatic conditions that in periods in which the rainfall is scarce, the LDR is low and practically linear with time (Torres et al., 2005; Nunes et al., 2010; Pariz et al., 2011; Mendonça et al., 2015). Thus, these experimental data can be well described by Eq. (7). In contrast, rainy periods yield to a high LDR, indicating an increase in k . Then, terms of a greater order in the TE must be accounted and Eq. (5) must be used to determine LDR in this case.

Given that the LDR depends on the rainfall, temperature, and air humidity, we propose that the decomposition data in semiarid regions (in which the rains are poorly distributed throughout the year, occurring in conditions of high temperatures) can be given by the mathematical model

$$P(t) = \Theta(t_r - t) P_0 (1 - kt) + \Theta(t - t_r) P_0 (1 - kt_r) e^{-k't} \quad (12)$$

where the decomposition coefficients k and k' , valid respectively for the dry and rainy seasons, have different values. $\Theta(\eta)$ is the step function, defined as $\Theta(\eta \geq 0) = 1$ and $\Theta(\eta < 0) = 0$ and t_r determines the time of the beginning of rainy seasons. The first term in Eq. (11) is related to dry periods, while the second accounts for rainy ones. It has been considered that $t=0$ in the beginning of the dry season, because in this period, after the harvest, litter is deposited on the soil.

In order to determine the HL resulting from the model described in Eq. (11), the following approximation is considered. Let it t_1 be the time needed (in the rainy season) for the litter to reach 50% of its initial quantity then the HL is defined as $t_{hl} = t_1 + t_r$, satisfying

$$\frac{P_0}{2} = P_0 (1 - kt_r) e^{-k'(t_{hl} - t_r)} \quad (13)$$

where the fact that $t_{hl} > t_r$ and $P(t_{hl}) = P_0/2$ is applied. The HL calculated from this approximation can be written, in the function of t_1 , as

$$t_{hl} = \frac{1}{k'} \ln \left[\frac{1}{1 - kt_r} \right] + t_r \quad (14)$$

From the analysis of Eq. (13), it can be noted that HL depends on the two decomposition coefficients k and k' . It is noteworthy that in the limit $t_r \rightarrow 0$, that is, if the rainfall is well distributed along the year, the HL determined from TAM is recovered, as it should be.

Results and Discussions

Experiment

From the experimental data, shown in Figure 2, one can conclude that the LDR is very low during the dry season and high in the rainy season. From the analysis in Figure 2, one can note that in dry seasons, the decay of the litter is practically linear, whereas, rainy seasons yield an exponential decay. This trend was observed in all the evaluated plant residues and makes clear the difference between the LDR in the dry and rainy seasons in the Brazilian semiarid regions.

The obtained data showed that the LDR in the dry period was 1.0, 0.5, and 1.8 Mg ha⁻¹ for brachiaria, corn, and sorghum, respectively. For the jack bean, pigeonpea, and leucaena, the LDR was 3.0, 2.4, and 4.6 Mg ha⁻¹. During January, there has been noted a higher LDR, in the proportion of 5.4, 5.9 and 4.3 Mg ha⁻¹ for Brachiaria, corn, and sorghum, respectively, and 5.5, 4.5, and 3.8 Mg ha⁻¹ for jack bean, pigeonpea, and leucaena respectively. It was noted that the crop residues after the last six months of the experiment were 34%, 35% and 38% for brachiaria, corn, and sorghum, respectively, and 14%, 30% and 15% for jack bean, pigeonpea, and leucaena, respectively (Figure 2).

The low LDR occurring in the dry season (October-December) is associated to the low soil moisture and high

soil temperature in the experimental area (Figure 1). Indeed, in the dry season, the measured average values of the soil moisture and temperature were 6.4% and 32 °C, respectively. In contrast, in the rainy season, the average values of moisture and temperature were 11.1% and 32 °C, respectively. Thus, it was noted that the presence of high temperatures and moisture availability, of the soil as in the waste crops, favors the decomposition of the residue deposited on the soil surface. With the beginning of the rainy season, in January, the soil moisture rises, increasing microbial activity and, consequently, the LDR. Thus, in February, the remaining percentage of litter is always statistically significant. These results accord with those of previous studies (Kliemann et al., 2006; Nunes et al., 2010; Silva et al., 2011; Mendonça et al., 2015), where it was observed that as a result of an increase in the soil biodiversity, an increase in the LDR rate also occurs (Sanches et al., 2009).

The lower LDR of the grass is related to lower levels of N and higher quantities of cellulose and a high C/N ratio in these crops. In contrast, the leguminous crops show high values of N and a low C/N ratio, resulting in a high LDR. Among leguminous crops, the pigeonpea residue has the highest levels of dry matter and cellulose and the highest C/N and lignin/N ratio, while still presenting a lower N content (Klieman et al., 2006; Nunes et al., 2010; Silva et al., 2011;

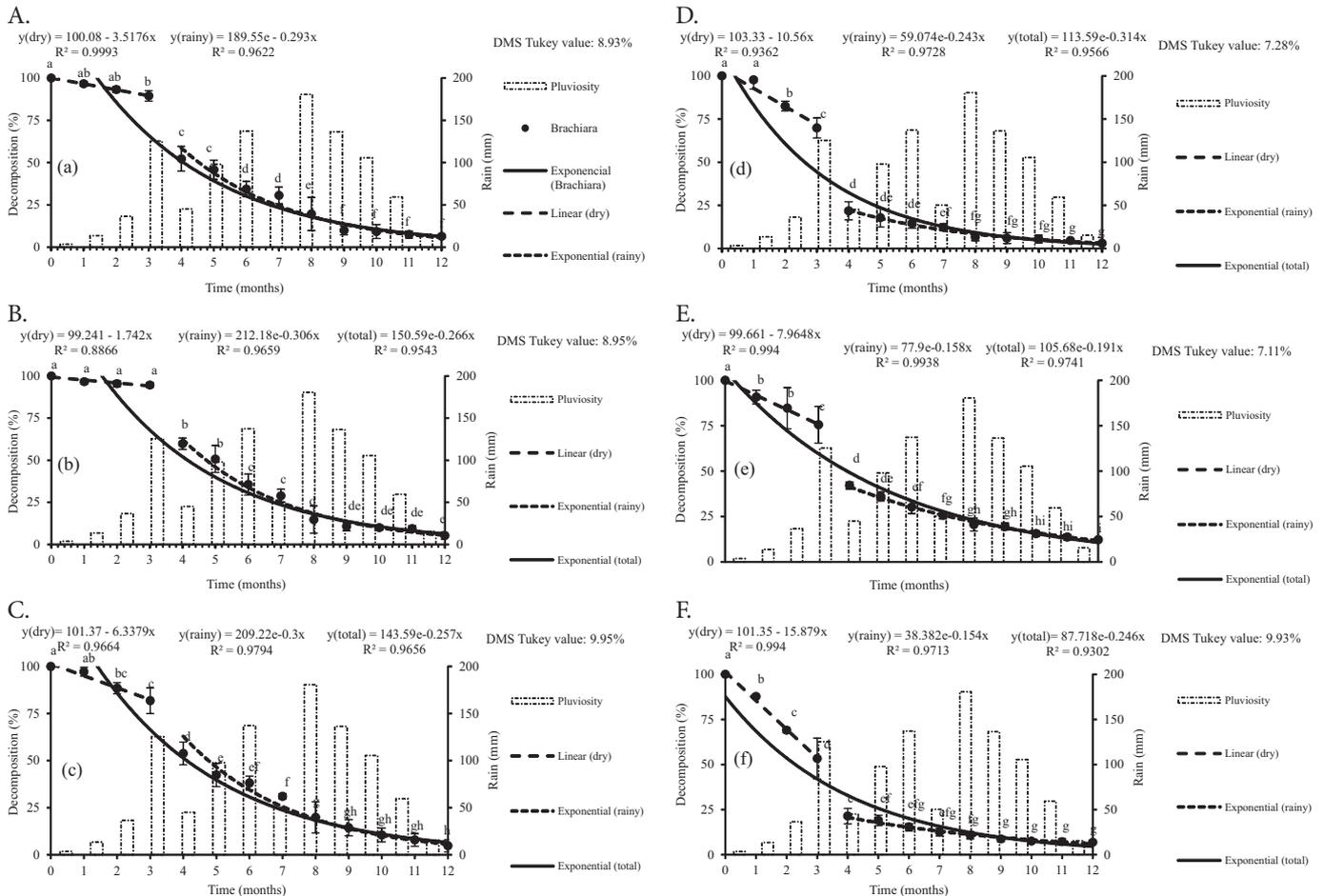


Figure 2. Remaining litter of (a) brachiaria, (b) corn, (c) sorghum, (d) jack bean, (e) pigeonpea and (f) leucaena. The adjustments were executed using the coefficients showed in Table 2 and Eq. (11).

Table 2. Decomposition coefficients (k and k') and half-life time for each studied crop.

Crop residue	k – Dry season	k' Rainy season	k TAM	t_{hl} Eq. (13)	t_{hl} Eq. (9) TAM	t_{hl} Experimental
Brachiaria	0.035	0.328	0.165	143	126	135 ± 5
Corn	0.021	0.335	0.159	146	130	150 ± 3
Sorghum	0.058	0.287	0.166	142	125	135 ± 5
Jack bean	0.091	0.710	0.248	106	84	110 ± 5
Pigeonpea	0.081	0.279	0.177	135	118	120 ± 5
Leucaena	0.153	0.430	0.269	95	77	100 ± 5

Mendonça et al., 2015). Thus, pigeonpea residue showed more resistance to decomposition (Table 2).

In order to implement a no-till system, it is important to maintain soil protection with plant residues. The more residues remain on the surface, the more protection is offered to the soil. The LDR on the soil surface is very high in semiarid regions, especially in rainy seasons. This fact presents a greater challenge to the implementation of the no-till system in such regions, since the litter amount for soil covering, after the rainy season, is considerably reduced (Silva et al., 2011; Nunes et al., 2010). In March, the month in which agricultural holding begins in the Brejo Paraibano microregion, corn presented 50.7% of waste, while brachiaria and sorghum showed 45.8% and 42.4%, respectively. Pigeonpea showed 36%, while leucaena and jack bean showed 19% and 17.9% residues on the soil surface, respectively. Thus, considering their litter and N supply, corn and pigeonpea are good alternatives for soil covering in the implementation of a no-till system in this micro region.

Application of the mathematical model to the experimental data

Aiming to test the approximation described in Eq. (11) and compare it with that of TAM, we plotted the data of the remaining matter in the function of the time, as well as the rainfall, as summarized in Figure 2. In the first three evaluated months, the decomposition rate is very low, presenting a linear decay. However, when the rainy season begins, the LDR increases, which can be explicitly observed in an abrupt reduction of the litter percentage.

From the proposed model, the coefficients for each culture and each period can be evaluated and are listed in Table 2 and Figure 2. As expected, dry seasons present a small decomposition coefficient, which increases in rainy seasons. Furthermore, the curves generated from the model given by Eq. (11) can be adjusted better to the experimental data than those generated by TAM. The HL associated to these coefficients must be promptly calculated and are, in days, 99, 100, 91, 80, 140, and 83 for brachiaria, corn, sorghum, Jack bean, pigeonpea, and leucaena, respectively. The HL predicted by TAM are, in this order, 80, 78, 81, 66, 109, and 85. That is, the HL predicted by exponential regression using TAM approximates to the experimental data only for pigeonpea and leucaena. Thus, it can be concluded that the results yielded by the mathematical model proposed in this paper show higher accuracy than TAM in the prediction of the real data. However, in order to verify this, experiments

using other cultures subject to semiarid climate conditions must be performed.

It was also observed that in the dry season, the plotted data of jack bean and leucaena behave as a linear function and the R^2 coefficient resulting from statistical analysis presents better values when we use our approximation (Figure 2). The analysis of Table 2 leads us to note that grass cultures present large coefficient values as compared to leguminous crops. For example, even in rainy seasons, leucaena decomposition could be well described by a linear adjustment; however, the exponential is well applied to this case too. This is associated with the fact that, in the dry season, there is rapid litter decomposition of leguminous crops.

Conclusions

In this paper, a mathematical model was proposed to describe the litter decomposition rate (LDR) by a piecewise continuous function, depending on the rainfall quantity. Using the proposed model, the half-life time (HL) of the litter can be calculated. For the model, the decomposition coefficients for each culture and each period were proposed.

Because of the climate seasonality of semiarid regions, it can be observed that Thomas & Asakawa's Model (TAM) did not describe the LDR found in our experiment with good accuracy. Thus, we believe that the mathematical model proposed in this work better fits the LDR in regions in which the climate conditions are similar to those in the Brazilian Northeast.

Although the proposed model was used in an experiment conducted in the Brazilian Northeast, it can be useful for describing the litter decomposition in other parts of the world with a climate presenting well defined dry and rainy seasons. However, the tested model needs validation and calibration.

Acknowledgements

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