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Research article

Modelos de descomposición del mantillo en ecosistemas templados del Noreste de México

Mulch decomposition models in temperate ecosystems in Northeastern Mexico

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Abstract

Mulch decomposition is an essential process for maintaining the net primary productivity and fertility of forest ecosystems. For this reason, a one-year study was conducted in the *Pablillo ejido* in *Galeana* municipality, state of *Nuevo León*, Mexico, to understand the process of mulch decomposition in three temperate forest ecosystems (pine, oak, and pine-oak) using mathematical models to predict the rate of decomposition. In each ecosystem, 60 black polypropylene bags containing 10 g of mulch were distributed in five 20 m×20 m plots. When comparing the three vegetation types, mass loss was 14 % for pine, 22 % for pine-oak, and 23 % for oak. According to the regression analysis, the Simple Negative Exponential (Olson) and simple linear models showed the best goodness of fit with respect to the logarithmic and power models. The simple linear model presented a better fit with R^2 values=0.719 (oak), 0.626 (pine), and 0.620 (pine-oak); for the Olson model, the R^2 coefficient ranged from 0.710 (oak) to 0.617 (pine-oak). The decomposition process showed significant differences between ecosystems attributable to the chemical composition of the mulch. The pine ecosystem showed the lowest decomposition percentage.

Key words: Coefficient of determination, temperate ecosystems, mulch, pine-oak, linear regression, decomposition rate.

Resumen

La descomposición del mantillo es un proceso fundamental para mantener la productividad primaria neta y la fertilidad de los ecosistemas forestales. Por tal motivo, se realizó un estudio en el ejido Pablillo, municipio Galeana, Nuevo León, México durante un año para conocer el proceso de descomposición del mantillo en tres ecosistemas forestales de clima templado (pino, encino y pino-encino) que incluyó modelos para predecir la tasa de descomposición. En cada ecosistema se distribuyeron en cinco parcelas de 20 m×20 m 60 bolsas de polipropileno negro con 10 g de mantillo. Al comparar los tres tipos de vegetación, la pérdida de masa fue de 14 % para pino, 22 % en pino-encino y 23 % para encino. De acuerdo con el análisis de regresión, los modelos exponencial negativo simple (*Olson*) y lineal simple mostraron la mejor bondad de ajuste respecto a los modelos logarítmico y de potencia. El modelo lineal simple presentó un mejor ajuste con valores de R^2=0.719 (encino), 0.626 (pino) y 0.620 (pino-encino); para el modelo de *Olson*, el Coeficiente R^2 varió de 0.710 (encino) a 0.617 (pino-encino). La constante de descomposición del modelo de *Olson* fluctuó de 1.017 (encino) a 0.946 años (pino-encino), y en el modelo lineal simple de 1.009 (encino) a 0.944 años (pino-encino). El proceso de descomposición tuvo diferencias significativas entre ecosistemas atribuibles a la composición química del mantillo. En el ecosistema de pino se presentó el menor porcentaje de descomposición.

Palabras clave: Coeficiente de determinación, ecosistemas templados, mantillo, pino-encino, regresión lineal, tasa de descomposición.

Introduction

The decomposition of organic matter provided by mulch is the precursor and regulator of nutrient availability patterns and is responsible for supplying, in part, the energy flow in forest ecosystems (Weltzin *et al.*, 2005). It is estimated that 80 % of the total nutrients that the plants require are released during this decomposition process (Liu *et al.*, 2006; Sayer *et al.*, 2020), therefore, it is key to the functioning of biogeochemical cycles, as it favors the physical, chemical and biological conditions of the soil (Liu *et al.*, 2004; Castellanos and León, 2010).

Mulch and soil decomposition have regulators in common that act differently, for example, soil aeration affects the decomposition of organic matter, but has very little impact on mulch decomposition. Other regulators that directly affect the decomposition process are climate, litter composition, soil fauna and microorganisms (Pando-Moreno *et al.*, 2018); vegetation structure and composition are some of the most important factors, as they determine local variation in mulch accumulation and decomposition processes (Gaspar-Santos *et al.*, 2015).

Cornelissen (1996) highlights that the chemical composition of the mulch is a key element in the rate at which organic matter decomposes. In general, the decomposition process of the organic matter provided by the mulch consists of two stages: an initial stage of rapid development due to the leaching of soluble compounds and the decomposition of sugars, phenols and proteins (Arellano *et al.*, 2004), and a second phase, characterized by slower decomposition due to the content of cellulose, lignin, and hemicellulose (recalcitrant substances), resulting in a lower decomposition rate (Crespo, 2015).

In temperate forest ecosystems dominated by the *Pinus* and *Quercus* genera, the *in situ* decomposition process has shown that certain climatic variables, species composition and distribution tend to be factors that determine the rate or dynamics of mass loss (Moreno *et al.*, 2018). Therefore, the study of the process of mulch decomposition in temperate ecosystems is essential to attain a large-scale understanding of nutrient release (Bohara *et al.*, 2019). Therefore, the objective of this study was to understand the process of mulch decomposition in pine, oak, and pine-oak ecosystems, including models to predict the decomposition rate in each plant community, based on the following hypothesis: decomposition in the pine ecosystem is slower than in the oak and pine-oak ecosystems, where the mulch has different physicochemical characteristics due to the conditions of the vegetation structure.

Materials and Methods

Study area

This research was carried out in three different ecosystems (pine, oak and pine-oak), which are located in the *Pablillo ejido*, *Galeana* municipality, state of *Nuevo León*

(Figure 1), whose climate is arid, temperate, with over 18 % of the rainfalls per year occurring between summer and winter (García, 2004). The predominant plant communities in the area are scrub and coniferous forests with the presence of *Pinus pseudostrobus* Lindl. and mixed stands with *Pinus teocote* Schltdl. & Cham., *P. ayacahuite* var. *brachyptera* Shaw, *P. arizonica* Engelm., *P. cembroides* Zucc., *P. hartwegii* Lindl., *Pseudotsuga menziesii* (Mirb.) Franco var. *glauca* (Mayr) Franco and the association of *Pinus pseudostrobus* with *Quercus* spp., as well as with *Quercus sideroxyla* Bonpl., secondly: *P. culminicola* Andresen & Beaman, *Arbutus glandulosa* M. Martens & Galeotti, *Quercus crassifolia* Bonpl., *Alnus acuminata* Kunth, and *Juniperus deppeana* Steud. var. *robusta* Martínez (Tapia y Návar, 2011).

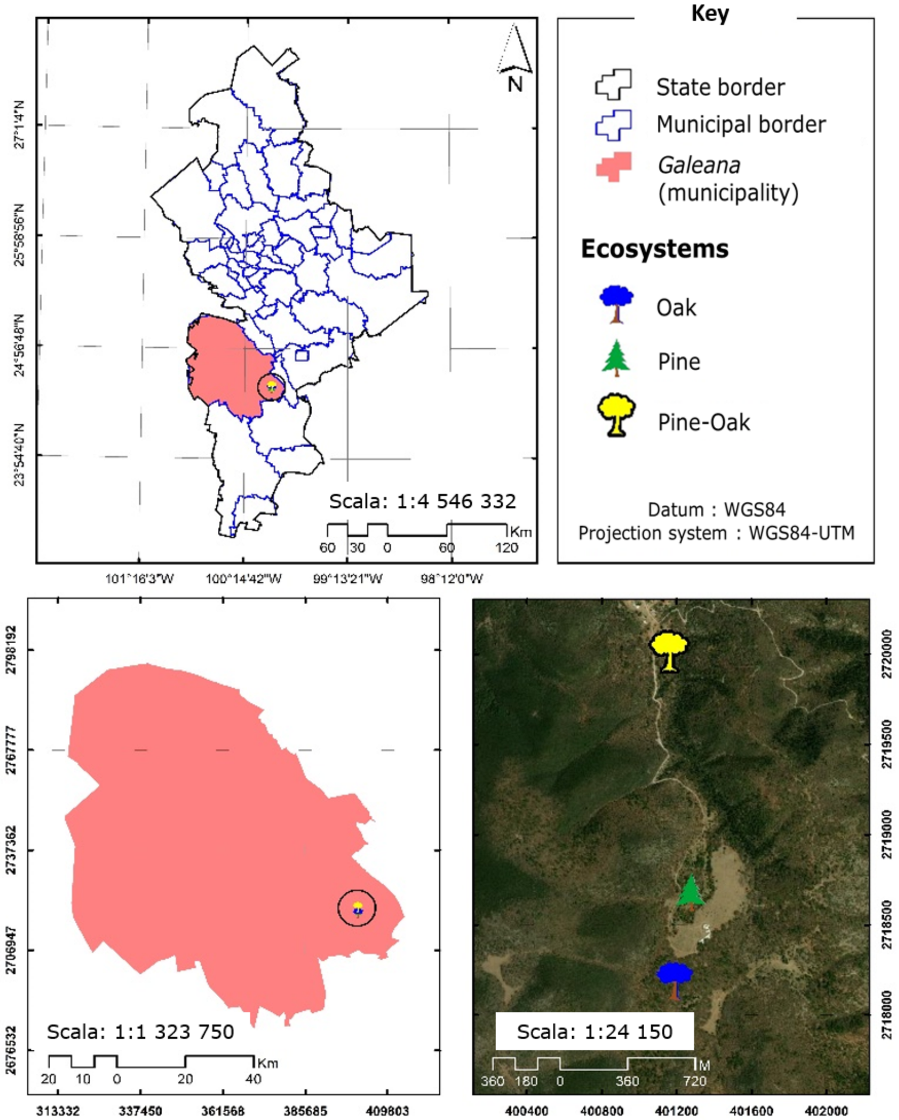


Figure 1. Location of the study sites in *Galeana* municipality, *Nuevo León*, Mexico.

The altitudinal range in which the ecosystems under study develop is 2 267 masl for pine (geographic location: 24°34'44.34" N; 99°58'30.12" W), 2 313 masl for oak (geographic location: 24°34'28.32" N; 99°58'33.180" W), and 2 160 masl for pine-oak (geographic location: 24°35'27.66" N; 99°58'34.50" W).

Mulch degradation and harvesting frequency

Based on the litter decomposition bag method proposed by Bocock and Gilbert (1957), the decomposition process of mulch in three temperate ecosystems was evaluated over a one year period under outdoor conditions. Mulch corresponds to all the material that is formed once the leaf litter falls to the ground forming an organic layer (Pérez-Vázquez *et al.*, 2021); it was handled uniformly in the three ecosystems, for this purpose, 10 g dry weight of a uniform mixture of the litter components (leaves, branches, bark, reproductive structures and other miscellaneous components), collected in each of the ecosystems one month before the start of the experiment so that it would be fresh material and placed in paper bags, it was then dried at 65 °C. The collection was carried out randomly at each site (López-Hernández *et al.*, 2018).

A total of 60 decomposition bags were used for each ecosystem type; 12 were randomly distributed in five 20 m × 20 m experimental plots adjacent to one other in order to cover the total area of the site in each ecosystem. The 25 cm × 20 cm bags were made of 1 mm nylon fabric (Rodríguez *et al.*, 2019), allowing invertebrate detritivores to access the interior but minimizing fragmentation losses (Martínez-Atencia *et al.*, 2020). Each bag was placed on the surface of the soil without altering the conditions of the decomposing substrate, in order to avoid modifying the natural conditions in which the decomposing microorganisms develop, in addition to maintaining contact with the organic matter of the soil (Rodríguez *et al.*, 2019).

The assessment was carried out during 12 sampling dates between February 2021 and January 2022; five bags were collected every 30 days from each plot and study ecosystem. The material was transported to the Chemistry Laboratory of the Graduate School of Forest Sciences of the *Universidad Autónoma de Nuevo León*, where the methodology proposed by López-Hernández *et al.* (2018) was applied to dry it in a FE-292AD Felisa® forced-air oven at a constant 65 °C temperature, until a constant weight (g) was obtained. Several studies (Rivera *et al.*, 2013; Tapia-Coronado *et al.*, 2022) consider that soil particles adhering to the plant material do not alter the results and can be regarded as negligible, however, in order to remove them, the subsamples were cleaned with a brush. The remaining weight (g) of the mulch from each repetition was obtained in order to estimate the degree of decomposition by the difference between the initial weight and the final weight of each sampling date, both were recorded with a LC 620 S Sartorius® digital balance, with a 0.001 g resolution.

Using the Simple negative exponential model proposed by Olson (1963), the decomposition rate of the uniform mixture of the mulch components (10 g) was estimated for each ecosystem. In addition to Olson's (1963) exponential model, and in order to estimate mulch decomposition rates, other mathematical models (simple linear, logarithmic, and power) were tested to determine which had a better fit in estimating the decomposition rate compared to the reference model:

Model 1 (Olson, 1963): $H(t)= \beta_0 \times e^{-\beta_1 \times t}$

Model 2 (Moreno *et al.*, 2018): $H(t)= \beta_0+\beta_1 \times (t)$

Model 3 (Moreno *et al.*, 2018): $nl\ H(t)= \beta_0+\beta_1 \times nl(t)$

Model 4 (Moreno *et al.*, 2018): $H(t)= \beta_0 \times t^{\beta_1}$

Where:

H = Remaining mulch fraction (years)

T = Time (years)

nl = Natural logarithm

β_0 = Percentage of initial weight of mulch

β_1 = Mulch degradation rate

Statistical analyses

The averages of the remaining mulch fraction by sampling date and ecosystem were subjected to statistical analysis to test the assumptions of normality (Kolmogorov-Smirnov test with Lilliefors correction) and homogeneity of variances (Levene's test) (Ott, 2001). Since both assumptions were demonstrated, an analysis of variance was performed according to an experimental design with a classification criterion (Steel and Torrie, 1980) in order to detect the differences in the amount of remaining mulch fraction between forest ecosystems for each sampling date. A comparison of means of the remaining mulch fraction by date was performed using Tukey's HDS test (p=0.05) (Ott, 2001). The evaluation of the goodness of fit of each utilized model for determining the mulch decomposition rate was carried out based on the graphs of the residues, the root mean square values of the error, and Pearson's coefficients of determination (R^2) and correlation (r) (Ott, 2001). All statistical analyses were performed with the Statistical Package for Social Sciences (SPSS) version 22.0 for Windows (IBM, 2016).

Results and Discussion

Mulch decomposition

Table 1 shows the average remaining mulch fraction by ecosystem. The statistics and *p*-values of the Kolmogorov-Smirnov test and Levene's test (*L*), as well as the *F* and *p*-values of the analysis of variance by sampling date, are also included. According to Tukey's HDS test, most of the collection dates showed significant differences ($p<0.05$) between ecosystems, except for the fourth (MAY-21), sixth (JUL-21) and last (JAN-22) sampling dates.

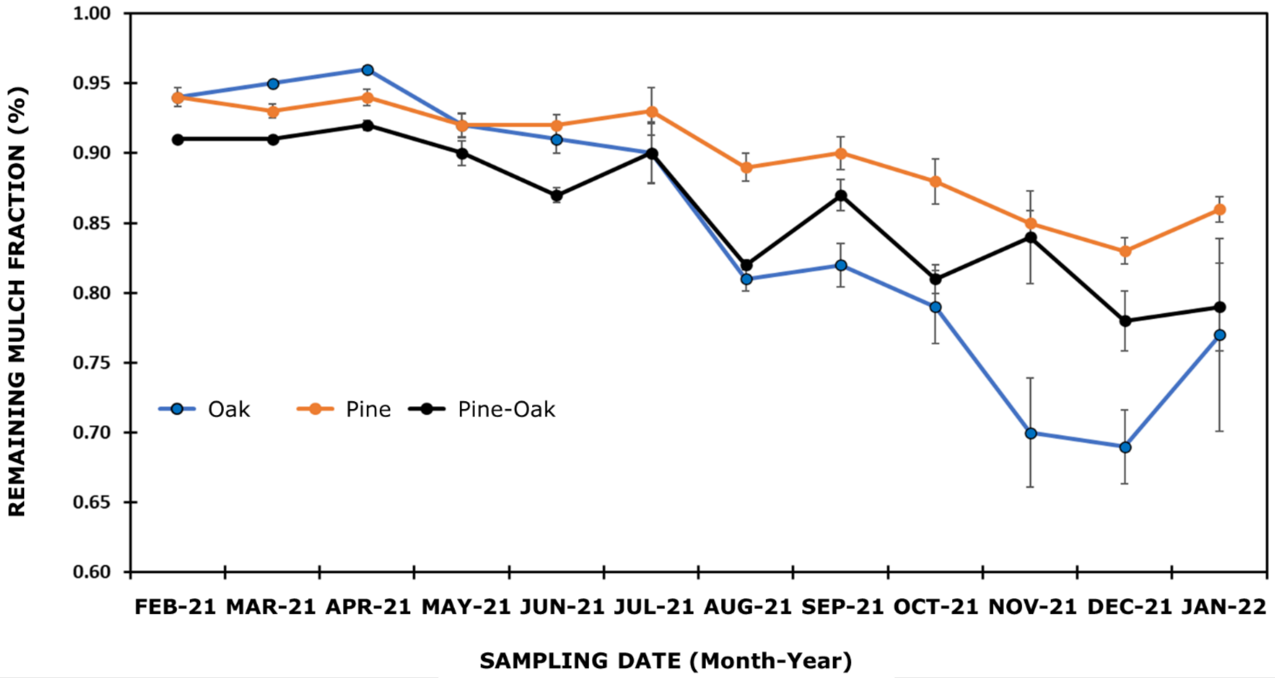
Table 1. Average remaining mulch fraction by date of collection and ecosystem.

Collection date	Remaining mulch fraction			*K-S*	*P* Value	*L*	*P* Value	*F*	*P* Value	EMSE
	Oak	Pine	Pine-Oak							
1. FEB-21	0.944^{a}	0.935^{a}	0.913^{b}	0.193	0.139	5.54	0.020	14.26	0.001	0.0042
2. MAR-21	0.947^{a}	0.928^{b}	0.914^{c}	0.218	0.052	1.69	0.225	25.95	0.001	0.0033
3. ABR-21	0.958^{a}	0.944^{a}	0.920^{b}	0.142	0.200	1.86	0.198	21.14	0.001	0.0042
4. MAY-21	0.924^{a}	0.920^{a}	0.905^{a}	0.156	0.200	0.03	0.975	1.46	0.270	0.0085
5. JUN-21	0.907^{a}	0.918^{a}	0.871^{b}	0.118	0.200	1.01	0.392	9.58	0.003	0.0078
6. JUL-21	0.897^{a}	0.928^{a}	0.896^{a}	0.200	0.111	0.05	0.951	0.82	0.462	0.0201
7. AGO-21	0.812^{b}	0.891^{a}	0.820^{b}	0.206	0.085	1.63	0.237	30.50	0.001	0.0079
8. SEP-21	0.819^{b}	0.904^{a}	0.866^{ab}	0.120	0.200	0.32	0.731	10.58	0.002	0.0130
9. OCT-21	0.792^{b}	0.880^{a}	0.806^{ab}	0.171	0.200	1.24	0.330	5.18	0.029	0.0213
10. NOV-21	0.704^{b}	0.848^{a}	0.838^{a}	0.196	0.148	1.45	0.276	7.61	0.008	0.0322

11. DIC-21	0.692[b]	0.826[a]	0.776[a]	0.161	0.200	1.45	0.281	12.79	0.002	0.0198
12. ENE-22	0.765[a]	0.857[a]	0.788[a]	0.230	0.187	7.36	0.024	1.18	0.369	0.0441

EMSE = Estimated mean standard error. ** Means of the remaining mulch fraction with the same letter are not statistically different (p>0.05) according to Tukey's HSD test.

Figure 2 shows the dynamics of the remaining mulch fraction for the three ecosystems during the study period. In the first three dates (FEB-21 to APR-21), the remaining fraction of mulch ranged between 0.913 (pine-oak ecosystem) and 0.958 (oak ecosystem). Between APR-21 and DEC-21, the fraction of remaining mulch in the pine ecosystem gradually decreased to 0.83 %, while in the pine-oak and oak ecosystems this fraction was 0.78 % and 0.69 %, respectively; decomposition was more noticeable in the oak ecosystem. With respect to the last collection date (JAN-22), a slight increase in the remaining fraction of mulch was observed in the three ecosystems, according to Pinos *et al.* (2017), this phenomenon happens due to the particular climatic conditions that develop during the decomposition process, which act in a direct way, slowing or increasing the process. In the same sense, von Arx *et al.* (2012) state that the decomposition process is strongly influenced by climate characteristics such as humidity, temperature, and precipitation, which actively slow down decomposition during specific periods of time, and even stop it.



Each plotted value represents the mean of n_{ij} observations of ecosystem *i* on sampling date *j*, with *i* = 1, 2, 3; *j* = 1, ... , 12 ± Standard error of the mean.

Figure 2. Fraction of remaining mulch of the three ecosystem types.

The results of the present study are congruent with the research conducted by Xuluc-Tolosa *et al.* (2003), but differ from that documented by Torres *et al.* (2018), who indicate that the rate of decomposition in the first months is higher and then the slope becomes slower and is significantly reduced, which largely responds to the type of ecosystem studied; the rapid mass loss in the first period is associated with the low presence of tannins and nitrogen released during the decomposition process of mangrove-associated species. On the contrary, temperate forest ecosystems may exhibit a slow decomposition process in the first phase due to the chemical composition of pine needles (Moreno *et al.*, 2018).

Rivera *et al.* (2013) point out that the first stage is controlled by fragmentation by the soil fauna and is related to water-soluble compounds, while in the second stage it is more directly related to the lignin content of the mulch, which slows down decomposition. This may explain the differences in mulch decomposition in the pine ecosystem, which was slower than in the oak ecosystem (Figure 2).

This reasoning allows us to assume differences in the chemical composition of the mulches in the ecosystems studied. In this regard, Bruno-Eutimio *et al.* (2022) document that the chemical composition of the mulch is a determining factor that is reflected during the decomposition process. In the same sense, Avendaño-Yáñez *et al.* (2020) and Berg and McClaugherty (2020) conclude that the differences observed during the decomposition process are associated with the type of litter and its chemical composition, which can pause or drive the process in different ecosystems. The percentage of mulch decomposition at the end of the study was 14 % for the pine ecosystem, 22 % for the pine-oak ecosystem, and 23 % for the oak ecosystem.

According to the results of Rodríguez *et al.* (2019), the loss of the remaining mulch fraction for pine, oak, and pine-oak ecosystems was 17, 27 and 23 %, respectively; which coincide with the intervals observed in the present study. Therefore, the decomposition process in pine, oak, and pine-oak ecosystems follows a trend, even when these ecosystems are located in different areas, with different soil types and particular characteristics, and these similarities can be explained at the local scale by the chemical composition of the mulch typical of mixed forests, which generally have low fertility (Reed *et al.*, 2012).

From the research study developed by Soong *et al.* (2015) under laboratory conditions at the Colorado State University, mulch fraction losses for pine (*Pinus ponderosa* P. Lawson & C. Lawson) is 28 %, and 58 % for oak (*Quercus macrocarpa* Michx.), with higher decomposition compared to the results of the present research for oak, results that are associated with some factors acting passively in the decomposition process, for example: chemical and biotic factors that play a fundamental role in the behavior of mulch mass loss, even when they are species of the same genus (Bangroo *et al.*, 2017).

An important factor to consider in mulch decomposition studies is the time to evaluate the process of mass loss, mainly associated with forest ecosystems, as suggested by Prescott (2005), who indicates that decomposition patterns can be modified in long-term experiments, since the percentage of decomposition of mulch in the long term reaches a higher disintegration and thus a better understanding of the process is achieved. In this regard, Horodecki and Jagodziński *et al.* (2019) document that, in order to understand processes such as mineralization and humidification, it is necessary to fully analyze the process, whereby a more accurate understanding of nutrient release can be attained.

The study period for the present study was one year, considered convenient for temperate climate species associated with forest ecosystems (Edwards, 1977; Rocha-Loredo and Ramírez-Marcial, 2009; López-Hernández *et al.*, 2018), which compared to other studies in tropical climate ecosystems is sufficient to stabilize the decomposition process. For example, Oliveira *et al.* (2019) only analyzed leaf litter decomposition over a period of 136 days for *Urochloa brizantha* (Hochst. *ex* A. Rich.) R. D. Webster, and conclude that the residual mass of mulch after one day of decomposition adds to the mass of newly deposited mulch that continues to decompose day after day; thus, it is a continuous process that needs to be studied at continuous time intervals. Rivera *et al.* (2013) studied the process of disintegration of organic matter in a temperate ecosystem in the *Selva El Ocote* Biosphere Reserve for 223 days, including several species, among them: *Enterolobium cyclocarpum* (Jacq.) Griseb., *Salix bonplandiana* Kunth, *Cecropia peltata* L., *Heliocarpus appendiculatus* Turcz. and *Mastichodendron capiri* (A. DC.) Cronquist. The most determining factor in the decomposition process was the age of the individuals. Tapia-Coronado *et al.* (2022) in 210 days analyzed the decomposition behavior of leaf litter from forest species [*Gmelina arborea* Roxb. *ex*

Sm., *Tabebuia rosea* (Bertol.) DC. and *Acacia mangium* Willd.] in tropical dry climate silvopastoral systems, whose decomposition process is similar to that of the present work, with a rapid initial loss of material that favors the active release of nutrients, and then becomes a slower process. Zhang *et al.* (2008) observed that variations in mulch decomposition rates are mainly due to differences in litter quality, microclimates, microbial community type and composition, and soil properties, with mulch quality being the main factor in the decomposition process.

In general, in broadleaved forests where precipitation and temperatures are high, the decomposition process is usually more accelerated than in ecosystems where temperature and precipitation are lower, for example, coniferous forests. Another determining factor is the acidity of the soils in coniferous forests, which, being more acidic than in other ecosystems, such as grasslands, limits microbial activities and, therefore, reduces the decomposition process of mulch (Gholz *et al.*, 2000).

Mulch decomposition models

The values of the fit statistics of the four decomposition models evaluated are described in Table 2; it is observed that the Coefficient of determination presented a fluctuation from 0.455 to 0.719, relatively lower values in relation to those documented by Moreno *et al.* (2018) in mixed ecosystems (0.965 to 0.069), and Rodríguez *et al.* (2019) who refer for this statistic an interval between 0.577 and 0.899 in forest ecosystems in the north of the country.

Table 2. Regression models fitted for the estimation of the fraction of remaining mulch during the study period for the three ecosystem types.

Model	Ecosystem	Estimated coefficient	95 % confidence intervals		Estimated coefficient	95 % confidence intervals		Statistics		
		β_0	LL β_0	UL β_0	β_1	LL β_1	UL β_1	R^2	*RMSE*	Pearson's coefficient
Exponential	Oak	1.017	0.983	1.051	0.352	0.290	0.414	0.71	0.054	0.843
	Pine	0.961	0.946	0.976	0.128	0.101	0.156	0.621	0.026	0.788
	Pine-Oak	0.946	0.926	0.967	0.180	0.141	0.220	0.617	0.034	0.785
Simple linear	Oak	1.009	0.979	1.039	-0.303	-0.354	-0.252	0.719	0.053	0.848
	Pine	0.960	0.946	0.975	-0.116	-0.141	-0.092	0.626	0.025	0.791
	Pine-Oak	0.944	0.924	0.963	-0.156	-0.190	-0.123	0.62	0.034	0.788
Logaríthmic	Oak	-0.276	-0.312	-0.24	-0.126	-0.157	-0.094	0.537	0.085	0.733
	Pine	-0.144	-0.158	-0.13	-0.044	-0.056	-0.031	0.462	0.034	0.680
	Pine-Oak	-0.203	-0.224	-0.183	-0.063	-0.081	-0.045	0.489	0.047	0.699
Power	Oak	0.770	0.744	0.797	-0.112	-0.140	-0.084	0.543	0.068	0.737
	Pine	0.867	0.854	0.880	-0.042	-0.054	-0.029	0.455	0.031	0.675
	Pine-Oak	0.819	0.802	0.836	-0.059	-0.076	-0.042	0.485	0.04	0.696

β_0 and β_1 = Model coefficients; LL and UL = Lower and upper limit of the model coefficients, respectively; R^2 = Coefficient of determination; *RMSE* = Root mean square error.

The values obtained from the fit of the models in the three ecosystems under study for the Correlation coefficient ranged between 0.675 and 0.848, which are low compared to those cited by Del Valle-Arango (2003) of 0.966, and Ibarra *et al.* (2011) of 0.946. The Simple negative exponential model (Olson, 1963) presented a good fit according to the Coefficient of determination, ranging from 0.617 (pine-oak ecosystem) to 0.710 (oak ecosystem). Pearson's correlation coefficient was distributed between 0.785 and 0.843. This model is the most commonly used to describe the rate of mulch decomposition (Swift *et al.*, 1981; Burghouts *et al.*, 1998; Gama-Rodrigues *et al.*, 2003; Tapia-Coronado *et al.*, 2022).

The Simple linear model had a Coefficient of determination (R^2) ranging from 0.620 (pine-oak ecosystem) to 0.719 (oak ecosystem). The logarithmic and power models presented low determination coefficients (0.462 to 0.543), with respect to the exponential and simple linear models.

Mulch decomposition rate

The decomposition rate (constant k) of mulch resulting from the exponential and simple linear models, which were considered as a reference based on the highest values of the coefficients of determination, are presented in Table 2; it is observed that this constant for the three ecosystems was 0.352, 0.180, and 0.128, respectively, from which the theoretical time required for 25 %, 50 %, and 75 % of the mulch to degrade was estimated. The estimated values, according to the model proposed by Olson (1963), ranged from 0.866 (oak ecosystem) to 10.455 years (pine ecosystem) (Table 3).

Table 3. Estimated time (years) to disintegrate 25 % ($t_{0.25}$), 50 % ($t_{0.5}$), and 75 % ($t_{0.75}$) of the mulch in the three types of ecosystems.

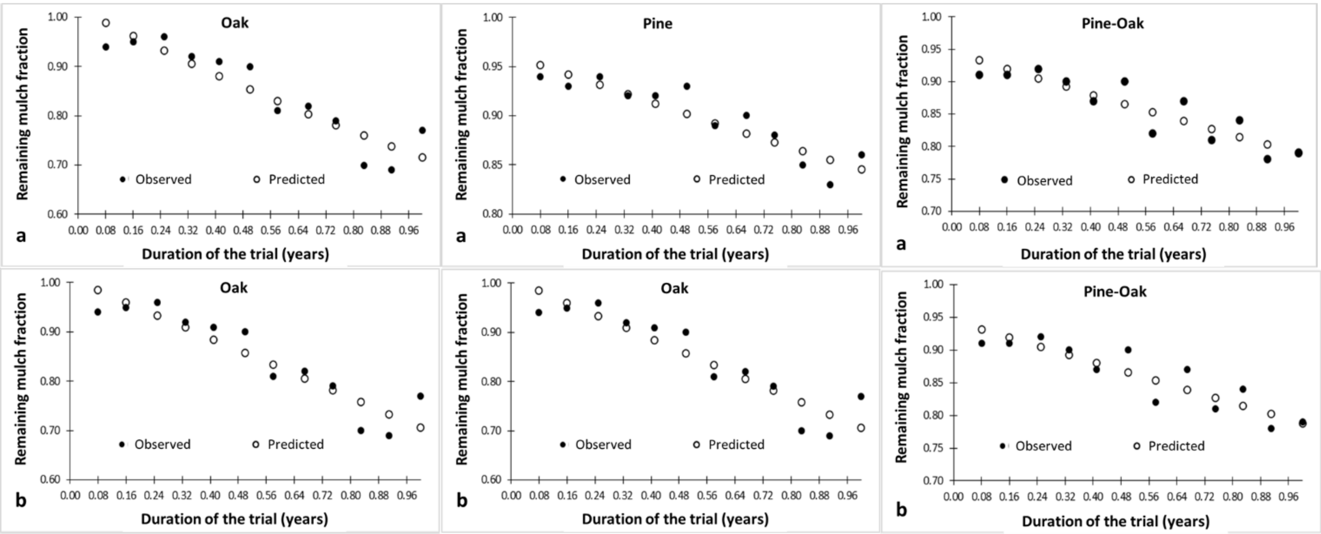
Model	PD	Ecosystems								
		Oak			Pine			Pine-Oak		
		Estimate	LL	UL	Estimate	LL	UL	Estimate	LL	UL
Exponential	25	0.866	0.656	0.934	1.929	1.690	2.294	1.289	1.156	1.494
	50	2.018	1.635	2.330	5.076	4.285	6.291	3.534	2.997	4.368
	75	3.985	3.309	4.717	10.455	8.721	13.123	7.370	6.144	9.281
Simple linear	25	0.854	0.646	1.147	1.803	1.389	2.434	1.240	0.918	1.739
	50	1.678	1.351	2.138	3.942	3.159	5.137	2.835	2.230	3.772
	75	2.503	2.056	3.130	6.080	4.928	7.840	4.430	3.542	5.805

PD = Percentage of decomposition; LL = Lower Limit: UL = Upper Limit. Both limits with a 95 % confidence interval.

The values of the decomposition constant (*k*) of the Simple linear model ranged from -0.116 (pine-oak ecosystem) to -0.303 (oak ecosystem) (Table 2). Estimates of the time required to degrade mulch 25, 50, and 75 % ranged from 0.854 (oak ecosystem) to 6.080 years (pine ecosystem) (Table 3). These results indicate, in general, that the estimation of mulch decomposition is higher with the Olson model than when using the Simple linear model, as the average decomposition times are longer. It should be noted that the decomposition times of mulch at 25, 50, and 75 % in both models should be considered with reservations, since the environmental conditions —biotic, abiotic, and chemical— do not remain constant.

In this sense, Tresch *et al.* (2019) point out that the process is influenced by the environmental conditions of each site, which modify the decomposition rates; Correa-Araneda *et al.* (2020) refer to the fact that the environmental conditions prevailing at specific time intervals control decomposition through various direct and indirect processes that are rarely constant, for example, Bölscher *et al.* (2020) mention that high temperatures and precipitation facilitate soil acidification, which probably increases the presence of decomposing agents, and therefore microbial activities, which can be altered by extraordinary climatic phenomena, and, consequently, decomposition rates are modified.

Figure 3 illustrates the dispersion of the data (observed and predicted) of the remaining mulch fraction considering the Exponential model and the Simple linear model during the study period in the three temperate forest ecosystems.



a = Predicted values obtained with reference to the Exponential model for each ecosystem under study; b= Predicted values obtained by reference to the Simple linear model for each ecosystem under study.

Figure 3. Observed and predicted values of mulch decomposition during the time (year) of the trial in each ecosystem.

The values of *k* in comparison with those obtained for other ecosystems seem low. Rocha-Loredo and Ramírez-Marcial (2009) recorded in pine-oak, pine, and oak forests a *k* constant of 1.40, 1.44 and 1.74, respectively, while Rivera *et al.* (2013) estimated that the time required to degrade 50 and 99 % of the mulch in low deciduous forest is 75.9 and 504.3 days, respectively. Tapia-Coronado *et al.* (2022) documented that the decomposition rate for forest species is more accelerated than that of grasses, with *k* values of 1.77, which allows inferring that the decomposition rate of mulch is influenced by the composition of plant species and their distribution (Peña-Peña and Irmler, 2016; Djukic *et al.*, 2018). The present study did not consider the chemical analysis of the mulch components, therefore, it is possible to assume that the differences in the values of the Decomposition constant (*k*) between the ecosystems studied depend directly on the species composition and the successional stage of the ecosystems, as indicated by Rocha-Loredo and Ramírez-Marcial (2009). On the other hand, the nutritional and structural components of the mulch are factors that act directly on decomposition rates and account for their differences, although these are not usually studied (Berg and McClaugherty, 2020).

Conclusions

The decomposition process of mulch in the three ecosystems was different during the experimental period. The pine ecosystem has the lowest percentage (14 %) of decomposition, compared to oak (23 %) and pine-oak (22 %), which suggests that the quality of the organic material has a direct relationship with the decomposition process. In the oak ecosystem, more accelerated decomposition implies a more rapid release of nutrients and, consequently, better quality. In addition, species composition plays a fundamental role, although the chemical composition of the litter and the environmental factors are the main regulators of the decomposition rate. Species distribution and composition are factors influencing the supply of organic material.

Given the conditions of the ecosystems studied, the best-fitting models for predicting mulch decomposition are the exponential and simple linear models.

As for the estimated decomposition rate for the three ecosystems, the time required shows a difference for all decomposition rates, according to the reference models. Based on the Exponential model, the oak ecosystem requires the least time (0.866 years), followed by pine-oak (1.156 years) and pine (1.929 years), these results are due, in part, to the chemical composition of the recalcitrant material. With respect to the decomposition rates estimated with the Simple linear model, the pine ecosystem requires more time due to the presence of chemical substances in the pine needles.

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Conflict of interest

The authors declare that they have no conflict of interest.

Contribution by author

César Gerardo Ramos Hernández: research development, data analysis and drafting of the manuscript; Juan Manuel López Hernández: planning and development of the research and field data collection; Marco Vinicio Gómez Meza: data analysis and revision of the manuscript; Israel Cantú Silva: experimental design and revision of the manuscript; María Inés Yáñez Díaz: revision of the manuscript; Wibke Himmelsbash: experimental design and revision of the manuscript; Humberto González Rodríguez: planning and development of the research, selection of the study area, and revision of the manuscript.

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