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## Litterfall deposition and leaf litter nutrient return in different locations at Northeastern Mexico

H. González-Rodríguez · T. G. Domínguez-Gómez ·  
I. Cantú-Silva · M. V. Gómez-Meza · R. G. Ramírez-Lozano ·  
M. Pando-Moreno · C. J. Fernández

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**Abstract** The aim of this study was to determine the litterfall production and macronutrient (Ca, K, Mg, N, and P) deposition through leaf litter in four sites with different types of vegetation. Site one (Bosque Escuela) was located at 1600 m a.s.l. in a pine forest mixed with deciduous trees, second site (Crucitas at 550 m a.s.l.) in the ecotone of a *Quercus* spp. forest and the Tamaulipan thornscrub and third and fourth sites (Campus at 350 m a.s.l. and Cascajoso at 300 m a.s.l., respectively) were in the Tamaulipan thornscrub. Litter constituents (leaves, reproductive structures, twigs, and miscellaneous residues) were collected at 15-day intervals from December 21, 2006, throughout December 20, 2007. Collections were carried out in ten litter traps

(1.0 × 1.0 m) randomly situated at each site of approximately 2,500 m<sup>2</sup>. Total annual litterfall deposition was 4407, 7397, 6304, and 6527 kg ha<sup>-1</sup> y<sup>-1</sup> for Bosque Escuela, Crucitas, Campus and Cascajoso, respectively. Of total annual litter production, leaves were higher varying from 74 (Bosque Escuela) to 86% (Cascajoso) followed by twigs from 4 (Cascajoso) to 14% (Crucitas), reproductive structures from 6 (Bosque Escuela) to 10% (Crucitas), and miscellaneous litterfall from <1 (Campus) to 12% (Bosque Escuela). The Ca annual deposition was significantly higher in Cascajoso (232.7 kg ha<sup>-1</sup> y<sup>-1</sup>), followed by Campus (182.3), Crucitas (130.5) and Bosque Escuela (30.3). The K (37.5, 32.5, 24.8, 7.2, respectively), Mg (22.6, 17.7, 13.7, 4.5, respectively) followed the same pattern as Ca. However, N was higher in Campus (85.8) followed by Crucitas (85.1), Cascajoso (68.3), and Bosque Escuela (18.3). The P was higher in Campus and Crucitas (4.0) followed by Cascajoso (3.4) and Bosque Escuela (1.4). On an annual basis for all sites, the order of nutrient deposition through leaf litter was Ca > N > K > Mg > P, whereas on site basis of total nutrient deposition (Ca + N + K + Mg + P), the order was Cascajoso > Campus > Crucitas > Bosque Escuela. Ca, K, Mg, N, and P nutrient use efficiency values in leaf litter were higher in Bosque Escuela, while lower figures were acquired in Cascajoso and Crucitas sites. It seems that the highest litterfall deposition was found in the ecotone of a *Quercus* spp. forest and the Tamaulipan thornscrub; however, the Tamaulipan

H. González-Rodríguez (✉) · T. G. Domínguez-Gómez · I. Cantú-Silva · M. Pando-Moreno  
Facultad de Ciencias Forestales, Universidad Autónoma de Nuevo León, Apartado Postal 41, 67700 Linares, NL, Mexico  
e-mail: humberto.gonzalezrd@uanl.edu.mx

M. V. Gómez-Meza  
Facultad de Economía, Universidad Autónoma de Nuevo León, Monterrey, NL, Mexico

R. G. Ramírez-Lozano  
Facultad de Ciencias Biológicas, Universidad Autónoma de Nuevo León, Monterrey, NL, Mexico

C. J. Fernández  
Texas AgriLife Research and Extension Center at Corpus Christi, 10345 Agnes St., Corpus Christi, TX 78406, USA

thornscrub vegetation alone had better leaf litter nutrient return.

**Keywords** Litterfall production · Litter components · Leaf litter nutrient return · Tamaulipan thornscrub · Northeastern Mexico

## Introduction

Litterfall and litter decomposition are key processes in nutrient cycling of forest ecosystems (Baker et al. 2001; Isaac and Nair 2006). In addition to these processes, throughfall and stemflow are the main sources to maintain soil fertility to the forest floor (Vasconcelos and Luizão 2004). Litterfall plays a fundamental role in nutrient turnover and in the transfer of energy between plants and soil, the main source of organic material and nutrients being accumulated in the uppermost layer of the soil. Nutrient release from decomposing litter is an important internal pathway for nutrient flux in forest ecosystems (Santa-Regina et al. 2005).

Evaluation of litterfall production is important for understanding nutrient cycling, forest growth, successional pathways, carbon fluxes, disturbance ecology, and interactions with environmental variables in forest ecosystems (Vasconcelos and Luizão 2004; Zhou et al. 2007). However, litterfall inputs vary widely among forest ecosystems in terms of quality (Duchesne et al. 2001; Vasconcelos and Luizão 2004) and quantity (Rothe and Binkley 2001; Zhou et al. 2007). The quality of soil organic matter is of great importance for the majority of the functional processes occurring in the soil of forest ecosystems (Santa-Regina et al. 2005). Despite the great number and well-documented floristic studies carried out at the Tamaulipan thornscrub or subtropical thornscrub woodlands, Northeastern Mexico, few studies have been carried out to address the spatial and temporal patterns of litterfall and nutrient deposition at different altitude gradients where plant species composition is different.

The nutrient cycling is of key importance in forest communities where sustainable litterfall production is an essential part of the aboveground net primary production and depends upon the nutritional status of

soil, such as those found in the northeastern region of Mexico, whose vegetation depends on the biogeochemical cycles of plant nutrients contained in plant detritus (Vasconcelos and Luizão 2004). Therefore, this region provides an opportunity to investigate litterfall production and nutrient returns of forest and native vegetation in order to gain a better understanding of how to sustain and improve productivity in response to changes in resource availability. Thus, the aim of this study was to assess the annual cycle of litterfall production and nutrient deposition through leaf at different ecological sites in Northeastern Mexico.

## Materials and methods

### Study area

This study was carried out at four undisturbed sites located in the state of Nuevo Leon, Northeastern Mexico. Site one (Bosque Escuela) was located in a pine (*Pinus pseudostrabus* Lindl.) forest mixed with deciduous trees located in the Experimental Forest Research Station of the Universidad Autónoma de Nuevo León in the Sierra Madre Oriental Mountain, Iturbide county (24°43'N; 99°52'W; 1600 m a.s.l.). Mean annual air temperature is about 13.9°C. Average annual rainfall is approximately 639 mm. The soil of the site is mainly rocky and comprises upper cretaceous lutite or siltstone. Site two (Crucitas) was located in the ecotone of a *Quercus* sp. forest and the Tamaulipan thornscrub (24°46'N; 99°41'W; 550 m a.s.l.). Average total annual rainfall is 755 mm with an annual mean air temperature of 21°C (Bravo-Garza 1999). Site three (Campus) was located at the Experimental Research Station of the Faculty of Forest Sciences of University Autonomous of Nuevo León (24°47' N; 99°32' W; 350 m a.s.l.). The climate is subtropical and semiarid with warm summer. Monthly mean air temperature ranges from 14.7°C in January to 22.3°C in August, although daily high temperatures of 45°C are common during summer. Average total annual precipitation is about 805 mm with a bimodal distribution. The peak rainfall months are May, June, and September (González-Rodríguez et al. 2004). Site four (Cascajoso) was located in the Hacienda Guadalupe “Ejido” (24°54'N; 99°32'W; elevation, 300 m a.s.l.). Averaged annual temperature

is 21°C with a mean maximum and mean minimum of 30 and 12°C, respectively. Total cumulative annual rainfall is 672 mm. Crucitas, Campus, and Cascajoso sites are located in Linares county. Vegetation of Campus and Cascajoso sites is known as the Tamaulipan thornscrub or subtropical thornscrub woodlands (SPP–INEGI 1986). In the last three sites, the dominant soils are deep, dark-gray, lime-gray, lime-clay Vertisols, with montmorillonite, which shrink and swell noticeably in response to changes in soil moisture content. Physical and chemical characteristics of the soils (four sites) at a profile depth of 0–20 cm are shown in Table 1. In addition, registered mean monthly air temperatures (°C) and cumulative monthly rainfall (mm) are shown in Table 2.

### Collections of litterfall production

At each site, ten litter traps (1.0 m<sup>2</sup>), made with wooden sides fitted with the nylon net bottom (1 mm mesh size), randomly scattered over the entire area (2,500 m<sup>2</sup>) were used for litterfall collections. Each trap was placed approximately 0.30 m above the soil level to intercept litterfall. Trap contents were collected at 15-day intervals between December 21, 2006, and December 20, 2007. Since area and height above the ground of litter traps as well as the sampling period of collection in litterfall studies are variable, which in many circumstances depends on the total area sampled, type of vegetation, the temporal and spatial variation in litterfall production,

and to prevent significant decomposition and leaching loss of nutrients by throughfall between collections resulting in an underestimation of the true litterfall flux of nutrients to the forest soil, in this study, the area of sampling, number of traps and height above soil level, and litter collection period are within the range of previous studies (Ukonmaanaho and Starr 2001; Finotti et al. 2003; Read and Lawrence 2003; Yang et al. 2004, 2006; Fang et al. 2007; Zhou et al. 2007). Litter contents were manually sorted into the following categories: leaves, reproductive structures (flowers, fruits, and seeds) twigs or branches (<2 cm in diameter), and miscellaneous residues (unidentified, fine plant tissue such as bark, pieces of insect bodies or feces). Corrections were not accounted for weight sample losses from litter that might have decomposed between sampling dates or amount of litter blown into or out of traps by wind. Samples were oven-dried to a constant weight at 65°C for 72 h and weighed to the nearest milligram. In this study, the duration of the drying temperature is within the range of earlier reports (Vasconcelos and Luizão 2004; Zayed 2004; Pavón et al. 2005; Mlambo and Nyathi 2007; Zhou et al. 2007). Dry samples were ground in a Wiley mill (Thomas Scientific) to pass 1.0-mm mesh sieve and were kept in closed paper envelopes.

### Chemical analyses

By quintuplicate, leaf litter samples, in each trap, were subjected to mineral analysis. Mineral content

**Table 1** Physical and chemical characteristics of soils (profile depth 0–20 cm) at the studied sites in Northeastern Mexico

Item	Sites			
	Bosque Escuela	Crucitas	Campus	Cascajoso
Sand (g kg <sup>-1</sup> )	170.0	120.0	250.0	130.0
Silt (g kg <sup>-1</sup> )	430.0	420.0	500.0	610.0
Clay (g kg <sup>-1</sup> )	400.0	460.0	250.0	260.0
Bulk density (Mg m <sup>-3</sup> )	0.9	1.2	0.8	1.2
Organic matter (%)	6.0	4.0	7.0	2.0
pH (CaCl <sub>2</sub> ; 0.01 M)	6.6	6.8	6.6	7.1
EC (μS cm <sup>-1</sup> )	255.0	103.0	216.0	123.0
Ca (mg kg <sup>-1</sup> )	8839.1	5063.5	8555.6	8000.2
K (mg kg <sup>-1</sup> )	297.4	307.7	109.5	134.7
Mg (mg kg <sup>-1</sup> )	150.3	310.4	216.0	98.5
P (mg kg <sup>-1</sup> )	5.1	10.2	9.3	5.2
N (mg kg <sup>-1</sup> )	2957.3	3461.2	5604.6	1897.3

**Table 2** Mean monthly air temperature (°C) and cumulative monthly rainfall (mm) at research sites in Northeastern Mexico

Month–year	Sites							
	Bosque Escuela		Crucitas		Campus		Cascajoso	
	°C	mm	°C	mm	°C	mm	°C	mm
December 2006	10.8	24.2	14.7	26.4	15.1	32.2	16.0	6.6
January 2007	10.1	31.8	17.2	32.4	11.8	39.8	12.3	29.6
February 2007	12.4	10.0	19.5	64.8	16.2	64.2	17.1	22.0
March 2007	15.2	12.2	19.8	14.0	21.2	9.2	22.0	1.6
April 2007	17.0	19.6	20.6	52.6	21.8	30.8	23.8	49.8
May 2007	18.9	71.4	23.7	285.8	25.1	156.2	26.4	101.8
June 2007	20.6	109.4	25.5	127.8	26.8	86.8	28.3	24.4
July 2007	19.7	139.2	25.0	3.4	26.3	148.2	28.0	75.8
August 2007	19.4	179.2	25.6	118.2	26.7	159.2	28.3	73.2
September 2007	18.4	129.4	24.5	154.8	25.6	112.8	26.6	58.6
October 2007	16.4	31.8	22.0	35.2	23.0	19.2	23.8	15.6
November 2007	13.6	13.6	17.5	25.8	19.2	23.8	20.0	3.0
December 2007	13.6	2.4	16.2	0.8	17.3	0.6	18.3	1.6
Total annual		774.2		942.0		883.0		463.6

was estimated by incinerating samples in a muffle oven at 550°C, during 5 h. Ashes were digested in a solution containing HCl and HNO<sub>3</sub>, using the wet digestion technique (Cherney 2000). Concentrations of Ca (oxide nitrous/acetylene flame), K, and Mg (air/acetylene flame) were determined by atomic absorption spectrophotometry (Varian, model SpectrAA-200), whereas P was quantified spectrophotometrically using a Perkin-Elmer spectrophotometer (Model Lamda 1A) at 880 nm (AOAC 1997). The Kjeldahl procedure was employed for total N analyses (AOAC 1997). Nutrient deposition at each site was calculated by multiplying leaves litter production by each sampling date by nutrient concentration for the same sampling date and site and adding them over the entire year. The accumulated values at each site were used as an estimate of the annual nutrient deposition. The leaf litter annual nutrient deposition values of Ca, K, Mg, P, and N were used to estimate within-site leaf litter nutrient use efficiency (LLNUE) defined as the ratio of annual leaf litter mass to annual leaf litter nutrient content deposition ( $\text{kg ha}^{-1} \text{y}^{-1}$ ) (Vitousek 1982; Read and Lawrence 2003).

#### Statistical analyses

Litterfall deposition data, per sampling date, belonging to each litter constituent as well as leaf nutrient

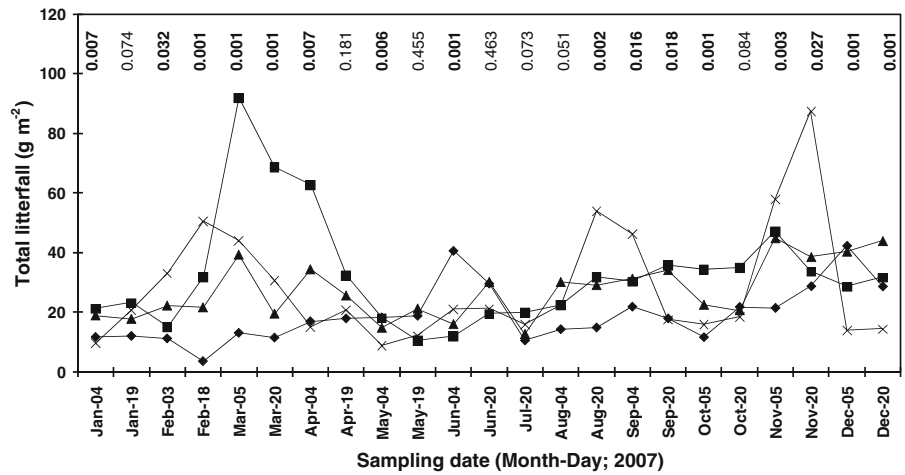
content data were subjected to one-way analysis of variance (Steel and Torrie 1980). Normal distribution and homogeneity of variances for each litter constituent and nutrient content data tested using the Kolmogorov–Smirnov, Shapiro–Wilk, and Levene tests (Brown and Forsythe 1974; Steel and Torrie 1980) indicated that litterfall and nutrient content data are non-normally distributed. Since for most sampling dates, ANOVA did not show the assumption of equality of variances, Kruskal–Wallis non-parametric test was employed (Ott 1993) to detect significant differences among sites at each sampling date. Hence, differences in litter deposition and nutrient content between sites were validated using the Mann–Whitney *U* nonparametric test with the Bonferroni's correction method at  $P = 0.05$  (Wackerly et al. 2002). All applied statistical methods were according to the SPSS<sup>®</sup> (Statistical Package for the Social Sciences) software package (standard released version 13.0 for Windows, SPSS Inc., Chicago, IL).

## Results

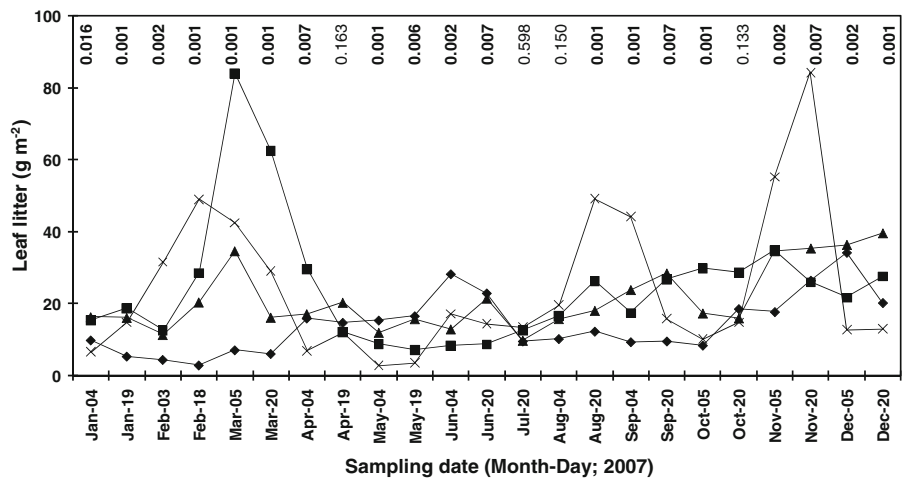
#### Litterfall deposition

Total litterfall deposition by site is shown in Fig. 1. In Bosque Escuela, it ranged from 3.6 to 42.4  $\text{g m}^{-2}$ ;

**Fig. 1** Total litterfall deposition pattern at research sites. *P*-values of the Kruskal–Wallis test to detect significant differences among sites are shown at each sampling date within the graph. *P*-values  $\leq 0.001$  are denoted as 0.001. Statistically significant probabilities ( $P \leq 0.05$ ) are shown in boldface. Bosque Escuela (*filled diamond*), Crucitas (*filled square*), Campus (*filled triangle*), Cascajoso (*times symbol*)



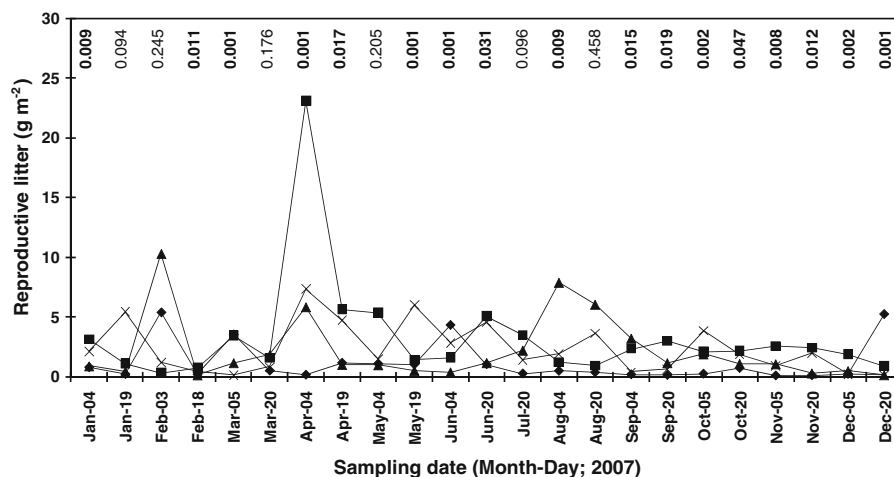
**Fig. 2** Leaf litterfall deposition pattern at research sites. *P*-values of the Kruskal–Wallis test to detect significant differences among sites are shown at each sampling date within the graph. *P*-values  $\leq 0.001$  are denoted as 0.001. Statistically significant probabilities ( $P \leq 0.05$ ) are shown in boldface. Bosque Escuela (*filled diamond*), Crucitas (*filled square*), Campus (*filled triangle*), Cascajoso (*times symbol*)



in Crucitas, from 10.6 to 91.9; in Campus, from 12.7 to 44.8; and in Cascajoso, from 8.8 to 87.6. Leaf litter deposition (Fig. 2) for Bosque Escuela varied from 2.9 to 34.2; for Crucitas, from 7.1 to 83.9; for Campus, from 9.8 to 39.5; and for Cascajoso, from 2.7 to 84.2. The dynamics of reproductive structures litter inputs is shown in Fig. 3. Mean minimum reproductive structure deposition values for Bosque Escuela, Crucitas, Campus, and Cascajoso sites were 0.1, 0.3, 0.2, and 0.2  $\text{g m}^{-2}$ , respectively, whereas maximum deposition was 5.4, 23.1, 10.3, and 7.3, respectively. The twig litter seasonal deposition (Fig. 4), mean minimum values ranged from 0.06

(Bosque Escuela) to 1.37  $\text{g m}^{-2}$  (Crucitas), while mean maximum deposition values varied from 4.08 (Cascajoso) to 14.23  $\text{g m}^{-2}$  (Crucitas). The Fig. 5 shows the seasonal trend of miscellaneous litter deposition, which illustrates that the minimum and maximum observed values ranged from 0.0 (Campus) to 7.0  $\text{g m}^{-2}$  (Bosque Escuela).

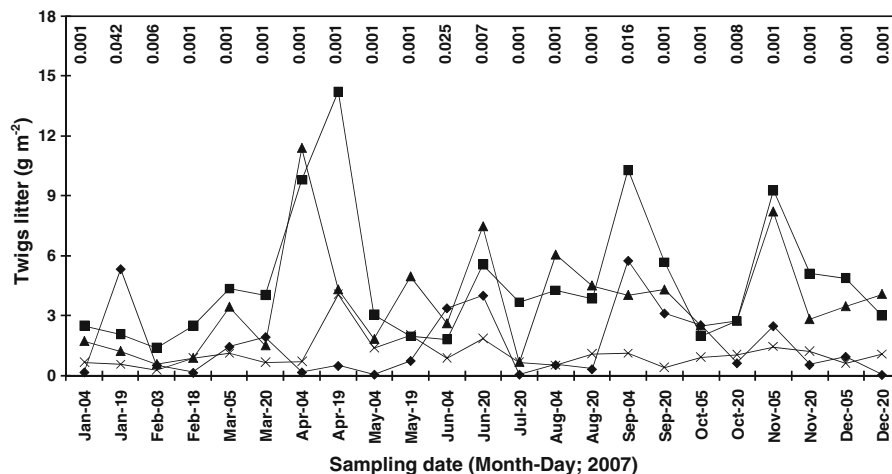
Total annual litter production and its components (leaves, reproductive structures, twigs, and miscellaneous) are shown in Table 3. Crucitas site showed the highest values followed by Cascajoso, Campus, and Bosque Escuela. Leaves represented the main component with a deposition that ranged from 74 (Bosque



**Fig. 3** Reproductive litterfall deposition pattern at research sites. *P*-values of the Kruskal–Wallis test to detect significant differences among sites are shown at each sampling date within the graph. *P*-values  $\leq 0.001$  are denoted as 0.001. Statistically

significant probabilities ( $P \leq 0.05$ ) are shown in boldface. Bosque Escuela (filled diamond), Crucitas (filled square), Campus (filled triangle), Cascajoso (times symbol)

**Fig. 4** Twig litterfall deposition pattern at research sites. *P*-values of the Kruskal–Wallis test to detect significant differences among sites are shown at each sampling date within the graph. *P*-values  $\leq 0.001$  are denoted as 0.001. Statistically significant probabilities ( $P \leq 0.05$ ) are shown in boldface. Bosque Escuela (filled diamond), Crucitas (filled square), Campus (filled triangle), Cascajoso (times symbol)



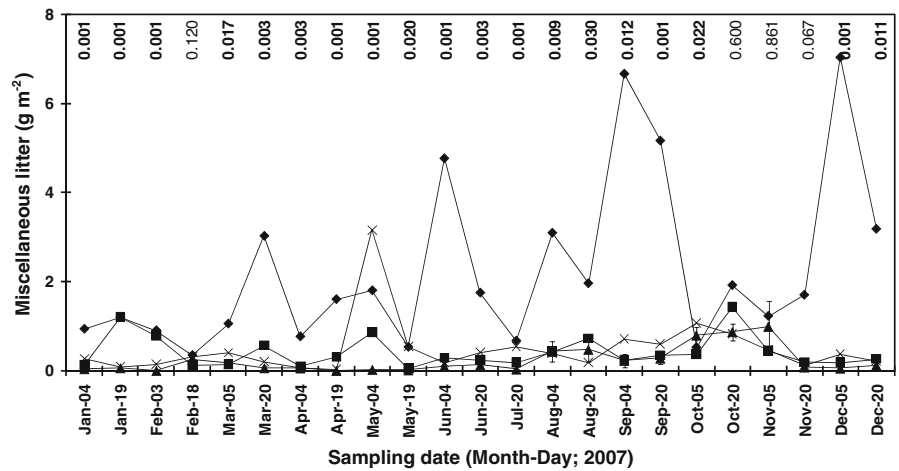
Escuela) to 86% (Cascajoso). Reproductive structure (flowers, fruits, and seeds) deposition ranged from 6.3 (Bosque Escuela) to 9.5% (Crucitas). Twig annual deposition varied from 4 (Cascajoso) to 14% (Crucitas). The contribution of the miscellaneous constituents of litterfall ranged from <1 (Campus) to 12% (Bosque Escuela) of total annual litter deposition.

#### Leaf litter nutrient contents

The Ca content (Fig. 6a) in Bosque Escuela ranged from 5.3 to 14.5 mg gdw<sup>-1</sup>; in Crucitas, from 18.4 to 30.5; in Campus, from 31.9 to 43.0; and in Cascajoso,

from 33.1 to 48.5. Leaf litter K content (Fig. 6b) for Bosque Escuela varied from 1.1 to 4.2 mg gdw<sup>-1</sup>; for Crucitas, from 1.8 to 9.1; for Campus, from 2.5 to 11.0; and for Cascajoso, from 1.9 to 13.4. As a general seasonal trend, Bosque Escuela, Crucitas, Campus, and Cascajoso acquired an average Mg content of about 1.4, 2.4, 3.5, and 4.0 mg gdw<sup>-1</sup>, respectively, during the experimental period (Fig. 6c). Averaged monthly leaf litter P content for Bosque Escuela, Crucitas, Campus, and Cascajoso were 0.4, 0.8, 0.8, and 0.7 mg gdw<sup>-1</sup>, respectively (Fig. 6d). The N content (Fig. 6e) in Bosque Escuela varied from 3.9 to 7.6 mg gdw<sup>-1</sup>; in Crucitas, from

**Fig. 5** Miscellaneous litterfall deposition pattern at research sites. *P*-values of the Kruskal–Wallis test to detect significant differences among sites are shown at each sampling date within the graph. *P*-values  $\leq 0.001$  are denoted as 0.001. Statistically significant probabilities ( $P \leq 0.05$ ) are shown in boldface. Bosque Escuela (filled diamond), Crucitas (filled square), Campus (filled triangle), Cascajoso (times symbol)



**Table 3** Annual means of litter and leaf litter nutrient depositions and LLNUE at research sites in Northeastern Mexico

Deposition features	Sites			
	Bosque Escuela	Crucitas	Campus	Cascajoso
Total (kg ha <sup>-1</sup> y <sup>-1</sup> )	4407.3	7397.1	6304.1	6527.2
Leaves	3254.0	5560.5	4892.0	5612.6
Reproductive	277.8	700.9	504.2	545.5
Twigs	356.3	1041.1	855.5	255.5
Miscellaneous	519.2	94.5	52.3	113.5
Ca	30.3	130.5	182.3	232.7
K	7.2	24.8	32.5	37.5
Mg	4.5	13.7	17.7	22.6
P	1.4	4.0	4.0	3.4
N	18.3	85.1	85.8	68.3
LLNUE				
Ca	107.4	42.6	26.8	24.1
K	451.9	224.2	150.5	149.7
Mg	723.1	405.9	276.4	248.3
P	2324.3	1390.1	1223.0	1650.8
N	177.8	65.3	57.0	82.2

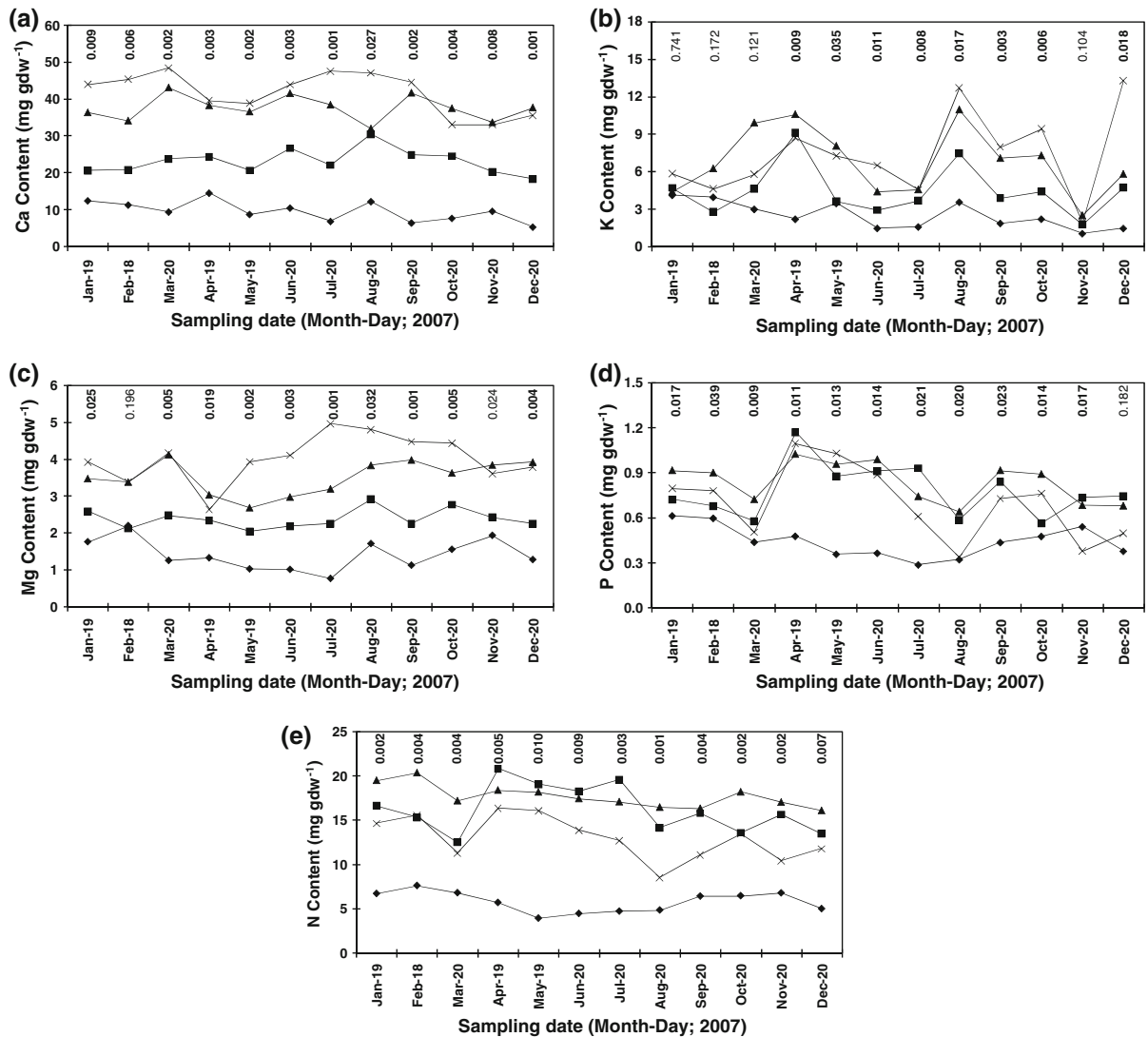
Leaf litter nutrient use efficiency (LLNUE) was calculated as (kg leaf litter ha<sup>-1</sup> y<sup>-1</sup>)/(kg leaf litter nutrient ha<sup>-1</sup> y<sup>-1</sup>)

12.5 to 20.2 mg gdw<sup>-1</sup>; in Campus, from 16.1 to 20.4; and in Cascajoso, from 8.5 to 16.3.

The Ca annual deposition was higher in Cascajoso followed by Campus, Crucitas, and Bosque Escuela. The K and Mg followed the same pattern as Ca. However, N was higher in Campus followed by Crucitas, Cascajoso, and Bosque Escuela. The P was similar in Campus and Crucitas and both were higher

than Cascajoso and Bosque Escuela (Table 3). Regardless of site, the annual nutrient inputs through leaf litter exhibited the following rank order: Ca > N > K > Mg > P (Table 3). Total annual nutrient deposition (Ca + K + Mg + P + N) for Bosque Escuela, Crucitas, Campus, and Cascajoso was 61.7, 258.1, 322.3, and 364.5 kg ha<sup>-1</sup> y<sup>-1</sup>, respectively.





**Fig. 6** Monthly variations of Ca, K, Mg, P, and N contents in leaf litter at research sites. *P*-values of the Kruskal–Wallis test to detect significant differences among sites are shown at each sampling date within the graph. *P*-values  $\leq 0.001$  are denoted

as 0.001. Statistically significant probabilities ( $P \leq 0.05$ ) are shown in boldface. Bosque Escuela (filled diamond), Crucitas (filled square), Campus (filled triangle), Cascajoso (times symbol)

Leaf litter nutrient use efficiency for Ca, K, and Mg exhibited the following rank order: Bosque Escuela > Crucitas > Campus  $\geq$  Cascajoso; meanwhile, the P and N trend order was Bosque Escuela > Cascajoso > Crucitas  $\geq$  Campus (Table 3). Calcium LLNUE ranged from 24 (Cascajoso) to 107 (Bosque Escuela), K from 150 (Campus and Cascajoso) to 451 (Bosque Escuela), Mg from 248 (Cascajoso) to 723 (Bosque Escuela), P from 1,223 (Campus) to 2,324 (Bosque Escuela), and N from 57 (Campus) to 178 (Bosque Escuela).

## Discussion

It appears that litterfall and its constituents (leaves, reproductive structures, twigs, and miscellaneous) and nutrient (Ca, K, Mg, P, and N) deposition through leaf litter significantly differed quantitatively and qualitatively on a seasonal and annual basis among research sites. In addition, these differences could be extended to the LLNUE estimated for each site. It has been reported that litter production and litter chemistry in forest ecosystems is determined by age and rainfall

(Lawrence 2005), species composition (Pavón et al. 2005; Sariyildiz and Anderson 2005), soil and nutrient availability (Read and Lawrence 2003; Vasconcelos and Luizão 2004; Dent et al. 2006), stand structure (Yang et al. 2006; Zhou et al. 2007), and successional stage (Yankelevich et al. 2006). In addition, rates of nutrient return to the forest soil are controlled not only by the amount of litter production but also by the nutrient concentrations in litter components (Yang et al. 2006; Mlambo and Nyathi 2007). Since at the research sites, there are not conclusive studies related to global warming and long-term tendencies, in this study, the significant seasonal differences in biomass production might have been related, to some extent, to concurrent seasonal extreme environmental conditions such as droughts and frosts, which are typical in the northeastern region of Mexico (González-Rodríguez et al. 2000, González-Rodríguez et al. 2004, 2007) and or changes in phenological events such as leaf abscission and shedding, shoot initiation, flowering, and fruiting (Palma et al. 2000). Previous findings in Northeastern Mexico (González-Rodríguez et al. 2007) have revealed that during wet months (August and September) when rainfall was heavy, branches and fruits were the main litter constituents, whereas in the dry and winter months, there was a greater contribution of leaves due to drought and freezing temperatures.

Even though, in this study, litterfall deposition occurred throughout the experimental period, there were significant main seasonal peaks for the different litter components in relation to input quantity, variability, and order of magnitude (Figs. 2, 3, 4, 5). This litter production varied regardless of total or individual litter components studied at each site. In addition, since leaf litterfall significantly differed within and between sites and sampling dates, seasonal leaf litter nutrient peaks were also registered for elements such as K and P, while Ca, Mg, and N showed a relatively constant content throughout the year (Fig. 6a–e). In fact, Ca, K, Mg, P, and N in Bosque Escuela, and Ca and Mg at Crucitas leaf litter nutrient content remained fairly steady and lower throughout the year. Thus, leaf litter was the primary source of nutrients and consequently determined to some extent the seasonal peaks of nutrient deposition as has been previously documented (Callaway and Nadkarni 1991). Although in this study nutrient content and deposition was not measured in other litter constituents such as twigs or reproductive

structures, other studies have shown that nutrient concentrations were higher in leaf litter than other litter components (Yang et al. 2006).

Foliar nutrient movements from senescing leaves to active plant tissues or woody structures have been considered as a physiological mechanism of nutrient cycling since it plays a major role in nutrient conservation by deciduous tree species because nutrients following this pathway are not lost through litterfall (Duchesne et al. 2001). In this regard, it can be suggested that woody plant species from Bosque Escuela (70% hard woody-deciduous) could be more efficient in nutrient transfers than plant species from the other sites, since annual deposition levels of Ca, K, and Mg observed in leaf litter from Bosque Escuela were lower compared with Crucitas, Campus, or Cascajoso (Fig. 6a–c). This suggestion is supported by the high nutrient use efficiency, observed in Bosque Escuela with respect to other three sites (Table 3), in order to minimize nutrient losses; however, this statement has to be taken cautiously since seasonal determinations of nutrients in active foliar tissue and leaching (e.g., dry and or throughfall) deposition were not quantified in this study. The lower leaf P levels throughout the year observed in Bosque Escuela (Fig. 6d) compared to Crucitas, Campus, or Cascajoso as well as its achieved marginal annual deposition through leaf litter (Table 3) compared with Ca, K, Mg, and N suggest that this nutrient is available at very low levels in the soil solution or rather; it is easily retranslocated from leaf tissue to stems, branches, or other plant structures. Thus, further measurements are required to accurately estimate P nutrient resorption pools as has been previously pointed out (Duchesne et al. 2001; Read and Lawrence 2003; Dent et al. 2006). Conversely, the low levels of N deposition in Bosque Escuela compared with Crucitas, Campus, or Cascajoso could be associated with the capability of symbiotic nitrogen fixation potential of Fabaceae plant species observed at research sites (Zitzer et al. 1996), since at Bosque Escuela, plant species belonging to the Fabaceae family represented only 4% of total species richness in the experimental plot, while in Crucitas, Campus, and Cascajoso, this taxonomic proportion reached values of about 20, 25, and 12%, respectively. Thus, it seems that N nutrient use efficiency in leaf litter showed an inverse relationship with the proportion of Fabaceae plant species. In addition, it has been proposed that tree species on fertile soils tend to

produce leaves and leaf litters with high nitrogen content, which in turn decompose rapidly and support high plant production through fast turnover of the nutrient pools (Sariyildiz and Anderson 2005). Furthermore, Forrester et al. (2005) and Rothe and Binkley (2001) argued that mixed forests stands containing N-fixing species increase and improve nutrient cycling through litterfall when compared with monoculture or stands containing fewer N-fixing species.

However, Read and Lawrence (2003) proposed that nutrient limitation in the dry tropics is related to water deficits since dry conditions prevent nutrient absorption from soil and consequently affect the release and mineralization of nutrients by slowing decomposition. Dent et al. (2006) have also suggested that the quantity and nutrient content of small litter decreased along a gradient of soil nutrient availability from alluvial forest (fertile soil) through sandstone forest (least fertile).

On an annual basis, the contribution of leaves, reproductive structures, twigs, and miscellaneous to total litterfall deposition in Campus and Cascajoso sites are within the range of previously documented studies (González-Rodríguez et al. 2007) in the subtropical woodlands of Northeastern Mexico. However, observed differences in leaf fall in Crucitas, Campus, and Cascajoso compared to Bosque Escuela could be related to the continuous shedding of leaves of deciduous plant species, which is a characteristic of the Tamaulipan thornscrub ecosystem, as a morphological and physiological mechanism to cope with water deficits and high temperatures to avoid plant tissue dehydration and water lost through transpirational flux (Stienen et al. 1989; González-Rodríguez et al. 2004).

## Implications

The statistical analysis indicated that more sampling dates were significant for total annual litter and its constituents (leaves, reproductive structures, twigs, and miscellaneous residues) than for macronutrient (Ca, K, Mg, N, and P) deposition of leaf litter. Therefore, there is a relative homogeneity among sites with respect to the amount of macronutrients, particularly P and K contents, where the *P*-values > 0.001 for the 13 sampling dates are considered. In general, the statistical differences found by sites were not systematically associated with specific sampling dates

or related to special behavior of sites. In addition, site one (Bosque Escuela) provided relatively low means for almost all the studied variables. Thus, results of this study suggest the importance of litterfall production not only in terms of nutrient cycling to the forest soil in different stand communities but also to maintain fundamental ecological and ecosystem processes such as soil formation, prevent soil erosion, maintain soil fertility and substrates for plant and microbial species, support and sustain life for invertebrate fauna, increase organic matter mineralization, improve soil physical and chemical properties such as soil water availability and infiltration to enhance nutrient absorption, plant regeneration and establishment, and root growth; all of these are interrelated and integrated to sustain and maintain ecosystem productivity and biodiversity. Moreover, results of the present study could be used to implement site-specific management practices. Furthermore, although this type of investigations date back since more than 100 years, to some extent, the present work, as far as is known to the authors, could be considered as one of the main and basic studies carried out in the Northeastern ecosystems of Mexico, which provides and opens new research horizons and opportunities to understand nutrient cycling in forests soils. Further research projects could be suggested in order to explain how litter constituent decomposition processes are affected by their own chemistry composition, physicochemical environmental variables, soil properties, microbial communities and consequently elucidate nutritional fluxes.

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