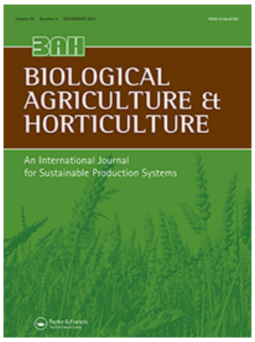

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Litter production and litter dynamics in different agroforestry systems in the arid western region of India

Archana Verma[a], Praveen Kumar[a], M. L. Soni[b], Navraten Pawar[a], Upendra Pradhan[c], S.P. S Tanwar[d] and Shrawan Kumar[a]

[a]Division of Integrated Farming System, ICAR-Central Arid Zone Research Institute, Jodhpur, India; [b]RRS, Bikaner, ICAR-Central Arid Zone Research Institute, Jodhpur, India; [c]ICAR-Indian Agricultural Statistics Research Institute, New Delhi, India; [d]Division of Livestock Production and Range Management, ICAR-Central Arid Zone Research Institute, Jodhpur

ABSTRACT

Litterfall production, decomposition and nutrient release was investigated for three prominent agroforestry tree species, *Prosopis cineraria, Tecomella undulata* and *Hardwickia binata*, grown in the arid western region of India. The highest litterfall was recorded for *H. binata* (9.44 Mg ha^{-1} y^{-1}) followed by *P. cineraria* (8.94 Mg ha^{-1} y^{-1}) and *T. undulata* (3.74 Mg ha^{-1} y^{-1}). It took 15, 12 and 9 months for decomposition of 90% of the litter of *H. binata, P. cineraria* and *T. undulata*, respectively. Regression analysis showed that rainfall and air temperature had significant impacts on the decomposition process. Soil moisture and soil microbial biomass carbon showed high correlations ($R^2 > 0.70$, $p < 0.01$) with litter decay. The rate of release of N ($k_N = 0.0014$, surface (0–15 cm); $k_N = 0.0015$, sub-surface (15–30 cm)) and K (k_K = 0.0041, surface; k_K = 0.0047, sub-surface) was highest from *P. cineraria*, whereas release rates of P were statistically equivalent for all species. N release from the decomposing litter increased initially, but then decreased as decomposition progressed. Concentrations of P, K and Mg in the litter decreased throughout the decomposition, with some fluctuations in P and Mg for *P. cineraria* and *H. binata* at the later stage. Ca release did not follow any specific trend. *P. cineraria*, with considerable amounts of litterfall, the highest nutrient inputs to the soil and the most rapid release of nutrients during the decomposition, was concluded to facilitate greater fertility build-up of the soil compared with the other two species.

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Agroforestry system; *Hardwickia binata*; litterfall; litter decomposition; *Prosopis cineraria*; *Tecomella undulata*

Introduction

Arid and semi-arid areas are characterised by very high temperatures, low rainfall, high evapotranspiration and strong prevailing winds and as a result biomass production is very low in these areas. The soils in the arid areas of India have a loose structure, coarse texture, low water holding capacity and low nutrient status (Chauhan et al. 2003). Thus, the production of crops in arid regions is unpredictable and for this reason people living in the regions practice mixed farming, livestock rearing and other income-generating activities to sustain their livelihood. The introduction of tree species in agricultural fields can not only reduce the risk of crop failure but also enhance soil fertility (Kumar et al. 2017). Trees can improve the fertility of the soil by fixing N, by taking up of nutrients from deeper soil layers, and through the production and decomposition of tree biomass (Jose 2009; Nair 2011).

CONTACT Archana Verma vermaarchana29@gmail.com ICAR-Central Arid Zone Research Institute, Jodhpur 342003, India

Litterfall and litter decomposition are important vectors of nutrient recycling in agroforestry systems. The litter from woody perennials adds nutrients to the soil and provides inputs for decomposers to break down the complex dead organic matter to simple mineral forms. The addition of nutrients through these processes in agroforestry replenishes the fertility of the soil (Yadav et al. 2008; Notaro et al. 2014). Litterfall rates are determined by factors like the tree basal area and stand age, species variation, site characteristics, temporal variations and tree management practices, whereas the interaction of the quality of the litter, climatic factors and soil biota affects the rate of the breakdown of the litter (Kumar 2008).

Prosopis cineraria (L.) Druce, *Tecomella undulata* (Sm.) Seem. and *Hardwickia binata* Roxb. are major agroforestry species in the Thar Desert region of India. Agroforestry systems based on *Prosopis cineraria* are the most dominant agroforestry system in western Rajasthan, occupying 47% of the total agroforestry area (Tewari et al. 2007). *P. cineraria* has great economic significance as almost every part of the tree can be utilised. The pods, locally called 'Sangri', are considered as the 'dry fruit of the desert' and are sold at the rates of Rs 800–1000 ($10-13) per kg. The dried leaves of *P. cineraria* serve as quality fodder for the animals during lean periods. Additionally, *P. cineraria* has been reported to enhance the productivity of the soil and to increase crop yields (Singh 2009). *T. undulata* is a multipurpose and vital species for the arid-rural poor and produces excellent timber and is, therefore, also referred to as the 'Marwar Teak of Rajasthan' (Kalia et al. 2014). Due to its survival under extreme weather conditions, it plays a crucial role in arid zone agroforestry systems and is included in 26% of the total area of Indian arid zone agroforestry. *H. binata* was introduced to arid regions of India in late 1960s and is considered as a good quality, nitrogen fixing, fodder yielding tree. It provides extremely hard and durable timber, as well as fuel-wood (Roy 1996) and highly palatable and nutritious fodder (Patidar and Mathur 2017). These three species are well adapted to inhospitable arid land conditions and can be grown on soils with poor fertility and conditions of moisture deficit and high temperatures. Thus, these species are dominant and play a crucial role in arid zone agroforestry. As the trees remain in the fields for long periods, there is need to understand the synchronisation between the addition of nutrients, the release of nutrients from the leaf litter and the nutrient demand of crops, to enable appropriate species selection and management regimes. Nutrient cycling occurs to varying degrees in all land use systems and depends not only on the type of land but also on the type of trees and field crops and the combinations of these (Raj et al. 2017). Further understanding of the addition of nutrients through the litterfall, its decomposition and nutrient release patterns is required for the adoption of appropriate nutrient management practices in these low input cropping systems. Accordingly, this study focussed on investigating litterfall production, litter decay rates and nutrient release pattern from the decomposing litter of the three predominant arid zone agroforestry species; *Prosopis cineraria, Tecomella undulata* and *Hardwickia binata*.

Materials and methods

Study area

The study site was located on research farm of ICAR-Central Arid Zone Research Institute, Jodhpur, India. At the site, the average annual rainfall of 360 mm is received mostly during July – October (Figure 1). The mean maximum air temperature at the site is 45°C, with extremes of up to 50°C during the summer. Three distinct seasons are observed in the year, as summer (March – June), rainy (July – October) and winter (November – February). The soils in the region have very low organic matter content (0.2–0.3%). Taxonomically these soils belong to Aridisols soil order, subgroup Typic Haplocambids (Baillie 2001).

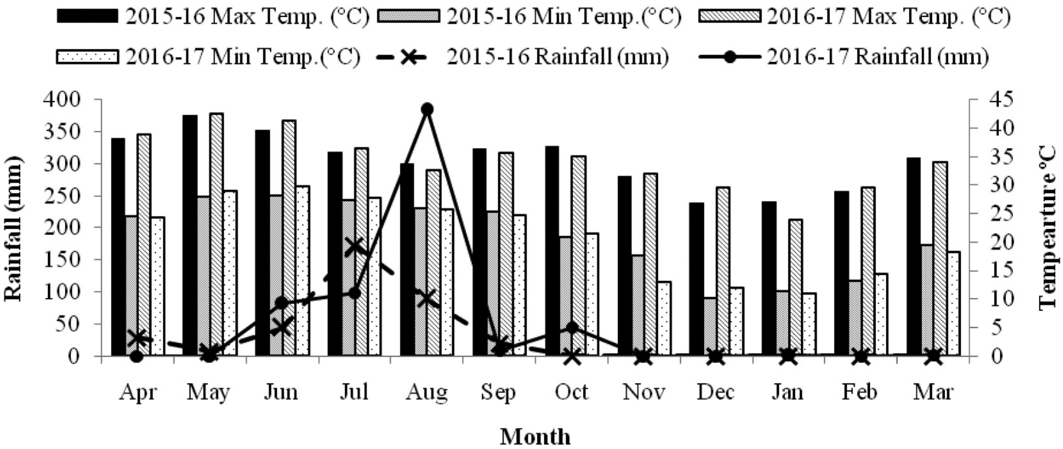

Figure 1. Mean monthly meteorological data observed during the study period (April 2015–March 2017).

The experimental area consisted of three major agroforestry tree species, *P. cineraria, T. undulata* and *H. binata*. The sizes of the fields for the *P. cineraria, T. undulata* and *H. binata* agroforestry systems were 500 m^2, 648 m^2 and 567 m^2, respectively, and were designed with three replications, by dividing each field into three equal blocks, as shown in Figure 2. The general details of the species regarding age, diameter, crown area, spacing, density per hectare and initial soil characteristics under these species are given in Table 1. In the rainy season, moth bean (*Vigna aconitifolia*) and cluster bean (*Cyamopsis tetragonoloba*) were intercropped with the tree species. FYM at 5 t ha^{-1} was applied in the field before sowing the beans, but no other fertiliser inputs were applied for the crops. Manual weeding was carried out in the crops 2–3 times. No pesticides or insecticides had been used since the

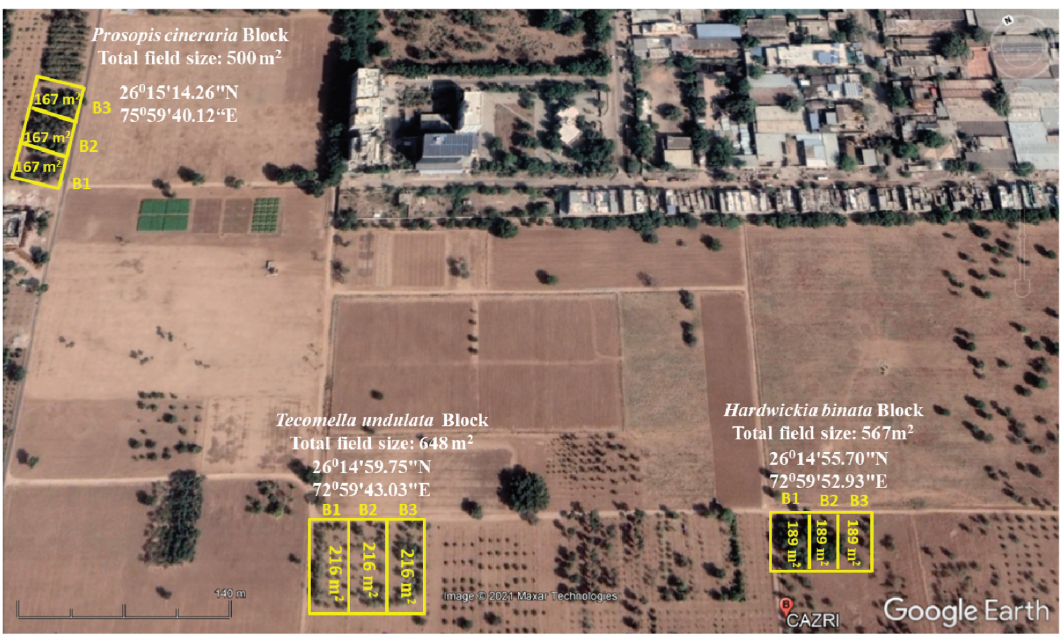

Figure 2. The layout of the agroforestry systems of the three species at three different sites.

Table 1. Age, growth parameters, spacings and initial soil characteristics (0–15 cm) for the three tree species in the agroforestry systems.

Tree species	Age (years)	Diameter (cm)	Crown area (m^2)	Spacing (m)	Density (ha^{-1})	OC (%)	N ($kg\ ha^{-1}$)	P ($kg\ ha^{-1}$)	K ($kg\ ha^{-1}$)
Prosopis cineraria	38	25.65 ± 1.34 (17.07–46.94)	7.03 ± 0.28 (3.70–10.25)	5 × 5	400	0.29	93.9	14.8	366.5
Hardwickia binata	25	19.87 ± 1.21 (11.46–32.96)	5.40 ± 0.30 (2.95–8.45)	4.5 × 4.5	494	0.27	89.0	12.5	360.4
Tecomella undulata	27	15.27 ± 0.64 (6.87–28.47)	4.69 ± 0.11 (2.00–7.10)	6 × 6	278	0.22	87.6	11.6	354.3

establishment of the plantations and nor were they used for the cultivation of the crops during the experimental period. The management practices were in accordance with the principles and practices of organic farming standards, though the land was not certified for organic production.

Litterfall sampling

Litterfall traps, of a size 1 m × 1 m, were placed at random in the tree stands, with ten replications in each stand (one tree was considered as one replication; ten trees were randomly selected for placement of the litter trap, so that each of the blocks for each of the species contained at least three replicates) and at the height of 50 cm above ground. In *Prosopis cineraria* new foliage appears in the extreme summer months of March – June and defoliation occurs during cold season (November – January). *T. undulata* is a deciduous, or nearly evergreen, tree of the arid and semi-arid regions, starts defoliation from November, though complete leaf shed never occurs. New leaves emerge in February and tree blooms fully in the months of April – May, after which it bears fruits. In India, *H. binata* is leafless for a short time towards the end of the cold season. The leaves and pods shed in April–May, with the commencement of new leaves subsequently. In this study, the litterfall was collected over two consecutive years (2015–2016 and 2016–2017), between April and March, on a monthly interval basis, and was averaged for the two years. The litterfall was collected from each litter trap in paper bags brought to laboratory where it was cleaned, weighed and dried at 70°C until constant weight (g m^{-2}).

Litter decomposition

Twenty gram of air-dried leaflitter of each species were placed in nylon litterbags of a size of 20 cm × 15 cm (mesh size of 2 mm), to limit the loss of decomposing litter from the bag and to allow the passage of air for microbial activity. In July 2015, a total of 72 bags for each species, in the three replicates, were placed randomly at two different depths; at the soil surface (0–15 cm) and at a sub-surface depth (15–30 cm), that is the plough layer of cultivated field (as the crop cultivation required ploughing the field to place the litter at the deeper layers). The bags were gently placed at the different soil depths using a spade to slice through the soil under the corresponding tree canopy of *P. cineraria, T. undulata* and *H. binata*. Iron pegs were fixed in soil to locate the buried litter bags. Three litter bags for each species were retrieved monthly and brought to the laboratory. To avoid loss of material from the litter bags, the retrieved bags were placed in paper bags and brought to laboratory, where the litter bags were gently rinsed with water to remove soil and other foreign material. The decomposed material was then dried at 70°C to a constant weight and the loss of weight in comparison with the initial weight was recorded.

Chemical analysis of litter

Oven-dried litter of the different species were powdered using a Wiley Mill (M/S Manglam agencies, Jodhpur, India) with stainless steel screen to pass through a 1 mm sieve for analysing chemical parameters. The analysis of physical and chemical characteristics of the soils was carried out following standard analytical procedures (Jackson 1973). The nutrients in litter analysed were nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and carbon (C). Cellulose and lignin were analysed as described by Van Soest (1991). C was estimated using Eurovector C analyser. The total N content was determined by the standard Kjeldahl digestion method (Subbiah and Asija 1956). P, K, Ca and Mg in leaves were estimated after tri-acid digestion (Jackson 1973). Phosphorus was analysed by vanado-molybdo-phosphoric acid yellow colour method (Olsen et al. 1954). K was determined by flame photometry and Ca and Mg by versene titration (Jackson 1973). The total nutrient input was calculated by multiplying dry weight mass of the leaf litter with the nutrient concentration of the litter.

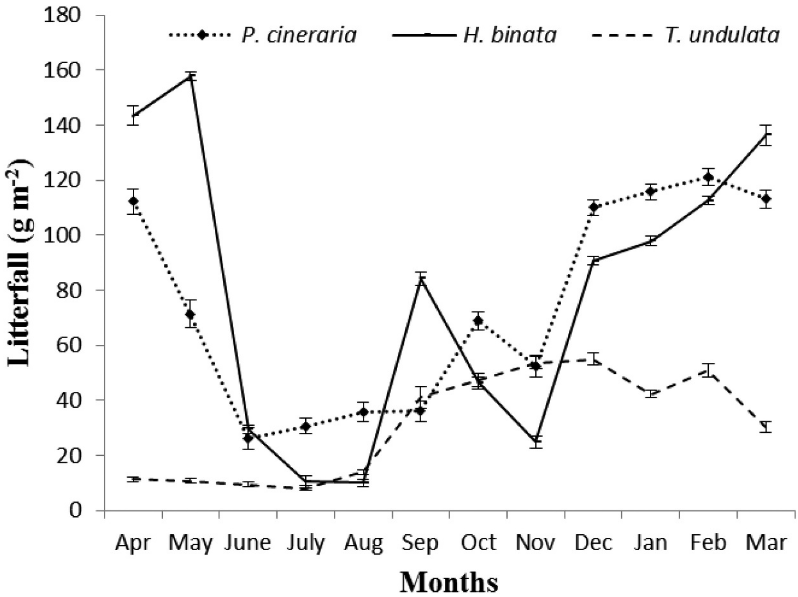

Figure 3. Average litterfall (2015/16 and 2016/17) of the three tree species *P. cineraria, H. binata* and *T. undulata* (mean ± 1 SE, *n* = 10).

Table 2. Annual litterfall, nutrient composition and nutrient input (kg ha^{-1} year^{-1}) of the different species grown in the agroforestry systems.

		Nutrient composition (%)			Nutrient input (kg ha^{-1} y^{-1})		
Tree species	Litterfall (Mg ha^{-1} y^{-1})	N	P	K	N	P	K
Prosopis cineraria	8.94 a	2.21 a	0.24 a	0.71 a	197.61 a	21.46 a	63.48 a
Hardwickia binata	9.44 a	1.41 b	0.21 a	0.56 a	133.15 b	19.83 b	52.88 b
Tecomella undulata	3.74 b	2.31 a	0.25 a	0.51 a	86.43 c	9.35 c	19.08 c
n	10	6	6	6	10	10	10

Note: *Values in columns marked with the same letter are not significantly different using Tukey's HSD post hoc test at $p < 0.05$.

Soil microbial biomass carbon was estimated using the chloroform fumigation method (Vance et al. 1987) and soil moisture by gravimetric method (Black 1965). From July 2015, at three times every month during the decomposition process, a total of six soil samples from each agroforestry system (one sample from each depth (0–15 cm, 15–30 cm depth) in the three replications for each tree stand) were collected using a soil auger in the centre of the field (between two rows of trees).

Statistical analysis

The basis of the analyses in this study was the negative exponential decay constant (k) derived using the model of Olson (1963) to determine the loss of mass in the litter bags, as follows:

$$W_t/W_0 = e^{-kt} \quad (1)$$

where W_0 was the initial dry weight of the litter; W_t was the weight of litter after time t (days); e was the base of the natural logarithm and k was the decomposition constant. The decomposition constant (k) was estimated as the slope of the linear regression between $log\ e\ (W_t/W_0)$ and t. The half-life ($t_{0.50}$), the time required for 50% decomposition, was calculated as $0.693/k$ and the t_{99}, the time required for 99% decomposition, was calculated as $5/k$. Both negative exponential and linear

Table 3. Initial chemical characteristics of the litter of the different tree species.

Parameter	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Cellulose (%)	Lignin (%)	Carbon (%)	C:N	L:N	C:P	N:P
Propsopis cineraria	2.21 a	0.24 a	0.71 a	2.28 a	0.58 b	20.38 b	11.68 b	43.17 ab	19.66 b	5.33 c	177.19 a	9.04 a
Hardwickia binata	1.41 b	0.21 a	0.56 a	1.99 a	0.67 ab	25.81 a	13.88 a	43.85 a	32.82 a	13.88 a	212.87 a	6.58 b
Tecomella undulata	2.31 a	0.25 a	0.51 a	1.13 b	0.98 a	11.20 c	9.30 c	42.07 b	19.91 b	9.30 b	172.40 a	8.62 a

Notes: Values in columns marked with the same letter are not significantly different ($p < 0.05$) using Tukey's HSD post hoc test.

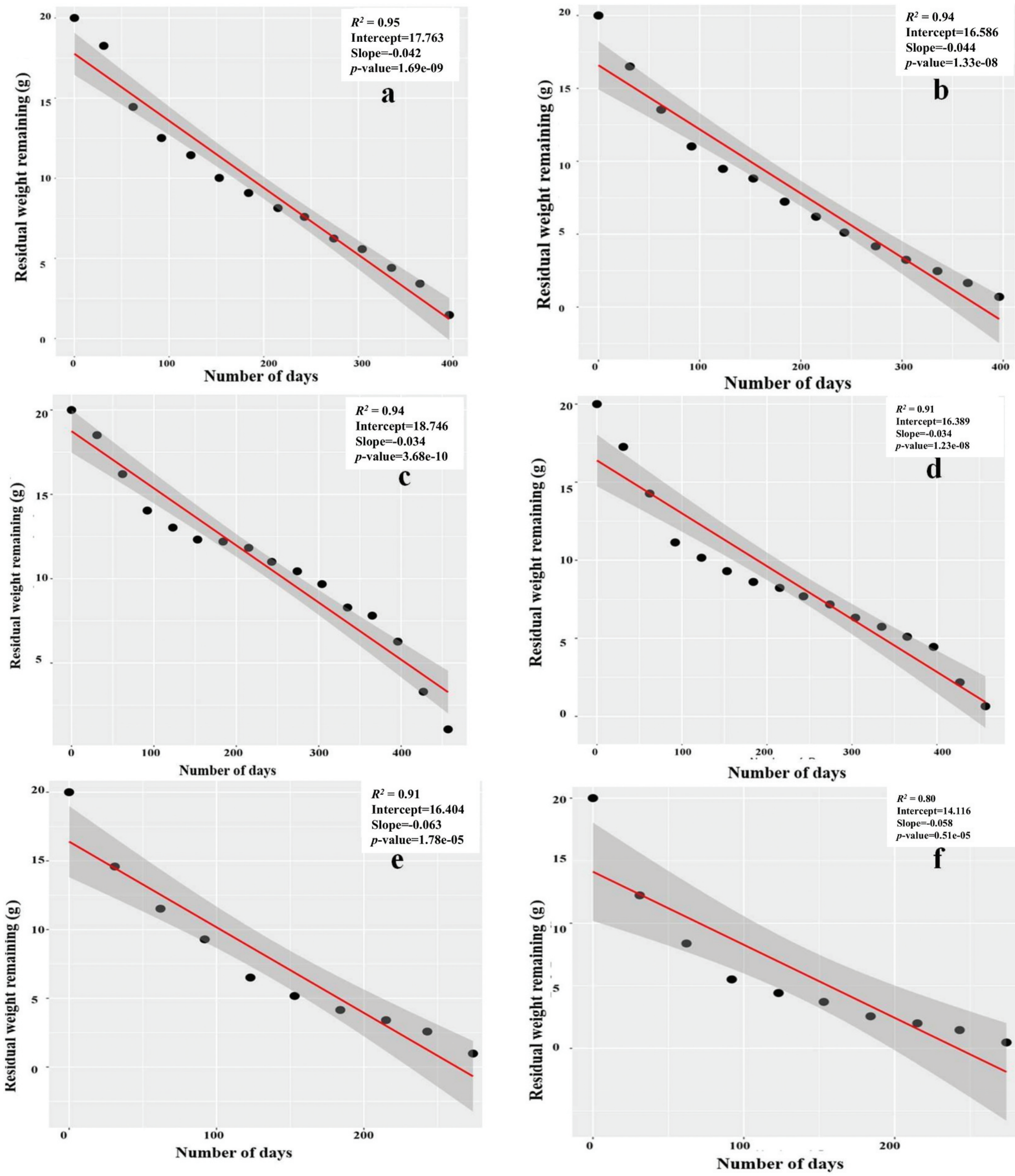

Figure 4. Mean values of residual weight (g) of litter remaining in the bags during the decay of the leaf litter of *P. cineraria*, a) 0–15 cm, b) 15–30 cm; *H. binata*, c) 0–15 cm, d) 15–30 cm; and *T. undulata*, e) 0–15 cm, f) 15–30 cm, fitted as linear curves. The shaded area represents the 90% confidence level.

regression models were applied to decipher the relationship between biomass decomposition with number of days, soil MBC and soil moisture. The most suitable model was selected based on the R^2 and RMSE (root mean square error) of the model.

The percentage of the nutrient remaining in the decomposed litter was calculated as (Bockheim et al. 1991):

$$\%\ nutrient\ remaining\ =\ C/C_0\ x\ DM/DM_0\ x\ 100 \tag{2}$$

Table 4. Decomposition constant (k_D), time required (days) for 50% (t_{50}) and 99% (t_{99}) loss of mass, and rate of release of N (k_N), P (k_P) and K (k_K) release for the different species.

	k_D		k_N		k_P		k_K		t_{50}		t_{99}	
	Surface	Sub-surface	Surface	Sub-surface	Surface	Sub-surface	Surface	Sub-surface	Surface	Sub-surface	Surface	Sub-surface
Propsopis cineraria	0.0066 b	0.0085 b	0.0014 a	0.0015 a	0.0007	0.0011	0.0041 a	0.0047 a	105.48 a	81.94 a	456.61 a	354.73 a
Hardwickia binata	0.0064 b	0.0076 b	0.0013 b	0.0014 b	0.0009	0.0010	0.0025 b	0.0034 b	108.46 a	92.29 a	469.52 a	399.52 a
Tecomella undulata	0.0111 a	0.0137 a	0.0003 c	0.0003 c	0.0012	0.0014	0.0024 b	0.0032 b	62.96 b	50.57 b	272.53 b	218.90 b
Species	**	**	**	***	NS	NS	*	*	**	*	**	*
Depth	**		NS		NS		**		**		**	
Species×Depth	NS		NS		NS		NS		NS		NS	

Notes: Values in columns marked with the same superscript letter are not significantly different ($p < 0.05$) using Tukey's HSD post hoc test.

Table 5. Multiple regression analysis between litter decomposition, rainfall and temperature.

Species	Litter placement	Regression equation	R^2
Prosopis cineraria	0–15 cm	$Y = 0.70 + 0.014\ X_1 + 0.007X_2$	0.88**
	15–30 cm	$Y = 2.38 + 0.011\ X_1 + 0.041X_2$	0.76**
Hardwickia binata	0–15 cm	$Y = -0.57 + 0.005\ X_1 + 0.043X_2$	0.52*
	15–30 cm	$Y = 0.24 + 0.004\ X_1 + 0.019\ X_2$	NS
Tecomella undulata	0–15 cm	$Y = 1.88 + 0.007X_1 + 0.103X_2$	0.77*
	15–30 cm	$Y = 0.46 + 0.018\ X_1 + 0.011X_2$	0.95**

where DM_0 = the initial weight of the dry litter; DM = the weight of the decomposing litter after given period; C_0 = the initial concentration of the nutrient element and C = the concentration of the nutrient element in the decomposing litter after the given period.

The descriptive statistics, like mean and standard error (SE) were calculated for monthly litterfall, decay rate coefficients and absolute mass of nutrient contents which were represented graphically. The Pearson's correlation coefficient matrix and regression analysis was computed using R software. The nutrient input and leaf chemical parameters in all the tree species were subjected to analysis of variance (ANOVA) using SPSS v.22 (SPSS, Armonk NY).

Results

Leaf litterfall and nutrient fluxes under different tree species

The mean monthly litterfall of the three tree species, *P. cineraria, H. binata* and *T. undulata* is shown in Figure 3. There was a marked variation in the amount of litterfall across tree species and seasons. The total litterfall showed a unimodal distribution, but seasonal variations were observed in all the species month-wise. The litterfall under *H. binata* was higher than the other species under investigation. The three species could be divided into two groups on the basis of the seasonal litterfall pattern: (i) *P. cineraria and T. undulata* with maximum leaves shed in the winter season and (ii); *H. binata* with maximum shed in the summer season. The total litterfall from the trees ranged from as high as 9.4 (± 0.10) for *H. binata* to 8.9 (± 0.27) and 3.7 (± 0.13) Mg ha^{-1} y^{-1} for *P. cineraria* and *T. undulata*, respectively (Table 2).

The nutrient inputs to the soil in the form of N, P and K for the different species showed significant differences ($p < 0.001$). The return was in the order of N > K > P. The highest return of nutrients through litterfall was in *P. cineraria*, followed by *H. binata* and lowest amount of nutrients returned were recorded for *T. undulata*. The total flux of N was found to be the highest under *P. cineraria* (197.61 kg ha^{-1} y^{-1}) followed by *H. binata* (133.15 kg ha^{-1} y^{-1}) and *T. undulata* (86.43 kg ha^{-1} y^{-1}). The phosphorus flux through the litterfall of the different species ranged from 9.35 to 21.46 kg ha^{-1} y^{-1}, whereas the K flux ranged from 19.08 to 63.48 kg ha^{-1} y^{-1} (Table 2).

Nutrient content of leaves

The initial chemical characteristics of the leaves of the different species are presented in Table 3. The concentration of N in the leaves was significantly different ($p < 0.05$) between the species and followed the order: *T. undulata* > *P. cineraria* > *H. binata*, whereas the concentrations of P and K were not statistically different between the species. The concentration of calcium was highest in *P. cineraria* and Mg in *T. undulata*. The percentages of cellulose, lignin and carbon were highest in *H. binata* leaves, followed by that in *P. cineraria* and were lowest in *T. undulata*. The C:N ratios varied considerably between species, ranging from 19.66 to 32.82. *H. binata* showed the highest C:P ratio (greater than 200:1) followed by *P. cineraria* and *T. undulata*, though the differences in the C:P ratios between the species were not significant. The initial L:N and N:P ratios were highly variable between the different litter types, ranging from 5.33 to 13.88 for L:N and 6.58 to 9.04 for N:P.

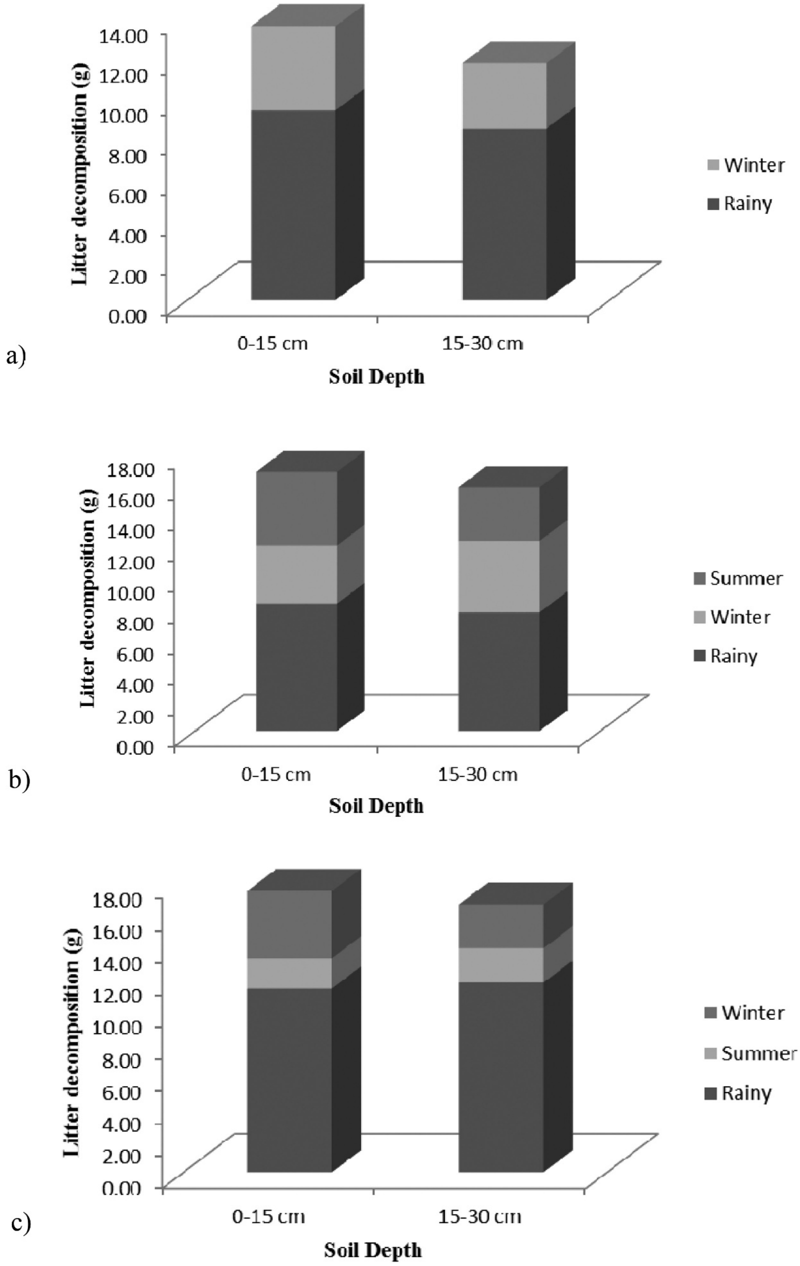

Figure 5. Seasonal variation in litter decomposition for a) *Tecomella undulata*, b) *Prosopis cineraria* and c) *Hardwickia binata*.

Litter decomposition

The decomposition of the litter followed a triphasic pattern in all species, with rapid initial phase, slower middle phase, and an increase towards the end. The periodic loss of weight pattern for all species, at both depths, is depicted in Figure 4a-f. The litter of the different species decomposed in the following order (maximum to minimum time for decomposition): *H. binata* >*P. cineraria* >*T. undulata*. It took 15, 12 and 9 months for decomposition of 90 % of the litter of *H. binata, P. cineraria* and *T. undulata*, respectively. Decomposition of *H. binata* and *P. cineraria* followed a linear decline whereas, that of *T. undulata* followed an exponential pattern.

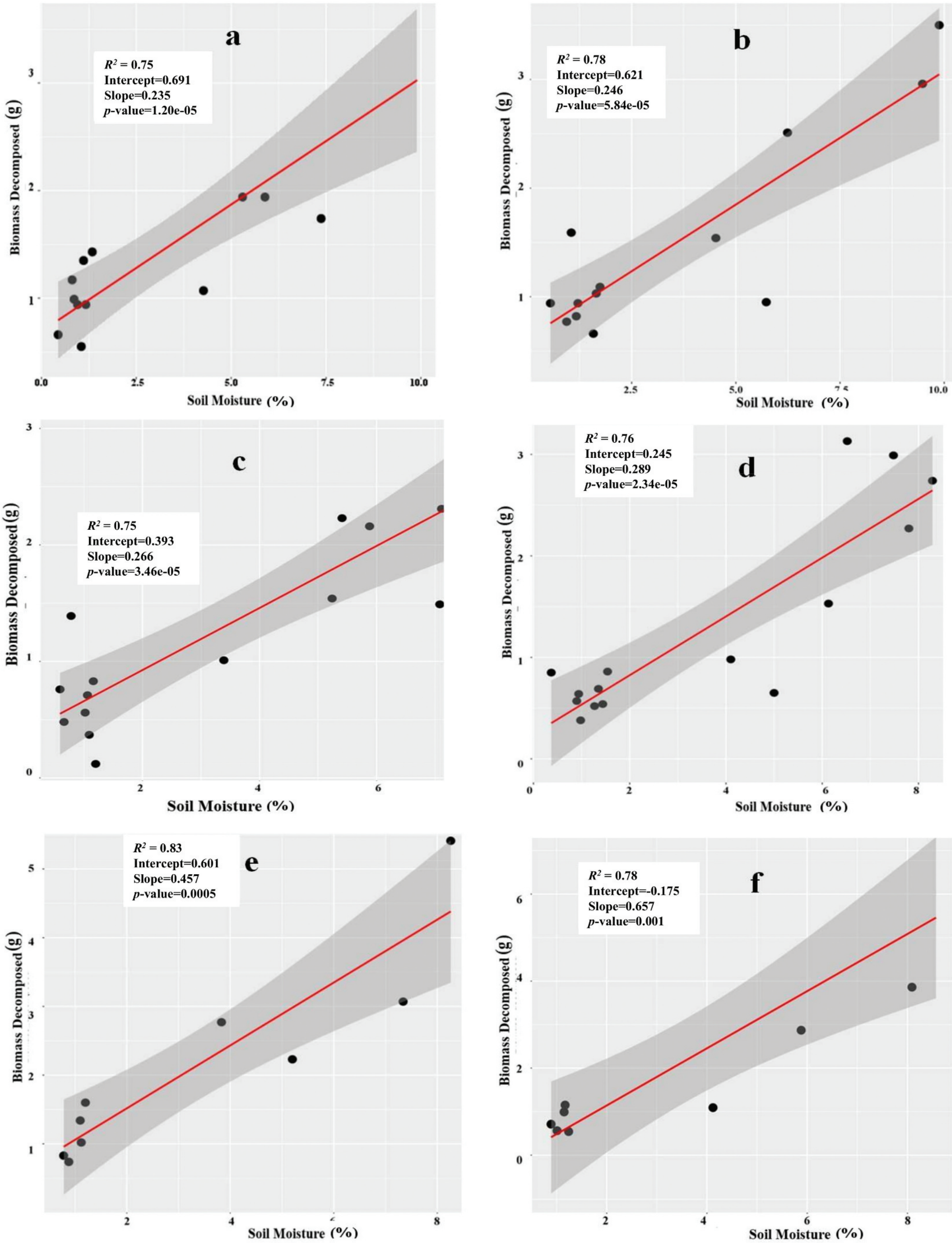

Figure 6. Regression between monthly soil moisture (%) and decomposed biomass (g) and 90% confidence intervals (shaded area) for *P. cineraria*, a) 0–15 cm, b) 15–30 cm; *H. binata*, c) 0–15 cm, d) 15–30 cm; and *T. undulata*, e) 0–15 cm and f) 15–30 cm.

The decay rate coefficients (k) for the decomposition of the litter, the nutrient depletion during decay, the time period taken for 50% and 99% decomposition of litter in the three species are presented in Table 4. Decomposition coefficient varied considerably ($p < 0.001$) between the species at both soil depths. The decomposition rates showed that *T. undulata* placed, at both the surface

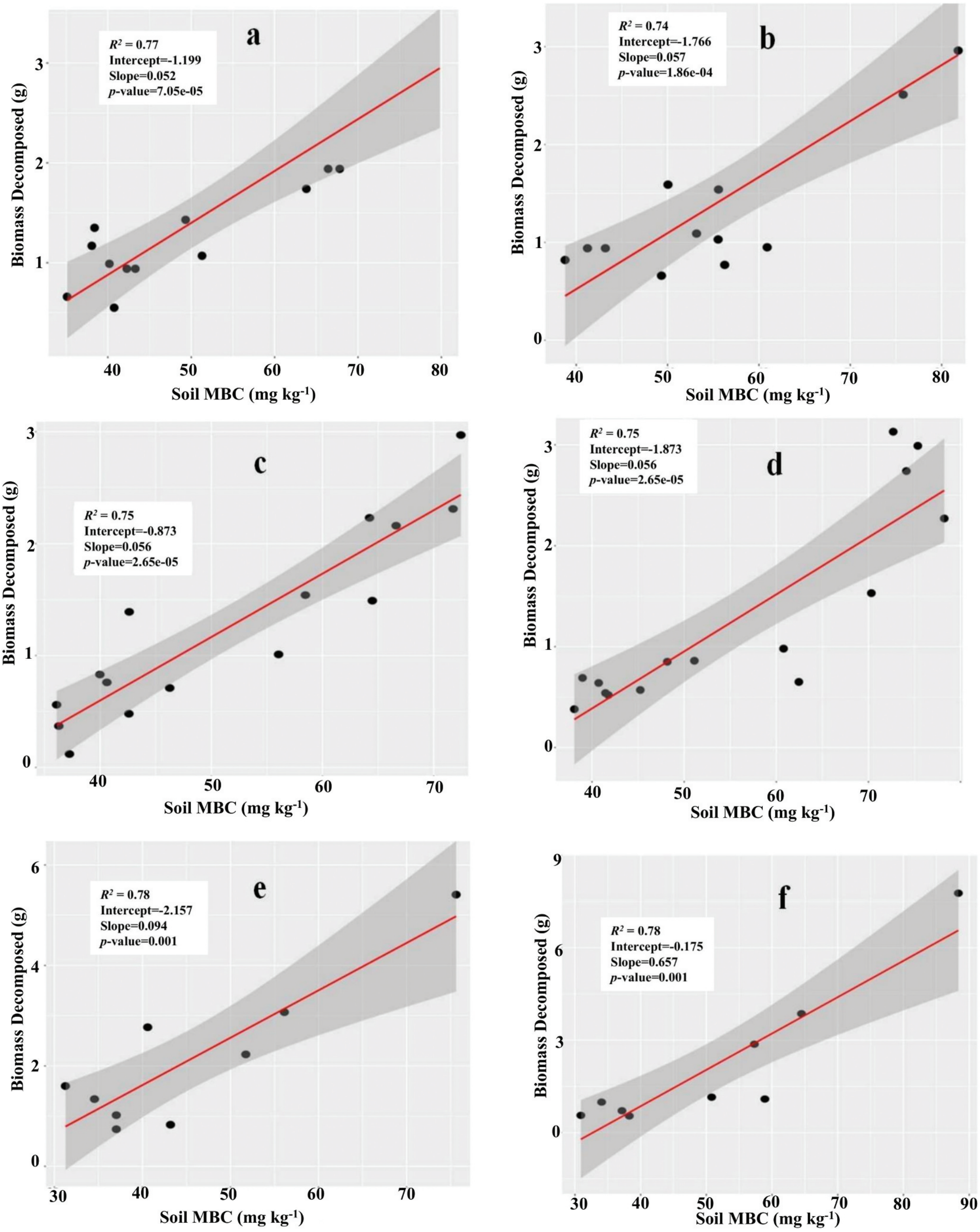

Figure 7. Regression between monthly soil microbial biomass carbon (MBC) (mg kg^{-1}) and decomposed biomass (g) and 90% confidence intervals (shaded area) for *P. cineraria*, a) 0–15 cm, b) 15–30 cm; *H. binata*, c) 0–15 cm, d) 15–30 cm; and *T. undulata*, e) 0–15 cm and f) 15–30 cm.

(k_D = 0.0111) and the sub-surface depth (k_D = 0.0137), had the highest decomposition constant values indicating the most rapid decomposition. Differences in the decomposition rates for all the species were also statistically significant ($p < 0.001$) across the depth of placement of the litterbags. The rate of release of N (k_N = 0.0014, surface; k_N = 0.0015, sub-surface) and K (k_K = 0.0041, surface

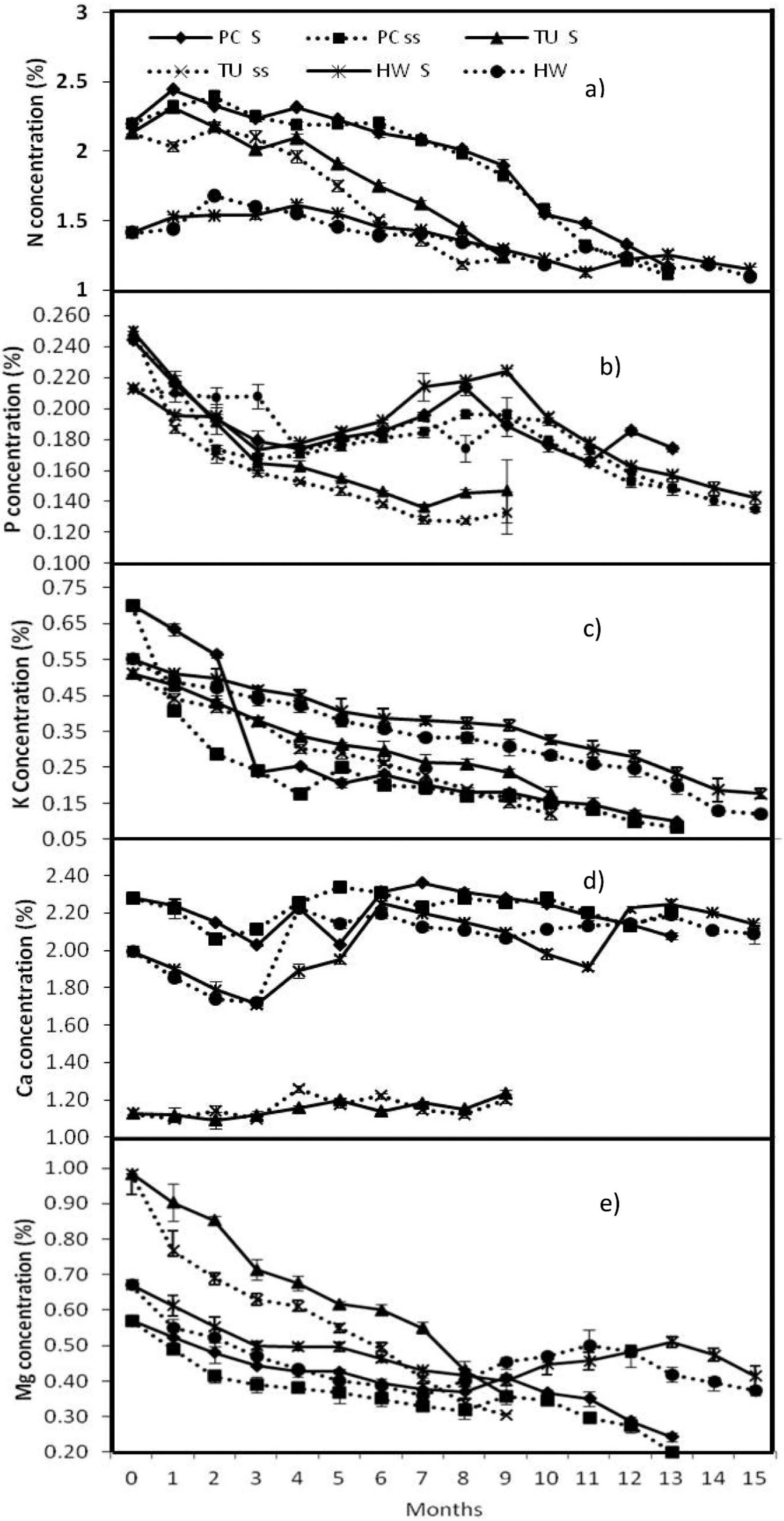

Figure 8. Nutrient concentration (%) of a) Nitrogen, b) Phosphorus, c) Potassium, d) Calcium and e) Magnesium. Mean ± SE in decomposing leaf litter of different tree species. Pc – *P. cineraria* S (0–15 cm), SS (15–30 cm); Hb – *H. binata* S (0–15 cm), SS (15 – 30 cm); and Tu-*T. undulata* S (0–15 cm), SS (15–30 cm).

Table 6. Pearson correlation coefficients (*r*) between the initial chemical parameters of the litter of the three species and the decomposition constant (k_D) and release rates N (k_N), P (k_P) and K (k_K).

Parameters	k_D S	k_D Ss	k_N S	k_N Ss	k_P S	k_P Ss	k_K S	k_K Ss
N	0.615**	0.691**	−0.517*	−0.523*	0.215	0.763**	0.361	0.295
P	0.720**	0.785**	−0.632**	−0.637**	0.350	0.846**	0.227	0.157
K	−0.666**	−0.588**	0.750**	0.746**	−0.923**	−0.500*	0.982**	0.993**
Ca	−0.960**	−0.928**	0.987**	0.986**	−0.987**	−0.884**	0.732**	0.778**
Mg	0.968**	0.938**	−0.991**	−0.990**	0.982**	0.897**	−0.712**	−0.760**
Cellulose	−0.943**	−0.971**	0.897**	0.900**	−0.707**	−0.991**	0.198	0.267
Lignin	−0.895**	−0.935**	0.835**	0.839**	−0.614**	−0.967**	0.075	0.145
Carbon	−0.939**	−0.969**	0.891**	0.895**	−0.699**	−0.989**	0.187	0.256
C:N	−0.518*	−0.600**	0.412	0.419	−0.098	−0.681**	−0.469*	−0.405
L:N	−0.079	−0.177	−0.041	−0.034	0.359	−0.280*	−0.815**	−0.773**
C:P	−0.621**	−0.696**	0.523*	0.529*	−0.222	−0.767**	−0.355	−0.288
N:P	0.390	0.480*	−0.277	−0.284	−0.045	0.569*	0.590**	0.532*

Notes: * Significant ($p < 0.05$), **Significant ($p < 0.01$), S, surface (0–15 cm) and Ss, sub-surface (15–30 cm).

and $k_K = 0.0047$, sub-surface) was most rapid in *P. cineraria*. The rate of release of P ($k_P = 0.0012$, surface, $k_P = 0.0014$, sub-surface) was higher in *T. undulata*, but it did not reveal any statistical difference between the species. Irrespective of the species, the rate of release of K was high, as compared with the release of N and P from the leaf litter. The half-life, i.e. the time required for 50% decomposition of the litter, was the lowest for *T. undulata* (surface = 63 days; sub surface = 51 days) followed by *P. cineraria*, which had similar values as *H. binata*. The 99% degradation of the litter was in the following order: *T. undulata* >*P. cineraria* > *H. binata* (Table 4).

Rainfall, temperature, soil moisture and soil microbial biomass carbon (soil MBC) effects on decomposition

The multiple regression analyses undertaken to investigate the associations of the litter decomposition with rainfall and temperature, revealed that the linear combination of both rainfall and temperature explained 52–95% of the variability in the decomposition of the litter in all species, except for in the sub-surface layer of *H. binata* (Table 5). Furthermore, it was evident from Figure 5 that in all three species, maximum decomposition of the litter took place in the rainy season followed by that in the summer and winter seasons.

The impact of soil moisture and soil MBC on decomposing litter mass are shown in Figure 6(a-f) and Figure 7(a-f), respectively. The results showed that soil moisture had a significant impact ($p < 0.01$) on litter decomposition. Soil moisture and soil MBC enhanced the decomposition of litter in all the species, at both depths. Maximum decomposition took place in the rainy season, which was likely due to high soil moisture as well increased microbial activity. The R^2 values ranged from 0.75 to 0.83 for different species at both depths (Figure 6). Soil MBC also influenced litter decomposition significantly ($p < 0.01$), with R^2 between the decomposed mass of the litter of three species and soil MBC ranging from 0.74 to 0.78 (Figure 7). Soil MBC could thus explain 77%, 75% and 78% of the variation of the decomposition values for *P. cineraria, H. binata* and *T. undulata* litters, respectively, at the surface depth, while it could explain 74%, 75% and 78% of the variation of the decomposition for *P. cineraria, H. binata* and *T. undulata*, respectively, at the sub-surface depth (Figure 7(a-f)).

Nutrient release pattern of leaf litter

Release of N, P and K

The pattern of loss of nutrients from the decaying litter is presented in Figure 8(a-e). Initially, the concentration of N in the litter of all the three species increased slightly in both placements, but later decreased with the process of decomposition, with slight fluctuations at the later phase in *H. binata*

(Figure 8(a)). The percentage of the N (average across the depths) left in the residual litter after the decomposition, calculated as shown in Equation 2, was 2.80%, 2.1% and 3.47% for *P. cineraria, T. undulata* and *H. binata*, respectively.

The concentration of P in *T. undulata* declined at steady rate in both placements, but then increased slightly at the end of the decomposition process. In contrast, in *P. cineraria* and *H. binate*, the P concentrations decreased during initial phase of decomposition followed by rise in P concentration and then finally a declined as the decomposition process progressed towards completion (Figure 8(b)). The percentage of the P left in the residual litter at the end of decay process in *P. cineraria* was 5.26% (surface) and 2.14% (sub-surface), 2.77% (surface) and 1.22 % (sub-surface), for *T. undulata* and for *H. binata* it was 3.52% and 2.02 % in surface and sub-surface layer, respectively. The concentration of K declined throughout decomposition phase in *T. undulata* and *H. binata*. For *P. cineraria* decline was rapid in initial phase, but after 120 days of the decomposition the K concentration increased and then decreased in later stage of decomposition (Figure 8(c)). The percentage of the K in the remaining litter at the end was 1.61% (surface) and 0.41 % (sub-surface) in *P. cineraria*, 2.28 % (surface) and 0.66 % (sub-surface) in *T. undulata* and 1.71% (surface) and 0.71 % (sub-surface) in *H. binata*.

Release of Ca and Mg

The concentration of calcium in the decomposing leaf litter did not follow any specific trend (Figure 8(d)). The percentage of Ca present in the residual mass following litter decomposition in *P. cineraria* was 6.71 % in surface and 3.41% in sub-surface layer, 5.37% in surface and 2.47% in sub-surface for *T. undulata* and 5.78% in surface and 3.41 % in sub surface for *H. binata*.

Magnesium concentration showed at trend to decrease for *T. undulata*, whereas in *P. cineraria* after 250 days of decomposition the concentration of Mg increased and then decreased as the decomposition process was completed. Similarly, some minor fluctuations were observed for *H. binata t*owards the end of the decomposition process, when the concentration tended to increase (Figure 8e). The percentage of Mg remaining in the decomposed mass on an average for both the depths was 2.34 %, 1.28% and 2.53% in *P. cineraria, T. undulata* and *H. binata*, respectively. The general order of release of nutrient from the litter was: K > Mg > N > P > Ca in *P. cineraria*, P > Mg > K > N > Ca in *T. undulata* and K > Mg > P > N > Ca in *H. binata*.

Relationships between the initial quality of litter and the decomposition and nutrient release rates

Significant positive correlations ($p < 0.01$) were established between the decomposition constant (k_D) and the initial N, P, Mg concentrations of the litter, at both depths, while significant negative correlations were observed for K, Ca, cellulose, lignin, carbon (sub-surface), C:N, C:P and L:N ratios (sub-surface) (Table 6). All the parameters except L:N and N:P exhibited the strongest relationship ($p < 0.01$, C:N ($p < 0.05$)). The highest value for the correlation was observed for Mg ($r = 0.968$, $p < 0.001$), followed by Ca ($r = -0.960$, $p < 0.001$) and cellulose ($r = -0.943$, $p < 0.001$) at surface depth, whereas cellulose ($r = -0.971$, $p < 0.001$) followed by carbon ($r = -0.969$, $p < 0.001$) and Mg ($r = 0.938$, $p < 0.001$) showed the highest values for the sub-surface samples. The initial chemical characteristics of the litter also showed correlations with the release of N, K and P (Table 6). The rate of release of N (k_N) showed significant positive correlations ($p < 0.01$) with K, Ca, cellulose, lignin, carbon, and C:P ratio and negative correlations with N, P and Mg, at both depths.

Discussion

Leaf litterfall and nutrient flux in litter

The litterfall ranged between 3.74 and 9.44 Mg ha^{-1} y^{-1}, which was within the range reported also for other species (*Leucaena leucocephala, Acacia nilotica, Azadirachta indica, Prosopis juliflora*) grown in arid, semi-arid, tropical and sub-tropical regions (Singh 1992; Jha and Mohapatra 2010; Huang et al. 2017). The litterfall production has been reported to vary with time and space and to be affected by the growth of the trees, as well as by other natural and anthropogenic factors (Lopes et al. 2015). Spatial variations occur across different elevations causing variation in microclimate, solar radiation and soil water movement, which critically affect vegetation and, hence, litter production. Carrera et al. (2008) and Kumar (2008) enunciated that the pattern of litterfall was mainly correlated with the development of the canopy and the growth pattern of the species. Wind velocity in summer months remained high, which may also have been a reason for the higher litter fall in *H. binata* as compared to other species. The dry period coupled with hot dry winds can enhance litterfall (Kumar 2008) and also force the shedding of non-senesced leaves (Cuevas and Lugo 1998). In this study reported here, nearly 50% of the total litterfall in *P. cineraria* and *T. undulata* occurred in the winter season when wind velocity was comparatively low. Yadav et al. (2008) also reported large seasonal variation in litter production by different multipurpose trees in semi-arid regions of western Rajasthan and a large pulse of litter production coincided with the winter months (November–February) and the period of reduced litterfall with the wet season (July–October).

The species under study varied significantly in respect to the chemical characteristics of the leaflitter. Interspecies variation in the initial nutrient content of plant material is well known (Yadav et al. 2008; Kaushal et al. 2012). The return of the major nutrients (N, P, and K) through the litterfall was broadly similar to that reported for arid and semi-arid region species by Jha and Mohapatra (2010) and Solanki and Arora (2015). The higher return of nutrients through the litterfall in *P. cineraria* and lower nutrient additions by *T. undulata* (with a lower level of litter production) was also reported by Kumar et al. (2017) and was explained to be related to the quantity of litter production and the chemical composition of the litter (Singh et al. 2007; Kumar et al. 2017).

Litter decomposition

Most earlier studies have also reported either exponential or linear trends of litter decay (Jamaludheen and Kumar 1999; Issac and Nair 2006; Carrera et al. 2008; Yadav et al. 2008; Kuruvilla et al. 2016). Leaf and litter characteristics, climatic factors, leaf litter quality and substrate quality are known to affect the process of litter decay as well as the pattern of nutrient release from the litter (Zhang et al. 2008; Yadav et al. 2008). The decomposition constant, as well as the rate of release of N, P and K from litter, varied between the different species. *T. undulata* had higher initial N and low lignin content compared to other two species, which likely helped in stimulating the decomposition. Significant positive correlations between the decomposition rates and the initial N (Jamaludheen and Kumar 1999; Jacob et al. 2010), P (Kaushal et al. 2012; Upadhyaya et al. 2012) and Mg (Chen et al. 2011) concentrations of the litter have also been reported previously. The rate of decomposition was faster in *T. undulata*, but the release of nutrients was faster in *P. cineraria* as compared with other two species. The variations in the pattern of decomposition in different months were due to the variation in rainfall and temperature (Kaushal et al. 2012). The rainy season provides favourable environmental conditions in terms of temperature and moisture for the activity of the decomposers (Dutta and Agrawal 2001; Pandey et al. 2014). A similar pattern was also shown in this study as the rainy season resulted in high soil moisture and soil MBC with significant impacts on the decomposition of the litter. The faster decomposition of the litter at the sub-surface depth, compared with the surface depth, could also be attributed to higher soil moisture and soil

MBC at this depth. The more rapid decomposition of the buried litter due to high soil moisture and faunal activity was supported by the findings of Beare et al. (1992), Kaushal et al. (2012) and Erdem and Karavin (2016).

The rates of N, P and K release were also correlated with the initial chemical attributes of litter. The positive correlations of lignin and negative correlations of initial N with the release of N from the litter showed more pronounced effect of climatic variables (rainfall, temperature and relative humidity) rather than the litter quality (Upadhyaya et al. 2012). Lignin content was found to be the best predictor of annual N and P mineralisation (Singh et al. 1999; Osono and Takeda 2004), as was also evidenced in this study reported here. The initial P concentration and C:P ratios have also been reported to be good indicators of P release (Upadhyaya et al. 2012; Zhu et al. 2016). The release of K showed a strong positive relationship with initial K content in litter. Similar results were reported by Laskowski et al. (1995) and Seta et al. (2016). A broad body of literature has shown that decomposition and nutrient release rates of species depend greatly on C:N ratio (Carrera et al. 2008; Jacob et al. 2010; Upadhyaya et al. 2012).

Nutrient release pattern of the leaf litter

The release of nutrients from decomposing litter took place in different phases. The nitrogen concentration in the leaf litter during the decomposition affects the microbial activity and influences the mineralisation of the organic carbon (Swarnalatha and Reddy 2011). The increase in N concentration initially was likely due to immobilisation of N by the microbes. The C:N ratio and the initial concentration of N are known to be the crucial factors for the mineralisation process. The leaf litter of *T. undulata* had a higher initial N concentration and a C:N ratio below 20, which were likely reason for the faster mineralisation, and the situation was vice versa in *H. binata*. The decline in N concentration in later stages of decomposition was likely due to high N demand from the microorganisms (Kaushal et al. 2012) and loss of easily leachable components from leaf litter (Upadhyaya et al. 2012; Thomas et al. 2016). The initial decrease in the P concentration was attributed to the rainy season that encouraged the leaching process and leaching has been reported to escalate the release of P (Zaharah and Bah 1999; Kaushal et al. 2012). The increase in the concentration of P at the later stages was the consequence of immobilisation. The immobilisation of P during initial stages of decomposition was also observed in earlier studies (Adams and Angradi 1996; Yadav et al. 2008). In case of K, like in this study, many other studies have also reported a rapid initial release (Swarnalatha and Vikram 2011; Thomas et al. 2016). K is prone to physical leaching as it is not structurally bound in organic compounds and K has high potential solubility (Kaushal et al. 2012; Bargali et al. 2015; Thomas et al. 2016).

The release of Ca through leaching is less as Ca forms a structural component of plants; covalently bonded to pectin within the middle lamella (Osono and Takeda 2004) and released after prolonged biotic activity (Blair 1988). Studies by earlier workers reported accumulation (Koukoura 1998) and immobilisation (Adams and Angradi 1996) of Ca in decomposing litter as a result of which Ca showed a bi-phasic pattern of release. Similar, to the findings in this study, a trend for an initial release of Mg from the decaying litter and then immobilisation in the later phase has also been reported by other authors (Osono and Takeda 2004; Thomas et al. 2016).

Conclusions

The study provided data on litterfall, litter decomposition patterns and the subsequent release of elements to the soil for the three major agroforestry tree species of the arid region of India. The different species varied both in terms of the quantity and the quality of the litterfall. Litterfall was recorded to be the highest in *H. binata* and the nutrient input (N, P and K) through the litterfall was highest in *P. cineraria*. The decomposition of the leaf litter was in following order *T. undulata* > *P. cineraria* > *H. binata*. The rate of nutrient release from the decomposing litter of *P. cineraria* was higher compared with that for *T. undulata* and *H. binata*. It was concluded that agroforestry systems based on *P. cineraria*, with considerable litter production, providing the highest additions of nutrients to the soil and the most rapid release of nutrients from the decomposing litter, would likely result in greater build-up of soil fertility and improvement of the soil, compared with agroforestry systems based on *H. binata* or *T. undulata*.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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