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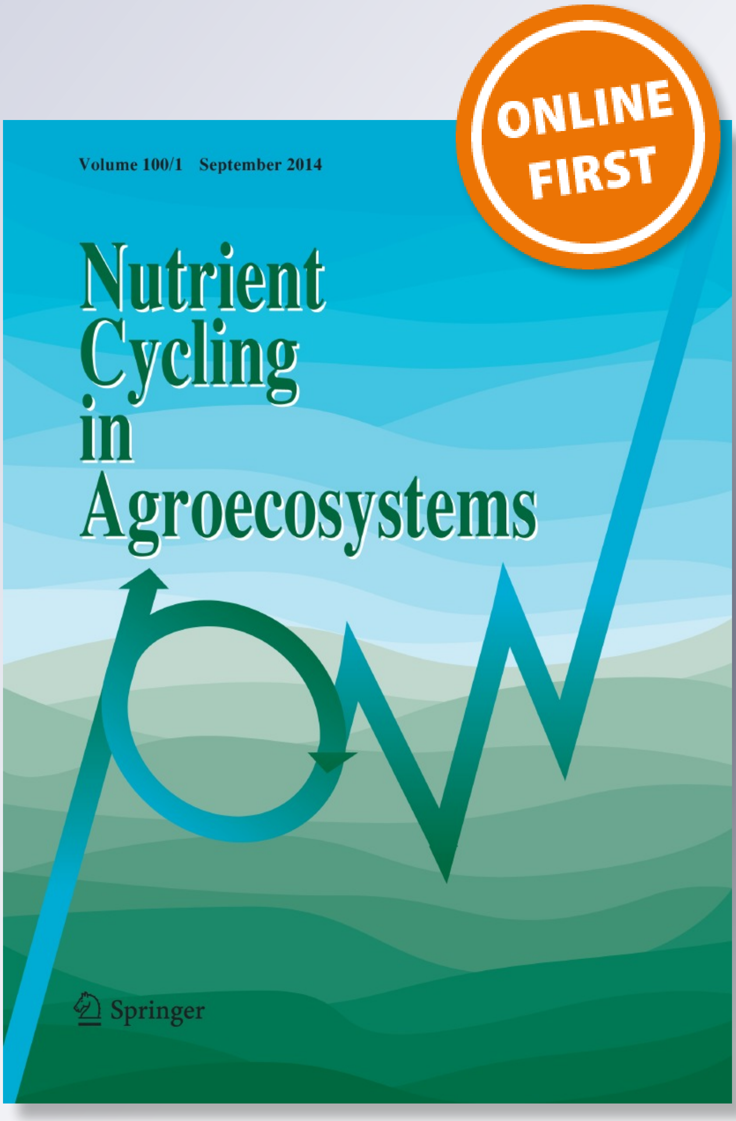

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ORIGINAL ARTICLE

Assessment of nutrient returns in a tropical dry forest after clear-cut without burning

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Abstract Tropical dry forests (TDFs) are being deforested at unprecedented rates. The slash/burn/agriculture/fallow-extensive livestock sequence causes significant nutrient losses and soil degradation. Our aim is to assess nutrient inputs and outputs in a TDF area under an alternative management system, for exclusive wood production. The study involved clear-cutting a preserved caatinga TDF site without burning, quantifying nutrients exported in firewood/timber and nutrients returned to the soil from the litter layer plus the slash debris, left to decompose unburned on the soil surface. Before clear-cut, the litter layer on the forest floor contained 6.1 t ha of dry matter (DM). After clear-cut, the aboveground biomass was 61.9 t DM ha^{-1} (consisting of 21.5 t DM ha^{-1} of commercial wood and 40.4 t DM ha^{-1} of clear-cut debris that did not include the underlying litter layer). The litter layer was composed of fine and coarse litter, with turnovers of 0.86 and 0.31 year^{-1}, respectively, separately measured in uncut control plots during two rainy seasons (Dec-2007/June-2008 and Dec-2008/June-2009). In a single season, its decomposition returned to the soil 48.4, 1.16 and 12.3 kg ha^{-1} of N, P and K. The clear-cut debris was mainly composed of branches, 33.4 t ha^{-1}, bromeliads, 5.63 t ha^{-1} and green leaves, 1.32 t ha^{-1}. In-situ decomposition rates for branches and bromeliads were 0.24 and 1.47 year^{-1}, respectively. After two rainy seasons the clear-cut debris released 206, 6.5 and 106 kg ha^{-1} of N, P and K respectively. This input plus that of the underlying litter layer exceeded exports in the commercial wood, and replenished a soil nutrient stock (0–30 cm) of approximately the same magnitude.

Keywords Caatinga · Litter decomposition · Nutrient cycling · Debris decomposition

Introduction

Tropical dry forests (TDF) are present in most continents, covering an area that varies from 1 to 7 million km^2, depending upon the criteria used to

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define them (Miles et al. 2006). The largest extension of TDFs are in Mexico and Brazil, where 73 % (Maass et al. 2005) and 46 % (MMA 2011) of this ecosystem, respectively, has been degraded, altered or converted to other uses. The conversion is usually initiated by an agriculture cycle that involves clear-cutting the forest, removing the wood with commercial value (fence poles, charcoal or firewood) and burning the clear-cut debris, to "clean" the area for subsistence agriculture. When crop yields are no longer satisfactory, the land is abandoned to bush-fallow, that is sometimes associated with extensive cattle/goat production or conversion into pastures. Other uses include selective logging, to promote growth of native grasses, for extensive cattle raising.

Land use changes associated with the slash-burn-agriculture system strongly modifies nutrient cycling. Losses of up to 96 % of the N, 56 % of the P (Kauffman et al. 1993) and 74 % of the K (Giardina et al. 2000) contained in the clear-cut debris were determined in experimental fires of TDFs areas. In addition to the interruption in litterfall inputs, soil organic matter mineralization is enhanced through cultivation and erosion (Fraga and Salcedo 2004), requiring 10 years or more of bush fallow to recover the organic matter losses (Tiessen et al. 1992).

The soil degradation that results from these management systems causes loss in aboveground biodiversity, and also in the soil micro and mesofauna (Malmström et al. 2009), with reduction of 44 % in the microbial biomass of TDF in NE Brazil (Nunes et al. 2009). Oppositely, in bush-fallow systems where the litterfall is left on the soil surface, carbon and nutrients slowly return into the soil through decomposition and mineralization processes (Jara et al. 2009). This cycling seems to be crucial for the maintenance of TDFs ecosystems (Eaton and Lawrence 2006; Jara et al. 2009).

When not burned, the decomposition of the debris, which is mainly composed of the litter layer plus the fine branches left behind after clear-cut and firewood/timber removal, may last from a few months to years, depending on the size (Eaton and Lawrence 2006) and composition (Dossa et al. 2009) of the plant material as well as on climate (Chambers et al. 2000).

Studies regarding decomposition rates of the litter layer or of clear-cut debris in TDFs are scarce, particularly for woody debris with diameters smaller than 3 cm. Studies focusing on decomposition of woody debris have looked at branches between 3 and 10 cm (Eaton and Lawrence 2006) or <10 cm (Harmon et al. 1995), mostly ignoring stocks of bromeliads, which, when present, are also affected by clear-cutting.

This study followed the decomposition rate of the debris left unburned on the forest floor during two rainy seasons, after clear cutting a mature TDF forest site for wood harvesting. The clear-cut debris had a high spatial variability so a stratified sampling scheme was used to obtain a robust estimate of its mass and chemical composition.

The litter layer biomass in TDF's is much smaller than in tropical wet forests but, nevertheless, it represents a significantly active pool in nutrient cycling. Most litter layer data is derived from litterfall traps placed above the ground (Costa et al. 2007). However, differential decomposition rates of the various litterfall materials would likely modify their relative contribution once on the forest floor. To obtain baseline data of the litter layer mass and nutrient composition in a mature TDF forest, we sampled the experimental area intensively before clear cutting. After clear cutting, we followed the decomposition rate of the clear-cut debris. Specific litter layer dynamics were independently followed in control, uncut plots during two consecutive rainy seasons.

Summarizing, we aimed at determining, (1) how much dry matter (DM) and nutrients accumulate in the litter layer of a mature TDF, how much remains as debris after the TDF is clear-cut, and how much is exported as commercial wood, and (2) how fast the nutrients in the litter layer and the clear-cut debris return back into the soil, when left unburned to decompose on the soil surface.

Materials and methods

Description of study site

The study area is located at a research station administered by the Brazilian Agricultural Research Corporation (Empresa Brasileira de Pesquisa Agropecuária - EMBRAPA), in Petrolina, Pernambuco, Brazil (9°03′53″S and 40°18′49″W), with an altitude of 365 m.a.s.l. The local climate is BSwh', according to the Köppen classification, which corresponds to a hot and semiarid region, with summer rains beginning

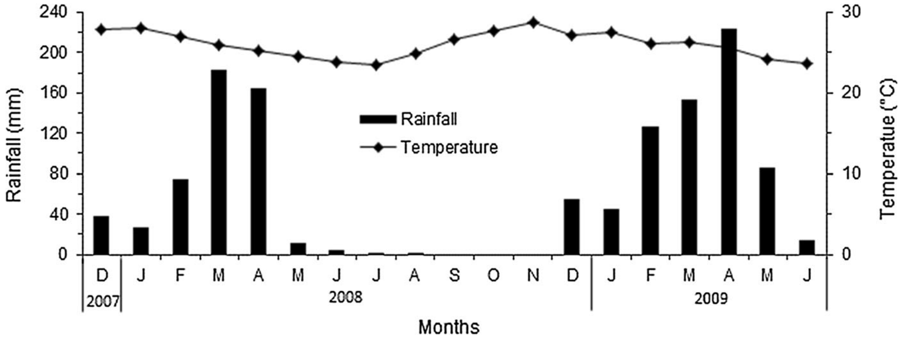

Fig. 1 Rainfall and temperature between December 2007 and June 2009 in the Bebedouro experimental station, Petrolina, Pernambuco, Brazil. *Source*: Embrapa Semiárido (2009)

Table 1 Soil physical and chemical characteristics at the study site

Depth (cm)	Ds ($g\ cm^{-3}$)	Sand ($g\ kg^{-1}$)	Silt	Clay	Textural class
Physical properties					
0–10	1.45[a]	753	95	151	Sandy loam
10–20	1.45	739	97	164	Sandy loam
20–30	1.46	697	99	204	Sandy-clay-loam

Depth (cm)	pH (1:2.5)	TOC ($g\ kg^{-1}$)	P ($mg\ kg^{-1}$)	Al^{3+} ($cmol_c\ kg^{-1}$)	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}
Chemical properties								
0–10	5.41	13.2	4.23	0.25	1.61	0.45	0.22	0.06
10–20	5.18	8.21	2.12	0.32	0.99	0.32	0.17	0.05
20–30	5.19	7.03	1.46	0.44	0.97	0.38	0.16	0.05

Ds density, *TOC* total organic carbon

[a] n = 18

in November and ending in April (Fig. 1). The average annual precipitation and temperature of this area (calculated from 1975 to 2008) is 522 mm and 26 °C, with a difference of <5 °C between the hot and cold months (EMBRAPA Semiárido 2009). The predominant soil is Eutrophic Plinthic Red-Yellow Acrisol (Embrapa 2006), with a flat topography (Table 1).

The study area consisted of 36 ha with dense hyperxerophytic shrub and arboreal caatinga (Sampaio 1995), which is a deciduous semiarid tropical forest (TDF) that had been preserved for more than 40 years. The dominant species in the forest were determined in fifteen plots (10 m × 40 m), delimited and distributed in three blocks (Fig. 2). The average density of the arboreal vegetation was 1,912 individuals per hectare with a basal area (BA) of 8.2 $m^2\ ha^{-1}$ and a mean tree height of 4.67 m. The predominant tree species in the study area were *Poincianella pyramidalis* Tul. (catingueira); *Mimosa tenuiflora* Benth. (jurema preta); *Campomanesia guazumaefolia* Camb. (sete-cascas); *Cnidoscolus quercifolius* Pohl et Baile (favela); *Sapium glandulatum* (Vell.) Pax. (burra leiteira); *Manihot glaziovii* Müll. Arg. (cassava/maniçoba); and *Croton rhamnifolioides* Pax. & K. Hoffm. (quebra-faca). These seven species contributed with 79 % of the BA and 66 % of the total density of the tree plants. Moreover, *Neoglaziovia variegata* Arruda Mez. (caroá), an endemic caatinga bromeliad, was predominant on the forest floor. In spite of its socioeconomic importance it is a poorly studied species, used as a forage source during extended droughts. Its fibers are used by the textile industry, by handcraft workers, and also as a source of polymeric compounds (Silveira et al. 2013)

The fifteen plots and surrounding strips of variable width were clear-cut in December 2007 (white spaces in Fig. 2). Variations in width of the deforested strips are the treatments of a long-term experiment, to study

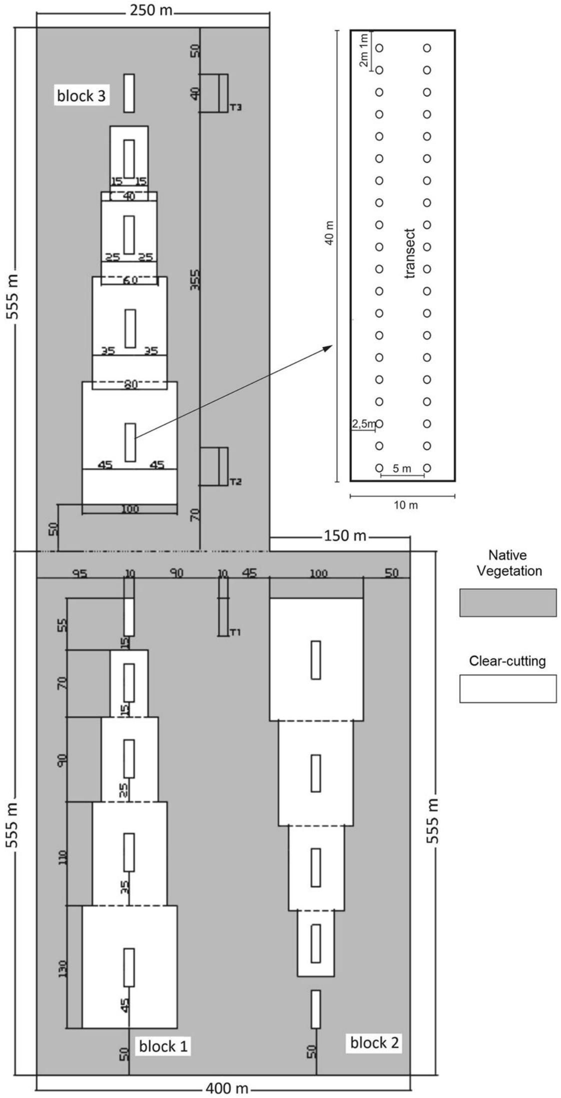

Fig. 2 Spatial arrangement of plots and blocks after clear-cutting the caatinga in the study site, in Petrolina, Pernambuco, Brazil and detail of a plot indicating sampling points for the biomass debris estimation

their effect on caatinga species regrowth and biodiversity, carried out by the Associação de Plantas do Nordeste–APNE (www.cnip.org.br). Variations in width did not show significant effects ($p < 0.10$) upon the decomposition rate of the clear-cut debris, which was followed during the first two rainy seasons after clear-cut. Three control plots of the same size (10 × 40 m), next to the experimental blocks, were left with untouched native vegetation and were also surrounded by preserved TDF (Fig. 2).

Quantification of litter layer and clear-cut debris dynamics

At the end of the dry period (December 2007), 1 week before clear-cutting, nine samples of the forest floor (litter layer) were taken from each plot (n = 15 plus 3 uncut control plots), at pre-defined sampling points, using a 1/8 m^2 (0.25 m × 0.25 m) square made of PVC, totaling 162 [(15 + 3) × 9] samples. In the laboratory, the litter was separated into coarse (branches and bark) and fine (leaves, flowers, fruits, seeds, insects, feces and other unidentified plant fragments) material and oven dried at 65 °C, for DM determination. After clear-cut, the debris on the soil surface of the 15 plots prevented further litter layer determinations, so seasonal changes were followed in the control plots (Fig. 2), that were sampled again in June 2008, December 2008 and June 2009, using the same procedure described above.

In December 2007 all the standing biomass was clear cut, removing from the plots and measuring the mass of wood with diameter ≥5.0 cm at breast height (DBH). This is the minimum size of wood suitable for firewood, charcoal production or fence poles. The average amount of wood extracted was 21.5 t ha^{-1} (dry wood) (or 71.4 steres, locally used unit). The debris that remained on the surface had a highly variable spatial distribution. To obtain a representative mean of its mass, we used a stratified sampling procedure (Petersen and Calvin 1996) (see also Fig. 2): two nylon ropes marking sampling points at 2 m intervals were extended along the 40 m-long plots, 5 m apart from each other and 2.5 m away from the sidelines. Each sampling point (40 points per plot × 15 plots) was numerically identified and visually classified into one of three degrees of debris accumulation: many, medium and few (strata). Subsequently, 15 points from each class were randomly selected and the clear-cut debris collected, using a 0.5 m^2 (0.71 m × 0.71 m) iron square. The debris was determined again in June and December 2008 and in June 2009 using the same procedure, thus extending for two consecutive rainy periods (Dec/07–Jun/08 and Dec/08–Jun/09). We thereby considered the contributions from the regrowth of grass and bromeliads minimal, and when identified as regrowth it was avoided in the sampling scheme.

The overall weighted mean of debris mass was calculated using the proportion of sampling points in each visually defined strata and its corresponding average debris mass. This sampling scheme had the sole purpose of obtaining a representative value for the average debris mass and, for this reason, only results of the weighted averages are shown in the tables. However, it seems interesting to exemplify the heterogeneity of debris distribution in December/2007, when 74, 268 and 258 sampling points were visually classified as having large, medium and small amounts of debris, respectively, with average ($n = 15$; ±s.e.) debris masses of 51.4 ± 3.0, 43.1 ± 4.6 and 33.7 ± 1.8 t DM ha^{-1}.

After quantifying the fresh mass, the debris samples were divided into four fractions: branches, bromeliads, leaves, and miscellaneous (flowers, fruits, seeds, and unidentified plant fragments). Subsamples from each fraction were oven-dried at 65 °C for 72 h for DM determination. The fraction of green leaves was measured only in December 2007 because it was all decomposed during the rainy season. Miscellaneous parts and old (dark brown) leaves sampled in Dec 07 and Jun 08, were not computed as debris DM because it were considered as part of the underlying litter layer. Since most of the litter layer is decomposed in one rainy season, small size materials sampled in Dec 08 and Jun 09 were computed as miscellaneous, originated from the two-year regrowth period.

Chemical analysis

The nine litter layer samples from each experimental plot were randomly composited in groups of three for chemical analysis of each fraction, while no compositing was used for the debris samples nor for litter layer samples from the control plots. After oven drying at 65 °C, plant materials were ground in a Wiley mill using a 0.5 mm mesh sieve. Subsamples (0.250 g) were digested with a mixture of H_2SO_4/H_2O_2 (Thomas et al. 1967). After appropriate dilutions of the digest, K was analyzed using flame photometry, P using the molybdenum blue color, and N using the Kjeldahl method. Subsamples (0.100 g) were passed through a 100 mesh sieve and their C content quantified after wet oxidation and diffusion (Snyder and Trofymow 1984). In the case of the litter layer, concentrations of N, P, and K were only determined in samples obtained in December/2007 and June/2008 (before and after the rainy season, respectively), while the debris was analyzed in all four sampling dates.

Statistical analysis

The overall mean of litter layer DM in the experimental plots before clear-cut was derived from the frequency distribution of coarse and fine litter layer DM, using the expression $\boldsymbol{\Sigma p_i.\ w_i}$ (for all intervals) where $\mathbf{p_i}$ is the proportion of samples in the $\mathbf{i}$ interval and $\mathbf{w_i}$ is the average DM mass of the $\mathbf{i}$ interval (Devore 2011). These samples were obtained before treatment implementation in the field (clear-cut plots + variable-width clear-cut strips), so each sample was considered a replicate representing the preserved TDF field with equal weight. Differences in nutrient stocks in the litter layer and in the debris among sampling dates, were tested for significance by the restricted maximum likelihood (REML) method using SAS PROC MIXED (SAS Institute 2002) after which group differences were specified using the Tukey–Kramer test. To compare nutrient stocks in the litter layer between two sampling dates we used Students *t* test.

The turnover rate (Tr) of the litter layer DM in two consecutive rainy periods was evaluated with data from the control plots ($n = 3$), using the linear expression: $Tr\ (year^{-1}) = [Mi - Mf](t\ ha^{-1}\ year^{-1})/Mi\ \ (t\ ha^{-1})$; where Mi is the initial mass in Dec/07 and Dec/08 ($t\ ha^{-1}$); and Mf is the final mass in Jun/08 and Jun/09 ($t\ ha^{-1}$). The debris mass in the clear-cut plots ($n = 15$) were considered as data points in a continuous decomposition period, with a single initial input (the clear-cut in December 2007), and fitted to a first order kinetic equation using non-linear regression: $M(t) = Mi\ e^{-k\ t}$ (Olson 1963) where M(t) is the mass at time t ($t\ ha^{-1}$), Mi is the initial mass (Dec/07) ($t\ ha^{-1}$), and k is the rate of decomposition ($year^{-1}$). Since most of the plant decomposition and nutrient cycling occurs once a year, during the rainy period (January to May), year was the time unit in the equation.

Results

Initial (pre-cut) litter layer stocks

Stocks of DM in the litter layer of the experimental plots ($n = 162$) varied from 0.49 to 17.9 t ha^{-1}. In spite of the differences in the frequency distribution shapes, the weighted averages of DM in the fine litter and coarse litter (Fig. 3) fractions were similar, 3.08 ± 0.12 and 3.23 ± 0.22 t ha^{-1}, respectively.

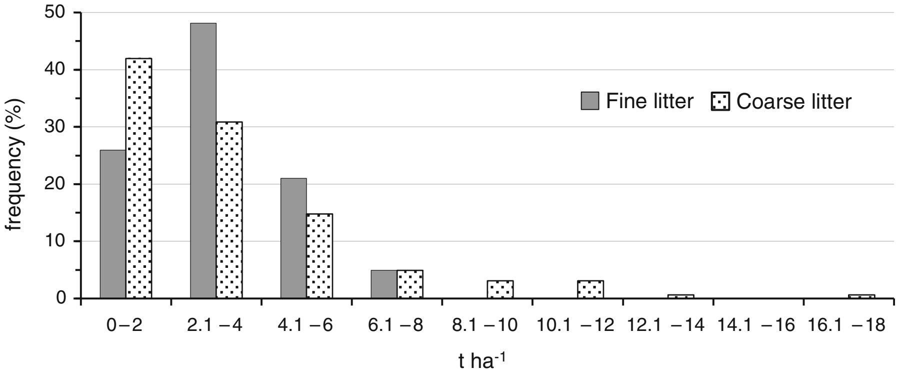

Fig. 3 Frequency distribution (n = 162) of fine litter and coarse litter (t DM ha^{-1}), sampled at the end of the dry season, in a hyperxerophilous Caatinga forest

Table 2 Seasonal variation and average (two rainy seasons) turnover rate (Tr) of litter layer mass (t DM ha^{-1}) in the control plots of an hyperxerophilous Caatinga forest

Fraction	Dec/07	Jun/08	Dec/08	Jun/09	Tr[1] (year^{-1})
Fine	3.31 ± 0.31	0.369 ± 0.032	2.70 ± 0.27	0.465 ± 0.046	0.86
Coarse	2.79 ± 0.26	2.19 ± 0.20	3.01 ± 0.54	1.81 ± 0.37	0.31
Total	6.10 ± 0.38	2.56 ± 0.20	5.71 ± 0.64	2.28 ± 0.38	0.59

The data are weighted means ± one standard error, n = 27. [1]Tr (year^{-1}) = [Mi − Mf] (t ha^{-1} year^{-1})/Mi (t ha^{-1}); where Mi is the initial mass (Dec/2007 and Dec/2008) (t DM ha^{-1}); and Mf is the final mass (Jun/2008 and Jun/2009) (t DM ha^{-1}). Dec–Jun is the rainy season at the study site

The fine fraction presented most of its samples (33 %) in the 2.1–3 t ha^{-1} range, while the coarse fraction in the 0–2 t ha^{-1} (42 %). The pre-cut total litter layer mass amounted to 6.31 ± 0.26 t DM ha^{-1}, which is very similar to the average mass found in the control plots (Table 2).

Litter layer dynamics

DM changes in the control plots (Table 2) had a similar pattern with time, decreasing ($p < 0.05$) during both rainy seasons and remaining unchanged ($p > 0.05$) in the inter-annual comparison of the same month. The average DM turnover rates (Tr) for the rainy period (mostly January to May for both years, Fig. 1) were 0.86, 0.31, and 0.59 year^{-1} for fine, coarse, and total litter layer DM, respectively.

Nutrient stocks (Table 3) where only determined before and after the first rainy season. The mean C concentrations in the fine and coarse litter layer materials were similar, 422 ± 5.5 and 441 ± 7.4 g C kg^{-1} DM, respectively (data not shown), and amounted to average carbon stocks of 2.62 and 1.16 t ha^{-1} before (December) and after (June) the rainy season. Average nutrient concentrations in the litter layer of the pre-cut (Dec/07) experimental plots were very similar to those of the control plots, so only these last ones were reported in Table 3. The seasonal decrease ($p < 0.05$) in nitrogen and phosphorus stocks was greater in the fine than in the coarse fraction, while potassium showed comparable decreases in both fractions (Table 3). The litter layer lost 48.4, 1.2 and 12.3 kg ha^{-1}, of N, P and K, respectively, during the rainy season, which represents 74, 65 and 72 % of its initial stock, respectively (Table 3).

Stock and decomposition of clear-cut debris

The clear-cut debris averaged 40.4 t DM ha^{-1}, most of it (83 %) consisting of small branches, bromeliads (14 %) and green leaves (3 %) (Table 4). Combining this amount with the stock of commercial wood (21.5 t DM ha^{-1}) and the underlying litter layer mass (6.10 t DM ha^{-1} before clear-cut), the aboveground biomass amounted to 68.0 t DM ha^{-1}.

The overall decomposition rate (k ± s.e.) for the branches was 0.24 ± 0.34 (year^{-1}) and 1.47 ± 0.37

Table 3 Seasonal variation of N, P, and K stocks (kg ha^{-1}) in the litter layer of control plots under hyperxerophilous Caatinga forest

Fraction	N		P		K	
	Dec/07	Jun/08	Dec/07	Jun/08	Dec/07	Jun/08
Fine	35.4^{a} ± 6.0	2.68^{b} ± 0.27	1.10^{a} ± 0.21	0.144^{b} ± 0.02	8.54^{a} ± 1.7	2.70^{b} ± 0.90
Coarse	29.7^{a} ± 5.4	14.0^{b} ± 1.1	0.680^{a} ± 0.10	0.472^{a} ± 0.05	8.56^{a} ± 2.6	2.09^{b} ± 0.32
Total	65.1^{a} ± 4.0	16.7^{b} ± 1.5^{b}	1.78^{a} ± 0.12	0.617^{b} ± 0.05	17.1^{a} ± 1.5	4.79^{b} ± 0.26

Data are weighted means ± one standard error, n = 27. Different superscripted letters denote a significant difference by the *t* test ($p < 0.01$) between means comparing sampling dates, for each nutrient and fraction

Table 4 Seasonal variation and rate of decomposition (k) of debris (t DM ha^{-1}) remaining after the clear-cut of an hyperxerophilous Caatinga forest

Fraction	Dec/07	Jun/08	Dec/08	Jun/09	k^{1} (year^{-1})
Branches	33.4 ± 1.7	30.1 ± 1.8	26.1 ± 1.6	23.5 ± 1.9	0.24
Bromeliads	5.63 ± 0.4	2.77 ± 0.24	1.57 ± 0.23	0.18 ± 0.06	1.47
Miscellaneous	n.d	n.d	1.89 ± 0.24	0.36 ± 0.10	n.d
Leaves	1.32 ± 0.3	n.d	n.d	n.d	n.d
Total	$40.4^{\S}$ ± 1.9^{a}	$32.9^{\S\P}$ ± 1.8	$29.6^{\P}$ ± 1.6	$24.0^{\P}$ ± 1.9	

The data are weighted means ± one standard error, n = 45. ^{1} $M(t) = Mi\ e^{-k\ t}$, where M(t) is the mass at time t (t DM ha^{-1}), Mi is the initial mass (Dec/2007) (t DM ha^{-1}), and k is the rate of decomposition (year^{-1}). The following abbreviation is used: n.d., not determined. Dec–Jun is the rainy season at the study site

§ The debris totals do not include miscellaneous because it was considered that these fraction belonged to the underlying litter layer

¶ The debris totals do not include the fraction of green leaves because it was all decomposed after a rainy season

(year^{-1}) for the bromeliad fractions (Table 4). Although k and Tr share the same unit, comparing them should be avoided, because Tr is a linear approximation of the rate, while *k* is estimated by an exponential equation. Exemplifying, *k* for bromeliads (1.47 year^{-1}) indicates a faster decomposition rate than Tr for fine litter (0.86 year^{-1}), although the fine litter lost 90 % of its initial DM after the first rainy season (Table 2) while bromeliads lost only half (Table 4).

Nutrient stock dynamics

After clear-cutting, 17.6 t C ha^{-1} were deposited on the soil surface as debris while 9.48 t C ha^{-1} was removed from the ecosystem as firewood/timber, yielding a standing carbon stock of 27.1 t ha^{-1} in December/2007. Adding the C in the litter layer, the total C stock was 29.7 t ha^{-1} of which 31.9 % were exported with the timber. Branches in the clear-cut debris accounted for 310 kg ha^{-1} of a total N stock in the debris of 369 kg ha^{-1} (Table 5) in December/2007; most of the P and K contained in the debris were also in the branches (Table 5).

While the bromeliads released most of its N, P and K to the soil during two rainy seasons, the branches lost about one-fifth of the K and one-half of the N and P stocks during the same period (Table 5). Overall, the debris released 206, 6.5 and 106 kg ha^{-1} of N, P and K, respectively, during two rainy seasons. Nutrient removal by timber (21.5 t ha^{-1} of commercial timber) amounted to 200, 6.3, and 63.7 kg ha^{-1} of N, P, and K, respectively, based on the chemical composition of the branch fraction.

Discussion

Litter layer dynamics

Stocks of litter layer found at the end of the dry season (December) were interpreted as the maximum annual contribution for that particular year, since most of the litter fall occurs during the dry season. In general, this compartment represents approximately 10 % (6–15 %) of the total aboveground biomass in TDFs (Kauffman et al. 1993; Jaramillo et al. 2003; Kauffman et al. 2003).

Table 5 Decrease of N, P, and K stocks (kg ha^{-1}) in the weighted average debris remaining after the clear-cut of an hyperxerophilous Caatinga forest

Fração	Dec/07[§]	Jun/08[§¶]	Dec/08[¶]	Jun/09[¶]
N				
Branches	310 ± 19^{a}	186 ± 18^{b}	173 ± 20^{bc}	151 ± 34^{bc}
Bromeliads	41.1 ± 4.8^{a}	15.2 ± 1.4^{b}	13.0 ± 2.6^{bc}	3.03 ± 0.79^{c}
Miscellaneous	n.d.	n.d.	29.6 ± 6.5^{a}	9.44 ± 3.5^{b}
Green leaves	17.9	n.d.	n.d.	n.d.
Total	369 ± 19^{a}	201 ± 18^{b}	215 ± 20^{bc}	163 ± 33^{c}
P				
Branches	9.82 ± 0.81^{a}	6.94 ± 0.65^{b}	6.45 ± 0.72^{bc}	5.07 ± 0.93^{c}
Bromeliads	1.56 ± 0.17^{a}	0.728 ± 0.07^{b}	0.617 ± 0.12^{c}	0.153 ± 0.05^{d}
Miscellaneous	n.d.	n.d.	1.23 ± 0.27^{a}	0.509 ± 0.20^{b}
Green leaves	0.882	n.d.	n.d.	n.d.
Total	12.3 ± 0.86^{a}	7.67 ± 0.6^{b}	8.29 ± 0.77^{bc}	5.74 ± 0.89^{c}
K				
Branches	99.1 ± 15^{a}	29.6 ± 3.4^{b}	28.5 ± 4.1^{b}	22.9 ± 4.3^{b}
Bromeliads	39.9 ± 5.3^{a}	14.1 ± 1.8^{b}	10.5 ± 1.7^{bc}	2.80 ± 0.80^{c}
Miscellaneous	n.d.	n.d.	25.7 ± 6.4^{a}	12.0 ± 5.8^{b}
Green leaves	4.98	n.d.	n.d.	n.d.
Total	144 ± 16^{a}	43.7[¶] ± 3.0^{bc}	64.7[¶] ± 8.0^{b}	37.8[¶] ± 7.7^{c}

Data are mean ± one standard error, n = 27. n.d. = not determined. Different superscript letters in the same line indicate significant differences between means according to the Tukey–Kramer test ($p < 0.05$). Dec–Jun is the rainy season at the study site

[§] Totals for these dates do not include miscellaneous because these materials were considered to belong to the underlying litter layer and leaves

[¶] Green leaves were not presented in the forest floor

Although some decomposition could have occurred during the dry period, litter layer stocks (Table 2) were, nevertheless, much larger than litter fall published results. The greater proportion of finer material in the litter fall (75 % in Andrade et al. 2008; and 80 % in Costa et al. 2007), as compared to that found in the present study (50 % coarse and 50 % fine) and also in Martins (2009) could explain this discrepancy. The relative increment of the coarser component results from its slower decomposition rate, 0.31 year^{-1} (similar to Martins 2009), when compared to 0.86 year^{-1} for the finer fraction (Table 2). Thus, litter layer stocks quantified at the end of the dry period are a better descriptor of the litter layer composition than measurements of annual litter fall. The combined annual decomposition rate for the litter layer was 0.59 year^{-1} (Table 2), which is a relatively uniform rate for TDFs [0.68 year^{-1} for Chamela, Mexico; and 0.60 year^{-1} for Chakia, India according to Martinez-Yrízar (1995)].

Biomass stocks dynamics

It is not clear if the proportion of harvested wood fuel found in our study (32 % of total aboveground biomass) will also apply to sites with different forest densities or BA. Forest densities can oscillate between 1912 (this study) to 5,800 individuals ha^{-1} (Francelino et al. 2003; Jara et al. 2009) due to differences in stand age, soil and climate, as well as the inclusion/exclusion criteria used for trees, and, mostly important, to the land use history.

It is important to notice that the clear-cut debris was almost twice the commercial wood exported from the area by this management technique (68 % of the total aboveground biomass). Under traditional management, burning of this material represents an important ecosystem loss (Kauffman et al. 1993) and an instantaneous contribution to greenhouse gases, leaving, an unprotected soil surface for the first rainfalls, when erosion normally sets in.

The only other experimentally determined data for clear-cut debris (diameter <2.55 cm) in caatinga forest amounted to 50 % of a total biomass of 74 t ha^{-1} (Kauffman et al. 1993), which is somewhat smaller than the 68 % (diameter <5.0 cm) found in this study. Other authors have estimated the debris for caatinga forest based on the production of dry wood (32–66 t ha^{-1}), considering that this fraction would amount to 65 % of the dry wood (Sampaio and Silva 1996). Thus, although experimental information available for TDFs is still limited, contribution from debris converges to 60 % of total aboveground biomass. This information is critical to assess the impact of forest management strategies in carbon and nutrient cycling.

The organic sources left to decompose provided extensive biological activity on the soil surface. The layer of branches slowly decomposing on the soil surface for four or more years provides effective cover from the erosive action of heavy rainfall, typical of tropical areas, until the secondary growth is developed enough. Decomposition and nutrient recycling are regulated by climate and litter quality (Chambers et al. 2000), which control the mesofauna and microbiological activity (Malmström et al. 2009). The concentration of lignin and polyphenols in the litter affect the decomposition process (Dossa et al. 2009), and these types of compounds are predominant in the coarse litter layer and branch fractions, yielding slower decomposition rates than other fractions.

Nutrient stocks dynamics

Nitrogen and P returns during two rainy seasons, approached exports by timber removal (206 vs 200 and 6.5 vs 6.3 kg ha^{-1} of N, P respectively). Because of its solubility within the plant tissue (Dossa et al. 2009), 72 % of the K in the clear-cut debris (106 kg ha^{-1}) returned to the soil in the same period and exceeded timber removal (63.7 kg ha^{-1}).

The litter layer was distributed in the whole area before clear cutting, with comparable DM and composition, so the N, P and K released in the control plots from this source (48.4, 1.16 and 12.3 kg ha^{-1} respectively) can be used as an estimate of inputs from the litter layer underlying the clear-cut debris. The rate or timing of this nutrient release is unknown, but it was probably even faster than in the control plots, due to the mulching effect of the debris, with new C sources and increased moisture, providing a very favorable environment for biological activity. During the two rainy seasons of the study, new litter production from the regrowth in the clear-cut plots was negligible compared to the amount of debris on the ground.

Although the contribution of the underlying litter layer was much smaller than from the clear-cut debris, nutrients released from both sources of decomposing materials are meaningful when compared with available nutrient stocks in the 0-30 cm layer of the soil (Table 1). Potentially available N, based on a C/N ratio of 11 and 3 % mineralization of organic matter during the rainy season (Alves et al. 1999) could amount to 112 kg ha^{-1}, extractable P was 11 kg ha^{-1} and extractable K, 311 kg ha^{-1} in the 0–30 cm layer of the soil. Thus, the unburned materials are an expressive source of N and P for the soil.

This management is in contrast with the widespread use of slash and burn at the beginning of an agriculture/livestock production cycle, which precedes land abandonment to bush-fallow. Almost 100 % of the C and N and up to 50 % of the P are lost by volatilization during burning, while nutrients returning in the ash (Ca, Mg and K) depend upon on-site ash deposition. Burning greatly affects nutrient balance (Salcedo et al. 1997), in addition to the well-known negative effect of fires on the soil biological activity and in species biodiversity (Kauffman et al. 1993, 2003).

Data provided by this work indicates that clear-cut without burning, although it appears a destructive (forest) management technique, allows a significant nutrient return to the soil, stimulates biological activity through carbon inputs and provides extensive protection against erosion of the soil surface by rainfall storms. Additionally, experiments with this kind of management have already demonstrated that losses of aboveground biodiversity are small (10–15 %) (Sampaio et al. 1998; Pareyn et al. 2009). All these aspects have a positive impact in the sustainability of resource use (Perrings et al. 1992) and are in contrast with the traditional way to clear forestland for agriculture and livestock, involving clear-cut followed by burning. This last management generates a value loss in the sustainability of resource use, caused by strong erosion/degradation processes (e.g., soil compaction plus nutrient and organic matter losses), among others (Finegan et al. 2009).

Concluding remarks

The expansion of human population, intensive wood fuel consumption by regional industries (gypsum, ceramics, food and others) and need for agricultural land are the main drivers of deforestation in the semiarid of NE Brazil and probably of other countries as well. This results in loss of forest areas, fragmentation of forest habitats and biodiversity losses (Fleming et al. 2011). Soil degradation arises from the sequential use of the same land area for wood extraction, food crops and livestock production, exporting nutrients at a fast pace (5–6 years) until land abandonment.

While subsistence agriculture and cattle rising have been declining during the last two decades, wood fuel consumption for industrial, commercial and domestic use has been increasing, mainly from caatinga forest (Riegelhaupt 2010). To address the continuing wood fuel demand in a most appropriate way, there is a need to incorporate forest management systems as a specific land use, in farms that still maintain forest areas. Sustainable forest management can easily be integrated in caatinga farming systems; as caatinga forest is widely used as natural pastureland, only very small farms (<20 ha) do not keep native forest at some stage of regrowth. Additionally, financial return of caatinga forest management equals or exceeds the reduced income return from agriculture and animal husbandry (Marques et al. 2011). In this context, areas under sustainable forest management, would contribute to the sustainability of farming systems in social and economic terms, while in the environmental perspective would help in the control of permanent deforestation.

To assess the long-term sustainability of clear-cut without burning, it is still necessary to improve our understanding of the relationships among soil fertility, annual rainfall, rates of secondary regrowth of various forest species and appropriate fallow time before the next clear-cut. Possible changes in the biodiversity of the flora and fauna after various cycles should also be assessed.

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