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BIOMASS AND NUTRIENT DYNAMICS ASSOCIATED WITH SLASH FIRES IN NEOTROPICAL DRY FORESTS[1]

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Abstract. Unprecedented rates of deforestation and biomass burning in tropical dry forests are dramatically influencing biogeochemical cycles, resulting in resource depletion, declines in biodiversity, and atmospheric pollution. We quantified the effects of deforestation and varying levels of slash-fire severity on nutrient losses and redistribution in a second-growth tropical dry forest ("Caatinga") near Serra Talhada, Pernambuco, Brazil. Total aboveground biomass prior to burning was ≈74 Mg/ha. Nitrogen and phosphorus concentrations were highest in litter, leaves attached to slash, and fine wood debris (<0.64 cm diameter). While these components comprised only 30% of the prefire aboveground biomass, they accounted for ≈60% of the aboveground pools of N and P. Three experimental fires were conducted during the 1989 burning season. In these treatments consumption was 78, 88, and 95% of the total aboveground biomass. As much as 96% of the prefire aboveground N and C pools and 56% of the prefire aboveground P pool was lost during combustion processes. Nitrogen losses exceeded 500 kg/ha and P losses exceeded 20 kg/ha in the fires of the greatest severity. With increasing fire severity, the concentrations of N and P in ash decreased while the concentration of Ca increased. This indicates greater amounts of these nutrients were volatilized (i.e., greater ecosystem losses occurred) with increasing fire severity. Following fire, up to 47% of the residual aboveground N and 84% of the residual aboveground P were in the form of ash, which was quickly lost from the site via wind erosion. Fires appeared to have a minor immediate effect on total N, C, or P in the soils. However, soils in forests with no history of cultivation had significantly higher concentrations of C and P than second-growth forests. Based upon the measured losses of nutrients from these single slash-burning events, it would likely require a century or more of fallow for reaccumulation to occur. However, current fallow periods in this region are 15 yr or less.

Key words: biogeochemical cycling; Brazil; Caatinga; carbon; deforestation; fire; nitrogen; nutrient loss; phosphorus; slash-and-burn agriculture; tropical forest; volatilization of nutrients.

INTRODUCTION

Dry forests (sensu Holdridge et al. 1971) are the most common of tropical forest types. They comprise ≈42% of all areas occupied by tropical or subtropical forests (Murphy and Lugo 1986). Dry forest regions also have the highest human population densities in the neotropics (Murphy and Lugo 1986). Because of relatively long and intensive land-use histories, tropical dry forests (TDF) are considered among the world's most exploited and endangered ecosystems (Janzen 1988). Increases in human population density are resulting in unprecedented rates of exploitation and conversion to agriculture (WRI 1990). In spite of their large areal extent and high level of exploitation, TDFs are probably the least studied of tropical ecosystems, receiving far less attention than either savannas or rain forests (Murphy and Lugo 1986). In particular, data are practically nonexistent with respect to nutrient losses associated with deforestation and biomass burning in this ecosystem.

The Caatinga region of northeastern Brazil is dominated by a semiarid deciduous tropical forest densely populated by people living at or below the subsistence level. Land use centers on shifting cultivation, conversion to livestock pasture, and fuel wood harvest. Shifting cultivation as well as conversion to pasture typically involves cutting and burning the extant veg-

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etation. In general, trees are cut early in the dry season, prior to leaf abscission. Prior to burning, some large wood debris is usually removed for use as fence posts, fuel wood, or charcoal production. Near the end of the dry season the slashed areas are burned, and crops are planted upon commencement of the wet season. Areas are cultivated for 2–7 yr and then abandoned.

During slash fires, nutrient pools may follow one of three pathways; they may be lost through volatilization or particulate transport, they may be deposited as ash, or they may remain within uncombusted organic debris. Numerous studies have examined nutrient losses related to slash fires in tropical moist ecosystems (e.g., Harwood and Jackson 1975, Ewel et al. 1981). Yet none have quantified how different fire severities interact with nutrient loss or redistribution. Fire effects are not a uniform phenomenon. For example, in Amazonian forests, Uhl et al. (1988) and Ward et al. (*in press*) reported levels of biomass consumption ranged from 25 to 89%. Fires of varying severity have resulted in dramatic differences in plant survival and, hence, biological diversity and the capacity for that site to hold and retain nutrients (Kauffman 1991).

Elemental losses from slash fires can negatively influence long-term site productivity if nutrient loss exceeds the replacement rate during fallow periods. While nutrient cycling and balances (i.e., inputs, internal cycles, and losses), are well known for many undisturbed tropical ecosystems (Vitousek and Sanford 1986, Jordan 1989, Bruijnzeel 1991, Singh and Singh 1991*b*), additional studies are warranted to quantify the effects of anthropogenic perturbations on ecosystem nutrient balances. In addition, little is known concerning the quantities of C, N, or P emitted to the atmosphere from TDF fires. In order to improve projections of nutrient loss and atmospheric emissions on a regional or global scale, an improved understanding of the variation encountered among slash fires of different severities is required. To address the paucity of knowledge of the dynamics of biomass burning in tropical dry forests, we established the following objectives: (1) to quantify the total aboveground biomass and aboveground pools of carbon (C), nitrogen (N), and phosphorus (P) in a slashed neotropical dry forest; (2) to determine the total C, N, and P pools in the soils of these stands at the 0–10 cm depth (i.e., the soil nutrient pools most likely to be directly influenced by fire); and (3) to ascertain the potential effects of varying levels of fire severity on nutrient loss and redistribution.

METHODS

Study area

The study sites are located at the Serra Talhada Research Station administered by Empresa Pernambucana de Pesquisa Agropecuaria (IPA-UEP). This research station is located 9 km north of the town of Serra Talhada, Pernambuco, in northeastern Brazil (7°59′00″ S, 38°19′16″ W). The elevation is ≈500 m. The mean annual precipitation (1958–1976) was 803 mm, with a pronounced dry season occurring from May through November (Encarnaçao 1980). The topography of the area is typified by rolling hills with slopes of 1–36%. The average slope of the study area was 10%. Rock outcrops are common on hill summits. Soils are classified as Alfisols and Inceptisols with a pH of 5.9–6.9 (I. H. Salcedo, *personal observation*).

The vegetation of this region is classified as "Caatinga," which is a deciduous semiarid tropical forest. The overstory canopy of the few remaining primary forests in this region is closed and 10–15 m in height. Dominant species in the forest canopy of the study area prior to cutting were *Croton sanderianus* Muell, Arg (Euphorbiaceae), *Cordia leucocephala* Moric. (Ehretiaceae), *Bauhinia cheillantha* Steud. (Leguminosae), *Mimosa* spp. (Leguminosae), and *Caesalpinia pyramidalis* Tul. (Leguminosae). Over 35 tree species were identified in the 1.6-ha study area. Understory vegetation consisted of a sparse cover of tree seedlings, vines, and herbs. A well-developed litter layer was prevalent, particularly during the dry season following leaf abscission.

The study area was previously slashed and burned in 1973. Following this primary slash-and-burn episode, it was cultivated for 3–4 yr and then abandoned until 1989. A closed canopy forest, 5–8 m in height, had regrown by this time. All arboreal vegetation was cut in early July 1989 prior to leaf abscission. Prior to burning some of the larger stems were removed from the site for charcoal production or fence posts.

To ascertain the variation in biomass consumption and hence nutrient fluxes that occur in fires of this region, we collected data from three areas that were burned at the onset, middle, and end of the time period in which local agriculturalists set fires to prepare sites for planting. Each of the three burn plots was slightly larger than 0.5 ha in size. These plots were burned successively on 19 September, 26 September, and 4 October 1989. These will be referred to as the first, second, and third slash burns, respectively. There was no precipitation during this period and, therefore, these three slash burns are indicative of the effects of fires along a gradient of decreasing moisture content of soils and slashed debris.

Total aboveground biomass

Aboveground biomass was partitioned into categories based upon plant morphology and relationships to combustion and fire behavior. We measured the diameter and length of each piece of wood removed by agriculturalists before burning to quantify the mass and nutrient export arising from wood removal. The prefire mass of remaining wood debris, the amount consumed by fire, and the residual debris following fire were estimated nondestructively using the planar intercept technique (Van Wagner 1968, Brown and Roussopou-

TABLE 1. Total aboveground biomass (Mg/ha) before and after burning and combustion factor (i.e., the percentage of biomass consumed) in tropical dry forest near Serra Talhada, Pernambuco, Brazil. Numbers are mean ± 1 SE. $N = 30$ transects per burn.*

	Slash burn 1 19 September 1989			Slash burn 2 26 September 1989		
Parameter	Prefire	Postfire	Combustion factor	Prefire	Postfire	Combustion factor
Litter	4.00 ± 0.59	0.23 ± 0.15	94.95 ± 3.05	3.74 ± 0.55	0.00 ± 0.00	100.00 ± 0.00
Foliage	6.15 ± 0.44	0.61 ± 0.20^a	85.00 ± 4.76^a	7.64 ± 0.56	0.002 ± 0.002^b	99.95 ± 0.04^b
Wood debris (diameter, cm)						
0–0.64	10.16 ± 0.73	1.01 ± 0.34^a	85.00 ± 4.76^a	12.63 ± 0.93	0.003 ± 0.003^b	99.95 ± 0.04^b
0.65–2.54	26.66 ± 2.66	3.78 ± 1.00^a	77.03 ± 6.31^a	24.33 ± 2.13	0.48 ± 0.20^b	97.45 ± 1.06^b
2.55–7.62	23.98 ± 3.22	9.95 ± 1.87^a	45.70 ± 7.56^a	19.02 ± 2.88	4.82 ± 1.24^b	74.10 ± 5.48^b
>7.62	2.81 ± 1.08	0.82 ± 0.51^a	81.70 ± 13.00	6.67 ± 1.83	3.01 ± 1.16^b	48.36 ± 13.77
Total wood debris	63.61 ± 8.87	15.56 ± 3.05^a	72.04 ± 5.01	62.64 ± 4.31	8.32 ± 1.89^b	86.63 ± 2.96
Total aboveground	73.75 ± 2.65	16.40 ± 2.98^a	77.59 ± 4.83^a	74.02 ± 5.00	8.32 ± 2.83^b	88.45 ± 4.61
Ash	···	3.86 ± 0.45	···	···	4.19 ± 0.52	···

* Biomass of all parameters was significantly different ($P \leq .10$) before vs. after fire. Different superscripted letters denote a significant difference shown by an LSD test comparing treatments.

lous 1974). It was necessary to re-parameterize the planar intersect technique for tropical dry forest because the technique had not been previously used for estimating mass in such forests. In each burn treatment, 30 planar intersects were systematically established to ensure sample dispersion throughout the plot. All wood particles that intersected each sample plane were measured for diameter size. Wood debris was partitioned into four standardized size classes based on their diameter, which is a good predictor of the rate of moisture loss (e.g., a time-lag constant) and, hence, of relationships to combustion and fire behavior (Deeming et al. 1977). The time-lag constant of a fuel particle is defined as the time required for a fuel particle to lose 63% of the difference between its initial equilibrium moisture content under standard conditions of 27°C and 20% relative humidity (Pyne 1984). Lengths of the sampling plane varied among particle size classes: 2 m for wood debris ≤0.64 cm diameter (1-h time-lag fuels); 3 m for wood debris 0.64–2.54 cm diameter (10-h time-lag fuels); 5 m for wood debris 2.55–7.6 cm diameter (100-h time-lag fuels); and 12 m for coarse wood debris ≥7.6 cm diameter (1000-h time-lag fuels). The diameter of each coarse wood debris particle that intercepted the plane was measured to the nearest half centimetre. The quadratic mean diameter of fuel particles in the 1-, 10-, and 100-h size classes was calculated through measurement of the diameter of 100 samples of wood debris within each size class. Thereafter, we counted the number of particles that intersected the sampling plane. Bias due to fuel particle tilt and slope was corrected for as outlined in Van Wagner (1968) and Brown and Roussopoulous (1974). All transects were marked with small metal stakes prior to burning. The same transects were then remeasured after burning.

The biomass of attached foliage (i.e., leaves, flowers, and seeds attached to the slashed woody debris) was ascertained through determination of the ratio between its biomass and that of wood debris <0.64 cm diameter (1-h time-lag fuels). Fifty randomly collected samples of the 1-h time-lag fuels and their associated attached foliage were collected and oven-dried, and their respective mass ratios were determined. The mass of the attached foliage was then estimated by multiplying the biomass of the 1-h time-lag fuels by this ratio.

The biomass of the litter layer was sampled in 20 microplots (50 × 50 cm) in each treatment prior to burning. Following fire, paired microplots were placed 2 m away from the prefire microplots and were sampled for residual litter biomass.

Ash mass was initially calculated from bulk density and mean depth measurements. In each plot the bulk density of ash was estimated through collection of 12 samples of known volume. As soon as it was possible to enter the plots after fire, depth of ash was measured to the nearest millimetre at 20 points along six transects in each plot. Ash mass was then calculated by multiplying ash bulk density by ash depth. This method yielded overestimates of ash mass because of difficulties in estimating ash depth and bulk density. Because of settling, the bulk density of our ash samples was probably higher than the bulk density of the undisturbed ash bed. In addition, the mean ash depth only ranged from 3.6 to 5.9 mm, and it was difficult to obtain an accurate measurement. Errors in mass estimation were likely because the depth of ash was consistently rounded up to the nearest whole millimetre. We were able to correct for this overestimate through calculation of the mass of Ca in aboveground biomass. Calcium volatilizes at a temperature above that of flaming combustion (>1400°C; Weast 1982), so we assumed that the mass of calcium in ash and uncombusted woody debris would be equivalent to that in the prefire above-

TABLE 1. Continued.

Slash burn 3 4 October 1989		
Prefire	Postfire	Combustion factor
3.58 ± 0.43	0.00 ± 0.00	100.00 ± 0.00
6.66 ± 0.04	0.002 ± 0.002[b]	99.97 ± 0.02[b]
11.01 ± 0.77	0.003 ± 0.003[b]	99.97 ± 0.02[b]
26.01 ± 1.94	0.30 ± 0.14[b]	98.77 ± 0.52[b]
25.30 ± 2.23	3.33 ± 0.85[b]	83.07 ± 4.31[b]
2.15 ± 0.80	0.38 ± 0.27[b]	81.20 ± 13.26
63.5 ± 3.90	4.02 ± 1.00[b]	93.37 ± 1.49
73.74 ± 1.93	4.02 ± 1.07[b]	94.58 ± 1.30[b]
...	3.41 ± 0.63	...

ground biomass. Some Ca was undoubtedly lost through particulate transport of ash, so it is probable that this correction yielded an overestimate of ash mass and hence a conservative estimate of nutrient loss from the site.

Nutrient pools

To determine nutrient loss and redistribution, we partitioned vegetation and soils into above- and belowground nutrient pools. The aboveground pools were partitioned in the same categories as total biomass. Ten random grab samples of each size class of woody debris and 12 randomly collected samples of litter and attached foliage were collected for laboratory analysis. Each sample consisted of a composited collection of material from a random transect bisecting the entire study area. Following fire, 10 ash samples were collected from each burn treatment for nutrient analysis.

To ascertain the effects of fire on soil nutrients, paired soil samples were collected before and after fire at 12 locations in each burn treatment. Sampling depths were 0–2 cm, 2–5 cm, and 5–10 cm. Samples were collected, air-dried, and ground to pass through a 2-mm mesh sieve. The bulk density for each depth was determined through collection of 5 cm in diameter volumetric cores. After drying at 100°C, the bulk density samples were passed through a 2-mm mesh sieve to remove stones. Bulk density, nutrient concentration, and soil nutrient pools are reported on a stone-free basis.

To describe the potential long-term influences of shifting cultivation on nutrient pools, we sampled an adjacent forest that had no prior history of cultivation. However, this forest had previously been exploited as a source of fuel wood. This site had been slashed one day before our sampling in preparation for cultivation. The prefire measurements for mass and nutrient concentrations in this stand were the same as those in the experimental burn plots, except that combustion and postfire measurements were not taken.

Laboratory analysis

All plant, soil, and ash samples were analyzed for total N, P, and C. The plant and ash samples were also measured for Ca. Prior to analysis, plant and ash samples were ground to pass through a 425-μm mesh screen in a Wiley mill. Total N was determined from Kjeldahl digestion (Bremner and Mulvaney 1982). Total C was analyzed by dry oxidation using a Leco furnace (Nelson and Sommers 1982). Total Ca was determined by atomic absorption. Total soil P was measured with the NaOH fusion method (Smith and Bain 1982). Total P in plant materials and ash was determined colorimetrically following wet digestion utilizing a Kjeldahl procedure.

Soil temperature maxima

Maximum temperatures of the litter layer and mineral soil were measured during fires with pyronometers similar to those described by Fenner and Bentley (1960). Temperature-sensitive paints with melting points of 38°, 59°, 104°, 204°, 316°, 538°, and 816°C were painted in thin lines along a 5 × 8 cm mica sheet. These were then stapled to a sheet of insulative material (Permafab) of the same size. Immediately prior to burning, 12 pyronometers per burn treatment were set in the soil so that 2 cm was above the soil surface while 6 cm was buried. After fire, the average belowground depth of melting for each paint line was determined. Temperature maxima at 1 and 2 cm aboveground were also recorded.

Climatic variables and fuel moisture contents

Immediately prior to burning, samples were collected to determine the moisture content of the soil surface (0–2 cm), attached foliage, 1-h time-lag fuels, and 100-h time-lag fuels. Twelve samples of each of these components were placed in airtight cans and immediately weighed to determine field masses. They were then oven-dried at 100°C for 24 h and reweighed. Moisture content is reported on a dry mass basis.

During each fire, temperature and relative humidity were measured with a sling psychrometer, and wind speed was measured with a hand-held anemometer. Flame lengths associated with the flame front were visually estimated at 18 points during each fire.

Statistical analysis

Our analysis consisted of using each transect or nutrient sample as an individual observation. Prefire/postfire differences within each slash burn were tested utilizing a paired t test. Statistical differences between the slash burns were examined through an analysis of variance in a completely randomized design. If significant ($P \leq .10$), the least significant difference (LSD) test was used to determine the statistical relationship between parameter means and the three treatments.

Because the slash burns were not replicated, we can only test for differences between the burn sites. Prior to burning, there were no significant differences between the three areas. Therefore, we concluded that any significant postfire differences were due to the fire effects.

RESULTS

Aboveground biomass

Slash biomass of this second-growth tropical dry forest was 74 Mg/ha prior to burning (Table 1). Wood debris in the 0.6–2.5 cm diameter and 2.5–7.6 cm diameter size classes accounted for the majority of the aboveground biomass (i.e., 32–36% and 25–34% of the total aboveground biomass, respectively). Large wood debris (≥7.6 cm in diameter) was not abundant (i.e., 2–9% of the aboveground total). The majority of the boles and stems that had attained this diameter at the time of slashing were removed prior to burning. Litter and foliage attached to wood debris comprised a relatively minor proportion of the aboveground biomass (≈5% and 8–10%, respectively).

The highest concentrations of N and P were in attached foliage (Table 2). Concentrations of these elements declined with increasing diameter of the woody debris. For example, the concentrations of N and P in attached foliage were approximately 6 times greater than for woody debris >2.5 cm in diameter. Calcium concentration was highest in surface litter (≈2%), and the concentration in attached foliage was similar to that of the small diameter (<2.5 cm) wood debris particles (1.2–1.4%). The concentration of C varied little and ranged from 46 to 48% for attached foliage and wood debris. In contrast, the concentration of C in litter was 37%.

Prior to burning, aboveground C pools were ≈33 Mg/ha (Table 3). Aboveground pools of N were 539–579 kg/ha (Table 4) and aboveground pools of P were 36–38 kg/ha (Table 5). Because of the higher concentrations of N and P in foliage, litter, and fine woody debris (<0.6 cm in diameter), their proportional nutrient mass was larger than their proportional total biomass. For example, while attached foliage comprised ≈8–10% of the total aboveground mass, it comprised 24–28% of the aboveground P pool. Approximately 57% of the aboveground P pool was in foliage, litter, and wood debris <0.6 cm in diameter. Similarly, ≈60% of the aboveground N pool was found in these fine-fuel classes. In contrast, aboveground C was similar in distribution to that of total aboveground biomass.

Belowground nutrient pools

Concentrations of soil nutrients were highest in the surface mineral soil layer (0–2 cm) and decreased with depth (Table 6). Prefire C concentrations ranged from 2.6 to 3.8% in the top 2 cm and from 1.4 to 2.1% at 5–10 cm depth. Total soil N concentrations at these same depths were 0.24–0.28% and 0.13–0.19%, respectively. Similarly, the concentration of total P was 0.026–0.037% at the 0–2 cm depth, and 0.020–0.032% at the 5–10 cm depth. Surface soils were not significantly different in N and P concentration from that of wood debris >2.54 cm in diameter. Concentrations of these larger fractions of wood debris were 0.331% for total N and 0.023% for P (Table 2).

The mean total prefire mass of soil C (0–10 cm depth) for the experimental area was 18 014 kg/ha (Table 6). The mass of soil N at 0–10 cm depth was 1577 kg/ha. Approximately 60% of the total soil C and N were in the top 5 cm. The mass of soil P was 223 kg/ha prior to burning. Approximately 54% was found in the upper 5 cm.

The total ecosystem C pool (i.e., soils and vegetation combined) ranged from 48 to 58 Mg/ha. Approximately 61–69% of the total pool was found in the aboveground mass (Tables 3 and 6). The combined mass of vegetation and soil N was 1905–2444 kg/ha. In contrast to C, aboveground N accounted for 22–28% of the total pool (Tables 4 and 6). The combined mass of P in soils and aboveground biomass ranged from 216 to 314 kg/ha. Aboveground P accounted for only 11–17% of the combined total (Tables 5 and 6).

Fire effects on aboveground biomass and nutrient stocks

All plots were cut and burned by local agriculturalists who utilized traditional methods—with the exception of the use of a drip torch for igniting the fires. Firing patterns were typical of those practiced in slash-and-burn agriculture of the area, except the use of a drop torch greatly reduced the time required to ignite the plots. All fires were ignited around midday (1100–1400).

TABLE 2. Concentration (%) of total carbon, nitrogen, phosphorus, and calcium in aboveground biomass of slashed tropical dry forest near Serra Talhada, Pernambuco, Brazil. Data are mean ± 1 SE. $N = 12$ for litter and foliage and $N = 10$ for wood debris.

Parameter	Carbon	Nitrogen	Phosphorus	Calcium
Litter	37.26 ± 1.85	1.667 ± 0.090	0.092 ± 0.005	1.98 ± 0.49
Attached foliage	46.89 ± 0.26	2.515 ± 0.060	0.141 ± 0.004	1.21 ± 0.10
Wood debris (diameter, cm)				
0–0.64	47.78 ± 0.35	0.903 ± 0.111	0.073 ± 0.003	1.35 ± 0.06
0.65–2.54	45.32 ± 0.27	0.514 ± 0.140	0.038 ± 0.003	1.16 ± 0.06
>2.55	45.90 ± 0.26	0.331 ± 0.338	0.023 ± 0.001	0.59 ± 0.06

TABLE 3. Total aboveground pools (Mg/ha) of carbon in slashed tropical dry forest plots before and after burning near Serra Talhada, Pernambuco, Brazil. Numbers are mean ± 1 SE. Data were derived through multiplication of the mass of each transect by the mean nutrient concentration. $N = 30$.*

	Slash burn 1 19 September 1989		Slash burn 2 26 September 1989		Slash burn 3 4 October 1989	
Parameter	Prefire	Postfire	Prefire	Postfire	Prefire	Postfire
Litter	1.49 ± 0.22	0.08 ± 0.06	1.39 ± 0.20	0.00 ± 0.00	1.33 ± 0.16	0.00 ± 0.00
Ash	···	1.52 ± 0.17	···	1.19 ± 0.15	···	0.86 ± 0.16
Foliage	2.88 ± 0.21	0.29 ± 0.10^{a}	3.58 ± 0.26	0.00 ± 0.00^{b}	3.13 ± 0.22	0.00 ± 0.00^{b}
Wood debris (diameter, cm)						
0–0.64	4.85 ± 0.35	0.48 ± 0.16^{a}	6.03 ± 0.44	0.001 ± 0.001^{b}	5.26 ± 0.37	0.001 ± 0.001^{b}
0.65–2.54	12.08 ± 1.20	1.71 ± 0.45^{a}	11.02 ± 0.97	0.21 ± 0.09^{b}	11.33 ± 0.88	0.14 ± 0.06^{b}
2.55–7.62	11.00 ± 3.22	4.57 ± 0.86^{a}	8.73 ± 1.32	2.21 ± 0.57^{b}	11.61 ± 1.02	1.53 ± 0.39^{b}
>7.62	1.29 ± 0.49	0.37 ± 0.24^{a}	3.06 ± 0.84	1.38 ± 0.53^{b}	0.99 ± 0.37	0.17 ± 0.12^{b}
Total aboveground	33.60 ± 4.19	9.03 ± 1.46^{a}	33.82 ± 2.09	5.01 ± 0.85^{b}	33.66 ± 1.94	2.71 ± 0.49^{b}
% loss of aboveground C		73.12 ± 4.72^{a}		85.11 ± 2.63^{b}		96.08 ± 1.60^{b}

* Different superscripted letters denote a significant difference ($P \leq .10$) in residual C biomass between the 3 experimental burns.

In these slash burns the entire perimeter was ignited, which resulted in the highest fire-line intensity near the plot center. Typically, flaming combustion lasted <30 min in all plots. Relative humidity, wind speed, and temperature were similar for all burns (Table 7). Flame lengths were not significantly different between the burns (i.e., a mean of 8.4–9.8 m). Flame lengths as great as 15 m were common during all fires.

Because there was no rainfall during the time period of this study, the moisture content of aboveground biomass remained stable or declined as the study progressed (Table 7). For example, the moisture content of wood debris 2.5–7.6 cm in diameter was 19.9% during the first slash burn and was 5.8% by the third burn. This represents an evaporative loss of 3.30 Mg/ha of water within this fuel category alone. Total water content of fuels in the three burns was 8.5, 7.2, and 4.3 Mg/ha, respectively.

Because the semiarid conditions in the northeast of Brazil result in relatively low fuel moisture contents, slash fires were very high in biomass consumption, and as moisture content declined, biomass consumption increased. Consumption of aboveground biomass within the three burns (i.e., the combustion factor) was 78, 88, and 95%, respectively (Table 1). Consumption of the litter layer was not significantly different among burns because nearly all litter was consumed (>95%). Biomass consumption of total wood debris and for all size classes except wood debris >7.6 cm in diameter was significantly greater in the second and third burns than the first burn (Table 1). Total consumption of wood debris was 72, 85, and 94%, respectively. While biomass consumption was high for all burns, there were significantly different quantities of uncombusted wood debris and ash remaining following fire. Postfire biomass of uncombusted wood debris was 15.6, 8.3, and

TABLE 4. Total aboveground pools of nitrogen (kg/ha) before and after fire in tropical dry forest slash near Serra Talhada, Pernambuco, Brazil. Numbers are mean ± 1 SE. Data were derived through multiplication of the mass of each transect by the mean nutrient concentration. $N = 30$.*

	Slash burn 1 19 September 1989		Slash burn 2 26 September 1989		Slash burn 3 4 October 1989	
Parameter	Prefire	Postfire	Prefire	Postfire	Prefire	Postfire
Litter	66.57 ± 8.76	3.76 ± 2.53	62.29 ± 9.10	0.00 ± 0.00	59.96 ± 7.16	0.00 ± 0.00
Ash	···	21.06 ± 2.57^{a}	···	20.19 ± 2.30^{a}	···	7.37 ± 1.51^{b}
Foliage	154.64 ± 11.18	15.37 ± 5.14^{a}	192.15 ± 14.20	0.05 ± 0.05^{b}	167.64 ± 11.79	0.05 ± 0.05^{b}
Wood debris (diameter, cm)						
0–0.64	91.75 ± 6.6	9.12 ± 3.05^{a}	114.01 ± 8.42	0.03 ± 0.03^{b}	99.46 ± 7.00	0.03 ± 0.03^{b}
0.65–2.54	136.99 ± 13.66	19.43 ± 5.14^{a}	125.03 ± 0.95	2.44 ± 1.04^{b}	128.58 ± 9.99	1.54 ± 0.73^{b}
2.55–7.62	79.41 ± 25.21	32.97 ± 6.18^{a}	62.98 ± 9.53	15.98 ± 4.11^{b}	83.80 ± 7.40	11.04 ± 2.80^{b}
>7.62	9.30 ± 3.59	2.70 ± 1.70^{a}	22.09 ± 6.07	9.98 ± 3.85^{b}	7.14 ± 2.66	1.26 ± 0.89^{b}
Total aboveground	538.67 ± 43.76	110.42 ± 17.52^{a}	578.56 ± 30.72	48.67 ± 6.20^{b}	546.69 ± 33.32	21.42 ± 3.85^{b}
% loss of aboveground N		79.30 ± 3.96^{a}		91.58 ± 1.62^{b}		96.11 ± 0.70^{b}

* Different superscripted letters denote a significant difference ($P \leq .10$) in residual N biomass between the 3 experimental burns.

TABLE 5. Total aboveground pools of phosphorus (kg/ha) before and after fire in tropical dry forest slash near Serra Talhada, Pernambuco, Brazil. Numbers are mean ± 1 SE. Data were derived through multiplication of the mass of each transect by the mean nutrient concentration. $N = 30$.*

	Slash burn 1 19 September 1989		Slash burn 2 26 September 1989		Slash burn 3 4 October 1989	
Parameter	Prefire	Postfire	Prefire	Postfire	Prefire	Postfire
Litter	3.68 ± 0.06	0.20 ± 0.02^a	3.44 ± 0.03	0.00 ± 0.00^b	3.30 ± 0.0008	0.00 ± 0.00^b
Ash	···	29.22 ± 7.04^a	···	15.24 ± 3.53^b	···	14.97 ± 4.52^b
Foliage	8.66 ± 0.63	0.87 ± 0.29^a	10.76 ± 0.00	0.0029 ± 0.0029^b	9.39 ± 0.66	0.0029 ± 0.0029^b
Wood debris (diameter, cm)						
0–0.64	7.42 ± 0.54	0.74 ± 0.25^a	9.23 ± 0.68	0.0025 ± 0.25^b	8.05 ± 0.57	0.0025 ± 0.0025^b
0.65–2.54	10.01 ± 1.00	1.42 ± 0.37^a	9.14 ± 0.80	0.18 ± 0.08^b	9.40 ± 0.73	0.11 ± 0.05^b
2.55–7.62	5.52 ± 1.61	2.29 ± 0.43^a	4.38 ± 0.66	1.11 ± 0.28^b	5.83 ± 0.51	0.77 ± 0.19^b
>7.62	0.64 ± 0.24	0.19 ± 0.11^a	1.53 ± 0.42	0.69 ± 0.26^b	0.49 ± 0.18	0.08 ± 0.06^b
Total aboveground	35.95 ± 3.02	34.73 ± 1.21^a	38.49 ± 2.08	17.23 ± 0.42^b	36.46 ± 2.01	15.94 ± 0.23^b
% loss of aboveground P		3.49 ± 4.08^a		55.24 ± 2.79^b		56.3 ± 0.85^b

* Different superscripted letters denote a significant difference ($P \leq .10$) in residual P biomass between the 3 experimental burns.

4.0 Mg/ha, respectively. Ash mass ranged from 3.4 to 4.2 Mg/ha.

The postfire aboveground nutrient pools were significantly different among the burned areas due to two fire-related phenomena. As expected, the higher biomass consumption lowered the mass of nutrients remaining in residual uncombusted organic debris. In addition, nutrient concentrations in ash also differed among treatments. The concentrations of N and C were significantly lower in the ash samples of the third burn treatment than the first or second burn treatment (Fig. 1). In addition, the concentration of P in ash of the first burn treatment was significantly higher than the other treatments. The concentration of Ca in ash increased significantly with increasing biomass consumption. Apparently fires of higher severity and biomass consumption not only resulted in lower quantities of N, P, and C present as uncombusted organic debris, but also in lower concentrations in the ash.

The relative amount of aboveground C lost through combustion was similar to the combustion factor for total biomass (i.e., 73, 85, and 96% of the C was lost during combustion processes for the three burns, respectively). The majority of residual C was in the form of uncombusted wood debris >2.55 cm in diameter (Table 2). The percentage of N loss was slightly higher than the combustion factors of the three burns (i.e., 79, 92, and 96% of the aboveground N was lost during combustion processes [Table 3]). The majority of residual aboveground N was also found in the larger wood debris. Approximately 27–41% of the postfire aboveground N was present in ash.

Losses and postfire redistribution of P were dramatically different from those of either C or N. Only a small percentage (3.5%) of the aboveground P pool was lost during combustion in the first burn (Table 4). However, ≈55% of the aboveground P was lost in the second and third burns. These differences are largely the result of the differences in P concentration in ash. The concentration of P in ash in the first burn treatment was 0.757% and ≤0.465% in the other treatments (Fig. 1). Apparently, fires in the later two burn treatments

TABLE 6. Percentage concentration and mass of carbon, nitrogen, and phosphorus in soils before and after burning tropical dry forest slash near Serra Talhada, Pernambuco, Brazil. Numbers are mean ± 1 SE. Data represent the combined results of the three slash burns. $N = 36$ per depth before and after burning.

Soil depth (cm)	Carbon		Nitrogen		Phosphorus	
	Prefire	Postfire	Prefire	Postfire	Prefire	Postfire
			Concentration (%)			
0–2	3.064 ± 0.257	3.375 ± 0.193	0.265 ± 0.014	0.259 ± 0.009	0.030 ± 0.002	0.034 ± 0.001
2–5	2.374 ± 0.161	2.487 ± 0.0126	0.207 ± 0.011	0.222 ± 0.008	0.028 ± 0.002	0.031 ± 0.002
5–10	1.750 ± 0.143	1.737 ± 0.190	0.158 ± 0.009	0.169 ± 0.007	0.026 ± 0.002	0.029 ± 0.003
			Mass (kg/ha)			
0–2	5117.0 ± 428.8	5536.8 ± 322.6	443.2 ± 23.9	432.8 ± 15.5	50.3 ± 4.1	56.6 ± 2.4
2–5	5983.7 ± 406.8	6266.4 ± 317.4	521.5 ± 27.4	558.2 ± 19.3	71.6 ± 5.8	77.0 ± 5.4
5–10	6913.6 ± 564.7	6862.5 ± 750.2	625.1 ± 34.4	668.6 ± 29.4	100.8 ± 9.3	116.5 ± 10.3
Total	18,014.3 ± 1275.6	18,765.7 ± 980.9	1576.9 ± 80.5	1,646.9 ± 54.3	222.7 ± 18.7	250.1 ± 17.2

TABLE 7. General weather data, fuel moisture at the time of burning, and the flame length of the fire front during fires in tropical dry forest slash near Serra Talhada, Pernambuco, Brazil. Numbers are mean ± 1 SE.

	Slash burn 1 19 September 1989	Slash burn 2 26 September 1989	Slash burn 3 4 October 1989
Relative humidity (%)	33	31	35
Temperature (°C)	32	34	32
Wind spread (km/h)	0–3	5–10	0–13
Moisture content (%)*			
Soil surface	1.3 ± 0.2^{a}	0.7 ± 0.1	0.5 ± 0.1
Attached foliage	5.8 ± 0.3^{a}	4.9 ± 0.5	4.5 ± 0.5
Wood 0–0.64 cm diameter	7.1 ± 0.2	7.7 ± 0.3	6.2 ± 0.4^{a}
Wood 2.54–7.6 cm diameter	19.9 ± 4.5^{a}	14.9 ± 3.2^{ab}	5.8 ± 0.9^{b}
Flame length (m)	8.4 ± 1.0	10.4 ± 1.0	9.8 ± 0.8

* Different superscripted letters denote a significant difference ($P \leq .10$) in fuel moisture content between treatments.

resulted in greater quantities of P volatilization than the first treatment. Unlike C or N, the vast majority of postfire aboveground P was in the ash (>84%), a pool highly susceptible to site loss through wind or water erosion.

Fire effects on belowground stocks of C, N, and P

There were few differences in temperature maxima aboveground; all had peak temperatures >800°C at the soil surface or 1–2 cm above the soil surface. Temperatures of 316°C were measured at a soil depth of ≈1 cm for all three burn treatments. However, with increasing biomass consumption, higher peak temperatures were measured at deeper soil depths. For example, a mean peak soil temperature of 59°C was recorded at a soil depth of 5–6 cm for the later two burn treatments. In contrast, peak temperatures of 59°C were found at 4 cm in the first burn treatment, with a negligible heat flux below this depth.

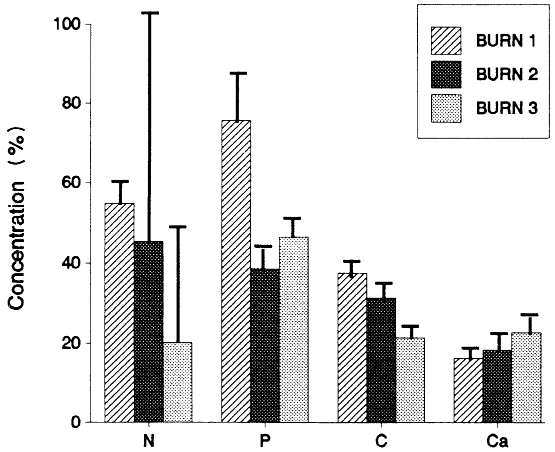

FIG. 1. Concentration of nitrogen, phosphorus, carbon, and calcium in ash following fires in slashed tropical dry forest near Serra Talhada, Pernambuco, Brazil (means and 1 SE). Concentrations of C and Ca are reported in percent, whereas the concentrations of N and P are reported as the percentage multiplied by 100.

Data on soil nutrients from all three treatments were combined because fires did not result in measurable or significant losses in soil nutrients (Table 6). In addition, soil C-to-N ratios were not significantly different before or after burning. In contrast, we found slight increases in nutrient concentration and mass following fire. Given the relatively high levels of heat flux into the surface layer (0–2 cm), we expected some loss of soil N. However, these data report nutrient concentrations only in soils and cannot account for exchanges between belowground organic debris and mineral soils as a result of combustion, other heat effects (i.e., other oxidative processes), or a downward flux of volatilized organic compounds that condensed on cooler soil layers. The slight increases in nutrients are not due to ash contamination because we were careful to completely remove all ash from sites when postfire soils were collected.

DISCUSSION

Fire effects on aboveground biomass and nutrient pools

The structure and mass of the aboveground vegetation of the Caatinga are similar to that reported for other tropical deciduous forests (Murphy and Lugo 1986, Singh and Singh 1991*a*). Globally, Murphy and Lugo (1986) reported that aboveground biomass of tropical dry forest (TDF) ranges from 30 to 273 Mg/ha. In a TDF in India, aboveground biomass was similar to that in the present study (i.e., a range of 42–78 Mg/ha; Singh and Singh 1991*a*). Previous studies of TDF have not partitioned aboveground biomass and nutrient pools into classes based upon their susceptibility to combustion or influences on fire behavior. Our approach facilitates an increased understanding of the location and potential susceptibility of nutrient losses by slash burning. As in most forests, the highest nutrient concentrations were located in foliage, litter, and fine woody debris (Buschbacher et al. 1988, Singh 1989, Singh and Singh 1991*b*). While these components accounted for <30% of total aboveground biomass, they accounted for 60% of the aboveground pools of N and P. It is these finer fractions of aboveground biomass that are the fuels primarily responsible for sustained combustion and fire spread (Rothermel 1972, Andrews 1986). As such, virtually all of these are consumed by fire; the combustion factors of these fine-fuel classes exceeded 85% in the first burn and 99% in the second and third burns.

In comparison to slashed tropical moist forest, the biomass of this forest was significantly lower in the amount of coarse woody debris—the woody material that is least susceptible to complete combustion during slash fires. While coarse wood debris comprised <10% of the aboveground biomass in this study, Uhl and Kauffman (1990) reported that coarse wood debris comprised 77% of the aboveground mass in a logged forest of the eastern Amazon. In another Amazonian tropical moist forest, Ward et al. (*in press*) reported a fire in slashed primary forest consumed 45% of the coarse woody debris and a fire in a slashed, 15-yr-old second-growth forest consumed 30% of the coarse woody debris. Total biomass consumption by these fires was 53 and 33%, respectively, as compared to 78–95% for the fires of this study. Therefore, in comparison to slash fires in more mesic tropical forests, total nutrient losses may be relatively higher in TDF because of an inherently greater susceptibility to higher levels of biomass consumption.

Although biomass consumption was relatively high in all burns, 16.4 Mg/ha of wood debris remained on site following the first slash burn. If left in place, this would represent a significant proportion of the residual aboveground nutrient pool. However, the agriculturalists who prepared the study site for cropping stated that there was an excessive quantity of wood debris remaining following the first slash burn that would require some removal prior to cultivation. Therefore, the remaining residual wood debris (and hence residual aboveground nutrient stocks) following the second and third burns was likely most representative of actual postfire conditions for this region.

The three major sources of nutrient loss associated with slash-and-burn activities include prefire wood export, atmospheric losses during combustion, and postfire erosion or leaching losses. An estimated 12.4 Mg/ha of wood was exported prior to burning. Because the wood removed consisted of large stems, it contained the lowest concentrations of N and P, and hence nutrient losses from these removals are relatively small in comparison to combustion losses. As much as 96% of the aboveground N pool and 56% of the aboveground P pool were lost during combustion. Additionally, 27–41% of the residual (postfire) aboveground N and 84% of the residual aboveground P were located in the ash component. We resampled the depth and mass of ash in the first burn 17 d after burning and found that 57% of the ash had disappeared, primarily as a result of wind erosion. This accounted for an additional site loss of 16.7 kg/ha, or 48% of the postfire aboveground P pool. Given the high combustion factors, the removal of residual wood debris by agriculturalists, and large losses of ash due to wind erosion, it is likely that nearly all nutrients held in aboveground biomass are lost through slash-and-burn activities.

With increasing levels of biomass consumption, we found not only declines in nutrient stocks associated with residual wood debris, but also differences in the elemental concentrations of ash. With increasing biomass consumption, we found decreases in the concentration of C, N, and P and increases in Ca (Fig. 1). We attribute this pattern to increases in volatilization (i.e., nonparticulate) losses of C, N, and P. Raison et al. (1985) reported nonparticulate losses of P were reflected in the Ca-to-P ratio in ash (i.e., increases in the Ca-to-P ratios in ash reflect greater losses through volatilization). Volatilization of N commences at 200°C and volatilization of some forms of organic P may occur at 300°C (Raison et al. 1985, Walker et al. 1986). In contrast, volatilization of Ca is likely to be negligible in slash fires because the volatilization temperature of Ca exceeds 1200–1400°C. The Ca-to-P ratio in ash was 21.7, 47.5, and 48.9 for the first, second, and third burn, respectively (Fig. 2), suggesting increasing losses in P due to volatilization. Nonparticulate losses of P are significant, and very important because these materials are likely to be permanently lost from burn sites (Raison et al. 1985).

Fire effects on belowground nutrient pools

Few differences were measured in belowground nutrient concentrations or mass following fires (Tables 5–7). This is surprising because mean temperatures at soil depths of 1–2 cm were 315°C. These temperatures should result in the volatilization of N and P and certainly alter forms of N (e.g., ammonium concentration increases when soil temperature is at 100°C; Russell et al. 1974). When soils were heated to a temperature of 460°C in a laboratory, Giovannini et al. (1990) reported dehydroxylization of clay particles, with concomitant decreases in the cation exchange capacity and concentrations of N and Ca. In contrast, we observed slight increases in soil N following fires in all treatments (Table 6). Debano et al. (1976) and Mroz et al. (1980) also reported increases in total soil N following fires. They suggested that increases in N concentration resulted from downward diffusion of vaporized organic compounds and ammonium-rich nitrogenous compounds. It is possible that this phenomenon, or oxidation of N from roots into the soil matrix, may have masked volatilization losses. Additionally, we did not measure soil bulk density after fire. Only prefire bulk density estimates were utilized for both preburn and postburn samples. If fires resulted in a decreased bulk density through losses in the organic matter content and/or decreases in clay and silt fractions through dehydroxylization, then our postfire estimates of soil nu-

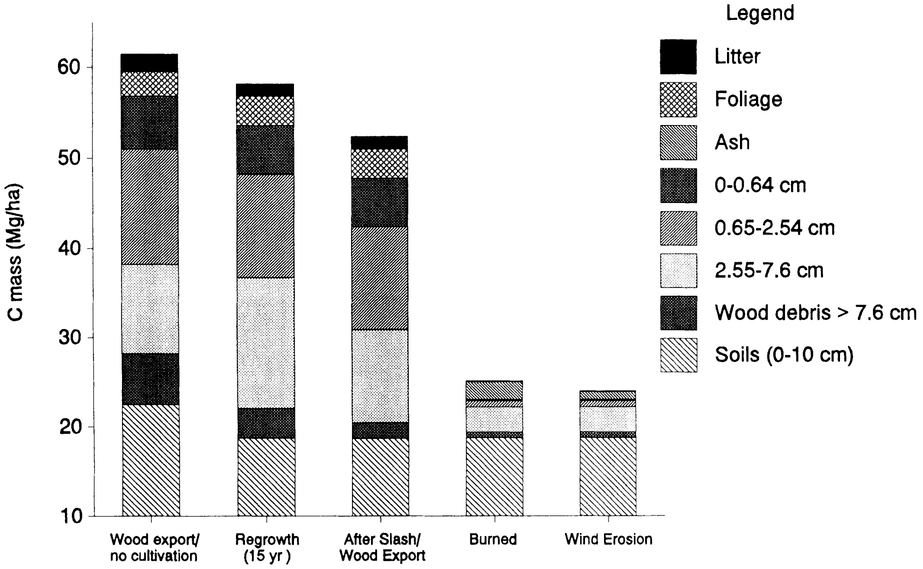

FIG. 2. Total carbon pools of tropical dry forest along an anthropogenic disturbance gradient associated with wood export and shifting cultivation near Serra Talhada, Pernambuco, Brazil. "Wood export/no cultivation" represents a primary forest that had no recorded history of cultivation yet had received some degree of perturbation through selective wood harvest. "Regrowth" forest represents the total aboveground biomass of a second-growth forest just prior to the return of a cropping period. "After slash/wood export" represents the biomass of slash after an area has been slashed and wood for building and charcoal has been removed. "Burned" represents the mass immediately following fire. These are the postburn means of treatments 1–3. "Wind erosion" represents the total 17 d after burning, a period when an estimated 57% of the ash had been lost from the site.

trient mass are too high. Additional investigations are warranted to quantify nutrient fluxes into soils, the potential nutrient exchange between roots and soils, and changes in physical properties as a result of soil heating.

Fire effects on long-term site productivity

Shifting cultivation results in dramatic declines in aboveground biomass, at least during the cropping phases. Additional losses of nutrients through erosion and leaching in cultivated slash-and-burn tropical dry forest can be severe. For example, Maass et al. (1988) reported erosional N losses of 187 kg/ha and P losses of 27 kg/ha the first year following the deforestation of a Mexican TDF. The lowered level of aboveground biomass during cultivation and early fallow phases will also result in declines in organic inputs into the soils via litterfall and a probable decline in the pool of mineralizable C and N (Brown and Lugo 1982). In the present study, mean C pools were 58 Mg/ha prior to slashing. The C in the wood that was exported prior to burning was 6 Mg/ha, fires volatilized a mean of 24–32 Mg/ha, and an additional 1 Mg/ha was immediately lost through wind erosion (Fig. 2). Comparison of C pools in second growth to that of an adjacent forest with no history of cultivation indicates that soil C was not replenished during the fallow period (Fig. 2). The concentration and mass of soil C at the 0–10 cm depth was significantly lower in the 15-yr-old second-growth forest than in that of the undisturbed forest (means of 22.5 Mg/ha and 18.7 Mg/ha for the primary and second-growth forest, respectively). The uncultivated site had been used as a source of fuel wood and, as a result, the aboveground C stocks were not different from those of the second-growth forests. These data indicate a similar pattern of C accumulation to that reported by Brown and Lugo (1990) for Puerto Rican TDF where 40–50 yr of fallow may be required for replenishment of soil C. However, in this region of Brazil, fallow periods are currently 15 yr or less.

Volatilization losses of P were as high as 21 kg/ha in our study. From a long-term site productivity perspective this is especially important because if natural rates of P replacement (dry fall and precipitation inputs) are as low as 0.2 $\mathrm{kg \cdot ha \cdot yr^{-1}}$ (Murphy and Lugo 1986), it could take well over a century to replenish the quantity of P lost by combustion alone. Losses associated with erosion, leaching, or human export would result in additional depletions of the P pool.

The potential declines of ecosystem P as a result of shifting cultivation were reflected through comparison of the second-growth plots and the adjacent primary forest. The concentration and mass of soil P were significantly higher in the adjacent primary forest than in the fallow second-growth forest (e.g., at the 0–2 cm depth soil P concentration was 0.030% in the second growth and 0.048% in the primary forest). Total soil

P mass was 351 kg/ha in the uncultivated primary forest and 223 kg/ha in the second-growth forest.

Our research has focused on those soil and organic components that are directly affected by combustion processes in tropical dry forests. Root biomass and soils deeper than 10 cm were not examined. Root mass in tropical dry forest may represent 8–50% of the total biomass in this ecosystem (Murphy and Lugo 1986). Additionally, the depth of soils in this forest ranged from 50 to 80 cm. These are additional locales of significant nutrient pools that undoubtedly are affected by shifting cultivation. In order to fully understand ecosystem-level effects of shifting cultivation, additional investigations to quantify the response of these nutrient pools are warranted.

CONCLUSION

Significant quantities of C, N, and P were lost as a consequence of the anthropogenic activities associated with shifting cultivation in the TDF of northeast Brazil. A single slash-burning appears to have negative impacts on the long-term site productivity. Total P loss through combustion and wind erosion was as high as 36 kg/ha. This quantity accounted for ≈17–20% of the pool consisting of aboveground biomass and soils 0–10 cm. Further losses in P were evident in the significant and important differences in the P content of primary forest and second-growth forest soils (i.e., 351 and 223 kg/ha, respectively). Site productivity can be maintained if anthropogenic disturbances that result in nutrient loss are balanced with the natural rates of nutrient inputs. However, this is a highly unlikely scenario considering current rates of human population expansion and exploitation of TDF. It is clear that the nutrient balance of these ecosystems is not maintained by shifting cultivation under a rotation period of 15–20 yr. Given the magnitude of these nutrient losses, coupled with increasing human pressures, it is likely that declines in long-term site productivity—including declines in crop yields, forest regrowth, carbon storage, and biological diversity—will occur.

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