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Effects of high- and low-intensity fires on soil properties and plant growth in a Bolivian dry forest

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Abstract

We compared soil nutrient availability and soil physical properties among four treatments (high-intensity fire, low-intensity fire, plant removal, and harvesting gap) and a control (intact forest understory) over a period of 18 months in a tropical dry forest in Bolivia. The effect of treatments on plant growth was tested using a shade intolerant tree species (*Anadenanthera colubrina* Vell. Conc.) as a bioassay. Surface soils in high-intensity fire treatments had significantly greater pH values, concentrations of extractable calcium (Ca), potassium (K), magnesium (Mg), and phosphorus (P), and amounts of resin-available P and nitrogen (N) than other treatments; however, a loss of soil organic matter during high-intensity fires likely resulted in increased bulk density and strength, and decreased water infiltration rates. Low intensity fires also significantly increased soil pH, concentrations of extractable Ca, K, Mg, and P, and amounts of resin-available P and N, although to a lesser degree than high-intensity fires. Low-intensity fires did not lower soil organic matter contents or alter soil physical properties. Plant removal and harvesting gap treatments had little effect on soil chemical and physical properties. Despite the potentially negative effects of degraded soil structure on plant growth, growth of *A. colubrina* seedlings were greater following high-intensity fires. Evidently, the increase in nutrient availability caused by high-intensity fires was not offset by degraded soil structure in its effects on seedling growth. Long-term effects of high intensity fires require further research.

Introduction

Prescribed burns produce several effects that are beneficial for the regeneration of shade-intolerant tree species, including vegetation removal, mineral soil exposure, and nutrient release (Bond and van Wilgen, 1996; Hungerford et al., 1990). Yet, the effects of prescribed burns on above- and below-ground processes vary widely, depending largely on the intensity of the fire (Bond and van Wilgen, 1996; Moreno and Oechel, 1994). While most studies of low to moderately intense fires report increases in available nutrients (DeBano et al., 1977; reviews by Dunn et al., 1977; Ewel et al., 1981; Humphreys and Craig, 1981; Hungerford et al., 1990; Neary et al., 1999; Wells et al., 1979; Wright and Bailey, 1982), intense fires may cause a net loss of nutrients from the forest system through volatilization, ash transport, and run-off (DeBano et al., 1977; Giovannini et al., 1990). Intense burns may also alter soil structure and texture (Dyrness and Youngberg, 1957; Ulery and Graham, 1993) resulting in increased soil bulk density (DeByle, 1981), and reduced soil porosity, water infiltration rates, and water holding capacity (Wells et al., 1979).

The changes in chemical and physical soil properties caused by fire may have important consequences for growth of tree seedlings. Increased nutrient availability after fire may benefit plant growth if nutrients are limiting prior to burning (Hungerford et al., 1990). On the other hand, seedling growth in intensely burned soils may be slowed due to high pH and toxic levels of minerals (Giovannini et al., 1990). Altered soil physical properties, such as soil strength, bulk density, and water infiltration rates, may also impair plant growth.

Table 2. Results of ANOVAs of soil nutrients, organic matter, water content, and soil pH in the 8–20 cm depth of soil of four gap treatments and forest plots at 3 times following burns. All variables were log transformed. Where a significant time × treatment interaction was found, variables were analyzed separately by month. Treatments with different letters are significantly different at $P<0.05$

No interaction time × treatment				Post-hoc test results					
Variable	Factor	*F*	*P*	Month	High	Low	Removal	Control	Forest
Phosphorus	Treatment	105.4	<0.001	9	a	b	bc	bc	bc
	Time	59.4	<0.001	12	a	b	bc	bc	bc
				18	a	b	b	b	b
Magnesium	Treatment	2.1	0.09	9					
	Time	7.3	0.001	12					
				18					
Calcium	Treatment	10.5	<0.001	9	a	b	b	b	b
	Time	4.7	0.013	12	a	ab	b	b	b
				18	a	b	ab	b	b
Water content	Treatment	5.6	0.001	9	a	a	a	a	b
	Time	51.2	<0.001	12					
				18	ab	ab	a	ab	b
pH	Treatment	70.9	<0.001	9	a	b	bc	c	bc
	Time	58.9	<0.001	12	a	b	c	c	c
				18	a	b	c	c	c

Significant time × treatment interaction				Post-hoc test results				
Variable	Month	*F*	*P*	High	Low	Removal	Control	Rorest
Potassium	9	34.6	<0.001	a	b	c	bc	bc
	12	17.5	<0.001	a	b	b	b	b
	18	9.5	<0.001	a	b	b	b	ab
Organic matter	9	1.7	0.16					
	12	2.7	<0.001	a	ab	ab	b	ab
	18	11.3	<0.001	b	b	a	c	c

surface soils. Low-intensity fires also significantly increased P, Mg, K, and Ca in the top 8 cm of soil, although increases were smaller than in high-intensity fire plots, did not persist as long, and were not detected at 8–20 cm. Plant removal and gap control treatments had no detectable effect on P, Mg, K, and Ca at either soil depth.

Both high- and low-intensity fires significantly increased resin-available NH_4^+-N (F = 58.7, P = <0.001), NO_3^--N (F = 6.3, P = 0.001), and PO_4^{-3}-P (F = 12.2, P = <0.001) during the first rainy season following burns (Fig. 2). Other than an increase in NO_3^--N in plant removal treatments during the first rainy season, the remaining treatments had little effect on NH_4^+-N, NO_3^--N, and PO_4^{-3}-P availability.

Soil pH after high-intensity fires at 0–8 and 8–20 cm was greater than in all other treatments throughout the 18-month sampling period (Fig. 3 and Tables 1 and 2). After low-intensity fires, soil pH was greater than in the remaining treatments at both depths at all sampling periods. The plant removal and gap control treatments had little effect on soil pH.

High-intensity fires significantly lowered soil organic matter content in surface soils; 2 months following after fires soil organic matter in the top 8 cm of soil was approximately 72% that of forest soils (Fig. 3 and Tables 1 and 2). After 18 months, soil organic matter recovered to concentrations comparable to the remaining treatments. Differences among the remaining treatments were small and varied throughout the sampling periods. Total soil N was strongly related to soil carbon (R^2= 0.93); thus, we expect patterns of total N differences among treatments to follow those for soil organic matter.

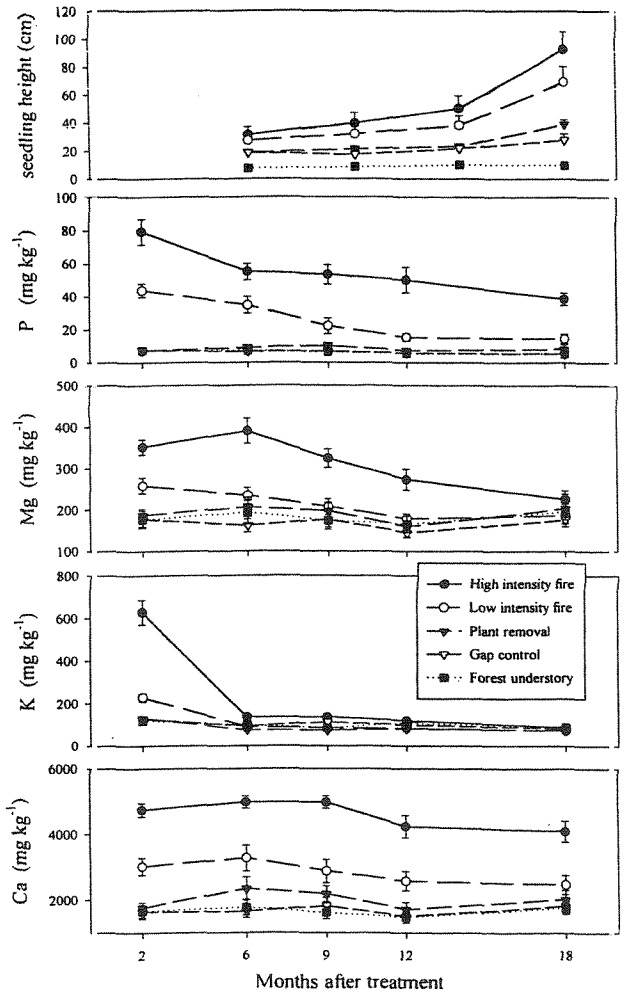

Figure 1. Seedling heights of *Anadenanthera colubrina*, and Mehlich-I extractable soil concentrations of P, Mg, Ca, and K in soil samples (0–8 cm depth) in four treatments and understory forest sites at five sampling times over an 18-month period following fires (bars = S.E., n=16).

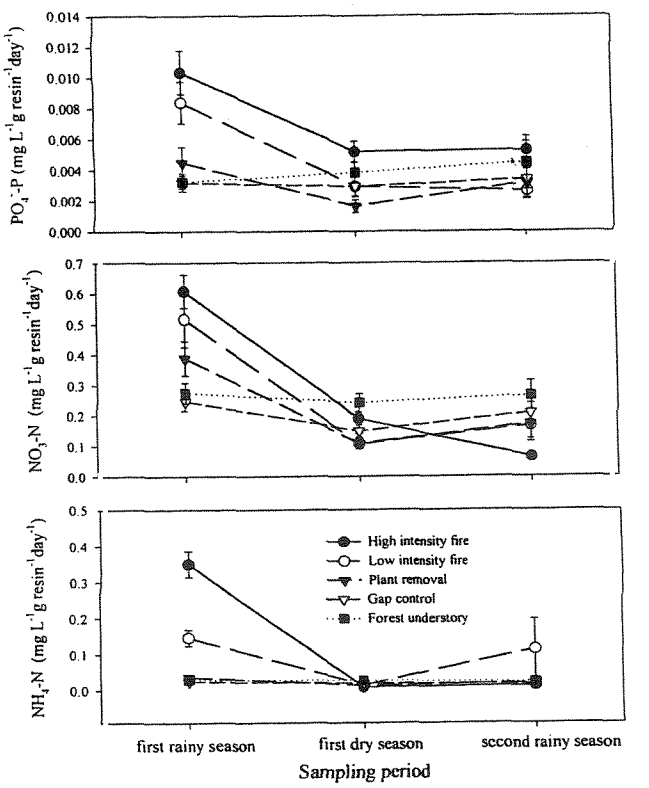

Figure 2. Resin-available ammonium, nitrate, and phosphate in four treatments and understory forest sites determined from exchange resins buried in soil at 5 cm depth during three periods following fires (bars = S.E., n=16). Resins were buried for approximately 3 months during each period. Time since fires of sampling periods were: first rainy season (2–5 months), first dry season (8–11 months), and second rainy season (15–18 months).

Although significant differences in soil water content were detected among treatments, differences were not large and patterns were not consistent over the sampling period (Fig. 3 and Tables 1 and 2). The forest understory plots had the lowest soil water content during the first 9 months, but this difference disappeared after 12 months. Larger differences in soil water content were due to seasonal changes.

Soil strength after high-intensity fires, initially the lowest among treatments, increased sharply during the first year (Fig. 3, Table 1). Water infiltration rates were significantly lower after high-intensity fires than other treatments ($F = 31$, $P < 0.001$; Fig. 4). Bulk density after high-intensity fires was significantly greater than in forest plots after 6 and 12 months ($F = 3.1$, $P = 0.02$, $n = 10$). There were no significant differences among the remaining treatments.

Treatment effects on seedling height

Seedlings in high- and low-intensity fire treatments were significantly taller than seedlings in the gap control or forest understory; seedling height in the plant removal treatment was intermediate ($F = 15.4$, $P < 0.001$, Fig. 1).

Discussion

Effects of high-intensity fire on soil properties

High intensity fires caused significant changes in both soil chemical and physical properties; increases in available nutrients were coupled with losses of soil organic matter, total soil nitrogen, and altered soil structure.

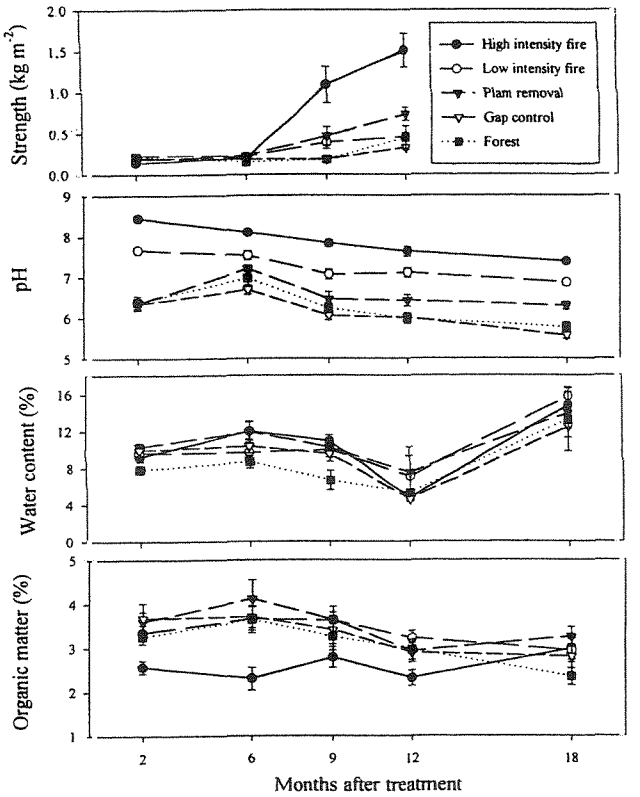

Figure 3. Soil pH, air-dry water content, and organic matter content measured in soil (0–8 cm depth) in the four treatments and understory forest sites at five sampling times over an 18-month period following burns. Soil strength was measured at the soil surface with a soil penetrometer at four sampling periods over a 12-month period following burns. Water content is expressed as percent of air-dry weight (bars = S.E., n=16).

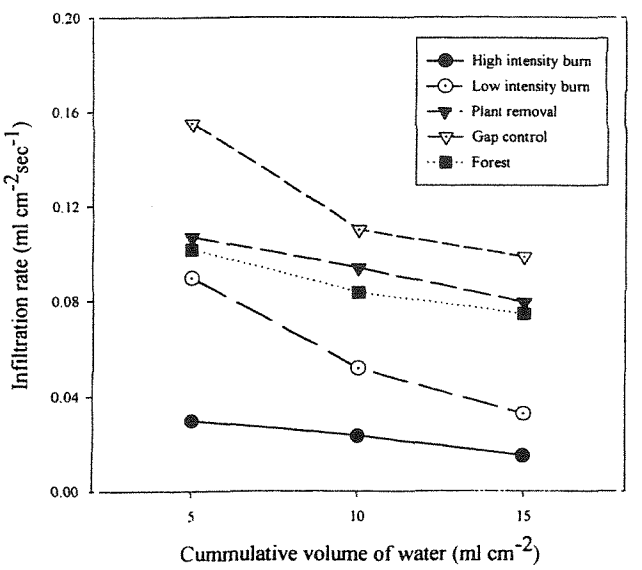

Figure 4. Water infiltration rates of soil in four treatments and forest understory sites. Infiltration was measured as the time required for the first 5 ml of a 10-ml column of water to infiltrate soil (n=4).

The large amount of ash deposited following high-intensity fires was likely the major contributor of increased soil pH and increased soil concentrations of extractable Ca, K, Mg and P. We estimated the masses of cations and P deposited in ash to be: 524 g/m^2 of Ca, 83 g/m^2 of K, 26 g/m^2 of Mg, and 7.7 g/m^2 of P. Soil heating may also have increased extractable Ca, K, Mg, and P through mineralization of organic forms (Giovannini et al., 1990), however this pathway was likely less important than contributions from ash. Inorganic P additions in ash were also likely the largest cause of increases in resin-available PO_4^{-3}-P. Rice (1993) found that soil PO_4^{-3}-P concentrations in Californian chaparral following fire were correlated with ash depth rather than fire intensity.

Increased resin-available nitrogen (NH_4^+-N and NO_3^--N) after high-intensity fires is attributed to the mineralization of organic forms of nitrogen found in soil organic matter and unburned slash fragments. Due to nitrogen's low temperature of volatilization (200°C; Weast, 1988), its concentration in ash was likely negligible. Increased NH_4^+-N following fires was probably enhanced by soil microbial death, which occurs at temperatures as low as 50–121°C (Neary et al., 1999). Similarly, Matson et al. (1987) attributed increases in net nitrogen mineralization to microbial death following slash and burn on volcanic soils in Costa Rica. Increased NO_3^--N concentrations were likely caused by increased nitrification rates following fires. Fire generally creates favorable conditions for nitrification by raising pH values and base saturation (Pritchett and Fisher, 1987). Both Matson et al. (1987) and Montagnini and Buschbacher (1989) attributed increased nitrate concentrations to enhanced nitrification rates following slash and burn in Costa Rica and Venezuela, respectively.

An important feature of the increase in resource availability produced by fire is the transient nature of the increases. Within 8 months of fires (after the first rainy season), inorganic N declined to levels found in adjacent forest. Decreases in cation concentrations over the 18-month post-fire period correspond with their mobility and susceptibility to leaching (K>Mg>Ca).

The net loss of soil organic matter caused by high-intensity fires was predictable based on the high soil temperatures measured during fires. Soil organic matter loss is a direct effect of soil heating; distillation of volatile organic compounds occurs between soil temperatures of 100–300°C and near complete loss of soil organic matter at temperatures >450°C (Giovannini

et al., 1990; Hosking, 1938). Decreases in soil organic matter are often reported following the intense fires typical of slash burning in the tropics (Rab, 1996; Mackensen et al., 1996; Uhl and Jordan, 1984). The recovery of soil organic matter during the second year following fires may have been due to decomposition of fine roots and litter from colonizing vegetation, although the rate of recovery is notably high and faster than anticipated.

Due to its low temperature of volatilization, patterns of total soil N loss is closely linked to the consumption of soil organic matter; thus, we expect the loss of total soil N during high-intensity fires approximates the loss of soil organic matter (~loss of 28%). Decreases in total soil N are reported following slash burning in the tropics (Costa Rica: Ewel et al., 1981; Venezuelan Amazon: Uhl and Jordan, 1984).

The decrease in soil organic matter caused by high-intensity fires likely influenced the substantial changes in soil strength, bulk density, and water infiltration rates. The increase in surface soil strength during the first year following high-intensity fires was likely due to the settling of soil minerals and ash into spaces left void by organic matter and fine roots. This settling of soil particles would also contribute to greater soil bulk densities. Decreased macro-pore space would explain the lower infiltration rates observed in this treatment.

It was expected that high-intensity fires would result in lower soil water contents than other gap treatments. Decreased soil organic matter content lowers soil water holding capacity, decreased albedo due to a blackened soil surface plus exposure can increase water evaporation from soil, and slowed infiltration rates can increase surface run-off. In this study however, soil water contents were not significantly lower after high-intensity fires than other treatments. The predicted changes may have been offset by reduced transpiration in high-intensity burn plots, where total vegetative cover recovered more slowly than in other treatments (Kennard, 2000). Also, the lowered infiltration rates after high-intensity fires likely did not result in surface runoff: the lowest infiltration rate recorded in a high-intensity burn plot was 5 times faster than the rate needed to absorb a 5 cm h^{-1} rainfall (0.002 cm^3 cm^{-2} s^{-1}).

Effects of low-intensity fires on soil chemical and physical properties

We attribute the increases in soil pH, and extractable P, Ca, Mg, and K concentrations after low-intensity fires to the release of these basic cations from soil organic matter during soil heating, as very little ash was deposited during this treatment. Low-intensity fires increased resin-available N levels, although to a lesser degree than high-intensity fires. Temperate zone studies have noted that soil inorganic N increases as fire intensity increases from low to moderate levels (Dunn and DeBano, 1977; Giovannini et al., 1990; Kutiel et al., 1990; McMurtrie and Dewar, 1997; Rice, 1993; Weston and Attiwill, 1996).

Average surface temperatures during low-intensity fires (160°C) were not high enough for the consumption of soil organic matter, as reflected by organic matter contents of soil sampled from this treatment. In fact, average soil organic matter contents after low-intensity fires were greater than those of adjacent forest soils. Increases in soil organic matter have been shown to occur during light to moderate fires due to the incorporation of unburned or partially burned slash fragments into soil (Hungerford et al., 1990; Stromgaard 1992).

Soil strength, bulk density, water infiltration, and water repellency following low-intensity fires were not different from those in unburned treatments. Again, this pattern may reflect the influence of organic matter on soil physical characteristics.

Effects of plant removal and canopy gap formation on soil chemical and physical properties

Soil moisture content was greater in all of the gap treatments than forest plots for the first 9 months following fires. This difference, likely due to decreased transpiration (Vitousek and Denslow, 1986), diminished over the first year as the amount of vegetation in gaps increased.

Other than the observed differences in soil moisture contents, plant removal and gap treatments did not significantly change soil chemical or physical properties from those in adjacent intact forest. Although it is hypothesized that the increased soil temperatures, moisture, and litter depth in tree fall gaps will increase nutrient availability (Bazzaz, 1980), conclusive evidence to suggest this is true has not been reported (Luizao et al., 1998; Vitousek and Denslow, 1986).

Most of the variation observed within the plant removal, gap control, and forest plots over time was due to seasonal changes. Soil moisture content varied predictably with changes in rainfall and NO_3^- availability declined slightly during the dry season. This observation agrees with the few studies of nutrient

cycling conducted in tropical dry forests which have shown that nitrification rates are highest during the rainy season and lowest at the end of the dry season (Garcia-Mendez et al., 1991; Singh et al., 1989; see also Smith et al., 1998).

Effects of treatments on tree seedling growth

Despite the potentially negative effects of increased bulk density and soil strength, lowered water infiltration rates, and possibly toxic effects of cations on plant growth, seedling heights of *A. colubrina* were greatest following high-intensity fires. This increased growth in intensely burned soils may be due to several factors. Initially, soil strength in high-intensity fire plots was the lowest of all treatments, therefore early colonizing seedlings should not have experienced mechanical impedance of root growth. Secondly, nutrient concentrations were highest following high-intensity fires, which may have offset decreased movement of nutrients in water through the soil. Also, toxic levels of cations may only have been a factor in small areas of high ash deposition or severely scorched soils; seedlings may not have been able to establish in these small areas and, therefore, the effects on growth were not observed. Most importantly, the density of plants colonizing after high-intensity fires was low, so that established tree seedlings likely benefited from reduced competition for soil water and nutrients.

Although seedlings that established soon after fires benefited from greater resource availability, the effects of high-intensity fires on tree seedling growth may not be as beneficial in subsequent years. Due to the decrease in nutrient availability during the first year following burns, seedlings establishing in following years may show the effects of degraded soil structure. As soil structure can take years to decades to recover, prescribed burns of low to medium intensity, which can increase nutrient availability without damaging soil, may be the best option in the long term.

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