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SHORT COMMUNICATION

Ground fires as agents of mortality in a Central Amazonian forest

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Although undisturbed tropical evergreen forests are often thought to be fire-resistant ecosystems due to lack of sufficiently dry fuel loads (Bond & van Wilgen 1996, Kauffman *et al*. 1988, Uhl *et al*. 1988), this myth is rapidly collapsing with the proliferation of recent forest fires throughout south-east Asia (Kinnard & O'Brien 1998, Leighton & Wirawan 1986), Central America (Anon. 1998*a*), and northern South America (Anon. 1998*b*) following unusually severe seasonal droughts. While crown fires consuming the canopy of tropical evergreen forest have received much publicity and leave visible landscape scars that can be easily resolved by conventional satellite imagery, those restricted to the forest floor often remain undetected even though they have affected far greater expanses of Amazonian forests in recent years (Alencar *et al*. 1997, Nepstad *et al*. 1997). Here I report the levels of plant mortality caused by a typical ground fire in a previously unburned primary forest of central Amazonia. I provide an estimate of the aboveground dry biomass resulting from this fire which will eventually become available as additional fuel load thus increasing the severity of future forest fires. These results suggest that, where conditions are appropriate, there is a considerable risk of a spiraling feed-back process in which recurrent El Niño dry seasons could trigger the conversion of large areas of evergreen Amazonian forest into structurally simplified scrub forests of considerably reduced value both in terms of species diversity and key ecosystem services, such as carbon storage and water cycling (Fearnside 1997*a*).

Tropical forest wildfires restricted to the understorey are likely to become a widespread and repeated phenomenon in perhaps 10–20% of Amazonia. As much as 10 000 km^2 y^{-1} of Amazonian forests may have been affected by ground fires in recent years (Alencar *et al*. 1997), and some 400 000 km^2 of Brazilian Amazonian forest could become moderately to highly susceptible to fires by the end of the next dry season (Nepstad *et al*. 1998). Yet little is known about how these fires could trigger large-scale changes in ecosystem structure and function (but see Cochrane & Schulze 1998). Such surface fires leave the forest canopy relatively intact, are relatively inconspicuous to conventional deforestation mapping exercises, and are thus generally considered to be relatively benign compared to crown fires. For example, estimates of undisturbed forest cover in the region of Paragominas, eastern Amazonia, declined from 65% to 6% once selectively logged and burned areas – identified on the basis of a ground survey – were excluded from the primary forest cover mapped on the basis of Landsat TM images (Alencar *et al*. 1997). I therefore selected a previously unburned primary forest of central Brazilian Amazonia that had been recently affected by an unprecedented ground fire, and asked what proportion of the vegetation succumbs to fire-induced mortality, subsequently becoming available as dry fuel for future forest fires.

Fieldwork was carried out within two 0.5-ha (10-m × 500-m) forest plots located 800 m apart and 3.5 km from Vila São Pedro, a village on the Arapiuns River, a tributary of the lower Tapajós River, westernmost Pará, Brazil (2° 34′ 53″ S, 55° 27′ 28″ W). The survey took place in January 1998, 45–50 d after a single but widespread accidental wildfire had swept through the study plots leaving an area of at least 400 km^2 of forests with a conspicuously scorched understorey. An intentional fire set to a small slash-and-burn plot occurring in the area was identified as the source of ignition. Prior to this wildfire, these plots had consisted of relatively undisturbed upland (terra firme) forest; selective logging had not taken place although there had been a history of game hunting and small-scale extraction of other non-timber forest products. Average annual rainfall at the nearest meteorological station (Santarém) is 2041 mm y^{-1} (range = 1287–2538 mm y^{-1}, 1992–1997: INFRAERO 1998), with a strongly demarcated dry season typically lasting 3–5 mo. The recent Arapiuns wildfires occurred in November–December 1997 at the end of the longest dry season in living memory, following a rainless period of at least 110 d linked to the 1997/98 El Ninõ/Southern Oscillation (ENSO) event. The two forest plots were dominated by podzolic soils of low water retention capacity, which are typical of the region's wider forest landscape burned by this unprecedented ground fire.

I recorded the DBH (diameter at breast height) and determined the survival status of plants with at least 0.5 cm DBH and 1.5 m in height including a sample of 1614 seedlings, saplings, poles and trees. All trees ⩾10 cm DBH were measured and inspected, but smaller plants were not exhaustively sampled. With the help of two local field assistants, it was possible to determine whether or not each stem had succumbed to fire-induced mortality on the basis of detailed bark and leaf inspections. Mortality in small plants was defined as the death of all aboveground tissue, but trees >10 cm DBH were considered to be dead or dying depending on visible cambial damage to the basal tree trunk, and the drying and abscission of most leaves. Estimates of aboveground dry biomass (AGDB) were simply based on conversions of DBH measurements using an allometric equation derived from 319 trees, ranging from 5 to 120 cm DBH, which were destructively sampled at a structurally similar terra firme forest north of Manaus, Brazil (Santos 1996). Because the species identity of most tree species could not be determined, it was not possible to use wood density correction factors in estimating AGDB, although this may be a key factor in converting volume data to biomass (Fearnside 1997*b*).

The Arapiuns ground fire visibly scorched all live vegetation from the leaf litter to a height of at most 2.5 m, and consumed all available fuel on the forest floor including the leaf-litter, the root mat, and most fine and coarse woody material. Only two small patches of unburned leaf-litter, with a combined area of less than 4 m^2, remained in the 10 000 m^2 sampled. A total of 52.5% of all 1614 plants inspected died during or soon into the aftermath of the ground fire, which acted as a highly selective mortality agent killing the vast majority of shrubs, seedlings, saplings and small trees, but sparing most large trees (Figure 1a). Mortality was highest for saplings of up to 2 cm DBH (89.1%) and lowest for trees ⩾40 cm DBH (8.2%). The total dead biomass which will eventually result from this fire is estimated at 43.3 t ha^{-1}, or 8.3% of the AGDB of all plants in both plots. Because AGDB increases exponentially with tree size, most of the residual dead biomass is accounted for by trees ⩾10 cm DBH (Figure 1b), even though as many as 78.9% (n = 631) of these may have survived the fire. This is a conservative estimate of mortality and AGDB, however, as many large trees surviving the fire in the short-term may have been lethally stressed by high temperatures, dying only several months thereafter (Holdsworth & Uhl 1997). Moreover, woody lianas and vines, which were common in this forest and had been heavily damaged by the fire, are not considered here. Finally, preliminary results indicate that the soil seedbank underneath the evenly burned organic horizon appeared to have been largely destroyed throughout both plots. Future forest regeneration may thus depend primarily on subsequent seed crops of plants surviving the fire, or on recolonisation by seeds dispersed from adjacent unburned forest tens to hundreds of kilometres away.

Short-term effects of this ground fire on forest wildlife appeared to have been equally disastrous. Several signs of direct casualties were observed in the forest plots, including skulls and other skeletal remains of marmosets (*Callithrix h. humeralifer*), common sloths (*Bradypus variegatus*), royal sloths (*Choloepus didactylus*), and beaks of a large toucan (*Ramphastos cuvieri*) and a lettered aracari (*Pteroglossus inscriptus*). Most noticeable was the absence of

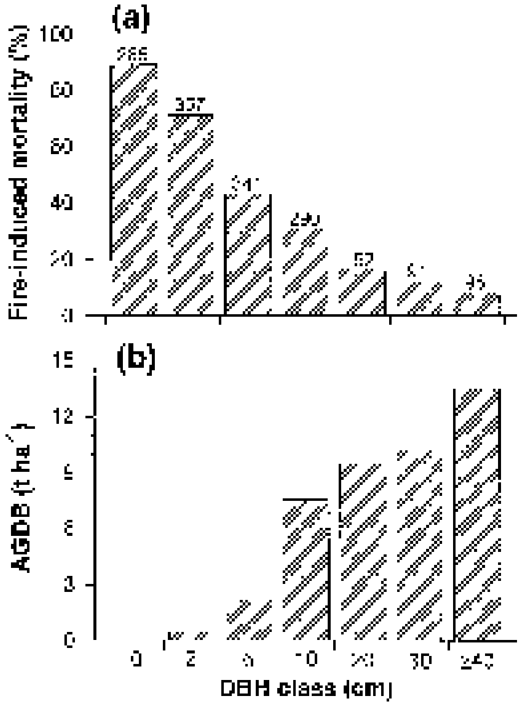

Figure 1. Plant mortality and dry biomass induced by a ground fire at two 0.5-ha forest plots sampled near the Arapiuns River, western Pará, Brazilian Amazonia. (a) Percentage of dead stems in seven DBH size classes. Largest size class represents all trees 40–130 cm DBH. Sample sizes are indicated above each bar. (b) Estimates of aboveground dry biomass (AGDB, t ha^{-1}) which could become available for forest fires during the subsequent El Ninõ dry season.

much of the understorey avifauna within the conspicuously silent burned forest, even during peak diurnal periods of vocal activity, compared to an unburned forest near Cachoeira do Maró, some 35 km upriver of Vila São Pedro. Although the fires clearly destroyed much of the foraging substrate (and prey items) for understorey insectivores, many bird populations were directly affected by the ground fires succumbing to smoke asphyxiation which probably took place over several days, since fires were reduced in intensity but were not extinguished during the cooler night periods (C. Aldo, *pers. comm.*). In addition, fires severely reduced food supplies for vertebrate frugivores because most of the maturing fruit crops from both small and large tree crowns were clearly destroyed or aborted in the aftermath of the fire (C. Peres, *pers. obs.*), apparently as a sublethal response to heat stress. Finally, there was unanimous consensus amongst villagers at São Pedro that ground fires left few unburned natural refuges in the forest understorey, rendering forest wildlife more vulnerable to subsistence hunters who have become increasingly desperate for alternative sources of protein, as fire-induced damage to food crops around villages was very considerable.

The ubiquitous occurrence of tropical forest fires has been recently demonstrated during the severe 1997/1998 El Niño event which disrupted rainfall patterns throughout the tropics, resulting in some of the most prolonged dry seasons in recorded history (Trenberth & Hoar 1996). Indeed an insidious and alarming climate-induced change in forest flammability now appears to be a widespread pantropical phenomenon in many lowland rain forest areas that were previously considered to be immune to fires. Similar El Niño events are expected to provide the conditions upon which relative humidity drops and fuel loads dry below the flammability threshold of closed-canopy forests (Holdsworth & Uhl 1997, Uhl *et al.* 1988, Uhl & Kauffman 1990). Forests previously affected by ground fires are thus likely to burn again in future El Niño years, provided that ignition sources continue to become available at the end of severe dry seasons, particularly if currently lacking effective fire suppression practices are not implemented. Fire intensity and flame residence time in previously burned forests are, however, expected to increase substantially during subsequent fire events because of the greatly enhanced AGDB resulting from the high volume of standing dead trunks and fallen branches and leaf litter that are likely to become available as combustible fine fuel for future fires (cf. Cochrane & Schulze 1998; C. Peres, J. Barlow & T. Haugaasen, unpubl. data). Other contributing factors are expected to enhance the intensity of future fires the second and third time around, which may no longer be restricted to the forest understorey. These include greater canopy openness resulting from the large proportion of dead canopy trees, which is expected to significantly change the understorey microclimate, and greater fuel continuity between the forest understorey and the canopy provided by dead lianas, standing dead trees and other residual dry woody biomass.

Of particular importance, understorey forest disturbance generated by selective timber extraction, which increases the amount and continuity of fuel loads, is not always a necessary precondition for the development of uncontrolled ground fires during El Niño years, as has often been implied. As opposed to pre-Colombian wildfires, which are thought to be associated with drier climates and scrub savannas (Turcq *et al.* 1998), contemporary fires are often viewed as a result of human disturbance that converts non-flammable undisturbed forest into flammable selectively logged and secondary forests (Holdsworth & Uhl 1997, Uhl & Buschbacher 1985, Uhl & Kauffman 1990). Although forest disturbance aggravates forest flammability, the forest plots studied here had not been selectively logged, and ground fires in the area rapidly became widespread, gaining catastrophic proportions despite relentless efforts by the local communities to control their propagation. This may also be the case of other areas dominated by sandy soils which are highly permeable and thus have a low water retention capacity. Indeed forests resting on sandy soils are relatively common in Brazilian Amazonia, and have become particularly susceptible to wildfires (Negreiros & Nepstad 1994, Nepstad *et al.* 1994).

Despite the long and repeated history of forest fires in the Amazon basin over the last 7000 y (Sanford *et al*. 1985, Turcq *et al*. 1998), the current pace of ecosystem changes mediated by both ground and canopy fires does not bode well for the future of the region's biodiversity. Much of the Amazonian forest flora and fauna appears to be extremely sensitive to fires (Uhl & Kauffman 1990; C. Peres, unpubl. data), which can be understood given the rarity of these events in both space and time. Yet ground fires are rapidly becoming a common occurrence in vast areas of both disturbed and undisturbed Amazonian forests. Understanding their impact on plant community structure and dynamics is critical for predicting changes in the biological diversity, forest biogeochemical cycles and hydrology of these ecosystems.

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