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IDEAS AND PERSPECTIVES

Large tree mortality and the decline of forest biomass following Amazonian wildfires

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Abstract

Surface fires in Amazonian forests could contribute as much as 5% of annual carbon emissions from all anthropogenic sources during severe El Niño years. However, these estimates are based on short-term figures of post-burn tree mortality, when large thicker barked trees (representing a disproportionate amount of the forest biomass) appear to resist the fires. On the basis of a longer term study, we report that the mortality of large trees increased markedly between 1 and 3 years, more than doubling current estimates of biomass loss and committed carbon emissions from low-intensity fires in tropical forests.

Keywords
Brazil, carbon emissions, El Niño, forest fire, tropical forest.

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During severe El Niño events, low-intensity ground fires in Amazonian forests could contribute as much as 5% of annual carbon emissions from all anthropogenic sources (Nepstad *et al.* 1999). However, considerable uncertainty still surrounds this estimate, because the total extent of surface fire coverage remains poorly known, and all estimates of post-burn tree mortality to date have been based on relatively short-term studies (≤ 2 years), during which large, thicker-barked trees appear to survive (Holdsworth & Uhl 1997; Cochrane *et al.* 1999; Barlow *et al.* 2002). Here we address this latter uncertainty, and report that the mortality of large trees, representing the majority of forest biomass (Clark & Clark 1996), increases markedly as little as 3 years post-burn. This additional mortality could double current estimates of biomass loss and committed carbon emissions resulting from low-intensity wildfires in Amazonian forests.

To quantify the temporal sequence of tree mortality in once-burned forest, we inspected all standing woody stems ≥ 10 cm diameter (measured at breast height or above the tallest buttress, d.b.h. hereafter) within seven 0.25 ha (10 × 250 m) plots spaced across 32 km^2 of *terra firme* forest in the Central Brazilian Amazon (see Barlow *et al.* 2002 for details on the study area and plot locations). These burned plots had been subjected to a low-intensity surface fire (only 34% of stems ≥ 10 cm were charred 30 cm above ground level) during the 1997–98 El Niño-mediated drought. Plots were censused both 1 year and 3 years after the fire, and trees were scored as dead if they presented a complete ring of dead cambium at breast height. Tree and liana diameters were converted to above-ground dry biomass using established equations (Putz 1983; Santos 1996).

In order to quantify the biomass loss associated with this increase in mortality, live biomass estimates in burned forest were compared with those in six 0.25 ha plots located across the fire-line within unburned forest. The underlying assumption that burned and unburned plots were similar before the fires was tested by comparing the number of standing stems (alive and dead) 1 year post-burn, before many dead trees in the burned forest had fallen over. In all comparisons, the stem densities and d.b.h. distributions of unburned and 1-year post-burn forests were statistically indistinguishable (standing stem densities: mean ± SE, burned forest = 136.2 ± 5.9; unburned forest = 138.7 ± 3.2; $t = 0.3$, $P = 0.8$; d.b.h. distributions: Kolmogorov–Smirnov $Z = 0.6$, $P = 0.8$). Plots were also similar floristically: trees from the families Burseraceae, Sapotaceae and Caesalpiniaceae accounted for > 28% of all measured stems in every plot, and the rank abundance of families in burned and unburned forest was highly correlated ($n = 42$, $r_s = 0.79$). Furthermore, as only minimal temporal change was detected in these control plots (live biomass = 380 Mg ha^{-1} and 381 Mg ha^{-1} 1 year and 3 years post-burn; Stems density per plot = 130.8 and 130.5 1 year and 3 years post-burn, respectively), mortality in the burned forest is most parsimoniously attributed to the effects of fire rather than to the associated ENSO-induced drought (Laurance *et al.* 2001).

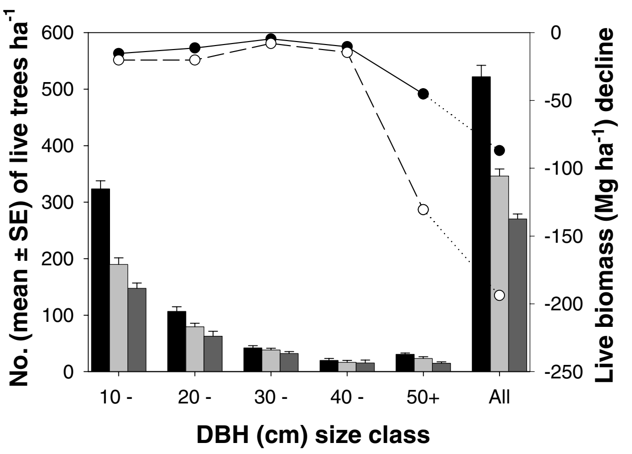

Figure 1 Mean number of live trees per plot in unburned forest ■, burned forest sampled 1 year after the fire □, and burned forest sampled 3 years after the fire ▨. Lines show the reduction of live above-ground biomass in each size class after 1 year (solid circles) and 3 years (open circles).

Patterns of stem mortality detected after 1 year were very similar to those reported up to 2 years after low-intensity surface fires in previous studies (Holdsworth & Uhl 1997; Cochrane & Schulze 1999; Cochrane *et al.* 1999), with smaller stems suffering the highest mortality and larger, thicker-barked trees tending to survive (Barlow *et al.* 2002). However, there was significant additional tree mortality between 1 and 3 years that reduced live tree density by a further 74 trees ha^{-1}, with large trees (≥ 50 cm d.b.h) showing the greatest decrease in abundance relative to their 1 year post-burn levels (36%; Fig. 1). Whilst temporal increases in tree mortality up to 2 years have been previously reported (Holdsworth & Uhl 1997; Cochrane *et al.* 1999), the increase in mortality of larger stems that we detected 3 years post-burn has not.

As most of the 1 year post-burn tree mortality occurred in the smaller d.b.h. classes, biomass in the burned forest declined less than live stem density (23% and 34%, respectively). However, after 3 years post-burn, the live stem density was just 52% of that found in the unburned forest, and live biomass had declined by an additional 107 Mg ha^{-1}, to just 49% of that found in the unburned forest. The delayed mortality of stems ≥ 50 cm d.b.h. accounted for 67% of this decrease in live biomass (Fig. 1). The biomass levels recorded in these 13 forest plots were confirmed as being representative of this region by comparing live biomass levels with a further 15 once-burned and 10 unburned plots sampled 3 years post-burn and located up to 40 km from the original study location (mean ± SE live biomass per plot in: six unburned forest plots = 95.4 ± 7.9; mean in 10 other unburned plots = 91.0 ± 7.0, $Z = 0.4$, $P = 0.7$; mean in seven burned plots = 46.8 ± 6.4; mean in 15 other burned plots = 54.0 ± 5.4, $Z = 0.9$, $P = 0.4$).

If our findings are characteristic of other burned areas in the Brazilian Amazon, committed carbon emissions from relatively conservative scenarios of fire incidence during severe El Niño events (Nepstad *et al.* 1999) could be equivalent to 10–12.5% of annual global carbon emissions from fossil fuels, even without further mortality or the considerable threat of recurrent burns (Cochrane *et al.* 1999). However, it should be emphasized that data are only available for three regions of Brazilian Amazonia, and that the potential processes leading to the delayed mortality of larger trees (such as reduced resistance to pathogens, increased water stress, vulnerability to wind throw, or simply an allometric relationship between tree size and the onset of death) are poorly understood. Levels of uncertainty therefore remain high, and our results highlight the need for more long-term monitoring to examine both the causes of post-fire tree mortality, and the temporal dimension of mortality beyond 3 years post-burn. What is clear is that surface wildfires in humid tropical forests can make substantial contributions to atmospheric CO_2 concentrations, a fact that will take on further significance should severe El Niño events become increasingly more frequent in the future (Timmermann *et al.* 1999).

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