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Contrasting fire damage and fire susceptibility between seasonally flooded forest and upland forest in the Central Amazon using portable profiling LiDAR

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ABSTRACT

Fire is an increasingly important agent of forest degradation in the Amazon, but little attention has been given to the susceptibility of seasonally flooded forests to fire. Satellite images suggest that forests flooded seasonally by nutrient-poor black waters are more susceptible to fire and may suffer greater fire damage than nearby upland forests. Reasons for this difference may include the presence of a root mat, more fine fuel as litter and a drier understory in the flooded forest. We investigated this difference in the field, hypothesizing that differences in the aboveground structure of the pre-burn forest can contribute to the difference in impacts of, and susceptibility to, fires. We employed a portable profiling LiDAR (PPL), first to compare damage between adjacent black water seasonally flooded and upland forests that were burned by the same fire event, and to then assess pre-fire canopy structure attributes known to affect fire susceptibility. For both assessments, we used PPL-derived metrics of leaf area and vertical and horizontal variation in the structure of vegetation in the canopy. Four years after the fire, the LiDAR metrics showed greater combined effects of high damage and slow recovery in the seasonally flooded forest; reduction of total Leaf Area Index (LAI) after burning was only 10% for upland forest but was 71% in the flood forest. Compared to unburned upland, the canopy of unburned flood forest had structural differences that increase susceptibility to fire, including drier microclimate. It had more gaps, a more open understory and a lower upper canopy. Small patches lacking canopy closure (LAI < 1.0) were far more abundant in the unburned flood forest. We conclude that black water seasonally flooded forest suffers greater fire damage than upland forest and canopy structure contributes to its greater susceptibility to the occurrence of fires. This must be considered in assessments of future Amazon fire risks and impacts, including flood forest acting as a potential conduit for spreading fire to upland forest.

1. Introduction

Tall and dense mature forests of Amazon upland (*terra firme*) are resistant to drought and to the penetration of surface fire. Deep shade of the understory, with few gaps, maintains high relative humidity, reducing the possibility of fire ignition (Ray, Nepstad, & Moutinho, 2005; Uhl, Kauffman, & Cummings, 1988), while rapid decomposition of litter keeps fine fuel stock low (Martius, Höfer, Garcia, Römbke, & Hanagarth, 2004). In contrast, Amazon upland forests that have suffered structural damage by mechanized logging and/or by a recent fire are vulnerable to recurring fire (Cochrane et al., 1999; Nepstad et al., 2001), especially in drought years (Alencar, Asner, Knapp, & Zarin, 2011). Logging and prior fire disturbance increase coarse and fine fuel loads on the ground and open large sunlit gaps, leading to hotter temperatures and lower relative humidity (Holdsworth & Uhl, 1997; Ray et al., 2005). When the understory relative humidity is <65%, litter layer fine fuel becomes vulnerable to ignition (Uhl et al., 1988).

Forests flooded annually by nutrient-poor acid black waters (*igapó*) suffer much greater post-fire impact than do upland forests (Flores, Piedade, & Nelson, 2012; Nelson, 2001). The difference in fire damage between these two widespread (Melack & Hess, 2010) Amazon forest types has, however, only recently been compared under identical recent precipitation history and similar proximity to ignition sources (Resende, Nelson, Flores, & Almeida, 2014). Very low tree growth and recruitment rates in black water flood forests (Junk et al., 2011) delay post-fire

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succession. Black water flood forests burned in 1926 and 1997 remained dominated by open non-woody vegetation in 2010 (Ritter, Andretti, & Nelson, 2012; Williams et al., 2005).

When compared in the dry season to nearby upland forest, the black water flood forest has a greater accumulation of fine combustible leaf litter above the ground and a thicker mat of combustible fine tree roots, just below the litter and above the mineral soil. Both are a consequence of slow leaf decomposition under water (Dos Santos & Nelson, 2013; Kauffmann, Uhl, & Cummings, 1988). During the late dry season, the now exposed litter and fine root mat of the black water flood forest become dry and flammable after just nine days without rain (Uhl et al., 1988). Furthermore, black water flood forests appear to have more open space in their canopy and understory, which would permit greater airflow. Together with the greater fine fuel and higher ignition risk environments of black water flood forest during dry conditions, this may increase the probability of fire spread relative to adjacent upland forest. Once a fire has initiated in flood forest, local residents report that a low intensity smoldering ground fire, similar to a peat fire, burns the root mat and causes high tree mortality.

As an indicator of susceptibility to fire establishment, Resende et al. (2014) compared the microclimate near the litter layer in unburned black water flood forest, at low water stage in the late dry season, to the litter layer microclimate in adjacent unburned upland forest. They found lower extremes of relative humidity and higher temperature extremes in the flood forest. They then compared post-fire damage between the two forest types, taking advantage of a natural experiment: the same fire event penetrating both forest types. Comparing replicate unburned and burned plots of each forest type, post-fire losses of basal area and stem density were highest in the seasonally flooded forest. However, forest structure attributes known to affect fire susceptibility were not measured or compared between the two pre-burn forest types.

Lower canopy height, lower leaf area index (LAI) and more canopy gaps are three canopy structure attributes known to increase the probability of ground fire establishment. Ray et al. (2005) have shown that, when controlling for recent rainfall history and for the microclimate and the wind velocity outside of different upland forests, the understory relative humidity decreases and fire spread rate increases with lower canopy height and lower LAI. Daytime relative humidity near the litter layer is lower in gaps where sunlight penetrates to ground level (Holdsworth & Uhl, 1997) and low humidity is a strong predictor of fire spread rate (Ray et al., 2005).

Here we expand on the work of Resende et al. (2014), using new data for the burned and unburned black water flood and upland forest plots of that Central Amazon study. Aboveground structural attributes were measured with a portable profiling LiDAR (PPL) (Parker, Harding, & Berger, 2004; Stark et al., 2012). These were compared between burned flood and upland forest plots to assess damage differences, and then compared between unburned plots of both types for the canopy attributes known to increase fire susceptibility. We examine three hypotheses:

(1) Fire impacts are higher in black water flood forests. Pre- to post-fire change in canopy height, canopy openness and LAI will reveal greater aboveground structural damage in the flood forest;
(2) Compared to unburned upland forest, unburned black water flood forest will have structural differences previously shown to increase susceptibility to fire establishment and spread. These include lower canopy height, higher gap fraction and lower LAI;
(3) We also hypothesized that PPL metrics may provide useful predictions of indicators commonly used to quantify fire damage severity: basal area (BA) and stem density (SD) loss. This hypothesis was motivated by prior foundational studies showing potential relations between PPL and forest parameters (Parker et al., 2004; Stark et al., 2015) and successful predictions for biomass growth (Stark et al., 2012).

2. Material and methods

2.1. Field site

Fire scars are common in the forests of the floodplain of the Rio Negro, the world's largest black water river, but few sites present a natural experiment where nearby upland and seasonally flooded forests were impacted by the same fire. We used a time series of Landsat Thematic Mapper satellite images to identify a field site 100 km south of Manaus (Figs. S1, S7), centered at 03°43′ S and 60°14′ W, where these two forest types were intercalated and burned only once, in November of 2009, during an El Niño-related drought. A burn severity map of the study region, based on pre- to post-fire change in the Normalized Burn Ratio (delta-NBR), suggested differential damage in the two forests types when exposed to the same fire event (Fig. S1). For reasons described in Supplementary Text 1, it is clear that forest damage at our site was caused by the 2009 fire and not directly by drought, nor by the record low water levels of 2010 (Marengo, Tomasella, Alves, Soares, & Rodriguez, 2011). Among these is the fact that forest damage occurred on only one side of the line of maximum fire advance (Fig. S1a) and that the post-burn image for the fire damage map (Fig. S1b), was from a date well before the extreme low water levels of 2010.

We distributed ten burned and ten unburned plots of each forest type, seasonally flooded and upland, on opposing sides of the line of maximum fire advance (Figs. S1, S2, S8 and S9). Each of the 40 plots was 0.5 ha in area, 250 m long by 20 m wide. We spread plots evenly on the unburned side of the fire line. On the burned side, plots were spread over a similar area and evenly within two groups, due to landholder permissions. Black water flood forest here is dry in the late dry season to early rainy season, from October to January. Seasonally flooded forest is restricted to the upper half of the annual flood range, which conveniently minimized the effect of inundation duration on forest structure and composition across all flood forest plots. More site details are provided by Resende et al. (2014).

Conventional inventories provided the basal area and the stem density per plot for all trees over 10 cm diameter at breast height (DBH). These were conducted 3–4 years after the fire. This was sufficient time for delayed fire-related tree mortality to more fully accrue (Barlow, Peres, Lagan, & Haugaasen, 2003), but insufficient time for post-fire regrowth to reach the minimum DBH of 10 cm. Two-dimensional LiDAR profiles of the canopy were collected along the center line of each plot in a single month, November 2013, to avoid any seasonal changes in leaf amount (Haugaasen & Peres, 2005). From these profiles we extracted structural metrics to compare the forest types, related to fire damage and to fire susceptibility. The forest canopy is here defined as all vegetation >1 m above the ground, which is the height of the instrument.

2.2. LiDAR data collection and analysis

The canopy profiling system employs a range-finder type laser, model LD90-3100VHS-FLP manufactured by Riegl (Horn, Austria). Laser wavelength is 900 nm, strongly reflected by vegetation. The distance measurement accuracy is ±25 mm and the nominal range is 200 m without a target plate. The instrument is held in a portable gimbaled structure that maintains vertical aim. A small 12 v battery and a water-resistant computer complete the PPL system (Fig. S3). The operator walks at a constant pace along the plot center line, controlling his speed with the aid of an electronic metronome and markers spaced every two meters. Each of 2000 pulses per second is recorded in an alternating sequence as either a height to the first (1000 pulses) or last (1000 pulses) reflecting object or as a non-returning "sky shot". The latter is useful to measure canopy openness. Raw pulse returns can be plotted as a side-view profile of 250 m length, with sky shots coded as zero height (Fig. S4).

The lidar beam has an oval footprint that, in push broom fashion, samples about 4% of each 1 m deep (across-track) voxel at 5 m height