

MICROMETEOROLOGICAL AND CANOPY CONTROLS OF FIRE SUSCEPTIBILITY IN A FORESTED AMAZON LANDSCAPE

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Abstract. Fire is playing an increasing role in shaping the structure, composition, and function of vast areas of moist tropical forest. Within the Brazilian Amazon, cattle ranching and swidden agriculture provide abundant sources of ignition to forests that become susceptible to fire through selective logging, severe drought and, perhaps, fragmentation. Our understanding of the biophysical factors that control fire spread through Amazon forests remains largely anecdotal, however, restricting our ability to model the Amazon fire regime, and to simulate the effects of trends in climate and land-use activities on future regimes. We used experimental fires together with measurements of micrometeorology (rainfall, vapor pressure deficit [VPD], wind velocity), canopy attributes (leaf area index [LAI], canopy height), and fuel characteristics (litter moisture content [LMC] and mass) to identify the variables most closely associated with fire susceptibility in the east-central Amazon. Fire spread rates (FSR, m/min) were measured in three common forest types: an 8-yr-old regrowth forest, a recently logged/burned forest, and a mature forest. One hundred fires were set in each study area during the last two months of the 2002 dry season. VPD, recent precipitation history, wind velocity, and LAI explained 57% of the variability in FSR. In combination, LAI, canopy height, and recent precipitation history accounted for ~65% of the variability in VPD, the single most important predictor of FSR, and approximately half of the total observed variability in FSR. Using logistic regression we were able to predict whether a fire would spread or die 72% of the time based on LAI, canopy height, and recent precipitation history. An approximate threshold in fire susceptibility was associated with a LMC of ~23%, somewhat higher than previously reported (15%). Fire susceptibility was highest under low, sparse canopies, which permitted greater coupling of relatively hot, dry air above the canopy with the otherwise cool, moist air near the forest floor. Fire susceptibility increased over time after rain events as the forest floor gradually dried. The most important determinants of fire susceptibility can be captured in ecosystem and climate models and through remotely sensed estimates of canopy structure, canopy water content, and microclimatic variables.

Key words: Amazon; canopy structure; drought; experimental fire; rain forest fire.

INTRODUCTION

Fire impoverishes vast areas of tropical forest in the Amazon Basin (Cochrane et al. 1999, Nepstad et al. 1999a, Mendonça et al. 2004) and Southeast Asia (Siebert et al. 2001, Page et al. 2002) through the interaction of drought and logging. These fires are especially severe during El Niño Southern Oscillation (ENSO), when these regions experience severe drought. During the 1997–1998 ENSO, approximately 40 000 and 14 000 km² of forest experienced understory fires in the Amazon Basin and Borneo, respectively, releasing 0.2–0.4 and 0.9 Pg of carbon to the atmosphere (Page et al. 2002, Alencar et al. 2004, Mendonça

et al. 2004). Drought in these regions may grow in severity and frequency in the future through changes in the ENSO regime associated with global warming (Trenberth and Hoar 1997, Timmermann et al. 1999), deforestation-induced inhibition of rainfall (Nobre et al. 1991, Silva Dias et al. 2002), and through greater evapotranspiration associated with rising temperatures (White et al. 1999). Hence, while fires have occurred in the Amazon for at least 6000 years (Sanford et al. 1985), the observation that their frequency is increasing from 400–700-yr return intervals that appear to have characterized the region in pre-Columbian times (Meggers 1994) to less than 25-yr return intervals in affected areas today (Cochrane et al. 1999) is of great concern.

The first time a mature Amazon forest burns, the fire tends to be low (~10 cm flame height) and slow moving (0.25 m/min), yet can cause high tree mortality rates even among large trees (23–44% of trees >10 cm dbh)

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because of the long contact time between the flame and the base of the tree (Holdsworth and Uhl 1997, Cochrane et al. 1999, Cochrane and Schulze 1999, Gerwing 2002, Barlow et al. 2003). Unlike grasslands, savannas, and many coniferous forests, in which periodic fires lower susceptibility to additional fire by reducing fuel loads (Pyne et al. 1996), wildland fires in moist tropical forests appear to increase the likelihood of further burning. Subsequent fires are more intense (higher flame heights and faster spread rates), perhaps because of the reduced canopy density and increased fuel loads associated with the tree mortality from the first fire, and can kill additional and larger trees (Cochrane and Schulze 1999). In the most extreme scenario, recurrent fires may promote the conversion of high forest to fire-adapted scrub vegetation in a process termed savanization (Cochrane and Schulze 1998, Kinnaird and O'Brien 1998). The effects of understory fires on forest fauna (mammals and large-bodied birds) appear also to be large (Kinnaird and O'Brien 1998, Peres et al. 2003, Barlow and Peres 2004).

It is hypothesized that canopy density (e.g., leaf area index, LAI) is an important determinant of forest susceptibility to fire in the Amazon (Nepstad et al. 1995), although this hypothesis remains to be rigorously tested. Large areas of mature, moist tropical forest in the Amazon remain resistant to fire even during dry seasons of >4 mo duration by maintaining a dense leaf canopy that prevents the solar heating of the forest understory that is necessary to dry the forest floor (Nepstad et al. 1995). Canopy maintenance during prolonged drought is possible through water absorption by root systems that penetrate >8 m into the soil (Nepstad et al. 1994, 1995, 2004, Jipp et al. 1998). Forest susceptibility to fire increases when canopy damage caused by selective logging (Woods 1989, Uhl and Vieira 1989, Uhl and Kauffman 1990, Holdsworth and Uhl 1997, Alencar et al. 2004), or resulting from tree death associated with previous understory fires (Cochrane and Schulze 1999, Cochrane et al. 1999), creates canopy gaps and reduces LAI, allowing more desiccating solar radiation to penetrate the forest interior, while adding to the fuel load on the forest floor. Regrowing forests may be more susceptible to fire than mature forests (Uhl et al. 1988) because of their relatively low LAI and, perhaps, their low stature, which allows tighter coupling of the canopy and forest interior air. Severe drought may also increase forest susceptibility to fire. As deep soil moisture is depleted, canopy thinning begins to take place, allowing greater penetration of solar radiation to the forest floor as recently documented in a large throughfall exclusion experiment (Nepstad et al. 2002). Forest edges may be more susceptible to fire because of drying and tree mortality associated with these environments (Kapos 1989, Laurance et al. 2001)

In the Amazon, severe seasonal drought, selective logging, and regrowing forests are concentrated along

the eastern and southern portions of the region (Nepstad et al. 1999*a, b*), and may expand into the region's interior as new highways are paved (Nepstad et al. 2001). Approximately 200 000 to 300 000 km² of land (between 30% and 50% of the previously deforested area) in the Brazilian Amazon is in some stage of forest recovery (Fearnside and Guimarães 1996, Houghton et al. 2000, Zarin et al. 2001), while 10 000–15 000 km²/yr of forest are selectively logged (Nepstad et al. 1999*b*). Simulation and prediction of both short-term trends in fire risk and fire occurrence, and long-term changes in the Amazon fire regime that may result from climate change and frontier expansion, will require a mechanistic understanding of the controls on forest susceptibility to fire. Information derived from controlled fire experiments is necessary to elucidate the underlying mechanisms. Past work has pointed to linkages between forest structure, understory microclimate and the moisture content of fine fuels (Uhl et al. 1988, Uhl and Kaufmann 1990, Holdsworth and Uhl 1997). However, rigorous testing of how these variables contribute to fire susceptibility has not been carried out within the seasonally dry Amazon, where these fires represent the greatest threat. Fire science remains a fledgling discipline in the moist tropics, and basic information is required to determine the appropriateness of extending existing fire modeling frameworks developed for temperate forests to these ecosystems (Cochrane 2003). Therefore, we conducted a large number of experimental fires in forests with markedly different structures in order to (1) determine the physical and environmental factors regulating the behavior of understory fires, and (2) assess the potential for applying the resulting relationships to the prediction of fire susceptibility in the eastern Brazilian Amazon.

METHODS

Study system

The study sites were located 100 km south of the city of Santarém in Pará State, Brazil (~3° S, 55° W). Measurements were carried out within three forest structure types with known disturbance histories. Included were (1) a mature forest (M_{for}) that was lightly logged (<10 m³/ha harvested) 14 yr prior in 1988; (2) a forest that was selectively logged two to three times between 1993 and 1997 (~30 m³/ha harvested), and burned soon after in 1997 (L/B_{for}); and, (3) a young regrowing forest (R_{for}) on a former swidden agriculture site, abandoned 8 yr prior. The L/B_{for} and R_{for} were located approximately 500 m apart; the M_{for} was situated ~10 km southwest of the other areas.

Rainfall in the region is strongly seasonal (Fig. 1). Between 1999 and 2002, the average annual precipitation was 2200 mm measured at a nearby research site (Nepstad et al. 2002), and 1843 mm/yr based on a 25 yr record from a long-term met station in Belterra, located ~50 km to the north. Approximately 75% of

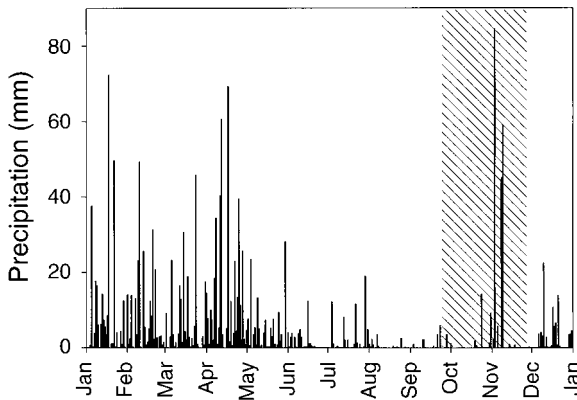


FIG. 1. Daily rainfall for 2002 from a nearby study site located ~ 36 km from the areas where experimental fires were conducted. Diagonal crosshatching indicates the period during the dry season when the experimental fires took place.

this annual total comes during the 6-mo wet season, between January and June, at both locations (Fig. 1). Soils in the area are deeply weathered clays (Oxisol, Haplustox), interspersed with pockets of coarser textured materials (Silver et al. 2000). Our study sites were located on the finer textured soils. These soils have a highly aggregated structure, and drain well.

Sampling design

A sampling grid was established within each area. At the M_{for} and L/B_{for} sites, four transect lines were established within ~ 25 -ha blocks. The parallel transect lines were 250 m long with 250 m between them, each consisting of 10 evenly spaced (25-m interval) grid points ($n = 40$ points/area). The sample grid at the R_{for} was smaller, covering ~ 2.5 ha in total area; here, four 100 m long transects were established at 50-m intervals, each having 10 grid points separated by 10 m ($n = 40$ points). Narrow trails (0.5 m wide) were created to provide access within each area; care was taken to avoid cutting of larger stems that might thin the canopy. Sampling points were established approximately 3 m from the access trail on both sides of each grid point, for a total of 80 sample points per forest. Twenty additional sample points were located at random in each forest type for a total of 100 sample points per area.

Rainfall and understory microclimate

Daily rainfall estimates for the study sites were provided by automated pluviometers (RainWise 20 cm diameter tipping-bucket; RainWise, Inc., Bar Harbor, Maine, USA) beginning on 25 October 2002. Two sampling locations were chosen, one in an open field at the entrance to disturbed sites (L/B_{for} and R_{for}), and within a large canopy gap along the access road to the M_{for} . This information was used to derive a weighted precipitation variable, obtained by dividing the size of the most recent event by the number of rainless days fol-

lowing the event. For example, five days after a 10-mm rain event the value of the weighted precipitation would be 2 mm/d (10 mm/5 d). When two or more rainfall events occurred close enough in time that the value of the first had not dropped below 1 mm/d, this remainder was added to the new rainfall total before dividing by the updated rainless days count. The objective was to derive a measure of precipitation that would incorporate differences in event size and their diminishing influence over time. Because pluviometers had not been set up prior to the initial experimental fire campaign we had to rely on rainfall estimates obtained from other sources for initializing our weighted precipitation variable. These included (1) the moisture content of the leaf litter when we first arrived at the sites to take measurements, as determined in the lab, (2) rainfall measured in a wedge shaped rain gage located at the entrance to the M_{for} (< 3 km away), and (3) conversations with local residents. All of these factors pointed to no measurable rainfall for at least 1-week prior. We then identified a median event size of 2 mm based on the previous months rainfall record from a pair of pluviometers located at a nearby study site. Thus, the value of the weighted precipitation variable was initialized at 0.29 mm/d (2 mm/7 d).

On 18 September 2002, we established a monitoring station for measuring temperature (T , $^{\circ}\text{C}$) and relative humidity (RH, %) within an open area located close to the M_{for} (< 3 km away). A pair of Hobo RH-T sensors (Onset Computer Corporation, Pocasset, Massachusetts, USA), mounted within a U.S. Weather Service approved cabinet and fixed to a wooden post 1.3 m above the ground, were used to log readings at half-hour intervals for the duration of the study period (18 September to 27 November 2002). Similar measurements were also available from a long-term meteorological station located ~ 36 km away (Nepstad et al. 2002). Average midday values for T and RH, determined between 13:00 and 15:00 local time, were used to calculate vapor pressure deficit (VPD, kPa).

Forest structure

Aboveground forest biomass was estimated for each area using allometric equations developed for primary (Chambers et al. 2001) and secondary (Nelson et al. 1999) forest species in the Brazilian Amazon. At the M_{for} , we measured all trees ≥ 10 cm dbh (diameter at breast height) within eight 20×50 m plots centered at randomly selected locations along our grid lines, and all trees ≥ 30 cm in 30×50 m plots at these same locations. At the L/B_{for} trees ≥ 10 cm dbh and ≥ 30 cm dbh were measured along five continuous vegetation transects of 4×500 m and 10×500 m, respectively. And at the R_{for} , live trees ≥ 5 cm dbh were sampled along four 5×50 m transects centered on the grid lines; stems between 1 and 5 cm dbh were measured on 1 m radius circular plots at 40 randomly selected grid points. An average canopy height was determined

for each study area based on clinometer calibrated ocular estimation of the height of the dominant vegetation within each area.

An estimate of leaf area index (LAI) was obtained for each grid point using a LI-COR LAI-2000 plant canopy analyzer (LI-COR, Inc., Lincoln, Nebraska, USA). Paired optical sensors were used to take simultaneous measurement of above and below canopy light conditions. Above-canopy measurements were obtained in large open areas nearby the study sites, while two below-canopy readings were taken ~1 m above the ground at each sample point. A 45° view cap was used to help isolate the individual point estimates of LAI; information from the fifth concentric ring of the optical sensor (62.3–74.1° view angle) was dropped from the analysis to address this same issue. These measurements were made at two times during the study period; sample points on the right-hand side of the access trails were done first (on 15–16 October), and points on the left-hand side were measured approximately one month later. We measured LAI early in the morning (6:00–7:30 local time) to minimize the influence of heterogeneous sky conditions and glare.

Litter biomass was determined by collecting all leaves and small twigs (<1 cm diameter) above the mineral soil within 40 cm diameter circular plots (0.13 m²/sample), at the times and locations when experimental fires were carried out. Litter samples were weighed at the time of collection, and biomass and moisture contents were determined after drying samples for 48 h at 65°C in the lab.

Experimental fire measurements

Five experimental fire campaigns were carried out approximately biweekly between 25 September and 27 November 2002. A typical campaign lasted three to four days. The first day consisted of measuring understory *T* and RH using a battery-powered, ventilated, wet-bulb-dry-bulb psychrometer, and litter mass and moisture content as described earlier. Psychrometer readings were taken just above (~5 cm) the forest floor at each sample point. All measurements were made simultaneously by two-person crews working independently in each area; these data were gathered between ~13:00–14:00 local time. The purpose of these measurements was to quantify variability in understory conditions across the entire study areas within a short timeframe, something that was not possible to do when carrying out the experimental fires. The final campaign did not include this initial day of area-wide measurements.

During the subsequent days of each campaign, we set between five and 10 experimental fires per day at randomly selected sample points within each area. These fires commenced at ~13:00 and were always completed before 16:00. As a result of differences between forests in terms of ease of movement and dis-

tance between sample points, the number of fires completed in each area on each day was not always the same. In total, 100 experimental fires were set in each area (300 total) over the course of 13 measurement days.

Crews of three to four people were responsible for carrying out the experimental fires in each area, allowing nearly simultaneous measurement of microclimatic and fire behavior variables at each grid point, and across areas. At each location, we first measured air RH and *T*, and collected a fixed area sample of the leaf litter for mass determination. Wind speed at the time of the fire was estimated by hanging a 1 m long piece of flagging tape at arm's length for a period of 1 min and noting the maximum degree of displacement from the vertical using three categories: zero to indicate no displacement, one if the tape was between 0° and 45° from the vertical, and two if it went above 45°.

Experimental fires were carried out by first placing a 20 cm radius circular metal hoop on the forest floor at the grid point. Steel pins were then pushed into the soil 30 cm outside of the hoop in each cardinal direction. Approximately 10 mL of kerosene was then applied to the litter within the metal hoop to ensure initial ignition. Fires were allowed to burn for a distance of up to 1 m in any direction from the plot center, or for a period of up to 5 min, whichever came first. The 1-m maximum distance criterion was established because of the risks associated with allowing the fires to burn for up to 5 min regardless of spread distance. Observers noted the time it took for the flames to reach each of the four pins, and the 1-m distance for fires that spread that far. Flame heights, measured perpendicular to the ground surface, were recorded when the fire reached 1 m, or had burned for 5 min; flame heights were not measured for fires that burned out. After each fire was extinguished, we measured the distance of spread in the direction of each pin, and also along the radius of maximum fire spread when it was different. To allow the calculation of spread rates in cases where the fire did not burn for at least 5 min or arrive at the 1 m distance threshold, we also recorded the time that each of these fires died. Fire spread rate (FSR) was determined by dividing the distance along the axis of maximum spread (less the 20 cm distance to the center of the circle where kerosene was used to ignite the fire) by the amount of time the fire was actively burning.

Finally, each fire was classified in regards to the likelihood that it would have continued burning if not extinguished. A binary response variable (spreading/dying) was assigned to each fire based on agreement among team members. Fire intensity (visual estimation of increasing/decreasing) and continuity of surrounding fuels provided the primary criteria for making these assessments. Fires that did not require manual extinction were assigned to the dying category.

Statistical analysis

The analyses view the three study areas as representing a continuum of forest structures. A combination of regression techniques (nonlinear, stepwise linear, and logistic) was used to identify relationships among the measured variables. Our approach was to construct a set of models that would allow prediction of fire behavior and risk based on (1) all significant measured variables, and (2) the subset of more easily measured variables that describe forest canopy structure (average canopy height and LAI) and recent precipitation history (weighted precipitation [mm/d]). Our estimate of wind speed was treated as a class variable because it was not measured on a continuous scale. Degrees of freedom were provided by the individual experimental fires carried out in each area ($n = 300$). A log-transformation was applied to the FSR variable in order to satisfy assumptions of the analysis. All significance tests were carried out at the $\alpha = 0.05$ level. Analyses were conducted using SyStat software (SPSS, Chicago, Illinois, USA).

RESULTS

Rainfall and understory micrometeorology

The study took place during the latter part of the 2002 dry season (Fig. 1). When the experimental fire campaigns began on 24 September, the region was in the midst of a severe seasonal drought. A total of 27.3 mm of rainfall was recorded over the preceding 54-d period at the nearby reference site, with an average of ~ 0.5 mm/d, compared to 108.8 ± 20.3 mm during the equivalent period over the previous three years. The number of rainless days preceding the experimental fire campaigns ranged from 2 to 24 (mean = 10 d, median = 7 d). One especially rainy period occurred during the study, extending over five days between 5 and 9 November; total inputs ranged from 54 mm at the mature forest site (M_{for}) to 136 mm at the disturbed forests (R_{for} and L/B_{for}) (see Fig. 2). Approximately half of the difference in precipitation between sites (38 mm) was associated with a single rain event on 8 November, which did not even register at the M_{for} . The next to last fire campaign began three days after these rains ended, on 12 November. The amount of rainfall recorded during this period at the nearby reference site was considerably higher (>30%) than at either of the study areas.

Average mid-day temperatures (T) at the forest floor were consistently higher at the disturbed forests than within the M_{for} (Fig. 2). The reverse was true for relative humidity (RH), where the moisture saturation of the air in the understory of the M_{for} remained much higher than at either of the disturbed forests (Fig. 2). Vapor pressure deficit (VPD), which integrates the variation in evaporative demand of the atmosphere associated with both T and RH, was consistently higher at the disturbed forests than at the M_{for} (Fig. 2). Under the

most extreme conditions (ambient met station VPD = 2.64 kPa), the average mid-day VPD was 4.7 and 3.6 times higher at the R_{for} and L/B_{for} forest sites than within the M_{for} understory, respectively. On average, midday VPD at the M_{for} remained between 2.7 and 2.1 times lower than those at the R_{for} and L/B_{for} , respectively. The maximum VPD recorded at individual sampling points in each forest structure type was 4.6, 3.2, and 2.4 kPa for the R_{for} , L/B_{for} , and M_{for} , respectively. In sum, the drying environment measured at the disturbed forests was more similar to that encountered at the met station than within the M_{for} understory.

Forest canopy and biomass

Forest canopies ranged from the short stature and low LAI of the R_{for} , to the relatively tall canopy height and high LAI of the M_{for} ; the L/B_{for} was intermediate in these characteristics (Table 1). Canopy gap fraction was four and 6.5 times higher at the L/B_{for} and R_{for} than for the M_{for} (Table 1). Standing aboveground biomass increased dramatically from the regrowth to the M_{for} ; again, the L/B_{for} was intermediate (Table 1). Small diameter lianas were abundant at R_{for} and L/B_{for} , although they were not inventoried. Large diameter coarse woody debris and standing dead trees were most abundant at the L/B_{for} . Litter mass was similar across all sites (Table 1).

Litter moisture dynamics

Average mid-day litter moisture contents (LMC) were relatively low at all three sites during the extended dry periods between rainfall events (Fig. 2). Excluding the sampling dates that fell within a week of substantial rains (25 October, 5, 12, and 13 November), average mid-day LMC during the dry season remained close to 14% at R_{for} (range of 5–34%), 16% at L/B_{for} (range of 8–42%), and 23% (range of 12–40%) at the M_{for} . This trend became reversed, however, immediately following the heavy rains, when higher LMC was recorded at the disturbed than the M_{for} (Fig. 2). This may have been result of differences in the size of the rain events affecting each area, and perhaps also due to differences in canopy interception among sites. The condition did not persist however, because declines in LMC were also more rapid at the disturbed forests.

Forest canopy controls of LMC and VPD

In combination, canopy height and LAI could explain $\sim 60\%$ of the variability in understory VPD across the range of conditions represented in this study (Fig. 3). The ability of the tall dense canopy of the M_{for} to buffer microclimatic conditions in the forest understory contrasts sharply with that of the disturbed forests. The strength of the relationship between understory VPD, canopy height, and LAI was increased slightly (by 5%, $R^2 = 0.65$) when the weighted precipitation variable was included.

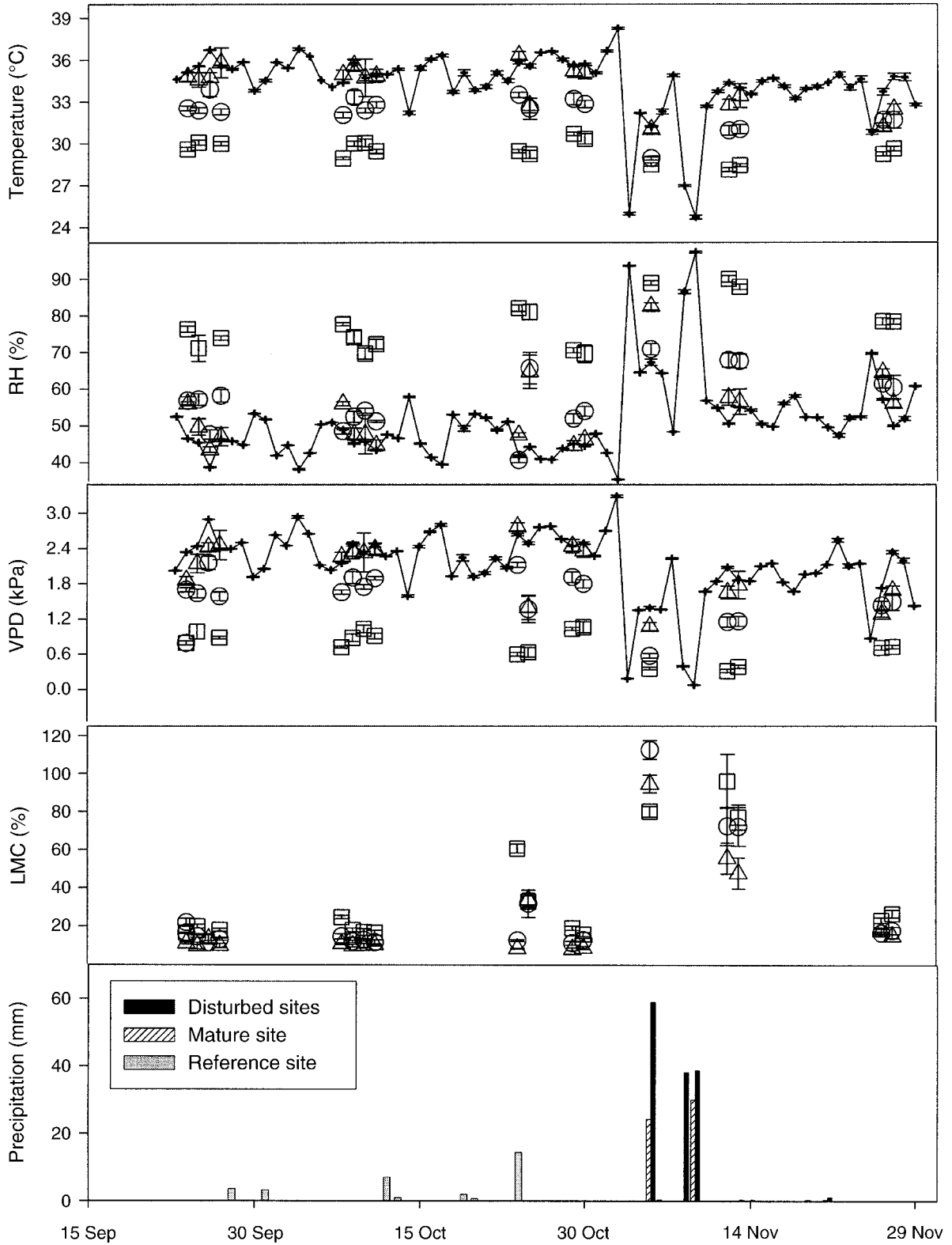


FIG. 2. Summary of micrometeorological measurements taken in the three forest types and in an open area during the period when experimental fires were being conducted. Panels show mean and standard error of midday (13:00–15:00) temperature (T), relative humidity (RH), and vapor pressure deficit (VPD) of the forest understory at the regrowth (triangles), logged/burned (circles), and mature (squares) forest sites, and at 1.3 m height in the open area (line and crosses), average moisture content of the leaf litter (LMC) at midday, and daily precipitation for the study sites and at a nearby reference location.

TABLE 1. Structural features of the three forests where experimental fires were conducted, Santarém, Pará, Brazil.

Forest	Average canopy height (m)	Leaf area index (m ² /m ²)	Gap fraction (%)	Standing live biomass (Mg/ha)	Leaf litter mass (Mg/ha)
Mature	30	6.07 ± 0.07	2.0 ± 0.2	319	4.2 ± 0.2
Logged/burned	20	4.14 ± 0.10	8.2 ± 0.6	165	4.6 ± 0.2
Regrowth	8	3.87 ± 0.14	13.0 ± 1.5	42	4.2 ± 0.2

Note: Biomass estimates for the mature and logged/burned forests are based on stems ≥ 10 cm dbh, and on stems ≥ 1 cm dbh in the regrowth forest. Values are mean \pm SE.

In contrast to the strong relationship we found between VPD and canopy height, and LAI, the combination of average canopy height and LAI were of limited use for predicting understory LMC across sites ($R^2 = 0.15$). The strongest predictor of LMC was short-term precipitation history, summarized by our weighted precipitation variable, which, in combination with canopy structure explained 72% of the variability in LMC across sites. During extended periods of dry weather LMC declined with increasing VPD at all study sites. However, this relationship broke down in the disturbed forests during times when the leaf litter was still wet but drying rapidly following a recent rain event due to the reduced buffering capacity of the canopy in those areas (Fig. 4). Relatively high VPDs, >1 kPa for example, were not associated with LMC $> 20\%$ in the M_{for} . By contrast, LMC between 60% and 80% were often associated with much higher VPD (between 1 and

2 kPa) at the disturbed forests at times when the weighted precipitation variable was relatively high (>7 mm/d). These findings suggest that the understory microclimate at the disturbed forests was more tightly coupled with the micrometeorological conditions above the canopy than at the intact M_{for} . Absorption and reflection of incoming direct solar radiation by leaves and other plant surfaces takes place closer to the ground in the disturbed forests, on average, heating the forest understory air more than in the M_{for} . Moreover, the amount of direct solar radiation that reaches the forest floor is also presumably higher in the disturbed forests given the lower LAI and correspondingly higher canopy gap fraction (Table 1).

In addition to regulating the amount of solar radiation making its way to the forest understory, canopy structure also strongly influenced the movement of air within that environment. Our measurements indicate that the relatively taller and denser canopy of the M_{for} , and to a lesser extent the L/B_{for} , maintained a more effective boundary between the above- and below-canopy environments than at the short-stature R_{for} . Average wind speeds at mid-day most often fell into the medium category across these areas (R_{for} , 58%; L/B_{for} , 47%; and

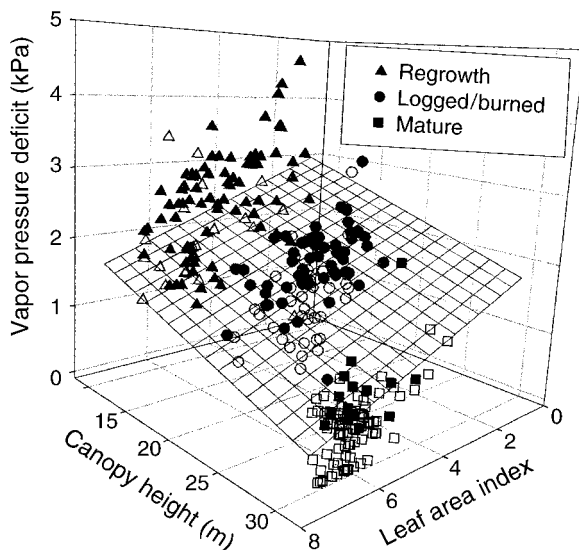


FIG. 3. The relationship between midday vapor pressure deficit (VPD), average canopy height (HT), and leaf area index (LAI), in the forest understory of the three forest structure types at times when experimental fires were conducted (13:00–16:00). Also plotted is the response surface resulting from a multiple linear regression analysis. Solid symbols indicate spreading fires, and open symbols are dying fires. VPD = $3.470 - 0.053(\text{HT}) - 0.207(\text{LAI})$; adjusted $R^2 = 0.59$, $P < 0.01$.

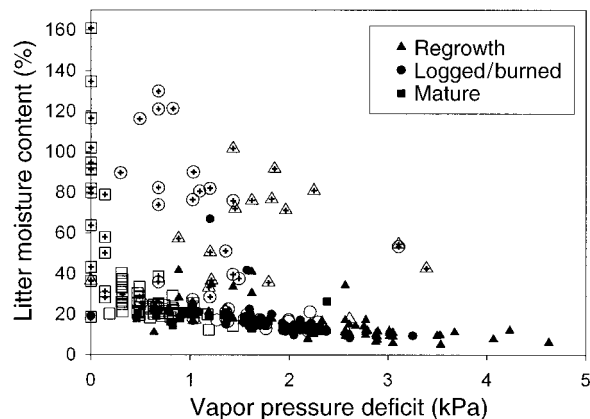


FIG. 4. The relationship between litter moisture content (LMC) and vapor pressure deficit (VPD) in the three forest structure types at times when experimental fires were conducted (13:00–16:00). Symbols containing a cross indicate measurements made in close proximity to a precipitation event (weighted precipitation >7 mm/d). Solid symbols indicate spreading fires, and open symbols are dying fires.

M_{for} , 54% of total). There was, however, a marked difference among them in regards to the frequency at which high winds were recorded (R_{for} , 26%; L/B_{for} , 7%; and M_{for} , 3% of total).

Fire spread rates and flame heights

Fire spread rates (FSR) differed significantly among the three areas (ANOVA, $F_{2,35} = 13.181$, $P < 0.001$). On average, FSR was more than three times higher at the R_{for} (0.257 ± 0.034 m/min) than M_{for} (0.067 ± 0.019 m/min). FSR was intermediate at the L/B_{for} (0.185 ± 0.023 m/min), yet still more than two times higher than at the M_{for} . According to a Bonferoni means separation, FSR was significantly higher at the disturbed forests than at the M_{for} ($P < 0.01$); there was no difference between the R_{for} and L/B_{for} in this regard ($P = 0.163$). Maximum FSR for individual experimental fires ranged from 0.93 m/min at R_{for} to 0.43 m/min in the M_{for} . Again, these values were intermediate at the L/B_{for} (to 0.63 m/min).

The average flame heights associated with spreading fires (fires that needed to be extinguished manually) also differed substantially among these sites (ANOVA, $F_{2,27} = 10.629$, $P < 0.001$). However, unlike for FSR, flame heights were higher at the L/B_{for} (38.1 ± 3.4 cm), than at the R_{for} (27.9 ± 1.5 cm) (Bonferoni $P = 0.016$). And, while flame heights measured at the M_{for} (19.6 ± 2.8 cm) were considerably lower than those at the L/B_{for} ($P < 0.001$), they were not dramatically different from those at the R_{for} ($P = 0.146$).

Consistent with expectation, a relatively strong positive correlation was found between flame height and FSR among spreading fires ($R = 0.45$, $P < 0.01$). In addition, FSR exhibited a weak but significant negative correlation with forest floor mass ($R = -0.20$, $P = 0.04$), however, no relationship was detected between flame height and forest floor mass ($R = 0.12$, $P = 0.44$).

Correlates of understory micrometeorology and fire spread

Understory VPD was the single strongest predictor of FSR measured in this study. Using a linear regression model, this variable explained 50% of the variability in FSR (Fig. 5a). We detected a break point in the behavior of our experimental fires at a VPD of ~ 0.75 kPa, below which spreading fires were strongly inhibited (Fig. 5a). For example, 95% (145/152 fires) of all experimental fires that required manual extinction took place at VPD above this apparent threshold. There was also a high proportion of fires that did not require manual extinction (47%, 70/148 fires), yet also took place above this threshold. However, of these, 40% (28/70 fires) took place in close proximity to a rain event (weighted precipitation variable > 7 mm/d), and therefore may have been limited by high fuel moisture. Predicted FSR was four times higher for fires taking place at VPD between 0.76 and 3.0 kPa (0.20 m/min) than for VPD between 0 and 0.75 kPa (0.05 m/min).

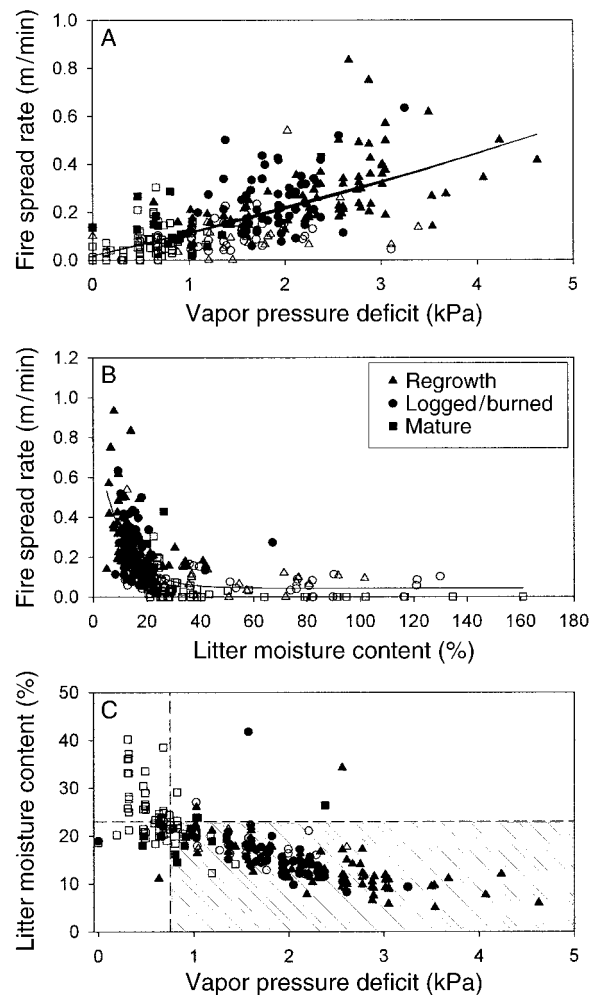


FIG. 5. The relationship between fire spread rate (FSR) and (A) vapor pressure deficit (VPD) [$\ln[\text{FSR} + 1] = 0.018 + 0.087[\text{VPD}]$; adjusted $R^2 = 0.50$, $P < 0.01$], and (B) litter moisture content (LMC) in the understory of the three forest structure types when experimental fires were carried out (13:00–16:00) ($\text{FSR} = 0.043 + 0.838 \exp[-0.107(\text{LMC})]$; adjusted $R^2 = 0.45$, $P < 0.01$). (C) Important thresholds associated with spreading fires during extended periods of dry weather (weighted precipitation variable < 2.5 mm/d). Dashed horizontal and vertical lines correspond to 23% LMC and 0.75 kPa VPD thresholds, respectively. The crosshatched area represents the intersection of the two environmental thresholds. Solid symbols indicate spreading fires, and open symbols are dying fires.

FSR, measured across the three forests, was strongly related to LMC; 45% of the variability in FSR could be explained by LMC using a negative exponential regression model (Fig. 5b). A threshold in fire susceptibility, corresponding to a LMC of $\sim 23\%$, was identified by solving for the tangent line with slope = -1 in relation to the first derivative of the equation describing that relationship. In addition, 93% (141/152 fires) of all fires requiring manual extinction took place

TABLE 2. Reduced regression model of fire spread rate (FSR; Eq. 1) on canopy structure variables (average canopy height and leaf area index [LAI]) and weighted precipitation (mm/d) developed across the three forest types based on $n = 300$ experimental fires.

Parameter	Estimate	SE	<i>t</i>	<i>P</i>
Constant	0.361	0.016	21.977	<0.001
Weighted precipitation (mm/d)	-0.009	0.001	-8.134	<0.001
Canopy height (m)	-0.005	0.001	-7.077	<0.001
LAI	-0.021	0.004	-5.226	<0.001

at LMC below that apparent threshold. Similar to what we found for VPD, there were also a substantial number of fires that did not require manual extinction (49%, 73/148 fires), yet took place when LMC was below the 23% threshold. Unlike what we found for VPD though, only a very small proportion of these fires were associated with proximate rain events (3%, 2/59 fires), as low LMC was seldom associated with high values of the weighted precipitation variable. However, a relatively high proportion (32%, 19/59 fires) of these self-extinguishing fires took place when VPD was below the 0.75 kPa threshold (Fig. 5b). Predicted FSR was five times higher for LMC between 5% and 23% (0.26 m/min) than for LMC between 24% and 100% (0.05 m/min).

Further insights were gained by examining the joint influence of VPD and LMC on FSR during periods of very dry weather (Fig. 5c). For this purpose we omitted the experimental fires that took place in close proximity to a substantial rain event (weighted precipitation variable <2.5 mm/d), thereby retaining 78% of the original sample (234/300 fires). This had the immediate effect of removing most of the high-VPD-high-LMC combinations observed in the disturbed forests (Fig. 4). Over 90% (130/143 fires) of the spreading fires that took place under these conditions conformed to both of the proposed fire susceptibility thresholds. The spreading fires that took place outside of this zone (represented by crosshatching in the bottom right, Fig. 5c), were either associated with high VPD (>0.75 kPa) or low LMC (<23%); in no instance did a spreading fire exceed both of these thresholds. On the other hand, 44% (40/91) of the fires that failed to spread shared these same characteristics. Nonspreading fires may have been limited by factors other than fuel moisture or air VPD.

Wind speeds at the time the experimental fires were conducted influenced fire behavior, as indicated by the positive association between spreading fires and increasing wind speeds. For example, over 70% (26/36 fires) of all fires associated with the high wind speed category required manual extinction; most of these took place at the R_{for} . By contrast, there were approximately twice as many self-extinguishing as spreading fires associated with the low wind speed category (69 vs. 36 fires, respectively). The association between the intermediate wind speed category and spreading or dy-

ing fires was closer to neutral, with 57% (90/159) spreading.

Models of fire behavior

The most parsimonious description of FSR was arrived at by combining information about understory VPD, mm/d, wind speed, and LAI. This model parameterization accounted for 57% of the variability in FSR measured across the three areas. The fact that VPD alone could explain 50% of the variation in FSR (Fig. 5a) suggests the other variables made modest, yet significant ($P < 0.001$ for all), contributions to the development of the full model. The influence of "forest type" was negligible ($P = 0.803$) after variability in understory microclimate and canopy structure had been accounted for. The highest degree of correlation observed between any two independent variables was $R = 0.64$ for VPD and LAI, reflecting the link between canopy density and understory microclimate. Interpretation of the independent variable effects was intuitive; FSR was positively correlated with VPD and wind speed, and negatively correlated with mm/d and LAI. Because wind speed entered the model as a categorical variable the full solution consists of three subtly different regressions, each scaled to the appropriate level of the wind speed variable. When the analysis was restricted to independent variables representing forest structure (average canopy height and LAI), and short-term precipitation history, model R^2 declined from 0.57 to 0.46. Even so, this approach was still able to capture 84% of the variability accounted for in the full model using fewer more easily obtained variables (Eq. 1, Table 2):

$$\ln(\text{FSR} + 1) = 0.361 - 0.009(\text{precip.}) - 0.021(\text{LAI}) - 0.005(\text{HT}) \quad (1)$$

where HT is average canopy height (m) and all other variables are as defined previously. The weighted precipitation variable turned out to be the most important predictor of FSR in the reduced model; average canopy height and LAI both contributed significantly (Table 2). The fact that canopy structure variables had proven such strong predictors of understory VPD (Fig. 3), which was tightly linked to FSR (Fig. 5a), suggested they would also be useful for predicting FSR. Average canopy height and LAI were positively correlated ($R = 0.60$).

TABLE 3. Reduced logistic regression model of understory fire susceptibility (pFire; Eq. 2) on canopy structure variables (average canopy height and leaf area index [LAI]) and weighted precipitation developed across the three forest types.

Parameter	Estimate	SE	<i>t</i>	<i>P</i>	Odds ratio	Upper	Lower
Constant	5.235	0.656	7.974	<0.001			
Weighted precipitation (mm/d)	-0.300	0.050	-6.000	<0.001	0.741	0.817	0.671
Canopy height (m)	-0.135	0.023	-5.837	<0.001	0.874	0.914	0.835
LAI	-0.360	0.139	-2.590	0.01	0.698	0.916	0.531

Note: The model was highly significant (chi-square $P < 0.001$; McFadden's rho-squared = 0.36) based on information from 152 spreading and 148 dying fires.

Models of fire risk

We assessed fire risk—the probability of a fire spreading under a given set of conditions—using logistic regression. This approach treats the experimental fires as a binary variable (spreading/dying), and provides information about the conditions under which the forests are likely to burn. The binary status of each fire was assigned conservatively (see *Methods*).

The full logistic model, arrived at through stepwise selection, included VPD ($P = 0.002$), LMC ($P < 0.001$), litter mass ($P = 0.001$), and average canopy height ($P = 0.013$). Of these, litter mass, LMC, and average canopy height were not included in the linear FSR model using FSR, while recent precipitation history, wind speed, and LAI were included in the full linear model, but not the corresponding logistic model. Although litter mass exhibited relatively weak correspondence with the measured physical characteristics of the experimental fires, it turned out to be an important predictor of fire success in the logistic analysis. Because forest floor mass provides a surrogate for available fuels, this variable can also be thought of as describing their continuity, which was a consideration in our classification scheme for spreading fires. The possibility that wind speed could have the effect of increasing FSR without necessarily increasing the likelihood that an experimental fire would be classified as successful or not, provides a possible explanation for its being dropped from the logistic model. For example, a fire that burned rapidly but only for a short time, perhaps due to some unique characteristics of the fuels in close proximity to the point of ignition, would have had a high FSR based on our calculation method (distance/time), yet would also have been classified as not spreading because it burned out. The canopy height and LAI variables contain similar information, and given the high proportion of the total variability already accounted for by the inclusion of VPD and LMC, it makes sense that only one of these canopy structure variables would be included in the model. This four-variable parameterization successfully predicted the outcome of 78% of the experimental fires (McFadden's rho-squared = 0.480).

A reduced logistic model was fit to the same canopy structure and precipitation variables used in the second stage of the FSR analysis. Average canopy height, LAI, and the weighted precipitation variable all contributed

significantly to the model's ability to distinguish between spreading and dying fires. The three-variable model (Eq. 2, Table 3) successfully predicted the outcome of 73% of the experimental fires, only a slight (5%) decrease in performance relative to the full model:

$$\text{pFire} = 1 - \left[\frac{1}{1 + \exp\{5.235 - 0.300(\text{precip.}) - 0.135(\text{HT}) - 0.360(\text{LAI})\}} \right] \quad (2)$$

where pFire is the probability of a spreading fire and the other variables are as defined previously.

Predicting susceptibility to understory fire

The most powerful ecological models capture the key mechanisms that regulate system behavior using a small number of easily measured or simulated variables. We therefore assessed fire susceptibility using the reduced logistic model (LAI, average canopy height, and weighted precipitation). These variables have the advantage of being estimable using remotely sensed data (canopy structure = average height and LAI), and the network of met stations distributed across the Amazon Basin (precipitation), and could be projected using stand dynamics and climate models.

The canopy structure variables in our data set described a fairly wide range of conditions: average canopy height ranged from 8 to 30 m, while average LAI extended from ~4 to 6 m²/m² (point measurements of LAI ranged from 0.5 to 7.2). The weighted precipitation variable ranged between ~0 and 17 mm/d over the period when experimental fires were conducted. To explore fire susceptibility as a function of rainfall, we divided the canopy structure variables into discrete classes and treated short-term precipitation history as the continuous predictor variable. Average canopy heights were represented by three levels: short, 10 m; medium, 20 m; tall, 30 m, while low, medium, and high levels of LAI were set at 3, 4.5, and 6, respectively. The weighted precipitation variable was allowed to range from 0 to 20 mm/d. All of these conditions approximate observed conditions at the study sites and during the study period. Of the nine possible combinations of canopy variables (three LAI × three canopy heights), we did not include either the tall-canopy–low-LAI, or the low-canopy–high-LAI forest structures, because they were not represented in our data, and do

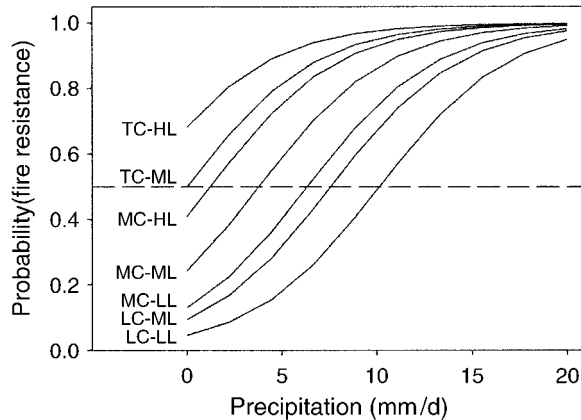


FIG. 6. The probability of an understory fire not spreading in association with different canopy structures and recent precipitation history during the dry season. Canopy structure variables are represented by three levels of average canopy height (short canopy [SC] = 10 m, medium canopy [MC] = 20 m, and tall [TC] = 30 m), and three levels of leaf area index (low LAI [LL] = 3, medium LAI [ML] = 4.5, and high LAI [HL] = 6). Each regression relates a combination of the two canopy structure variables to the weighted precipitation variable (e.g., MC-LL refers to the medium average canopy height and low leaf area combination). The horizontal dashed line indicates the break point in the probability of a fire spreading or dying ($p_{\text{Fire}} = 0.5$).

not reflect likely combinations of these variables across the landscape.

If we define the threshold of forest fire susceptibility as the conditions under which the probability of fire success is 0.5 (from the logistic model, scale 0–1), then the tall-canopied ecosystems remain resistant to fire even during periods of extremely low precipitation (Fig. 6). Also, the tall average height and medium LAI forest structure combination (TC-ML) just barely contacts the risk threshold at the minimum level of the precipitation variable (Fig. 6). The medium canopy height high LAI combination (MC-HL) was susceptible to fire at the lowest levels of the precipitation variable. By contrast, canopies of medium or short average height having either medium or low LAI became susceptible at increasingly higher values of the precipitation variable (Fig. 6). Consistent with the selection of average height as the single descriptor of canopy structure in the full logistic model, it emerges as the most important factor conferring fire resistance (Table 3). Preliminary evidence of this is provided by the fact that taller canopies with reduced LAI still appear more resistant than the next shorter canopy category combined with the next higher LAI category (e.g., TC-ML > MC-HL and MC-LL > LC-ML, where > indicates more fire resistance) (Fig. 6). Even so, recent precipitation history is the final arbiter of fire resistance for these disturbed forests; soon after a soaking rain the probability of a fire spreading is very low, and largely independent of forest structure or ignition source. All modeled forest types exhibited high fire resistance at

high levels of the precipitation variable (e.g., 10 mm/d; Fig. 6).

DISCUSSION

Rain forest fires in the Brazilian Amazon are inextricably linked to land-use change and associated anthropogenic ignition sources (Nepstad et al. 2001, Alencar et al. 2004). Therefore, to understand the physical and environmental controls on understory fire behavior our research focused on a mosaic of vegetation types spanning a range of disturbed and intact forests. Our approach to quantifying these relationships differed in some fundamental ways from those taken by past workers. To our knowledge the present study is the first to correlate measurements of forest structure and understory microclimate with large numbers of experimental fires carried out simultaneously over a wide range of forest structures. By using a large systematic sampling grid we were able to capture the broadest possible range of conditions. Thus, instead of characterizing conditions at the harvested site (L/B_{for}) on the basis of measurements taken only within canopy gaps, as others have done (Uhl and Kaufmann 1990), we focused on the disturbed forest matrix as a whole, providing a more objective representation of the effect such forest structures have on fire susceptibility. This is an important distinction because conventional harvests in the region typically leave >50% of the forest canopy intact (Uhl and Vieira 1989, Asner et al. 2004).

The ability to predict fire behavior was greatly improved by viewing the studied forests as a continuum of forest height and canopy density (Fig. 5a, b). Only by taking this approach were we able to demonstrate a strong connection between the measured independent variables and fire behavior. This finding may indicate either that the range of conditions presented at each study site was not broad enough to account for the difference in the behavior of the individual experimental fires, or that larger scale structural features (i.e., differences in canopy height and the abundance of canopy gaps) at each site had an overriding influence. We found some evidence in support of the latter hypotheses; for example, over 85% (26/30 fires) of the fires that took place under dry conditions (weighted precipitation <2.5mm/d) but at points on the sample grid with relatively high LAI (>4.5) were observed to spread in the R_{for} , yet only one of five fires behaved similarly at the M_{for} under those same conditions. There was only a slight tendency for experimental fires to be more likely to spread at the L/B_{for} when LAI was below 4.5 (77%, 40/52 fires) than when they were above this level (68%, 17/25 fires). So, while the incidence of spreading fires did increase with the overall level of canopy disturbance, they did not exhibit the tight correspondence with point level estimates of canopy density that might be expected if those conditions were the sole drivers of fire susceptibility. Unfortunately, the small numbers of experimental fires that were con-

ducted in the other studies of this type did not span a wide enough range of conditions to provide an independent test of this assertion.

Our findings provide additional evidence that rates of moisture loss from understory leaf litter are greatly accelerated in disturbed forests (Uhl et al. 1988, Uhl and Kauffman 1990), and for vegetation having shorter, less dense canopies (Uhl et al. 1988), than for intact mature forests. Uhl and Kauffman (1990) monitored leaf litter moisture within four different ecosystem types in the eastern Amazon (mature forest, logged forest gaps, regrowing forest, and pasture) over a period of 14 days following a 2-cm rain event. During that time LMC only fell below 15% (their flammability threshold) at the pasture site, and within canopy gaps at a logged forest. By contrast, seventeen days following a substantially larger rainfall input, our disturbed forests had average mid-day LMC that was equal to (R_{for}), or only slightly above (L/B_{for}) the 15% level. A possible explanation for this discrepancy lies in the fact that they took their measurements at the beginning of the dry season, when ambient RH is generally higher and would act to limit drying, and when LAI may have been higher because of greater soil moisture (Nepstad et al. 1994).

Aspects of fire behavior documented in this study are consistent with limited observations reported in the literature, namely that fire movement within the leaf litter layer is typically slow, and associated flame heights are rather short. Cochrane et al. (1999) reported spread rates of between 0.25 and 0.52 m/min for naturally occurring understory fires they observed in the eastern Amazon in forests that had suffered one to three previous burns, respectively. Experimental fires conducted in the moister Venezuelan Amazon exhibited average spread rates of between 0.17 ± 0.04 and 0.24 ± 0.04 m/min for a regrowing forest ($n = 8$ fires) and within treefall gaps in upland rain forests ($n = 7$ fires), respectively (Uhl et al. 1988); spreading fires at the disturbed forests in this study (R_{for} , L/B_{for}) averaged 0.27 ± 0.01 m/min ($n = 137$). Further, those authors were unsuccessful at starting fires under undisturbed rain forest conditions, which is largely consistent with our experience. Reports of flame heights on the order of tens of centimeters were attributed to initial fires moving through leaf litter in the logged forest understory (Cochrane 2003), and similarly as 21 ± 5 to 24 ± 4 cm tall for experimental fires in regrowing and upland rain forest treefall gaps, respectively (Uhl et al. 1988). Flame heights associated with spreading fires at the disturbed forests were somewhat higher in this study ($R_{for} = 29 \pm 2$; $L/B_{for} = 38 \pm 4$ cm).

Such findings support the notion that the tall, dense canopies of intact forests act to buffer the understory microclimate from the high temperatures and vapor pressure deficits acting on the forest canopy. As this buffering capacity is lost through disturbance (or severe drought), however, understory microclimate begins to

resemble the external conditions, allowing fuels to dry more rapidly, and to lower moisture contents. These conditions correspond to a higher probability of fire occurrence (Fig. 6), and, more intense fire behavior (greater spread rates and flame heights). Conversely, as recovering forests increase in height and canopy density, their resistance to fire is expected to increase.

The establishment of robust fire susceptibility thresholds requires a large number of observations relating the key variables and carried out over a broad range of conditions. Based on observations from two locations in Paragominas, Uhl and Kaufmann (1990) and Holdsworth and Uhl (1997), estimated that undisturbed moist tropical forest vegetation remained resistant to fire for at least two weeks following 2- and 1-cm rain events, respectively, based on their 15% litter moisture threshold. These same circumstances resulted in fire susceptibility in as few as four to five days within large canopy gaps, while regrowing forest was still considered resistant for up to 14 days. By contrast, their regrowth forest would have been considered flammable within approximately one week of the 2-cm rain if this threshold were expanded to the $\sim 23\%$ LMC level detected in this study. Another factor complicating the establishment of any absolute fire susceptibility thresholds is the possibility that they may vary as a function of ambient climatic conditions. For example, if the background RH is relatively high it will take a longer period of time for fuels to arrive at a moisture content where combustion is possible, assuming the RH drops low enough for this to happen. Likewise, it is plausible that sustained combustion can take place at higher LMC if VPD is also relatively high. Some evidence supporting this contention is provided by the observation that all successful fires that took place at $LMC > 23\%$ were also associated with VPD in excess of our 0.75-kPa threshold (Fig. 5c). And in fact, Uhl and Kaufmann (1990) established their LMC threshold early in the dry season (June), while our work was conducted later in the dry season (September–November).

While our study areas do represent a wide range of forest structure conditions, they do not incorporate the full spectrum of conditions present across the landscape. However, by selecting two approximate endpoints (R_{for} and M_{for}), and an intermediate case (L/B_{for}), we were able to span a considerable range. The resulting fire susceptibility thresholds will require validation across a broader range of forest structures. Findings from the present work indicate that the moisture content of fine fuels can vary widely between nearby areas as a function of forest structural controls over the understory microclimate as modified by recent precipitation history (Fig. 4). The ability to discriminate among areas on this basis is of critical importance for quantifying fire risk within this structurally diverse landscape. Other attempts to forecast fire susceptibility in the Amazon have relied on historical relationships between landscape features and fire occurrence ob-

tained from satellite images of anthropogenic landscapes and interviews of landholders (Alencar et al. 2004). This approach is useful for identifying the key features of land use most commonly associated with forest fires in the moist tropics, yet is not guided by any underlying mechanisms per se. Cochrane and Schulze (1999) derived susceptibility estimates for their study sites using LMC thresholds from Uhl and Kaufmann, (1990) as they relate to canopy openness (Holdsworth and Uhl 1997). The water balance-leaf area approach employed by Nepstad et al. (2004) is best suited to assessing vulnerability of mature forest, and therefore may overestimate resistance of disturbed forests. And other fire models are derived from maps of fire occurrence determined using thermal thresholds measured by satellites (Cardoso et al. 2003), but apply primarily to nonforest fires. The utility of these approaches is largely dependent on the assumption that the observed relationships are causal in nature, and unlikely to change over time. A mechanistic understanding of fire behavior provides the necessary foundation for building flexible models of fire risk (e.g., Deeming et al. 1978). Ultimately, we believe that most useful models will incorporate the best features of both approaches, because observational information will still be required to address the critical issues of ignition source in this study system.

Although not measured as a part of this study, other important characteristics of the fine fuel matrix may have contributed to the observed variability in the behavior of these experimental fires. For example, species-level differences in the physical structure of the leaf litter (large vs. small leaves, curled vs. flat edges) influence the amount of air that is able to move across the fuel surface, and thus speed or slow the drying process. Fuel chemical composition may also have a substantial influence on flammability characteristics of understory fuels (Whelan 1995). An extreme example of this is provided by laboratory tests of moisture of extinction, defined as the moisture content of a fuel beyond which combustion is not sustained, carried out on the foliage of 24 Mediterranean species that indicated an extremely broad range of between 40–140% LMC (Dimitrakopoulos and Papaioannou 2001). Our experimental fires appeared more intense where the leaf litter of certain species was abundant (e.g., *Breu resina*, *Tetragastris* sp., Burseraceae).

Further, this study does not directly address the effects of potential edge-related drying on forest susceptibility to fire. Warm, relatively dry air that moves into forest edges from neighboring agricultural lands increase understory VPD and, hence, fuel moisture drying. However, forest edges in the Amazon tend to fill quickly with regrowing vegetation, which diminishes this influence (Kapos 1989). Increased mortality among large trees in close proximity to edges, by reducing canopy cover, may also act to increase forest susceptibility to fire (Laurance 2001). Thus, our results may

underestimate the flammability of forest edges, since our measurements were concentrated in forest interiors.

Climatic factors provide another key input for reliably predicting forest fire behavior across large areas like the Brazilian Amazon. Topographical variation, which represents a significant consideration in mountainous terrain, is modest within this landscape, and is therefore expected to have limited bearing on fire behavior here. In regions like this where precipitation is strongly seasonal, conditions favorable to fire propagation are concentrated during the dry season, when soaking rains are much less frequent, cloud cover is reduced, and the moisture content of the air is lower. Uhl et al. (1988) encountered conditions that allowed fire propagation within an aseasonal rain forest environment in the Venezuelan Amazon, but this was only true for shorter and less dense vegetation types and within canopy gaps in the tall dense-canopied forest. Further, the climatic conditions that gave rise to those “windows of opportunity” were relatively infrequent based on examination of a long-term climate record.

Accurate predictions of fire risk depend on an appropriate characterization of the fuels available for combustion (Burgan et al. 1998). The present research was focused on one key component of the rain forest fuel matrix—the spatially contiguous leaf litter layer. A justification for having taken this approach is provided by the observation that understory fires need not be intense to cause severe damage to the moist tropical forest vegetation because of the thin bark of many tropical forest trees and the relatively long residence times associated with slow moving ground fires (Uhl and Kaufmann 1990, Cochrane et al. 1999, Barlow et al. 2003). Coarser fuel categories appear to play an important role in maintaining smoldering fires during periods when climatic conditions are unfavorable for active fire spread through the leaf litter (e.g., at night when RH is higher) (Cochrane et al. 1999). The abundance of coarse fuels in the forest understory increases with logging intensity (Cochrane and Schulze 1999, Gerwing 2002), and these may dry out to the point of supporting more severe fires as a consequence of the associated reductions in canopy cover.

The amount of time during the 2002 dry season (July–December, 184 days) that each of the critical precipitation levels identified in our logistic model of fire risk were present increased exponentially as canopy height and LAI declined. So, while the tall dense canopied forest structures maintained a high level of fire resistance throughout the dry season, the shorter less dense canopies were vulnerable most of the time. For example, a 20 m tall forest canopy having LAI = 4.5 (MC-ML) was vulnerable during ~70% of the dry season, and forests represented by the most disturbed canopy structure combination (SC-LL) were vulnerable for >80% of the time. Providing a source of ignition is available, a common feature of actively developing landscapes, it appears that even modest alterations to

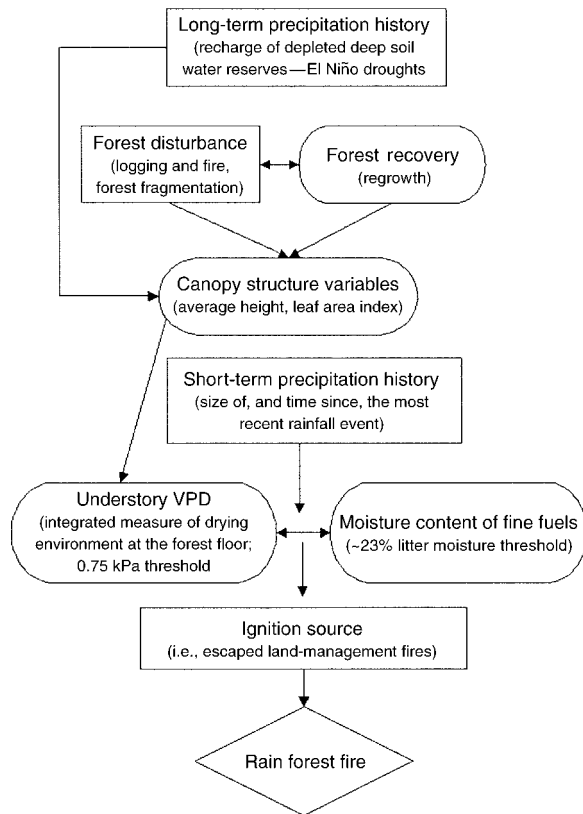


FIG. 7. Mature forest canopies exert strong control over understory microclimate, conferring fire resistance in seasonally dry rain forest environments. When these controls (oval-shaped boxes) are compromised by external factors (rectangular-shaped boxes) like extreme drought (e.g., El Niño cycles), selective logging, and fire, and perhaps through forest fragmentation, this capacity becomes diminished. Disturbed canopies allow conditions in the forest understory to become coupled with the external environment, and the leaf litter and air can dry to the point at which sustained combustion is possible. Once this internal regulation mechanism is lost, short-term precipitation history and ignition sources become the primary determinants of fire susceptibility.

canopy structure can put these forests at high risk of burning under moderately severe dry season conditions.

The flammability of forest understories in the east-central Amazon is regulated by long- and short-term rainfall patterns, forest height, and canopy density (LAI), as summarized in Fig. 7. Long-term precipitation history determines deep soil water content, which regulates LAI and, hence, the amount of radiation that reaches the forest interior. Seasonal recharge of the deep soil water that these forests depend on to maintain dense canopies during the dry season is prevented during periods of severe drought (e.g., ENSO years) (Nepstad et al. 2004). The flammability of disturbed forests is the dynamic outcome of processes that reduce LAI and forest height (logging, fire) and those that restore LAI and height (R_{for}). Short forests with low LAI are

more susceptible to fire than tall forests with high LAI because of the critical role of the canopy in buffering the forest interior from the hot, dry conditions of the external environment. Recent precipitation events, however rare during the dry season, confer fire resistance to all forest types, but for periods of time that are inversely related to the degree of structural alteration. The likelihood of fire-susceptible forests igniting is highest in landscapes where swidden agriculture and cattle ranching are prevalent (Nepstad et al. 2001). Forest fires are largely accidental in the Amazon, and programs to prevent them are being tested. By quantifying the important relationships between forest structure and understory microclimate this study provides a basis for improving fire susceptibility modeling in the Amazon Basin.

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