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Fire and soil temperatures during controlled burns in seasonally dry tropical forests of southern India

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Fire and soil temperatures were measured during controlled burns conducted by the Forest Department at two seasonally dry tropical forest sites in southern India, and their relationships with fuel load, fuel moisture and weather variables assessed using stepwise regression. Fire temperatures at the ground level varied between 79°C and 760°C, with higher temperatures recorded at high fuel loads and ambient temperatures, whereas lower temperatures were recorded at high relative humidity. Fire temperatures did not vary with fuel moisture or wind speed. Soil temperatures varied between < 79°C and 302°C and were positively correlated with ground-level fire temperatures. Results from the study imply that fuel loads in forested areas have to be reduced to ensure low intensity fires in the dry season. Low fire temperatures would ensure lower mortality of above-ground saplings and minimal damage to root stocks of tree species that would maintain the regenerative capacity of a tropical dry forest subject to dry season wildfires.

Keywords: Biligiri Rangaswamy Temple Wildlife Sanctuary, fuel load, fuel moisture, Mudumalai Wildlife Sanctuary, temperature indicating lacquers, weather.

OF the various aspects of fire regimes in natural ecosystems, varying intensity and severity of fires[1] are known to affect soil properties and below-ground processes[2], plant species demography[3,4] and plant community structure[5]. In a comparison of the effects of low and high intensity fires on soil properties in dry forests of Bolivia, lower levels of soil organic matter as well as altered physical properties were found after a high intensity burn, but such changes were not observed after low intensity fires[6]. The high post-fire mortality in small-sized individuals of tree species in seasonally dry tropical forest[7] could be due to high intensity fires, as observed for resprouts of a chapparal shrub species[3], and juveniles and saplings of Australian savanna tree species[4] after high intensity fires during experimental burns. Dissimilar floristic composition between plots burnt at differing intensities at sandstone woodland and shrubland sites in Australia[5] was due to an increase in the number of fire-tolerant species in plots subjected to high intensity burns. It is therefore important to characterize fire intensities for a region to assess the potential impact on the ecosystem and design appropriate fire management plans.

Fire temperature is one such measure of fire intensity[8] influenced by factors such as fuel load, fuel type, fuel moisture and weather conditions[9–13]. While a definite relationship of increasing fire temperature with increasing fuel loads has been established in many cases[6,9,11,12,14], the relationship between fire temperatures with fuel moisture is unclear. For example, a strong positive correlation of fire temperature with fuel moisture was reported in a study in mixed grassland sites in Texas[9], whereas another study in Texas conducted in grassland sites dominated by an invasive shrub (*Prosopis glandulosa*) did not find any correlation[12]. Fire temperatures were not correlated with wind speed in most studies[9,12,13], as well as with relative humidity[9,12], whereas ambient temperatures appeared to have an effect on fire temperatures in one study[9], but not in another[12]. However, all of the studies cited so far have examined the effect of the variables considered on fire temperature as single correlations. The combined effect of these factors on fire intensity in natural ecosystems has, yet, not been assessed. A multiple regression framework would allow an assessment of which variables are important in influencing variations in fire temperature.

In the present study we assess the combined effect of fuel load, fuel moisture and weather parameters on

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ground-level fire temperatures in seasonally dry tropical forest sites in southern India. We ask the questions: what are the variables that would explain variation in fire temperature recorded at the soil surface, and how does this relationship change with these variables? We also examine if soil temperatures 1 cm below the ground are related to fire temperatures recorded at ground level.

Data were collected during 19 days between 9 February and 12 March 2010 at two reserves in southern India – Mudumalai Wildlife Sanctuary in Tamil Nadu and Biligiri Rangaswamy Temple (BRT) Wildlife Sanctuary in Karnataka. During the dry season every year, Forest Department staff typically set fire to vegetation in 5–10 m strips along the roadside within these reserves. This controlled burn is done to extend the roads as effective fire-breaks in the event of an accidental fire outbreak. During the controlled burns, fire temperatures were measured using temperature-indicating lacquers (Tempil) ranging between 79°C and 927°C at approximately 50°C intervals (18 lacquers in total). For lacquers that are affected by fire melt, a change in texture was observed on cooling. The lacquers were painted onto 5 cm × 5 cm mica sheets. A mica cover sheet was placed on top of each painted sheet. Points along the road were selected for placing the sheets before the Forest Department staff set fire to vegetation along the roadside. One set was placed at ground level and another placed 1 cm below the soil. Ground-level temperatures are a measure of the heat released during a fire based on surrounding vegetation. Below-ground temperature is a measure of the heating up of soil during a fire. A wooden peg was placed close to the temperature measurement point to indicate the location of the lacquers. The time the fire front passed over the sheets was noted and the sheets observed for the temperature range affected. Vegetation (grass, herbs) was harvested and leaf litter collected from 1 m × 1 m quadrats set as close as possible to the temperature measurement point. Fuel load was estimated as the dry weight of these biomass samples (oven-dried until constant weight). Fuel moisture was calculated as the difference between the fresh and dry weights of biomass samples, expressed as a percentage of oven dry weight.

Weather conditions were measured using a Kestrel 4000 pocket weather meter. Variables measured were relative humidity (RH), ambient temperature and wind speed with readings recorded at 20 s intervals. The measurements were taken at a distance from the fire front (at least 50 m away). It was assumed that at this distance fire would not influence the readings recorded by the weather meter. RH, temperature and wind speed were averaged for 13 readings around the time that the fire front passed over the lacquer (6 before, 1 inclusive and 6 after).

A total of 142 measurements were taken at various times in the day between 10 am and 5 pm, out of which fire did not pass over 6 points. One point had extremely high total fuel moisture content due to a high load of *Chromolaena odorata* twigs in the litter. Since this point was an outlier in the range of data values, it was excluded from the analysis. Correlations of fire temperatures with fuel load, fuel moisture, RH, temperature and wind speed were investigated for 135 points using Pearson's correlation (in order to compare results with other fire temperature studies[9,12,13]). The effect of total fuel load, total fuel moisture (of live and dead fuels), RH, temperature and wind speed on ground-level fire temperatures was assessed using a linear regression model. The variables that contribute to explaining the variance in fire temperatures were assessed through stepwise deletion of terms from the model using F-tests at $\alpha = 0.05$ (ref. 15). Since RH and temperature were positively correlated ($r = -0.78$, $P \ll 0.001$), both variables were treated as a single variable in the model. Pearson's correlation between all other independent variables was less than 0.3; hence they were retained for testing in the regression analysis[16].

Maximum fire temperatures recorded at ground level ranged from 79°C to 760°C, and soil temperatures ranged from < 79°C (no lacquers were affected) to 302°C (Figure 1). The most frequently recorded temperature ranges at

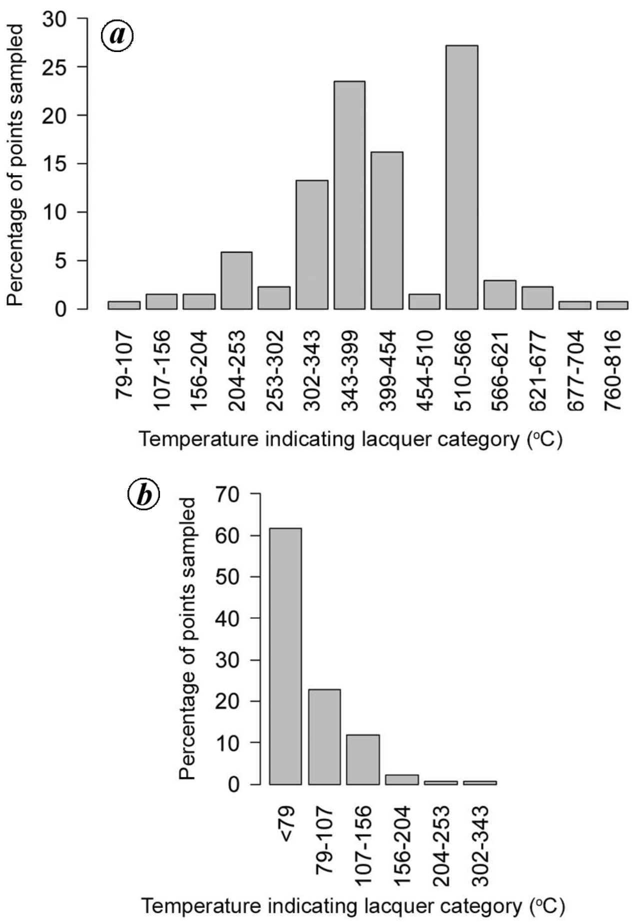

Figure 1. Frequency distribution of maximum fire temperatures recorded at (***a***) ground level and (***b***) 1 cm below the ground. The categories of temperature (°C) indicating lacquers are on the x-axis of each graph.

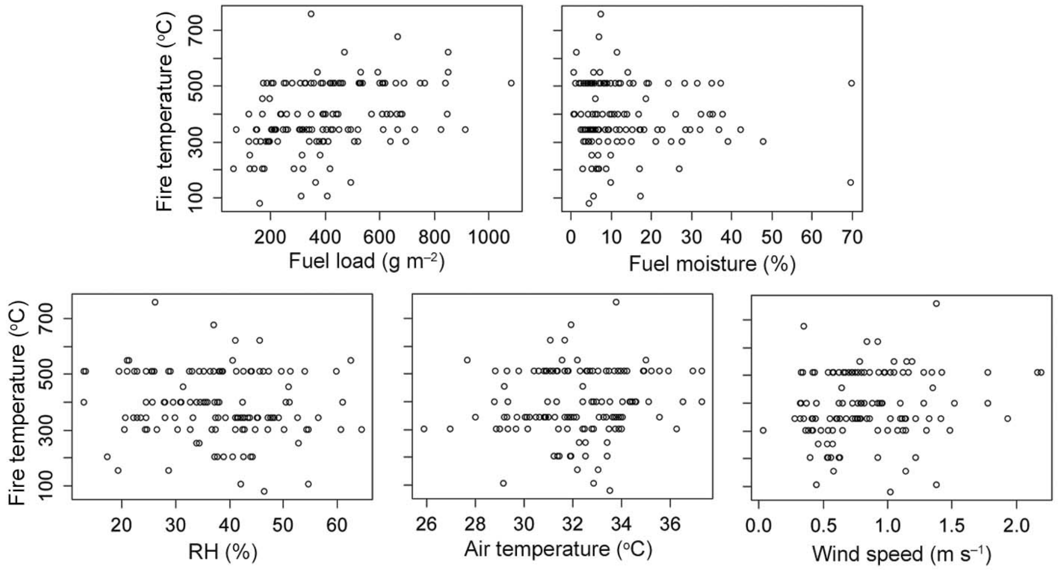

Figure 2. Scatterplots of fire temperature with each of the variables – total fuel load, total fuel moisture (live and dead fuels together), relative humidity (RH), ambient air temperature and wind speed.

ground level were at 343–399°C and 510–566°C. Temperatures recorded 1 cm below the ground were skewed to a lower range, with the most frequently affected temperature lacquer being the < 79°C category. Approximately 90% of the points sampled below ground recorded temperatures < 156°C.

Dry weight of biomass sampled ranged from 63 to 1081 g m^{-2}. Fuel at a majority of the points sampled consisted of leaf litter; 81% of the points sampled had more than 50% litter compared to 15% of the points that had more than 50% grass. Leaf litter at Mudumalai was mostly of *Tectona grandis*, and at BRT, *Anogeissus latifolia*. A few sample points were at places where the exotic invasive shrub *Chromolaena odorata* was present (six points). Total fuel moisture (live and dead fuels together) ranged between 0.5% and 86% of the oven dry weight of total biomass. However, 75% of the samples had fuel moisture that was 17% or less, and 95% of the samples had moisture content that was 37% or less. High fuel moisture in a few samples was mostly due to the high water content in *C. odorata*, which ranged between 115% and 188%. RH at the time of the controlled burns varied from 13% to 65%. Ambient air temperatures ranged from 25°C to 37°C. Wind speeds ranged from 0.03 to 2.2 m s^{-1}.

Ground-level fire temperatures were positively correlated with total fuel load ($r = 0.35$, $P \ll 0.001$, $n = 135$) and wind speed ($r = 0.17$, $P = 0.05$), and negatively correlated with RH ($r = -0.17$, $P = 0.05$). Fire temperatures were not correlated with total fuel moisture or ambient temperature ($P = 0.32$ and 0.17 respectively; Figure 2). Soil temperatures 1 cm below the ground were positively correlated with fire temperatures at ground level ($r = 0.22$, $P = 0.01$). From the stepwise deletion of terms in the linear regression, the variables total fuel load, RH and temperature were retained, and the variables total fuel moisture and wind removed from the model. Fire temperatures were higher at higher fuel loads and ambient temperature, whereas lower fire temperatures occurred at higher RH (Figure 3).

Fire temperatures recorded at the ground surface during controlled burns in the present study were similar to those measured in experimental burns using similar fire temperature indicators in the dry deciduous forests of central India[17] and Thailand[10]. Fire temperatures between 45°C and 510°C were reported for leaf litter burns with fuel loads of approximately 400 g m^{-2} in the study in central India, with the 399°C indicator having the largest proportion affected in two out of three years of the study[17]. A mean of 404°C (range 275°C to 700°C) was recorded at ground level during experimental burns conducted in leaf litter-dominated areas in Thailand (biomass values were not reported in the study)[10]. Grassland fires also have similar temperatures; experimental burns in the grasslands of Tanzania's Serengeti[11] produced temperatures between 407°C and 830°C from burnt fuel loads of 101–1064 g m^{-2}. Air temperatures during a fire ranged from 85°C to 350°C 1 cm above the ground in different cerrado vegetation types of central Brazil[18]. Average fire temperatures measured at ground level at prairie sites in Florida[19] using similar temperature indicators as in this study ranged from 107°C to 213°C for biomass that ranged between 340 and 1010 g m^{-2}. In contrast, the maximum fire temperature recorded in dry eucalypt forests of southwest Australia[13] was approximately 1100°C near the ground (their lowest measurement was at 0.5 m amsl) with surface and near-surface fuels that ranged between 8.6 and 22.1 t ha^{-1}.

As in this study, high fire temperatures have been recorded for large fuel loads at other sites as well[9,11,12,20]. The highest temperature of 700°C in the Thailand study[10] was recorded at a site with a litter layer of substantial depth. In the present study, the highest temperatures were not associated with the highest fuel load, but some points within abundant *Tectona* leaf litter registered temperatures between 621°C and 677°C. Although there was no correlation of flame temperatures with total surface and near-surface fuel load from experimental burns in dry eucalypt forests of Australia, there was a negative correlation with bulk density[13]. The authors attribute this to relative position of the thermocouple within the flame that passed through the experimental site. This might be a factor in this experiment, which was not measured. Flame angles[21] may be different for different fires depending on wind conditions and the slope of the terrain where the burn takes place[22]. Hence, the temperature recorded by the indicators might depend upon which part of the flame is exposed to the fuel, pre-heating the fuel[9] which is then registered as higher temperature by the temperature indicator. Another factor to be considered is that the fuel load measured pre-fire is the 'potential' fuel available for burning[22] and how much biomass has been consumed during the fire is a factor that would subsequently determine fire temperature[11].

In this study, fire temperatures were not correlated with total fuel moisture (live and dead fuels together) as in other studies[12,13], neither was fire temperature correlated with the moisture content of dead fine fuels alone, which was leaf litter in this case ($r = 0.1$, $P = 0.25$). Fuel moisture is more of a determinant of how flammable the fuels are. This parameter would be most important in determining the potential for fires to ignite and then spread[22]. At Mudumalai, forest fire watchers who set the control burns wait until the right time of the day (approximately 10 : 30 or 11 : 00 am), when 'temperatures are higher', that would ensure the fuels are dry enough to ignite, pointing to a presumption that fuel moisture plays a part in ignition. Fire temperatures were correlated with RH of the ambient atmosphere in the present study, and this also turned out to be a factor that explains a part of the variation in fire temperatures in the linear regression. This could probably be due to the absorption of heat radiated from the fire by higher moisture in the atmosphere. Higher RH in the atmosphere would also mean that moisture from the fuels, although heated, might not evaporate to the atmosphere too quickly. Cooler air is usually pulled in through convection at the base of a flame[22], and if the cooler air is moist, it might lower fire temperatures.

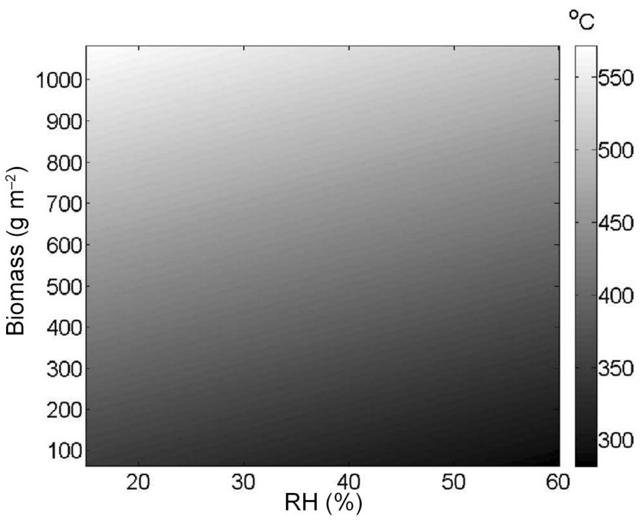

Figure 3. Estimated fire temperatures as a function of fuel load (biomass) and relative humidity (RH) using the final model: fire temperature ~ 188.8 + (0.22 * fuel load) – (1.46 * RH) + (5.16 * temperature). The greyscale key to the right represents the estimated fire temperatures given a certain fuel load and RH when ambient air temperature was held constant at the mean value of the range of temperature measurements in the dataset (32.3°C).

Soil temperatures recorded in this study, although positively correlated with ground-level fire temperatures, show a large difference from ground-level measurements. Other studies report similar results; below ground at 5 cm depth soil temperatures were always less than 75°C in experimental burns of the dry deciduous forests of Thailand[10]. During experimental fires in the cerrado of Brazil, soil temperatures recorded ranged from 29°C to 38°C at 2 cm depth, with a temperature of 55°C recorded at 1 cm depth[18]. Maximum temperatures recorded in experimental burns in eucalypt forests of southeast Australia were approximately 30–110°C at around 1 cm depth below the ground[23]. This illustrates the insulating role of soil, and the benefit that plant roots and meristems afford from this insulation. This might be a factor in the persistence of plants in these forest types, where sprouting from a non-damaged root stock is a common feature[24].

Monitoring of fire temperatures would be useful to assess its impacts on vegetation in seasonally dry tropical forest types. Results from this study suggest that ground-level fire temperatures increase with higher fuel loads, implying that ignitable fuel loads would have to be reduced in order to reduce the intensity of a fire. Fuel loads can be reduced both through natural and artificial means. Maintaining abundant populations of wild mammalian grazing herbivores would naturally keep the biomass of grasses at lower levels[25]. Grazing by domestic livestock in tropical dry forests would also have played a similar role, though they are now mostly excluded from protected areas in view of their potential to degrade forest ecosystems[26], transmit diseases to wild herbivores[27] and compete with them for resources[28]. Collection of grass by local communities for use as fodder[29] and thatch, a practice common in the past, but discouraged today in protected forests[30], would also have served to keep this fuel source low. Controlled burning of the understorey of dry forests has also been practised in the past by local communities[31] and also as part of forest management[32,33].

This practice would need to be revisited for effective fire management in seasonally dry tropical forests.

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