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Experimental assessment of forest flammability after selective logging in the Brazilian Amazon

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Tropical forests, strongholds of biodiversity and carbon storage, face increasing threats from selective logging and fires. Selective logging disrupts forest structure, leaving canopy gaps where commercially valuable trees once stood, potentially increasing fire susceptibility through heating and drying understorey microclimates and altering fuel conditions. Here, we empirically examine the effects of selective logging on microclimate and flammability in the Brazilian Amazon. Using a controlled fire experiment during the first dry season post-harvest, we found that logging gaps were hotter and drier than surrounding forests, with larger gaps showing steeper temperature gradients. Leaf-litter moisture, a strong predictor of ignition, was modestly lower in gap centres. Despite this spatial variability in fuel moisture, the propensity of fuels to catch and sustain fires consistently increased as the dry season advanced, suggesting the selectively logged mosaic may be uniformly vulnerable to fire once exposed to ignition sources. These findings suggest that selective logging does not act alone in driving fire risk, with seasonal drying and ignition sources also contributing to increased vulnerability. These results highlight the importance of ignition suppression in post-logging management of forests that continue to hold substantial conservation value, including biodiversity and ecosystem services, as dry seasons intensify under climate change.

Tropical forests safeguard biodiversity, store globally important carbon reservoirs, and provide key ecosystem services, including regional to global climate regulation[1,2]. Despite their conservation value, these forests endure escalating pressures from human activities, such as deforestation for pasture and croplands[3], compounded by other disturbances such as selective logging, fires and prolonged droughts[4–6]. Selective logging—the removal of specific commercially valuable trees while leaving most of the forest unharvested—is one of the most widespread forms of tropical forest disturbance and a growing driver of degradation globally[7,8]. Even though the harvest targets specific trees, the logging process causes substantial collateral damage to vegetation structure, changes tree community composition[9], compacts forest soils[10], and alters forest microclimates[11]. Taken together, these disturbances can change the forest from a carbon sink to a carbon source for at least a decade[12]. However, robust environmental regulation, combined with reduced-impact logging techniques, can greatly decrease the degree of damage caused by these operations[13,14].

Selectively logged forests are often considered degraded ecosystems, primarily because of their altered structure and decreased biomass, but there is increasing evidence that these ecosystems still hold valuable biodiversity, carbon stocks, energy flows, and vital ecosystem services[15,16]. These studies highlight the importance of preventing further disturbances (e.g., repeated logging and fire incursions) to allow the recovery of ecosystem structure and function, and prevent further degradation or conversion to other land uses[1 7–19]. While the impacts of selective logging on tropical forests can be substantial by themselves, forest fires can compound these effects, especially in environments like the Amazon, where vegetation is not adapted to fire[20].

Historically, fire in the Amazon rainforest was rare, with return intervals of hundreds or thousands of years[21,22], yet anthropogenic pressures such as land-use and climate change are dramatically altering

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fire regimes[23,24]. Extreme droughts, rather than expected seasonal drying, have been identified as a key driver of fire occurrence in the region, especially in the southwestern Amazon[25–27]. In parallel, the clearing and burning of biomass associated with land conversion for agriculture introduces ignition sources, creating opportunities for fires to escape into adjacent forests[28]. Tropical forest fires reshape community composition, reduce species richness[29], promote local extinctions[30], have profound effects on human health[31] and forests' economic value[6], all while amplifying climate change through carbon emissions both via immediate release as well as delayed mortality of vegetation for years after the fire[32,33].

Undisturbed, closed-canopy tropical rainforests typically maintain humid microclimates, making it unlikely for forest fires to sustain and spread under baseline climate conditions[20,34]. The selective harvest of trees disrupts the forest canopy, damaging its structure and creating gaps that expose the forest interior to wind and sunlight, affecting the understorey microclimate. Additionally, logging operations can increase fuel loads by producing woody debris from collateral damage to unharvested forest vegetation. Thus, selective logging can potentially increase the susceptibility of forests to fire through various mechanisms. Understanding the complex interplay between selective logging and fire is essential for effective forest management and conservation of tropical ecosystems, but determining the flammability of a hyper-diverse tropical forest presents several challenges. For example, available fuels may be composed of a mixture of species with different chemical and physical properties[35]. Furthermore, ignition sources from human activities vary in space and time, and a changing climate brings new extremes and unprecedented fire-prone climatic conditions[36]. Field observations and controlled experiments are critical to improve our understanding of the complex processes that are likely to act synergistically to increase a forest's vulnerability to fire. Despite their potential negative effects on forest integrity and functioning, few studies have empirically established and quantified the extent to which gaps and edges associated with selective logging affect the forest understorey microclimate and their interaction with forest flammability. This study aims to investigate whether and how selective logging alters the understorey microclimate of the remaining (i.e., unharvested) forest stand and increases its susceptibility to fire. We focus on a selectively logged forest in the southwest Brazilian Amazon, 1 year post-harvest, under mid-day dry season conditions. By focusing on the first dry season following harvest, we captured peak flammability conditions, as residual vegetation from harvest had time to desiccate, while limited regrowth meant there was not yet enough new vegetation to provide shading. Our flammability experiment explores: (1) the extent to which selective logging affects the understorey microclimate in gaps and the surrounding unharvested forest; and (2) how logging gaps affect forest flammability over time at the onset of the dry season. Logging gaps were hotter and drier than the surrounding unharvested forest (Fig. 1), creating modestly drier fuel conditions (Fig. 2a) that could increase fire susceptibility, as moisture content has proven to be an important predictor of ignition (Fig. 2b). Despite the spatial variability of fuel moisture and desiccation rates between gap centres and the surrounding forest, the ease with which fuel was able to catch and sustain a fire consistently increased throughout the landscape as the dry season progressed (Fig. 3), indicating that a selectively logged landscape may be uniformly vulnerable to fire once exposed to an ignition source at any given time during the dry season. Therefore, dry season progression was the strongest driver of flammability by reducing ignition delay and extending flame persistence, highlighting the critical role of climatic conditions on fire risk across selectively logged landscapes. These findings emphasise the importance of thoughtful harvest planning to minimise collateral damage to the vegetation structure and stringent ignition suppression policies for fire mitigation in selectively logged areas to conserve their biodiversity and critical ecosystem functions and services amid intensifying climate pressures.

Results

Gap effects on the understorey microclimate

During the hottest hours of the day (11:00 h to 15:00 h), both ambient temperature ($p = 0.01$, Fig. 1a) and maximum surface temperature ($p < 0.01$, Fig. 1b) declined with increasing distance from logging gaps. The strength of the relationships depended on logging gap size, with mean ambient air temperature dropping 1.10 °C (95% CIs = 0.82–1.38 °C), 0.90 °C (0.70–1.09 °C), and 0.48 °C (0.03–0.93 °C) with every 10 m into the forest around large, medium, and small logging gaps, respectively. Similarly,

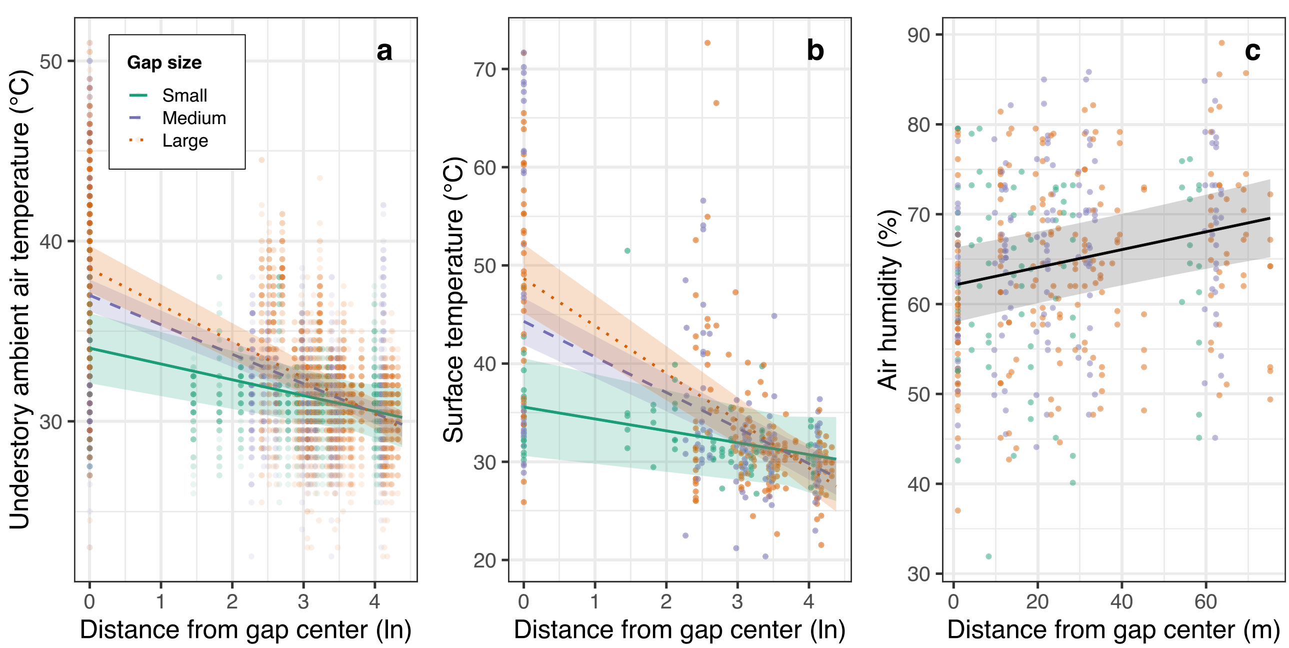

Fig. 1 | Influence of selective logging on the understorey microclimate in gaps and surrounding unharvested forests. Raw data (points) and fitted values (lines) with confidence intervals (shade) of each metric of understorey microclimate: air temperature (**a**), maximum surface temperature (**b**), and relative air humidity (**c**). Observed relationships can vary with logging gap size (line types and colours) and distance from gap centre (*x*-axis).

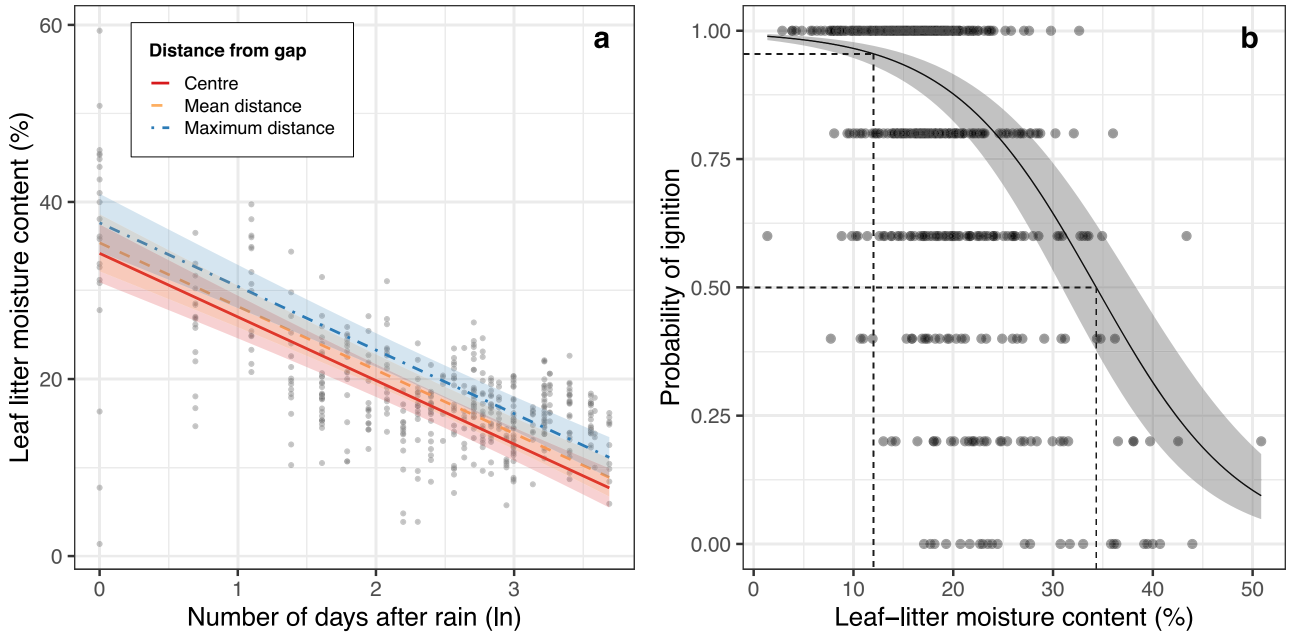

Fig. 2 | Fuel moisture in logging gaps and surrounding unharvested forests and its influence on ignition. Raw data (points) and fitted values (lines) with confidence intervals (shade) of: leaf-litter desiccation rate represented by change in moisture content with time since the last rainfall event (*x*-axis) and distance from gap centre (line types and colours) (**a**), and the probability of ignition determined by leaf-litter moisture content (**b**).

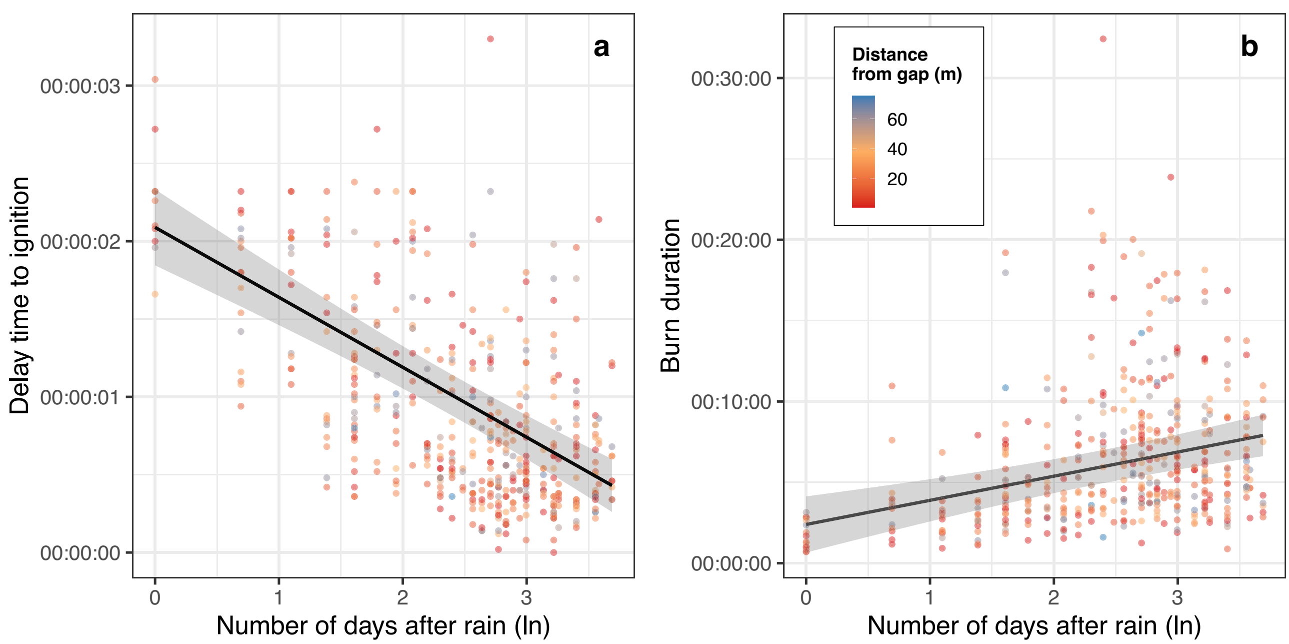

Fig. 3 | Fuel flammability across the dry season. Raw data (points) and fitted values (lines) with confidence intervals (shade) of delay time to ignition representing fuel ignitability (**a**) and burn duration representing fire sustainability (**b**). Colours represent distance from the gap centre.

maximum surface temperature dropped 2.64 °C (95% CIs = 1.88–3.40 °C), 1.98 °C (1.45–2.50 °C), and 0.66 °C (−0.49 to 1.81 °C) with every 10 m into the forest around large, medium and small logging gaps, respectively. The centres of logging gaps were both hotter and drier than adjacent forests, with air humidity increasing progressively with distance into the forest interior (0.1%, ±0.02 $p < 0.01$, Fig. 1c), irrespective of gap size.

Gap effects on forest flammability

Mean leaf-litter moisture content declined with time since the last rain, dropping at a rate of −7.18% with every unit (ln) increase in days since rain (±0.57; $p < 0.05$, Fig. 2a), irrespective of logging gap size. Moreover, leaf-litter moisture content was positively associated with distance into the forest interior, with a 4.6% increase in moisture content observed with every 10 m into the forest (±0.83; $p < 0.001$). Finally, the probability of ignition was strongly affected by moisture content, with an increase from ~50% probability of ignition under initial saturation condition to ~100% probability by day 40 at the end of the experiment (Fig. 2b). Logging gap size and distance into the closed-canopy forest interior had no measurable effect on the delay time to ignition. In contrast, days since rain markedly decreased the delay time to ignition, with fires igniting ~0.5 s faster for every unit (ln) of increase in days since rain ($\beta = -0.45 \pm 0.04$, $p < 0.05$; Fig. 3a). Likewise, burn duration was not affected by gap size or distance into the forest but increased with time since rain. We estimate a 1.5-min increase in flame duration with every unit of increase in days since rain ($\beta = 89.5 \pm 18.2$ s, $p < 0.01$; Fig. 3b). Finally, none of the variables affected combustibility.

Discussion

Selective logging has the potential to increase fire risk in tropical forests—by canopy disturbances associated with fallen trees and logging roads altering the understorey microclimate, and increasing fuel loads due to the accumulation of woody debris during harvesting activities[19,37,38]. This empirical study investigated these dynamics in a selectively logged forest in southwestern Amazonia to better understand the processes by which selective logging can drive fire susceptibility in tropical forests 1-year post-harvest—a period likely representing peak flammability conditions. We found that selective logging creates hotter and drier conditions within logging gaps and the surrounding forests, with larger gaps exhibiting higher temperatures and steeper gradients from the gap edge into adjacent areas of closed-canopy forest. Hotter and drier conditions reduced fuel moisture content, with gaps centres having slightly lower fuel moisture than surrounding forests, a pattern that persisted as fuels progressively dried out during the dry season. Despite this spatial variability in fuel moisture content, we found that time since the last rainfall event (reflecting the progression of the dry season) was the strongest predictor of both ignitability and sustainability of fire. Our study found that neither gap size nor distance from gap edges influenced the ease with which fuel ignited and sustained fire once exposed to an ignition source. Thus, the increased vulnerability of selectively logged forests to fire is likely driven by a combination of factors, including greater exposure to ignition sources—often associated with heightened human activity in production forest landscapes—and climatic variation, such as changes in rainfall patterns and temperature, all of which can collectively increase fire risk.

Gap effects on the understorey microclimate

Previous studies have shown that the thermal environment of selectively logged tropical forests can recover to primary-forest levels within a decade in Borneo[39] and five years in the Brazilian Amazon[11]. However, these studies did not examine the spatial distribution of the impacts of logging gaps, nor the influence of gap size. Our study addressed these limitations, finding that, 1-year post-harvest, larger gaps lead to higher temperatures, an effect that extends at least 40 m from gap edges into the surrounding forest (Fig. 1). The size of logging gaps reflects the severity of canopy disruption and the degree of damage to the vegetation structure, outcomes that are determined by the intensity of logging (volume of timber harvested) and the specific management practices employed[13,40]. Notably, even the largest gaps in our study were the product of reduced impact logging (RIL) techniques, by a logging company adhering to legally set timber volume offtake quotas for the region. Therefore, it is reasonable to infer that our study conditions are conservative and do not encompass the most severe impacts of selective logging on forest structure across the Amazon. Indeed, vast areas of the Amazon are subject to illegal and unplanned logging activities[41], which, according to our results, can increase susceptibility to fires both by impacting thermal environments and increasing ignition sources, suggesting that the broader situation could be worse than described here.

Gap effects on forest flammability

Hotter and drier microclimates within logging gaps contributed to a decrease in leaf-litter moisture content. This decrease was a consistent feature of logging gaps of all sizes, indicating a uniform vulnerability of fuel loads to drying, regardless of gap dimension. Additionally, moisture content increased from the gap edges towards the forest interior, demonstrating the forest's capacity to moderate the microclimate and promote moisture retention. Moisture levels establish flammability thresholds, which are critical in determining the risk of fire spread. Studies in eastern Amazonian forests have established thresholds of 12% and 15% fuel-load moisture content, below which fuel can ignite and fire can spread[34,42]. Our study in southwestern Amazonia, where the forests naturally exhibit a more discontinuous canopy, predicted a 95% and 93% chance of ignition at these thresholds, respectively. Even under near-saturated moisture conditions, leaf litter in our study still had a 10% chance of igniting when exposed to an ignition source for at least 3 seconds, suggesting that the established flammability thresholds for eastern Amazonia may not provide safe limits for fire risk in other parts of the Amazon. This understanding of moisture content and its impact on fire risk in different regions of the Amazon underscores the need to consider how the surrounding vegetation and environmental conditions influence forest flammability. The edge effects observed in our study as a result of selective logging are different from the typical edge effects seen along hard edges at the interface of forest and agricultural land (e.g., pasture or crop). Studies conducted in southern Amazonia and the Xingu region have demonstrated that these hard edges promote potent effects, substantially altering forest flammability[20,43,44]. Moreover, the type of surrounding landscape can lead to the invasion of grasses, which serve as fine fuels that burn intensely and rapidly, thereby increasing the likelihood of fire penetrating into the forest and facilitating its spread[45]. The softer and more variable edges associated with selective logging likely affect forest flammability differently, influenced by the complex vegetation matrices in these logged landscapes and their buffering capacity. We found that neither the size of logging gaps nor the distance into neighbouring closed-canopy forests had a measurable impact on ignitability. However, as expected, time since the last rainfall played a marked role, with fires igniting more quickly as the dry period extended. Similarly, while gap size and distance into the forest did not influence burn duration, the length of time since the last rainfall measurably prolonged flame persistence. This pattern suggests that the entire landscape becomes increasingly susceptible to fire as the dry season progresses, highlighting the critical role of climate—particularly the duration of dry seasons—on the moisture content of fuel loads, irrespective of the nature of logging activities. This is especially pertinent in light of severe weather events, such as prolonged droughts and extreme heatwaves, which can synergistically interact with logging practices to amplify forest vulnerability to fires[46,47]. Our findings emphasise the importance of suppressing ignition sources within and around production forests as a strategy for reducing fire risk. The combustibility metric, which relates to fire intensity and was measured in this study as the rate of biomass burned per second, showed no variation over time (days after the last rainfall event) or across space (from gap edge to forest interior). However, it is reasonable to infer that drier fuel, which ignites quickly and sustains fire for longer, would lead to more intense fires that consume greater amounts of biomass. This suggests that our study design, which used small samples and controlled conditions akin to a laboratory setting for the burning exercise, may not have effectively captured this fire intensity metric (i.e. combustibility). Conducting fire experiments over a larger area or with more fuel might be more effective for accurately assessing fire intensity in forest landscapes[48]. Our experimental results demonstrate that selective logging alters microclimate conditions and reduces fuel moisture. However, we acknowledge the limitations of extrapolating findings from controlled experiments to landscape-scale fire dynamics in a complex system such as the Amazon. Our study was conducted during a typical dry season using a controlled, laboratory-like experimental setup, and therefore likely represents a conservative scenario. Fire occurrence in tropical forests is influenced not only by fuel flammability, but also by the presence of ignition sources and the broader climatic context, including the severity and duration of drought events[33,49]. Additional landscape-level variables such as deforestation, fragmentation and surrounding land-use types can interact in ways that further drive fire risk and behaviour[6,28]. Nonetheless, by isolating the microclimatic and fuel-related effects of logging gaps, our findings provide mechanistic insights into how forest flammability may be amplified under more extreme or heavily disturbed conditions.

Conclusions

Recent research has revealed the increased vulnerability of ostensibly "intact" tropical forests to severe degradation resulting from various disturbances[5,6,50]. Compound impacts from disturbances like selective logging and fire under a changing climate may trigger a cascade of degradation, leading to widespread tree mortality and increased flammability[51,52]. Understanding the interconnected factors that enhance fire susceptibility and spread is crucial to inform effective fire-management policies, and one-size-fits-all approaches have proven insufficient[53]. Selectively logged forests have heightened fire risk, characterised by increased fuel loads, modified microclimates that promote fuel desiccation, and an increased likelihood of ignition from human activities enabled by the access to the forest that logging operations inherently create. Our study demonstrates that selective logging compromises the natural buffering capacity of otherwise closed-canopy forests by accelerating fuel load desiccation. Therefore, in areas where selective logging is deemed necessary, management should prioritise strategic and thoughtful harvest planning, including RIL techniques, to minimise structural damage. More critically, our findings demonstrate that even typical dry-season climatic conditions render selectively logged landscapes uniformly vulnerable to fire once exposed to an ignition source, emphasising the need to focus on ignition suppression. While selectively logged forests retain important conservation value[16], maintaining them and supporting their resilience rely on effective fire prevention strategies post-logging. Our study underscores the critical need for robust efforts to eliminate ignition sources within and around selectively logged forests, as increasingly hot and prolonged dry seasons amplify fire risks in these vulnerable and valuable ecosystems.

Methods

Site description

This study was conducted in a selective logging concession within the Jamari National Forest (2220 km^2 hereafter Jamari) in the state of Rondônia, Brazil, in southwestern Amazonia (−9.1689, −63.0199). The logging companies at Jamari complied with Reduced Impact Logging (RIL) techniques, including directional felling, liana cutting, and low-intensity harvest to facilitate post-harvest natural regeneration. The mean annual temperature is 25.9 °C[54], Supplementary Fig. 1b) and mean annual precipitation 2075 mm[55], Supplementary Fig. 2b). Rainfall is concentrated during the wet season from October to April, with a well-defined dry season from June to September (Supplementary Fig. 2a). The forests of Jamari are classified as Amazonian lowland open humid, the ecoregion as Madeira-Tapajós with moist forests, and the biome as Tropical & Subtropical Moist Broadleaf Forests[56].

Data collection

This study was designed to capture the potential spatial and temporal effects of selective logging on (1) the forest understorey microclimate and (2) flammability. We selected 18 logging gaps one year post-harvest. In each gap, we marked a study point at the gap centre and established a transect starting at the gap edge (i.e. at the forest wall bordering the canopy gap) that extended 50 m into the adjacent forest. We collected data at five points: gap centre, gap edge, 10 m, 20 m, and 50 m into the forest interior, for a total of 90 study points (18 logging gap sites × 5 sample points, Supplementary Fig. 3). All sites were selected using detailed geospatial data to ensure that the transect did not cross into neighbouring logging disturbances, such as logging gaps, skid trails, or roads. At each gap centre, we mapped the boundaries of the logging gap and calculated the polygon area in ArcGIS[57]. Gap sizes in our study ranged from 135 m^2 to 1172 m^2. Sampling was conducted during the dry season from June to October 2017, which was climatologically typical for the region and did not coincide with an El Niño event or extreme drought conditions. The success of fire ignition and spread, even under controlled conditions, can vary considerably with the severity of the dry season[48]. Although our study did not aim to establish specific temperature or fuel moisture thresholds, the progressive drying observed during this period enabled us to examine the gradual desiccation of fuels and quantify changes in flammability through time.

(1) Gap effects on the understorey microclimate. To assess how the presence and size of logging treefall gaps altered the understorey microclimate of logged forests, we used three response variables: ambient air temperature, maximum ground surface temperature, and relative air humidity. We collected understorey ambient air data using iButton data loggers (model DS1921G-F5; resolution of 0.5 °C) and a psychrometer at all study points. Each iButton was enclosed in a resealable zipper storage bag with a metal mesh sleeve and placed under a plastic funnel at 1.5 m above ground[11,58,59]. All 90 study points had active iButtons sampling ambient air temperature every hour for ~100 days. We used a subset of these data (11:00–15:00 h) to represent the hottest hours of the day. We derived relative air humidity from dry and wet bulb temperatures collected with the psychrometer at 1.5 m above ground.

We collected ground surface temperature data using a FLIR-E40 Thermal Imaging Camera. All thermal photographs were taken from 11:00 h to 15:00 h to capture surface temperature variation during the hottest hours of the day. At each visit across all study points, we took four photographs facing the orthogonal directions (North, East, South, and West), holding the camera at breast height and pointed at 45° towards the ground[11,39]. Each photograph captured an area of approximately 1-m^2 with a resolution of 120 × 160 pixels. The four photos taken during each visit were then considered as one large matrix (4 × 120 × 160). The maximum temperature value of each study point at each repetition was the mean of values above the 95th percentile of the distribution of temperature values. Raw data from thermal images were processed using the Thermimage R package[60]. The final dataset comprised 7052 thermal photographs, representing approximately 133 million temperature values (120 × 160 pixels × 7052 photos).

(2) Gap effects on forest flammability. To assess how the presence and size of logging gaps altered forest flammability over time, we conducted a controlled rainfall-exclosure fire experiment to examine leaf-litter desiccation, the probability of ignition, and the three main components of flammability: ignitability, combustibility and sustainability (as per refs. 61,62). The experiment started at the onset of the dry season (early June). At each study point, we established a 1.2 × 1.2 m quadrat on the ground covered by a 2 × 2 m plastic roof structure standing 1 m above ground to exclude dew, any sporadic rainfall event and leaves from reaching the ground. We subdivided each quadrat into sixteen 30 × 30 cm squares from which leaf-litter samples were to be taken. All quadrats were then evenly watered with 10 L of fresh water to fully saturate the leaf litter and soil, simulating the last rain event at the onset of the dry season.

The experiment started along each transect immediately after watering, marking 'Day 0' of desiccation. One randomly chosen 30 × 30 cm sample was collected from each quadrat to represent maximum leaf-litter moisture content, with sampling across sites arranged to allow sufficient replicates spanning a 40-day desiccation period. We divided each sample equally into two sub-samples: one used to determine fuel moisture content through drying in a laboratory oven, and the other burned under controlled laboratory conditions to derive data on each flammability component: ignitability (how well fuel ignites), combustibility (how well fuel burns), and sustainability (maintenance of burn over time). We focused on controlled laboratory burns rather than field burns due to the challenges of obtaining permits for experimental fires in National Forests, and the limited personnel and resources available for conducting safe field burns. To prevent moisture loss, we stored samples inside resealable plastic bags until the moment they were processed. To quantify fuel moisture content, we placed samples inside paper bags with identifying information (study point and collection date) and measured the wet weight. We then dried them in a laboratory oven at a constant 70 °C temperature for 48 h, after which we recorded their dry weight. The per cent difference between the wet and dry weight of each sample represents fuel moisture content (wet weight/dry weight * 100). To safely conduct the fire experiment, we constructed a flammability arena using a 60 × 85 cm metal barrel cut in half lengthwise. Each half was partially filled with clean sand and placed in an area shielded from wind. At each new burn, a single sample bag was weighed and then emptied into the arena. We held a controlled flame from a gas blowtorch (Carbografite 190 g) on each sample's top right corner for 3 s with timings made by a second observer using a stopwatch to measure: (i) Ignitability, defined as the delay time to ignition (i.e., time required for a flame to burn without the aid of the blowtorch); (ii) combustibility (g/s), defined as the rate of mass burnt per unit of flame duration (s)); and (iii) sustainability, defined as total burn duration (i.e., how long any sign of flame or ember was visible). We established 10 min as the maximum burning limit (reached on 0.61% of occasions) when measuring Sustainability. The blowtorch flame was held a total of 5 times per sample, for 3 s each time, starting at the top right corner, followed by the bottom right corner, bottom left corner, top left corner and ending at the centre. All the above metrics were recorded on each occasion.

Statistical analysis

We conducted exploratory analyses to examine the relative importance of different predictor variables (gap size, distance from gap centre, and lag time since the last rainfall event) in predicting each response variable of the understorey microclimate and forest flammability. We developed mixed-effect models, implemented using the *nlme* and *lme4* packages in the R programming environment[63–65]. We chose the final model for each response variable using Akaike's Information Criterion (AIC), which selects the most parsimonious model that explained observed variation in the data[66], while checking for heterogeneity and normality of residuals based on visual interpretation[67]. We also checked for temporal and spatial pseudoreplication (using the "acf" function in the *nlme* package) and adjusted the random structure by grouping data as 'study point' nested within the respective 'logging gap' and 'sampling date' as necessary.

(1) Gap effects on the understorey microclimate. We used understorey air temperature (maximum daily air temperature), maximum ground surface temperature (mean of values above the 95th percentile), and relative air humidity as response variables to represent the understorey microclimate. We modelled each of these responses against 'distance from logging gap' (which was log-transformed to meet residuals assumptions when necessary), interacting with 'gap area'.

(2) Gap effects on forest flammability. We assessed the effects of logging gaps on forest flammability both spatially (from the gap centre towards the adjacent forest) and temporally (from saturation mimicking a rain event to increasing desiccation). We first assessed whether the desiccation rate of leaf litter is affected by gap size and distance from the gap centre. For that, we modelled leaf-litter moisture content against 'desiccation' (i.e. number of consecutive days after the last rain event, which was log transformed to meet residuals assumptions), 'distance from logging gap', and 'gap area'. We then investigated the probability of ignition according to leaf-litter moisture content. For that, we modelled the probability of samples igniting a flame as the proportion of ignition success over all burning attempts (5 times per sample) using binomial Generalised Linear Mixed Modelling (GLMM), in which 1 means that all 5 attempts of ignition were successful and 0 means that the sample never ignited a flame across all 5 attempts. Finally, we modelled each flammability metric (ignitability, combustibility, and sustainability of fire) separately against 'desiccation' (log-transformed to meet residuals assumptions when necessary), 'distance from logging gap' and 'gap area'.

Ignitability is represented by the variable 'delay time to ignition' (DT). If the sample ignited a flame past the blowtorch assistance, the amount of time recorded was registered as 'delay time to ignition' (DT). If the sample never ignited but produced an ember during a 3-s application of the blowtorch, DT was considered equal to 3 s. In cases where neither a flame nor an ember was observed, DT was considered equal to 5 s—an arbitrary value outside our experimental time frame (3 s), intended to account for the fact that the sample would likely ignite under a prolonged exposure to an ignition source, so the true value is neither zero nor a missing value. We tried modelling these data using higher values of 30 and 60 s to represent longer hypothetical exposure to an ignition source, but because of the increased distance between these higher values and the experimental data values (<3 s), the scale of the response variable changed, causing errors in the analyses that made results difficult to interpret. The final DT variable represents the mean DT value of all 5 burning attempts made for each sample.

Combustibility of fuel relates to how efficiently fire can consume fuel and is represented here as the leaf-litter combustion rate (g/s), which is the mass burnt during the experiment divided by total flame duration considering all 5 burning attempts per sample. The selected model was not different from the NULL model.

Sustainability of fire is represented by the 'burn time' (BT) variable, which corresponds to the total time a sample showed any sign of flame or ember.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The datasets created in this study are deposited here: https://ora.ox.ac.uk/objects/uuid:b0fbedb6-edc9-4b23-9a62-d4edf7819bcf.

Code availability

Custom code created in this study is deposited here: https://ora.ox.ac.uk/objects/uuid:b0fbedb6-edc9-4b23-9a62-d4edf7819bcf.

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Author contributions
M.S.M., C.A.P. and D.P.E. conceived and designed the study. M.S.M. collected the data and performed the analysis with important contributions from M.G.H. M.S.M. wrote the paper with important contributions from M.G.H., M.N.M., C.A.P. and D.P.E. All authors reviewed and approved the paper.

Competing interests
The authors declare no competing interests.

Inclusion and ethics
This research was led by a Brazilian national and conducted in a federally managed National Forest in Brazil. Local field assistants contributed to data collection and are acknowledged accordingly. The study followed local ethical and environmental standards and did not require formal ethics approval.

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