Fire science for rainforests

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Forest fires are growing in size and frequency across the tropics. Continually eroding fragmented forest edges, they are unintended ecological disturbances that transcend deforestation to degrade vast regions of standing forest, diminishing ecosystem services and the economic potential of these natural resources. Affecting the health of millions, net forest fire emissions may have released carbon equivalent to 41% of worldwide fossil fuel use in 1997–98. Episodically more severe during El Niño events, pan-tropical forest fires will increase as more damaged, less fire-resistant, forests cover the landscape. Here I discuss the current state of tropical fire science and make recommendations for advancement.

Fires in the tropics generally bring to mind decades of media images of deforestation fires where slash-and-burn practices are used to convert lush rainforests into agricultural lands. However, beyond these intentional fires looms the burning of vast regions of standing rainforests as an unintended consequence of current land-use practices. Quantitative estimates of area burned are sporadic, incomplete or non-existent for most tropical countries but are nevertheless shocking. Within southeast Asia and Latin America, out-of-control fires burned more than 20 million hectares in 1997–98 (refs 1, 2). This is equivalent to half of California and is far from a complete accounting of unintentional burning in the tropics, because burning in many regions has not been well quantified.

Some perspective is necessary to grasp the scope of the problem faced in the tropics. The fire season of 2000 was one of the worst on record in the United States, with nearly 3.4 million hectares burned and over 1.4 billion US dollars in fire suppression costs (see the National Interagency Fire Center website, http://www.nifc.gov/stats/). By way of contrast, in 1997–98, Indonesia was faced with 8 million hectares of burning and a fire-fighting budget, including foreign aid, of only $25 million (ref. 3). The story is similar across the tropics: 3 million hectares burned in Bolivia[4], 2.5 million hectares burned throughout Central America[2], and in Brazil, 5 million hectares burned in a single Amazonian state[5].The ubiquitous nature of fire in the tropics is evident in satellite imagery. Over the years, several satellites have been pressed into service as fire-detection devices (Box 1). These and newer, more adept, satellites show a landscape that appears to burn every year (see http://earthobservatory.nasa.gov/Observatory/showqt.php3).

Throughout the last century, great efforts and vast resources have been applied to understanding and managing fire in forests. However, in the tropics, demographic and land-use changes have only recently made fire a matter of serious concern[6]. Consequently, critical knowledge and resources have been lacking. Fire science has come late to the tropics.

With so much existing knowledge about fire science it is fair to ask whether tropical fires merit specific study. Fire itself is simply a mixture of heat, fuel and oxygen. The particular mixture of these three components determines whether and how things burn. Integration of fire with the physical and biological components of the Earth leads to a remarkable amount of complexity in fire behaviour and effects. Add to this the evolutionary, economic and social context under which fire operates and it becomes clear that while the chemistry of fire may be universal, its effects are not. This review attempts to explain the present understanding of fire in tropical rainforests and outline areas needing further development.

Impacts of fire

Ecosystem effects

Burning of tropical evergreen rainforests alters forest composition and structure[7,8]. Common tree species suffer the greatest total mortality[9] but rare species are most likely to be locally extirpated[7]. Even 15 years after burning, forests show no evidence of regaining lost species[9]. Prospects for species recovery are diminished because surface fires reduce seed availability by 85% in the litter layer and 60% in the upper 1.5 cm of soil[10], while flowering and fruiting of trees in and near burned forests also decreases[11]. Conditions heavily weight post-fire regeneration toward wind-borne, light-demanding pioneer species. Unburned forest islands[7,10] and gallery forests[12] are key seed sources for post-fire recovery; however, recurrent fires rapidly reduce the size and density of surviving unburned forest fragments[7] and kill regenerating vegetation, further depleting the prospects for recovery of mature forest species[10]. Grasses and small vines also invade burned forests, slowing regeneration and increasing forest flammability[8,13–15].

Animal responses to fire are poorly understood but are complex and dynamic, with some groups, including small mammals, reptiles and amphibians, increasing in abundance or species richness[16] while other groups decline (for example, birds, insects)[16,17]. Most animals initially escape the fires but die through starvation or predation if they cannot find shelter and establish new territories[2].

With millions of hectares of fire-damaged forests spanning the tropics, studies of natural and managed ecosystem recovery are needed. In particular, the rates at which these damaged rainforests recover their near-fire-immune status need to be determined. Potential intervention or management strategies to enhance ecosystem recovery processes should also be assessed.

Emissions

Net annual carbon emissions from tropical wildfires are extremely variable, ranging from 7.5 to 70 Mg ha^{-1} depending on previous fire and land-use history[13]. Emissions from unplanned tropical peat fires are more severe, possibly exceeding 300 Mg C ha^{-1} (ref. 18). Few estimates of total atmospheric carbon emissions from tropical forest fires exist but include 4.6 Tg from Mexico[19], 23.2 Tg from Roraima, Brazil[20], and 810–2,570 Tg from tropical peat fires in Indonesia[18] for 1997–98 El Niño fires. These three fires alone may have equalled 41% of world fossil fuel emissions[21]. Millions more hectares are known to have burned in southeast Asia[1], Africa, Central and South America[2]. The vast majority of unconsumed biomass from killed trees will also slowly release carbon through decay processes[1,7].

Smoke from tropical forest fires causes human suffering and death. Across the tropics, hundreds have lost their lives in smoke-related accidents, including ship, automobile and plane crashes[1,2].

Box 1
Fire detection from space

Fire is a chemical reaction that releases energy in the form of heat and light. Burning changes the structure of vegetation and converts fuels into a host of combustion products that can remain in place (such as char and ash) or be transported from the site (such as aerosols). Conditions during and after fire change the spectrum of reflected and emitted energy from an affected area. Earth-observing satellite sensors can potentially make use of these changes to detect fires, quantify areas burned and determine the composition and distribution of smoke plumes.

Ideally, fires should be mapped by low-cost, frequently collected satellite imagery, but determining which tropical forests are burning or have burned has not turned out to be a simple exercise. Fire detection becomes a challenge of balancing missed detections of real fires and erroneous detections of false fires[80] (such as sun glint, clouds, bare soil surfaces). High-resolution satellites including the Landsat Enhanced Thematic Mapper (ETM+) and Systeme Probatoire d'Observation de la Terre (SPOT) can be used to detect fires but their relatively high cost, and limited spatial and temporal sampling, limit their usefulness for active fire detection[80]. Frequently used satellite systems include the Advanced Very High Resolution Radiometer (AVHRR), the Geostationary Operational Environmental Satellite (GOES) and the Defense Meteorological Satellite Program Operational Line Scanner (DMSP-OLS) satellites because of their frequent coverage of the Earth's surface. Although originally designed for cloud detection, each sensor has different strengths and limitations for fire detection[81]. Issues include sensor sensitivity and saturation characteristics, spatial resolution, number of observations per day and processing methods among others[2]. Several algorithms have been used to estimate the area burned with varying results. Threshold and contextual classifiers tend to detect different fires[82]. Within contextual classifications, different methods lead to differing detection capabilities of different types and sizes of fires[80], which is important in the tropics because deforestation fires are very hot and may smoulder for as much as a week[68] while forest fires can be of low intensity and low temperature[13] and fires in open vegetation types, such as cerrado and pastures, can burn intensely but cool quickly[83]. Where low-intensity fires are widespread over a region, they can even influence discrimination statistics of contextual classifiers in such a way that prevents detection of normally detected intense fires[80].

Newer satellite sensors are expanding these capabilities in monitoring the extent and frequency of fires[84]. The Tropical Rainfall Measuring Mission–Visible and Infrared Scanner (TRMM–VIRS), may be particularly useful for detecting unusually large or hot fires because of the reduced sensor saturation of its larger sampling area and potential for discriminating fires from other hot surfaces[85]. The Bi-Spectral Infrared Detection (BIRD) mission is currently testing a new generation of infrared array sensors that provide surface temperature, area, and geo-location of fires with a spatial accuracy of 300 m, better analysis capabilities for High Temperature Events (HTE) and the ability to discriminate between smoke and water clouds[86,87]. The higher saturation levels of Moderate Resolution Imaging Spectroradiometer (MODIS) satellite sensors provide better detection and monitoring capabilities for active fires than previous satellite platforms. In addition, improved spatial and radiometric resolutions of these satellites are useful for investigating aerosols in smoke plumes[27] and enhance the accuracy of burned area estimates[86]. Both coarse[88] and fine[89] spatial resolution sensors are useful for mapping forest burning in the tropics. Burn signatures are transient in imagery owing to rapid forest regeneration[90] but may be detectable for up to two years with some techniques[89]. ERS-2 Synthetic Aperture Radar (SAR) imagery is also promising for mapping burn scars in tropical evergreen forests because of its ability to penetrate clouds and smoke[64]; however, detection capabilities can be confounded by moisture, making knowledge of site weather information crucial.

Thousands more died from smoke-related illnesses from forest fires in Indonesia[22] and Brazil[23]. Health effects depend on the concentration, constituents and length of exposure to smoke[24] but include respiratory and cardiovascular difficulties among other illnesses[22]. The complex mix of particles, liquids and gaseous compounds released depend upon the type and efficiency of burning. Fire emissions have been studied and quantified for deforestation and savanna fires[25] but not for tropical forest fires. Emissions may change greatly between day and night because many of the fires then convert from flaming to smouldering combustion[13]. Emissions can be trapped beneath the rainforest canopy, potentially leading to toxic conditions. In addition, smoke plumes from biomass burning release large amounts of aerosols to the atmosphere, a substantial fraction of which is black carbon. In part owing to the black carbon fraction, the mix of aerosols in the tropics reduces the average solar radiation absorbed at the Earth surface by up to 35 $W m^{-2}$ and may double the heating of the lower 3 km of the atmosphere[26]. These changes affect atmospheric stability and cloud formation and can ultimately reduce rainfall over large areas[27–29].

Development, deforestation and fire

Development of forested areas has historically been synonymous with deforestation. The advent of slashing and burning tropical forests for agricultural purposes was thousands of years ago[30]. Periodic clearing and abandonment of tropical rainforests is potentially a sustainable practice, if rotation rates are long enough, but can only support low population densities. Higher population densities, extensive forest clearing and extreme drought conditions of periodic mega-El-Niño events may have resulted in widespread forest fires, frequent and severe enough to have influenced the distribution and migration of indigenous people[31]. In the modern era, tropical forests are the 'frontier' and, as always, fire is the tool of choice for clearing the land. Fire is very useful because it quickly and effectively reduces the biomass of newly cleared forests to nutrient-rich ash that can fertilize crops. Hard-won agricultural lands are managed using fire to keep forest regrowth at bay, reduce pests, and promote forage growth for domestic animals. Fire is needed to create charcoal, reduce trash and debris piles, and for cooking food.

Fire becomes a problem, however, when it escapes from its intended purpose and causes unanticipated economic and environmental damage. Heavy fire use has costs as well as benefits. Escaped fires destroy crops, pasturage, timber, infrastructure (for example, fence posts, buildings and so on), and livestock, at times leading to severe economic hardship for local populations[2,32]. Ill-timed fires can also spoil newly cleared lands by under- or overburning the slashed trees, resulting in reduced productivity or abandonment. Careless fire use and arson can lead to extensive fires in logged and unlogged forests and reduce the profitability or attractiveness of large-investment, high-profit permanent agriculture.

Fire and tropical forests

The crux of the fire problem in tropical rainforests is not so much the introduction of fire into these ecosystems but the frequency with which they are being burned. Historical records[1,33,34] and charcoal in soil profiles[35–38] show that tropical forest fires, even in the wetter forests, are not unprecedented. Fire can be considered endemic but rare in tropical rainforests[14] with return intervals of hundreds if not thousands of years[39]. Wetter forests burn less frequently but are more vulnerable to fire than drier forests because they have thinner protective layers of bark[40] and suffer much higher mortality rates from fires. Infrequent fire disturbance has left tropical rainforests evolutionarily ill-adapted to current patterns of burning[40,41].

Fire susceptibility in tropical forests occurs largely because of moisture stress, during periods of extensive drought, when normally moist fuels dry out and become potentially flammable. However, closed-canopy evergreen rainforests are remarkably resistant to drought[35]. Even after months without rain, these forests can maintain an evergreen canopy and high sub-canopy humidity levels, making sustained combustion impossible[35,39]. This apparent fire-immunity results from the effective trapping of transpired moisture such that most of the ambient forest humidity is derived from the trees themselves[42]. Resilience to climatic stress through moisture recycling[43,44], enhanced by the deep-rooting capacity of many tree species[45], allowed many tropical forests to persist through severe droughts of previous glacial periods[46]. But despite adaptations to drought conditions, rainforests can and do burn. Both natural and anthropogenic disturbances to forest canopies decrease the ability of forests to maintain moisture, making them more vulnerable to fire. In anthropogenic landscapes, fire is a continual presence, making it only a matter of time until a sufficiently intense drought opens up the forest to fire[2].

Fire occurrence in tropical forests is largely associated with forest edges[47–51] and is not randomly located throughout. Although tropical regions have the highest density of lightning strikes[52] and some associated tree mortality, these events are usually associated with heavy rainfall and rarely lead to forest fires[53]. Other natural causes of fire such as volcanic eruptions and burning coal seams[37] may be regionally important but, as in most locations throughout the world, fire in the tropics is primarily associated with human activity[34,54] and influence on land cover[47–51].

Land cover effects

Tropical land cover is rapidly changing[55]. Road construction in recent decades has provided access for millions of settlers to previously remote and inaccessible forests[56]. Deforestation has necessarily followed. Forest clearance fragments the remaining forests[55,57]. Resultant forest edges are buffeted by winds and desiccating sunlight. These edge effects lead to structural changes, including increased mortality of trees, decreased living biomass[57] and increased fuel loads (that is, woody debris)[58]. These changes predispose these forests to fire[48,49] (Fig. 1).

Selective logging is another major landscape modifier in the tropics. The combination of human access provided by logging roads[59] and the forest damage caused by logging activities[39] make logged forests extremely vulnerable to fire[60]. This vulnerability may last for decades after the logging activities have ceased[61] (Box 2).

Given the juxtaposition of fire-prone forests and fire-dependent agricultural lands, forest fires are almost inevitable. In new frontier areas with relatively low quantities of cleared land, extensive undamaged forests make large forest fires nearly impossible. However, as fire-prone agricultural land development continues, the forest becomes increasingly fragmented and the whole landscape becomes conducive to fire propagation[2]. The forest fires that do occur are often edge-related, moving into forests from deforested lands[48,51]. These fires can significantly alter fire regimes kilometres from forest edges (Fig. 2). Fire frequency becomes a function of distance from deforested forest edges[48,62] and fire severity increases with frequency[13]. In the absence of other modifying disturbances, these forests will continue to erode, with isolated fragments collapsing, unless future fires can be prevented[63]. This is a long-standing process in the African tropics[43]. Within the Brazilian Amazon alone, 26 million hectares of forest could currently be undergoing this process, leading to the eventual release of 3.9 Pg C (ref. 62).

Fire behaviour

Initial fires in relatively intact rainforests do not seem to be severe. Often progressing as slowly creeping ribbons of flame, 10 cm or so in height, burning little besides fallen leaf litter, these fires are still capable of killing 23–44% of the trees >10 cm in diameter at breast height (DBH)[7,8,10,15,40,60]. Fire propagation in tropical forests is largely controlled by variations in ambient relative humidity

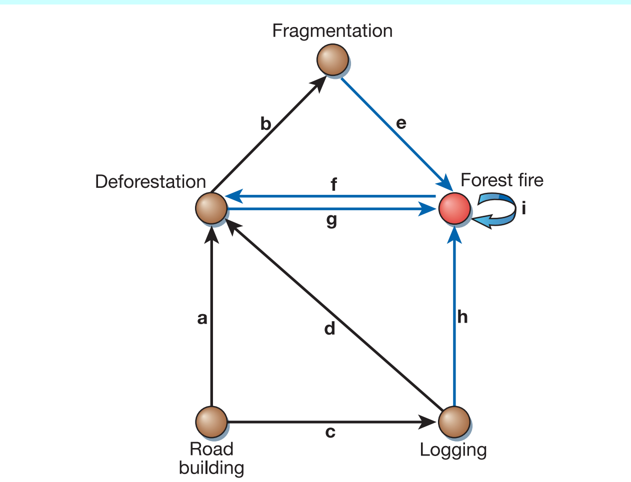

Figure 1 Diagram of interrelationships between tropical land-cover changes and forest fires. Arrows indicate forcing of each node upon others in the system. Blue arrows directly affect forest fire occurrence; black arrows indirectly influence forest fire occurrence. Events **a**–**i** are: **a**, Road building results in forest access that is strongly associated with deforestation[56]. **b**, Deforestation fragments the remaining forests, increasing amounts of edge[55,57]. **c**, Road building and paving directly affect transportation costs and area of economic accessibility[78]. **d**, Logging results in limited amounts of deforestation for roads and log landings. Post-logging colonization can increase deforestation[59]. **e**, Forest edges suffer biomass collapse and microclimate changes[57] making them susceptible to frequent fires[48]. **f**, Repeated forest fires can lead to unintentional deforestation[13]. **g**, Deforestation and pasture/land maintenance fires result in many accidental forest fires[62]. **h**, Logging degrades forests, increasing fire susceptibility[47,60,61]. **i**, Forest fires can create a positive feedback cycle where recurrent fires become more likely and more severe with each occurrence[13].

Box 2
Selective logging and fire

Millions of hectares of tropical forests have already been logged and millions more are being logged each year[61,91,92]. Logging in tropical forests is often selective in that only a few valuable trees are extracted, leaving most of the forest in place. Impacts of selective logging vary with extraction intensity and management practices[93–95], but can be substantial. Selectively logged forests can recover to pre-harvest levels of biomass if left undisturbed. However, many forests are revisited several times when loggers return to harvest additional tree species as regional timber markets develop[93]. These forests become very degraded and may have 40–50% of the canopy cover destroyed during these logging operations[93]. Selective logging increases fire susceptibility[39,60], and can catalyse fire use and deforestation by opening up unoccupied and protected lands to colonization[59].

Fire severity in logged forests can be high[2,8,61] owing to the large amount of available fuel in the form of slash piles and collateral damage caused by the logging operations[39,93]. When weighted by area, logged forests near forest edges may not be more likely to burn than unlogged edge-forests but burn severity and fire spread rates can be higher, leading to deeper penetration and increased damage by fire (refs 34, 50, 96; see also http://www.fire.uni-freiburg.de/se_asia/background/sea_5.html). In landscapes heavily affected by logging and fire, the relationship between fire frequency and distance from deforested edges can decrease or disappear completely because the entire forest will have similar fire-return intervals, often less than 10 years (ref. 48). Of deforestation, fire use or selective logging, none by itself is likely to create severe fire problems in tropical landscapes but the synergy and interaction between these land-uses when present together can promulgate fire throughout the landscape and rapidly degrade forests[2,47–50].

(Box 3)[13,39,64]. Although fire intensity is very low (4–55 kW m^{-1}), slow spread rates result in considerable heating of tree bark surfaces[13]. Most species in closed canopy evergreen forests have thin bark[39], so fires effectively girdle and kill them. Larger, thicker-barked trees and others without vulnerable cambium layers (for example, palms) survive[13,15,39]. In some forest types with root mats or deep organic layers, ground fires can accompany surface fires. These fires may consume everything down to the mineral soil and cause near-complete mortality[15,35]. Fires in logged or previously burned forests are more severe, owing to greater fuel loads and lower humidities[7,40,60], with fireline intensities of 82–728 kW m^{-1} and more extreme fire behaviour[13].

Although the chemistry and physics behind fire in tropical forests is no different from that in temperate or boreal forests, modelling fire susceptibility, behaviour, and effects in these forests will be more difficult owing to differences in tropical ecosystem characteristics. Closed-canopy tropical forests are species- and fuel-rich ecosystems that can regulate subcanopy humidity and hence the availability of fuels containing a variable mixture of numerous chemical compounds (for example, aliphatic and aromatic hydrocarbons, alcohols, aldehydes, gums, sugars, terpenes, fats, waxes and oils)[52]. This ecosystem modulation of atmospheric humidity modifies fire behaviour in complex ways by changing the ignitability, sustainability and combustibility of fuels with varied structure and chemical composition.

Modelling of fire susceptibility in tropical evergreen forests is in its infancy. Fire susceptibility models must incorporate not only ambient weather conditions but also forest type, structure and disturbance history, as well as the availability of and ability to tap into deep soil moisture. Current conceptual models of susceptibility, the time since rain[39] and leaf-shedding[65,66] fail to describe or provide the mechanistic understanding of forest moisture dynamics that are necessary to explain the behaviour of observed forest fires[13]. The deep-rooting nature[45] and tight hydrologic cycling[41] of these forests make fire-susceptibility modelling challenging. Current models[32] provide appropriate drought indices for these forests but cannot address the likelihood of actual fire ignition or spread owing to conceptual flaws that ignore the feedbacks of the forest upon the fire environment.

In the tropics, as elsewhere, models of fire spread and behaviour

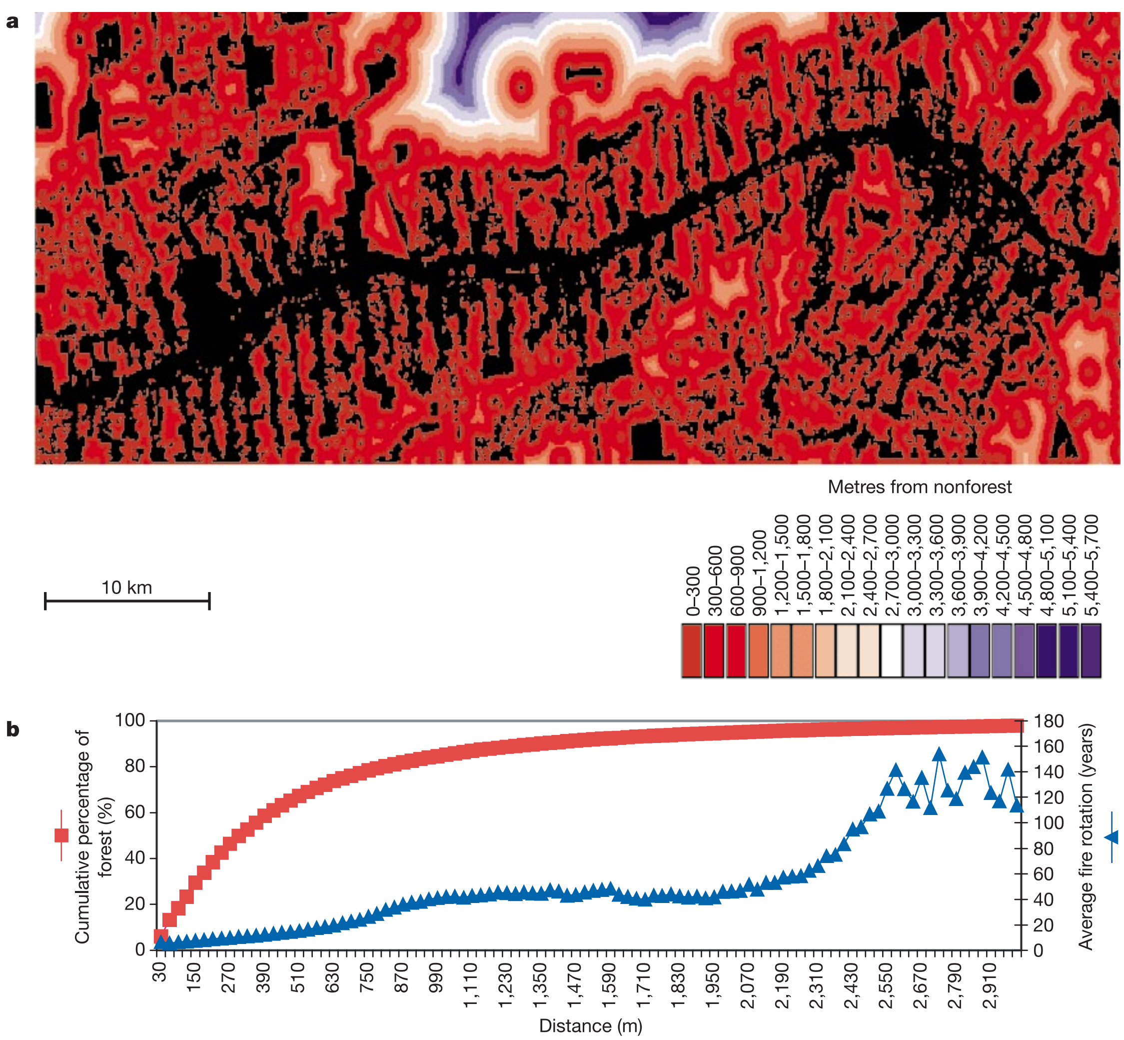

Figure 2 Spatial distribution of fire regimes[62]. **a**, Data is shown for Tailândia, Brazil, in 1997. Black areas are previously deforested, while other colours represent standing forests suffering different levels of fire impact. Forests in red are burning too frequently to persist as tropical evergreen forests and are turning into grassland and scrub[13] in a continual erosion process[43,63]. **b**, The graph shows both cumulative percentage of remaining forests and fire frequency (average return interval in years) as a function of distance from deforested edges in the eastern Amazon. Tropical forests around the world are affected similarly but to different degrees depending on climate, fire load, and previous land cover changes or disturbances.

will require appropriate fuel models. Such fuel models have been standardized for many ecosystems and forest types[67] but not for tropical forests. Fires in tropical forests frequently occur in surface fuels, so understanding the characteristics and compositions of litter systems will be essential for predicting burning characteristics. Litter arrangement, loading, moisture, type and composition are all important modifiers of fire behaviour. Although there are a few quantitative descriptions of fuel quantities and size distributions[13,39,68], there do not appear to be comparable studies of fuel composition and chemistry. Litter production and decay rates vary widely in the tropics. Furthermore, litter from different species have large variations in energy values and flammability. Therefore, the phytosociological mix of litter-generating species can influence the flammability, sustainability, spread and heat-release characteristics of fires[52]. The fuel structures of forests with deep root mats or peat layers must also be understood because locally devastating ground fires in these substrates can have globally significant impacts[18]. With their extremely species-rich complements and varieties of canopy, surface and subsurface fuel structures, tropical forests will probably require a whole new set of fuel models to parameterize existing fire models such as BEHAVE Plus (http://fire.org/cgi-bin/nav.cgi?pages=behave&mode=8) and FARSITE[69]. Dynamic relationships between fuels and forest moisture conditions will also be needed to address rapidly changing fuel availability and the potential involvement of green fuels.

Fire severity can be subjective but is often confused with intensity. This is understandable because severe fires in temperate and boreal forests are often intense surface or crown fires. The majority of tropical fires, however, are neither fast-spreading nor intense. They are severe nevertheless because the impact to the forest is quite large[7,8,10,15,40,60]. A severe fire can be rapidly spreading if it is intense but can also be of low intensity if it is slow-spreading. Relative severity for an ecosystem will depend on its specific adaptations, fortuitous or evolved, to the fires that are experienced. Prescribed burning is neither effective nor useful in tropical rainforests. Although burning favours the establishment of some commercial timber species[70] and temporarily reduces growth-inhibiting vine loads[71], collateral damage from fire use outweighs any benefits[70,71]. Fires are not useful for managing fuels either, because even very-low-intensity fires cause high mortality, creating more fuels than they consume[13]. Specific fire-protection and suppression recommendations are needed that can provide measurable results in reducing fire frequency.

Fires in tropical rainforests range from easily extinguished litter fires to nearly impossible-to-extinguish ground fires. In recurrent wildfires[13], average fire intensities are ten times greater (30 versus 307 $kW\,m^{-1}$) and can spread twice as fast (0.25 versus 0.52 $m\,min^{-1}$). These limited data should not be considered to limit the range of possible fire conditions in tropical forests. In particular, the potential for landscape-level interactions among multiple fires to create large-scale, rapidly spreading conflagrations must be considered. Mass fires, also known as 'firestorms', can spread rapidly and lead to fire-induced weather, including high-velocity winds, lightning, and extreme fire behaviour (for example, fire whirls)[72]. There is historical precedence[73] for widespread logging damage, previous fire damage and widespread clearing fires combining to create mass fires in other forests, with devastating environmental, economic and human consequences. Regions with

Box 3
Fuels and moisture

Fuels are commonly divided into different size classes that have been determined to have specific moisture flux characteristics, specifically 1-h, 10-h, 100-h and 1,000-h fuel classes (0–0.62, 0.62–2.54, 2.54–7.62 and >7.62 cm). The number reflects the amount of time a fuel particle of a given size requires to reach 63% of equilibrium after a change in ambient moisture conditions[97]. Smaller fuels (1-h) can either dry or become moist relatively quickly while larger fuels (1,000-h) take a long time to dry or recover moisture. Fuels 'available' for a given fire are simply those substances that require less heat to reach the point of combustion than is being radiated by the surrounding environment. Moisture increases the amount of heat necessary to reach the point of ignition. Sustained combustion occurs when ignited fuels conduct sufficient energy into adjacent fuels to start combustion before the currently burning fuels are consumed. If there is a continuous layer of fuels where this process can occur, then the fire will spread.

Closed-canopy forests are protected from the wind, and fire intensities and spread rates in such forests are also kept low by the high moisture content of fuels. But even at low intensities, slow-moving fires are severe because of the mortality caused by the long fire-contact times and the resultant heat transfer at the base of trees[13]. The moisture that protects tropical forests from fire is therefore also one of the reasons for the high mortality rates experienced when these forests do dry out enough to catch fire.

Owing to standard fuel monitoring practices in temperate forests, 10-h fuel-sticks have been used to evaluate fuel moisture and fire susceptibility in tropical forests[35,39,60]. However, in many tropical forests, 1-h fuels carry the fires while 100-h and 1,000-h fuels contain smouldering fires throughout moister periods (for example, nights, short rains and so on), allowing fires to persist and spread[13]. Consequently, moisture levels in the 10-h fuel class may actually be the least appropriate for characterizing fire susceptibility in tropical forests.

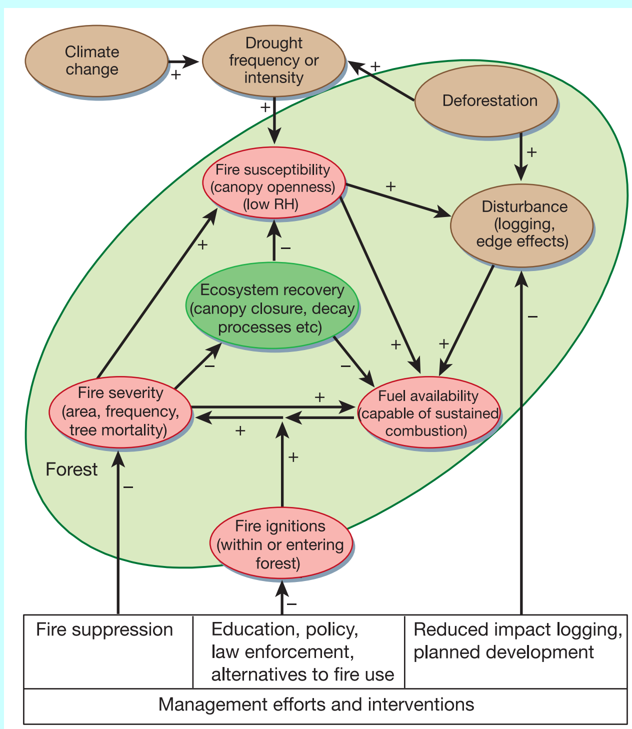

Figure 3 Positive and negative feedbacks controlling fire processes in tropical forests. Positioning indicates whether they occur within or outside the forest (green shading). Items in red control fire occurrence or behaviour. Items in brown modify the potential fire environment. Green indicates ecosystem processes acting in opposition to fire, specifically regrowth, canopy closure and decay of fuels. The management efforts and interventions box indicates how and where human actions can diminish tropical forest fires. Climate change encompasses effects of increased CO_2, land cover change, and aerosol loading that result in regional drying in the tropics[26,27,79]. RH, relative humidity.

extensive logging- and fire-damaged forests that experience widespread and heavy fire use (such as East Kalimantan, Indonesia[1,15,61]) are at greatest risk for such catastrophic fires.

Environmental impacts and climate feedbacks

Forest fires, deforestation and other forest disturbances effectively thin forests, reducing the amount of vegetation transpiring water. Reduced transpiration results in lowered local atmospheric humidity levels and increases the probability of future forest-fire occurrence[74]. Decreased atmospheric moisture can negatively affect montane cloud forests by reducing the extent of and increasing the minimum altitude of downwind cloud fields[75]. Regionally, transpiration from tropical forests is important for downwind precipitation, contributing 25% or more of annual rainfall in some regions[43,44].

Tropical forest fires reduce the ability of affected forests to retain water, exacerbating flooding, erosion and seasonal water shortages[2]. Smoke-borne aerosols from fires disrupt normal hydrological processes and reduce rainfall[28,29], potentially contributing to regional drought. Through the radiative effects of smoke-derived aerosols, fires reduce the relative humidity and temperature gradients of the lower troposphere[27], disrupting normal cleansing processes and increasing average residence times of smoke particles in the atmosphere[26]. Smoke plumes from tropical fires also increase the number and intensity of positive cloud-to-ground lightning strikes, long after and thousands of kilometres away from fires, altering 'natural' fire processes within and outside the tropics[76].

After a fire, leaves from newly killed trees quickly reblanket the ground while simultaneously opening the canopy, resulting in a more easily dried and fuel-laden forest[7,13]. Whether burned[7,14], logged[60] or subjected to wind-throw and other edge effects[48,49], these forests become fire-susceptible after a few weeks without rain instead of several months[7]. Increased fire intensity and heat-transfer capacity of recurrent fires make them deadly to even larger thicker-barked trees[13]. Forest burning can create a positive feedback whereby more frequent and severe fires result in complete deforestation[13] (Fig. 3).

Understanding fire in tropical rainforests

The existence of tropical forest fires has been periodically rediscovered and forgotten over the last century. Since Indonesia's large 1983 forest fires, studies of fire potential and effects have rapidly accrued in the literature but it is disturbing that Aubréville[43] was able to report much of this knowledge when he described fire effects in African forests in 1947. To move forward, tropical fire science needs to go beyond observation and description to provide increased understanding of the interactions between fire and tropical forests so that effective policy, management, modelling and monitoring efforts can be created.

Landscape-level knowledge of fire occurrence, behaviour and history is necessary for managing fire in the tropics. Tropical landscapes are a dynamic collection of intact, cleared, damaged and regenerating forests. To do more than chart the frequency and timing of burning at the landscape level, it will be necessary to relate fire-detection information to up-to-date land-cover maps. For ecological understanding of the importance of fire it will be necessary to know what is burning, how often and when. The need for high sampling frequency using high-resolution imagery currently makes the mapping of forest fires in the tropics expensive and labour-intensive[2]. Where possible, such work should be combined with ongoing land use and land cover classifications to maximize the efficiency of resource use and the synergy of site information (for example, deforestation, selective logging, previous burning, forest regrowth and so on).

Fires have an impact on millions of hectares of rainforest[2], increase deforestation rates by as up to 50% in some regions[13] and cause billions of dollars in damages in the tropics[1,2]. To avoid the continuous and insidious erosion[43] of forests by fire throughout the tropics, an increased level of attention, study and resources need to be directed to tropical fire science. This cannot be done by a blanket application of current fire knowledge from other parts of the world to the tropics, but neither does fire science need to be reinvented anew in tropical guise. Instead, current fire knowledge needs to be interpreted in the context of tropical forests and, where necessary, added to, by defining the mechanisms by which fire and ecosystem processes interact[77] in these forests. □

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