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FIRE MANAGEMENT IN TROPICAL FORESTS

An Introduction for Students of Forest Sciences of the Regional Fire Management Resource Center – South East Asia (RFMRC-SEA) at Bogor Agricultural University

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Foreword

This paper is based on the chapter *Fire Management* of the *Tropical Forest Management Handbook* (Goldammer, 2016). It provides an introduction to the history and ecology of fires in ecosystems of the tropics (closed evergreen forests; closed and open seasonal forests; fire climax pine forests in the tropical submontane and montane altitudes, subtropical lowlands; savannas and open woodlands; planted forests). In addition, the chapter provides references to other environmental impacts of tropical fires, notably the global impacts of fire emissions on atmosphere and climate. The main part of the paper provides different fire management options. Fire prevention methods include technical measures such as fuel management (treatment of combustible materials for fire hazard reduction) and the use of prescribed fire. The involvement of local communities in active fire prevention, the sound and safe use of fire in land management and the defense of rural assets against wildfires is essential. References are given on fire management on contaminated terrain. The section on fire suppression (firefighting) provides access to the most important guidelines and technical training manuals. The need of developing national fire management policies address the fire problems at landscape level including cross-sectoral / inter-agency approaches in fire management is underscored. The complexity of interactions between land use and other human activities, tropical vegetation characteristics, climate and climate change may require expert assistance in capacity building in fire management at national and local level. International networks and voluntary mechanisms are available for exchange of knowledge and expertise.

Keywords

Tropical fire ecology, fire regime, fire climax, forest fire, wildfire, wildland fire, vegetation fire, fire management, fuel management, prescribed burning, fire protection, fire suppression, community-based fire management, EuroFire standards

1 Introduction

The vast majority of global vegetation fires (fires occurring in forests, savannas, grasslands, and other wildlands, as well as agricultural burning), takes place in the subtropics and tropics. Here, fire is being widely used as a land management tool, e.g. for conversion of native vegetation, including forests, peatlands or wetlands to agricultural land, for maintaining grazing lands, and for utilization of the seasonal forests and savannas. Fire influence through traditional burning practices, has over past millennia, strongly favored some select plant communities and are since considered to be sustainable and long-term stable fire ecosystems. With increasing land-use pressure on those tropical ecosystems that are fire sensitive, however, the use of fire is associated with severe vegetation degradation processes and loss of forest cover (cf. synthesis by Goldammer, 1990). The first part of this chapter evaluates some instances of prehistoric, historic and the contemporary role of fire in tropical and subtropical ecosystems. Fire regimes are classified according to the main biome types and specific characteristics and impacts of fire. The second part of this chapter deals with fire management options and techniques.

2 Biogeography and Ecology of Tropical Fires

Evidence of prehistoric fires is found in many places throughout the globe. Charcoal layers embedded in coal seams (fusain) provide evidence of fires in ancient forests which were fossilized during the carboniferous period. Charcoal and lightning-struck fossilized trees found in swamps, reveal lightning as a major source of natural fires in the subtropics. Within the tropics and subtropics outside of Australia, where pre-Quaternary and Quaternary fires have been investigated, reliable information on prehistoric and historic fire is scarce. The lack of *in situ* materials suitable for radiometric age determination in the tropical lowland rain forests is explained by the transport of charcoal by water, floods, change of river beds, and erosion. However, scattered evidence of ancient fires in rain forests, which are presently considered as undisturbed "primary" rain forests, is available. Charcoal samples recovered in lowland rain forests of eastern Borneo, date back to the peak of the last Pleistocene glaciation c.18 000 ^{14}C yr BP (Goldammer and Seibert, 1990). Radiometric age determination of charcoal found in Amazon rain forests revealed prehistoric natural or early human-caused fires in the Holocene c. 3 500 to 6 000 yr BP (Sanford et al., 1985; Saldarriaga and West, 1986; Fölster, 1992).

During the Pleistocene, the role and influence of fire on vegetation may have changed in accordance with climatic fluctuations. During the interglacial periods, a prevailing warmer and more humid climate created conditions unfavorable for fire occurrence. During the glacial epochs, the tropical climate on the whole was cooler and in general more arid and seasonal than the present one. These glacial climates occupied ca. 80% of the last two million years. The prevailing arid climate conditions forced the rain forest to retreat into refugia, which were surrounded by savanna-type vegetation (cf. synthesis by Prance, 1982). It has been suggested, that the savanna vegetation between the refugia has been strongly influenced by fire, and that the "fire corridors" between the refugia may have contributed significantly to the genetic isolation of the rain forest islands (Goldammer, 1991). Other vegetation and landscape mosaics created by fire may have also induced the formation of genetic islands, which may explain the high genetic diversity of today's rain forest biota.

The evolutionary role of shorter climatic fluctuations associated with dry periods and long-return interval forest fires is not yet clear. Saldarriaga and West (1986) found that the radiometric dates of Amazon charcoal comply with the relatively dry periods postulated by the interpretation of pollen data.[1]

In the present equatorial climate, short-term climate oscillations (inter-annual climate variability) are common. One of the most prominent and well-investigated phenomena is the El Niño-Southern Oscillation (ENSO) event, which is associated with extended droughts in the West Pacific region. As it has been observed during the extreme ENSO events of 1982-83 and 1997-98, rain forests may become extremely flammable during these droughts. The occurrence of natural fires caused by dry thunderstorms, especially at the transition from the dry period to the rainy season, is very likely. In Eastern Borneo (East Kalimantan) it has been observed that rain forest fires spread from burning coal seams exclusively during drought years. This ignition source has been available at least since c.15 300 thermoluminescence (TL) years, but probably since more than 60 000 TL years (Goldammer and Seibert, 1989). These examples of old and contemporary rain forest fires may be unique. However, the assumed ancient fire occurrences in an environment, in which rain forests are currently growing, demonstrate the capability of the rain forest to cope with multiple environmental stresses.

In Africa, early humans, or hominids, have been using fire for at least 1.5 million years (Brain and Sillen, 1988). With the migration of humans into today's tropical forest lands, the anthropogenic use of fire started to develop as a dominant factor influencing vegetation (Schüle, 1990). In the seasonally dry regions adjoining the permanently humid equatorial rain forest zone, fires were set for hunting purposes, to improve grazing conditions for animal husbandry, and in general to keep forest lands open for reasons of security (improved visibility) and accessibility. The influence of these Neolithic fires in savannization and deforestation has been documented by pollen analysis.[2]

Since early man began to conquer tropical lands, the reasons and methods of fire use have not changed. However, with the present and unprecedented human population pressure on tropical vegetation resources, the consequences of regional climate change, coupled with changing fire regimes, the influence of fire is now a critical element in tropical vegetation development as well as a predominant driver of vegetation degradation and destruction.

2.1 Tropical Fire Regimes

Fire regimes in tropical forests and derived vegetation are characterized and distinguished by return intervals of fire (fire frequency), seasonality (time of occurrence during the dry season or dry spells) and fire behavior (fire intensity / fire severity) (Mueller-Dombois and Goldammer, 1990). Basic tropical and subtropical fire regimes as distinguished in Figure 1 are determined by ecological and anthropogenic (socio-cultural) gradients. Lightning is an important source of natural fires, which have influenced savanna-type vegetation in pre-settlement periods. The role of natural fires in the "lightning-fire bioclimatic regions" of Africa, was recognized early (e.g. Phillips, 1965; Komarek, 1968). Lightning fires have been observed and reported in the deciduous and semi-deciduous forest biomes as well as occasionally in the rain forest.

[1] These periods were c. 4200-3500, 2700/2400-2000, 1500-1200 and around 700 and 400 years BP (Absy, 1982; van der Hammen, 1982)
[2] The origin of fire-shaped savannas of Cambodia dates back to c.2000 yr BP, the Malawi savannas c.12,000 yr BP, the arid savannas of Rajastan (India) c.10,000 yr BP, the opening of forest lands in Sumatra by early hunters c. 18,000 yr BP and in New Guinea c. 25-28,000 yr BP (cf. synthesis by Goldammer, 1993).

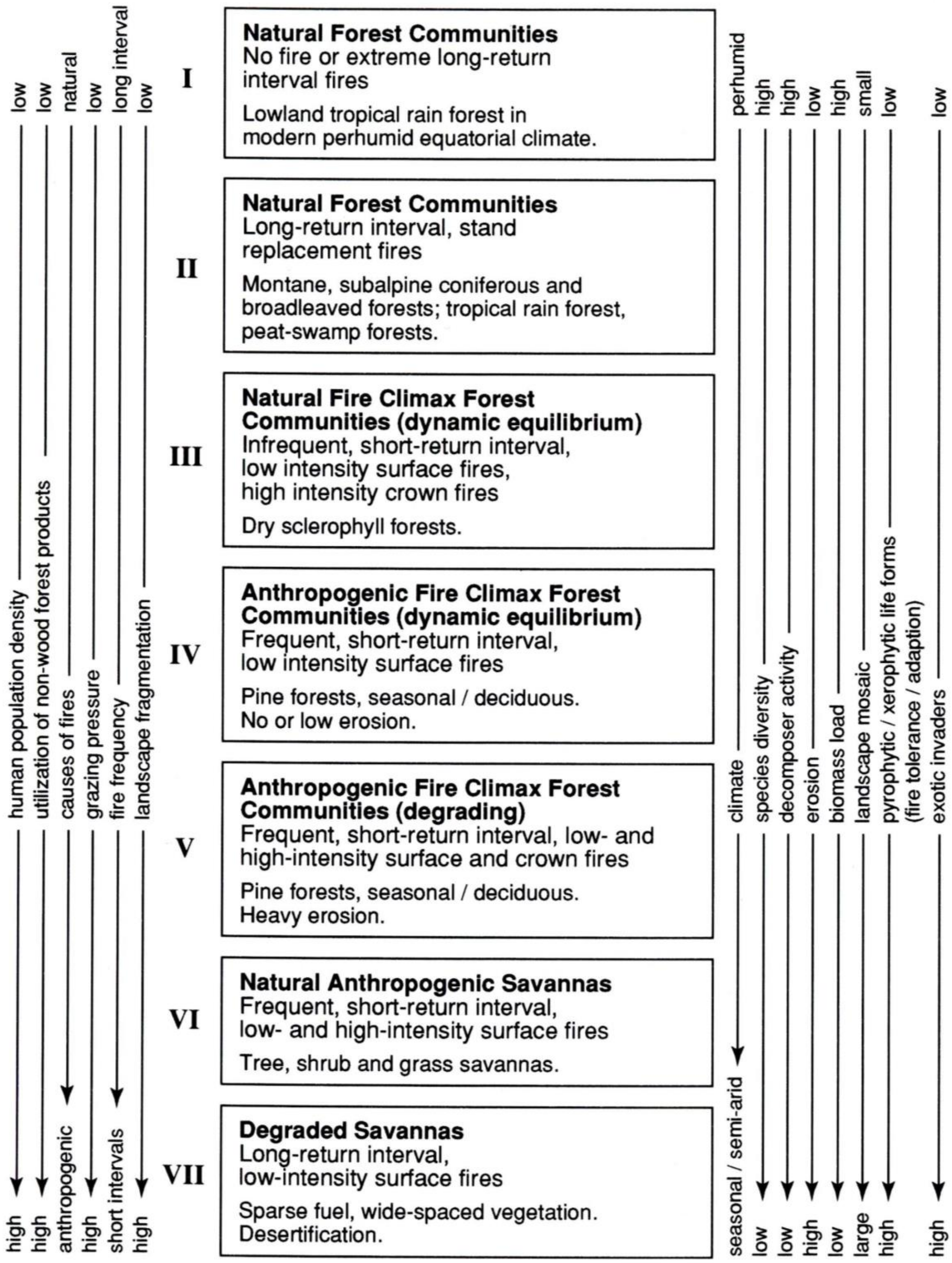

Figure 1. Types of tropical/subtropical fire regimes as related to ecological and anthropogenic gradients. Exemptions from this generalized scheme such as higher species diversity in certain fire climax communities must be noted.

However, with increasing human activities in tropical ecosystems, the contribution of natural ignition sources to the overall tropical wildland fire occurrence is becoming less significant as compared to human-caused ignitions or purposely-set fires. The main reasons or "underlying causes" for the use of fire, which have been described in-depth in the past, still remain valid in the 21st Century (Bartlett, 1955, 1957, 1961; Goldammer, 1988; Steensberg, 1993):

- Use of fire as the most convenient and inexpensive tool for conversion of forest and other native vegetation, including wetland and peatland ecosystems to other land-uses, e.g. establishment of plantations, agricultural lands, pastures, or for exploitation of other natural resources (mining);
- Traditional slash-and-burn agriculture;
- Grazing land/pasture management (fires set by hunters and herdsmen mainly in savannas and open forests with distinct grass strata [silvopastoral systems], and by managers of industrial livestock enterprises);
- Harvest of non-wood forest products (use of fire to facilitate harvest or improve yield of plants, fruits, and other forest products, predominantly in deciduous and semi-deciduous forests);
- Fires starting at the wildland/residential interface (fires from settlements, e.g. from cooking, torches, camp fires, etc.);
- Other traditional fire uses (religious, ethnic and folk traditions); and
- Targeted or collateral consequences of socio-economic, political and armed conflicts over questions of tribal land tenure, traditional land-use rights, or territorial/national sovereignty.

Guidance for the determination of wildfire causes and damages based on forensic investigation, is provided by de Ronde and Goldammer (2014).

Fire regimes of selected forest types and other vegetation are briefly described in the following section; additional examples illustrate the role of fire in tropical human-made forests.

2.1.1 Fire in Evergreen Equatorial Rain Forest Ecosystems

In general, the equatorial rain forests are classified as fire-sensitive ecosystems. As stated above the use of fire for forest clearing is the main issue:

- Shifting agriculture (slash-and-burn agriculture), where land is allowed to return to forest vegetation after a relatively short period of agricultural use
- Permanent removal of forest for conversion to plantations (e.g. oil palm plantations), livestock pastures or crop land, as well as other non-forestry land uses

In all instances, clearing and burning initially follow the same pattern: trees are felled at the end of the wet season, and the vegetation is left for some time to desiccate in order to obtain best burning efficiency. In the case of previously non-exploited rainforests the efficiency of the first burning is variable. Often it does not exceed 10-30% of the aboveground biomass. This low burning efficiency is due to the large fraction of forest biomass residing in the tree trunks, only a small portion of which tends to be consumed during the first burn. The remainder is treated by a second fire or is left on the site to decompose (Fig. 2).

Figure 2. Effects of a forest-conversion fire after clearcutting in a lowland dipterocarp forest of East Kalimantan (Indonesia). Only a small part of the wood biomass is utilized, and the remainder is burned. Ignition and combustion of heavy logs under average conditions of humidity and fuel moisture content is extremely difficult. The logs, which were not affected by fire, decompose in the following years. Photo: GFMC.

Shifting agriculture systems in their early practices and extent were largely determined by low human population pressure on the forest resources. They provided a sustainable base of subsistence for indigenous forest inhabitants, and their patchy impacts had limited effects on the overall tropical forest biome (Nye and Greenland, 1960; Watters 1971; Peters and Neuenschwander 1988). Today, traditional shifting agriculture is still practiced in many regions of the topics. However, in many regions shifting cultivation is becoming increasingly destructive because of larger individual sizes of areas cleared and shorter fallow (forest recovery) periods.

In addition to shifting cultivation, large forest areas are converted for permanent crop and grazing lands. The burning of primary or secondary rain forest vegetation for conversion purposes is continuing at a rapid pace since the 1980s. In 1985 alone, more than 26.5 million hectares (ha) of forest clearing and rangeland fires were observed in the southern Amazon Basin, thereof ca. 8.9 million ha were forest conversion fires. In 1987 a total of 20 million ha were burned in the "Amazonia Legal" region; 40% of the burned area was primary forest, the remainder secondary growth (Malingreau and Tucker, 1988; Setzer and Pereira, 1991). For the more recent developments in Southeast Asia and South America see Page et al. (2013) and Cochrane (2013).

The application of targeted fire use in the rain forest biomes, however, often results in wildfires that escape control. Observations of the impact of drought and fires on the rain forests of Borneo and on the Amazon rain forest in the 1980s, have already shown that undisturbed perhumid rain forest biomes may occasionally become flammable. Goldammer and Seibert (1990) evaluated the state of information on the extent and impact of rain forest fires in Borneo during the extreme drought of 1982-83, which affected the entire Western Pacific Region. Such droughts were reported in both the 19th and 20th centuries and were associated in several cases with rain forest fires. During the 1982-83 drought, the area of the fire-affected rain forest was very large as a consequence of numerous fires escaped from forest conversion and shifting agriculture fires. These fires totaled ca. 5 million ha in East Kalimantan and the Malaysian provinces of Sabah and Sarawak. Fifteen years later, the 1997-98 fire and smoke episode in SE Asia resulted in a similar dimension of fire-affected area in East Kalimantan: A total land area of ca. 5 million ha, including 2.6 million ha of forest, was burned with varying degrees of damage (Siegert et al., 2001; Heil and Goldammer, 2001; Goldammer, 2006).

Forest regeneration after fire shows no coherent pattern. While the dipterocarp forest in general is highly fire-sensitive, there is regeneration potential in moderately burned forests. The occurrence of a relatively common fire-adapted tree species (ironwood – *Eusideroxylon zwageri*) in the lowland dipterocarp rain forest of East Kalimantan may be an indicator of historical recurrent disturbances by fire.

Other examples of larger-scale rain forest fires were those in the Yucatan (Mexico) during 1989. These fires were the result of a chain of disturbance events. The hurricane "Gilbert" in 1987 resulted in large-scale wind damage creating an unusual amount of fuels available for consumption. Trees and other woody fuels downed by the hurricane desiccated during the subsequent drought of 1988-89; the entire forest area was finally ignited by escaped land-clearing fires. None of these single three factors, the cyclonic storm, the drought, and the ignition sources, if occurring alone, would have caused a disturbance of such severity and magnitude on an area of ca. 90 000 ha.

Kauffman and Uhl (1990) described the environmental conditions required for potential flammability of surface fuels and downed woody material in the Amazon rain forest. The research shows that the microclimate of undisturbed rain forest is less favorable to allow ignition of surface fuels and fire spread as compared to disturbed forests. They also investigated and summarized research on the susceptibility of rain forest tree species to fire. A variety of vegetative adaptations were identified that may influence species persistence following fire, e.g. thick bark, subterranean sprouting, coppice, epicormic sprouting, characteristics of seed banks, and seed dispersal.

It is generally observed that recurring fires in tropical rain forest biomes lead to successive forest degradation by impoverishment of forest cover and species diversity, and in the final degradation stage to the invasion of pyrophytic grasses, e.g. *Imperata* spp. Large tracts of tropical lowlands formerly occupied by rain forest are now degraded *Imperata* grasslands that are maintained by short fire-return intervals (Fig. 3a to f).

Figures 3a to f. This long-term series of photographs illustrate the fire-induced destruction of a lowland tropical rain forest in East Kalimantan, Indonesia (Goldammer et al., 1996; Goldammer, 1999). In sequence they show: (a) Pristine *dipterocarp* rain forest in Eastern Borneo (1985); (b) surface fire burning in the same, selectively cut forest (1982); (c) post-fire stage after three years (1985). Most trees are killed by the surface fire, some by drought stress, but some trees are still standing; (d) post-fire stage after 13 years (1995). More standing trees have died and collapsed. Undergrowth dominated by pioneer tree species (predominantly *Macaranga* spp.) comes in vigorously. This secondary succession becomes highly flammable in extremely dry years. (e) The effect of the second burn in 1998. The tree layer, including the post-fire secondary succession, is nearly completely killed by a high-intensity fire. (f) Final stage of savannization in a nearby former forest site. The area is dominated by an aggressive post-fire invading grass species (*Imperata cylindrica)*. Photos: GFMC.

2.1.2 Fire in Seasonal Forests

The occurrence of seasonal dry periods in the tropics increases with distance from the perhumid equatorial zone. The forests gradually develop to more open, semi-deciduous and deciduous formations (e.g. moist and dry deciduous forests, monsoon forests). Between a more-or-less closed deciduous forest (characterized by fuels from the tree layer), and a grass savanna (fuels exclusively grasses), a broad range of ecotones can be found. Since varied terminology exists for the non-evergreen forests and for the ecotonal transitions towards savannas, it was suggested that the prevailing fuel type, a parameter more meaningful from the point of view of wildland fire science, be used to distinguish the diverse formations (Goldammer, 1991, 1993). The term "forest" is used if trees and tree residuals are dominating elements of the fuel complex (cf. paragraph 2.1.4). The main fire-related characteristics of these formations are seasonally available flammable fuels (grass-herb layer, shed leaves) which allow the grass layer, other understory plants (shrub layer), and the overstory (tree layer), to survive and furthermore to take advantage of the regular influence of fire. The most important adaptive traits are thick bark, ability to heal fire scars, resprouting capability (coppicing, epicormic sprouts, dormant buds, lignotubers, etc.), and seed characteristics (dispersal, serotiny, fire cracking, soil seed bank and other germination requirements) (Stott et al., 1990; Goldammer, 1993). These features are characteristic elements of a fire ecosystem.

During the dry season, the deciduous trees shed their leaves and provide the annually available surface fuel. In addition, the desiccating and (finally) dried grass layer, together with the shrub layer, adds to the available fuel which together generally ranges between 5-10 t ha^{-1}. Forest users such as herdsmen and collectors of non-wood-forest products usually set these fires. The forests are underburned in order to remove dead plant material, to stimulate grass growth, and to facilitate or improve the harvest of other forest products. The fires usually develop as surface fires of moderate intensity (usually less than 400 kW m^{-1}; cf. Stott et al., 1990), and tend to spread over large areas of forested lands. The canopy layer is generally not affected by the flames, although isolated torching and crowning may occur earlier in the dry season when the leaves are not yet shed. In some cases, fires may affect the same area two or three times per year, e.g. one early dry season fire consuming the grass layer and one subsequent fire burning in the shed leaf litter layer (Goldammer, 1993; Wanthongchai et al., 2011). The size of these fires is usually larger than the area that was intended to be burned. This is mainly due to the uniformity of available fuels.

The ecological impacts of annual fires on deciduous and semi-deciduous forest formations are significant. Fire strongly favors fire tolerant trees, which replace the species potentially growing in an undisturbed environment (Fig. 4 and 5). Many of the monsoon forests of continental Southeast Asia would be reconverted to evergreen rain forest biomes if human-made fires were eliminated (Fig. 6). Such phenomena have also been observed in Australia where the aboriginal fire practices and fire regimes were controlled and rain forest vegetation started to replace the fire-prone tree-grass savannas. Fire adaptations and the possible fire dependence of economically important trees such as Sal (*Shorea robusta*) and Teak (*Tectona grandis*) have been the focus of a controversial discussion regarding the traditional fire control policy in British Indian Forestry for a long time (Pyne, 1990; Goldammer, 1993; Goldammer and Wanthongchai, 2008).

The tropical deciduous forests largely constitute a “fire climax”, i.e. their composition and dynamics are predominantly shaped by fire. However, these fire-climax forests are not necessarily in an ecologically stable condition. Long-term impacts of the frequent fires lead to considerable site degradation. For instance, the erosion rate tends to be high because of the depletion of protective litter layer by fire just before the onset of the monsoon rains (Fig. 7; Goldammer, 1993).

Figure 4. Typical surface fire in a dry dipterocarp forest in Thailand. Photo: GFMC (K. Wanthongchai).

Figure 5. Typical pure stand of *Shorea robusta* (sal) in northern India and southern Nepal. Fires occurring in 1- to 3-years intervals favor the fire-resistant sal trees and eliminate the most important competing tree species, thus leaving large pure stands of sal. Photo: GFMC.

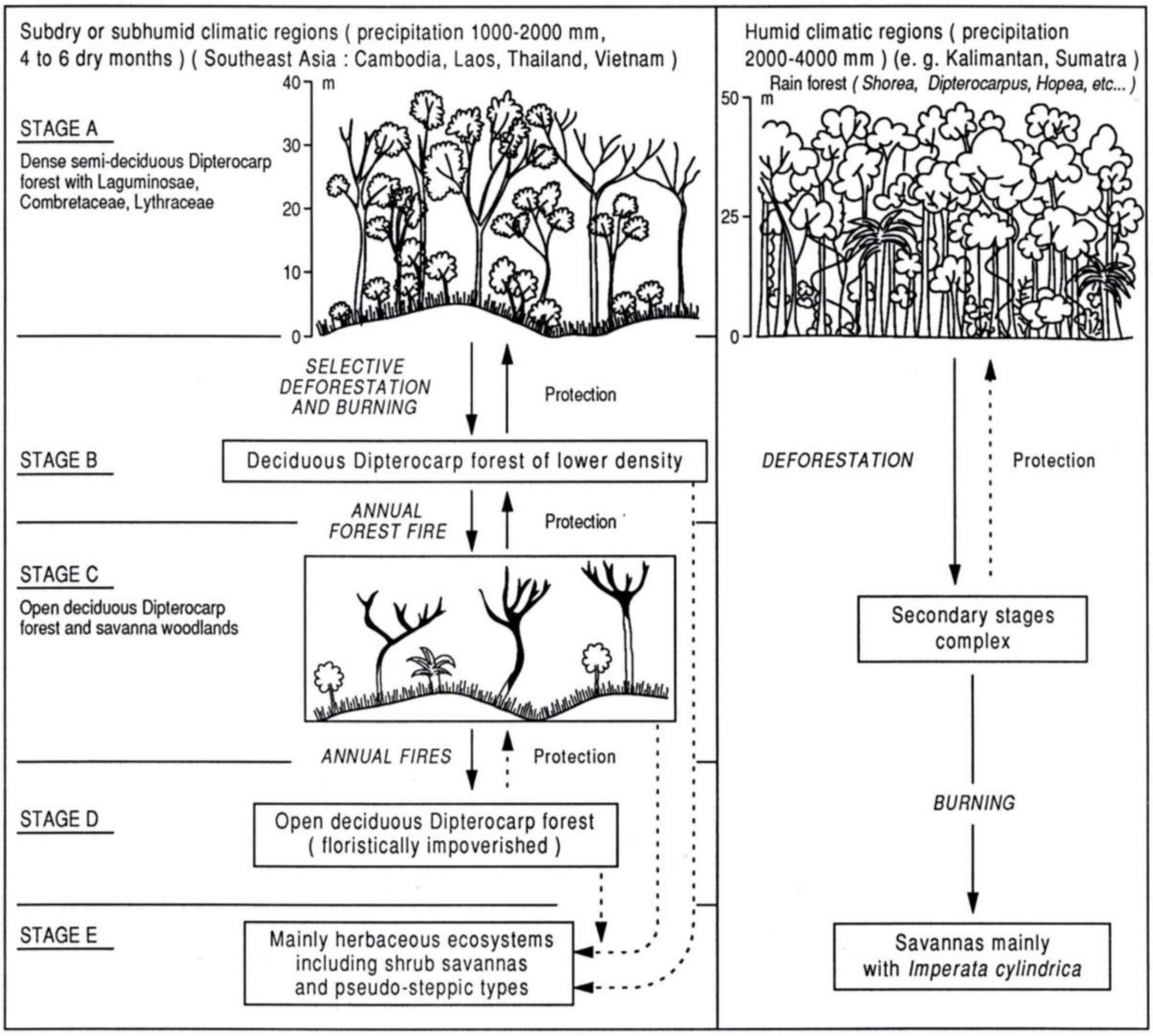

Figure 6. Examples of evolution of seasonal and perhumid forest biomes in continental and insular Southeast Asia as influenced by fire and fire protection (modified after Blasco, 1983).

2.1.3 Fire Climax Pine Forests in the Tropical Submontane and Montane Altitudes and in the Subtropical Lowlands

Approximately 105 species of the genus *Pinus* are recognized. Some species extend into the tropics. There are no pines occurring naturally between the tropics of Africa and in the whole of the Southern Hemisphere except Sumatra. In the tropics, the pines are largely confined to the zone of lower montane rain forest. They are usually found on dry sites and prefer a slight to distinct seasonal climate. Most tropical pines are pioneers and tend to occupy disturbed sites, such as landslides, abandoned cultivation lands and burned sites. In the subtropics pines are also found in the lowlands, e.g. in the South of the North American continent.

Besides the pioneer characteristics, most tropical pines show distinct adaptations to a fire environment (bark thickness, rooting depth, occasional sprouting, high flammability of litter) (Goldammer and Peñafiel, 1990). The tropical pure pine forests of Central America and South Asia, most often are the result of a long history of regular burning. As in the tropical deciduous forests, fires are generally set by graziers, but also spread from escaped shifting cultivation fires and the general careless use of fire in rural lands. Fire return intervals have become shorter during the last decades, often not exceeding 1 to 5 years. These regularly occurring fires favor the fire-adapted pines, which replace fire-sensitive broadleaved species. The increased frequency of human-caused fires has led to an overall increase of pines and pure pine stands prevalence outside the potential natural area of occurrence in a non-fire environment. In the mountainous zones of the tropics, fire also leads to an increase of the altitudinal distribution of pines, e.g. by expanding the mid-elevation pine forest belt downslope into the lowland rain forest biome and upslope into the montane broadleaved forest associations (Kowal, 1966). These tropical fire-climax pine forests are found throughout Central America, the mid-elevations of the southern Himalayas, throughout submontane elevations in Burma, Thailand, Laos, Cambodia, Vietnam, Philippines (Luzón) and Indonesia (Sumatra).

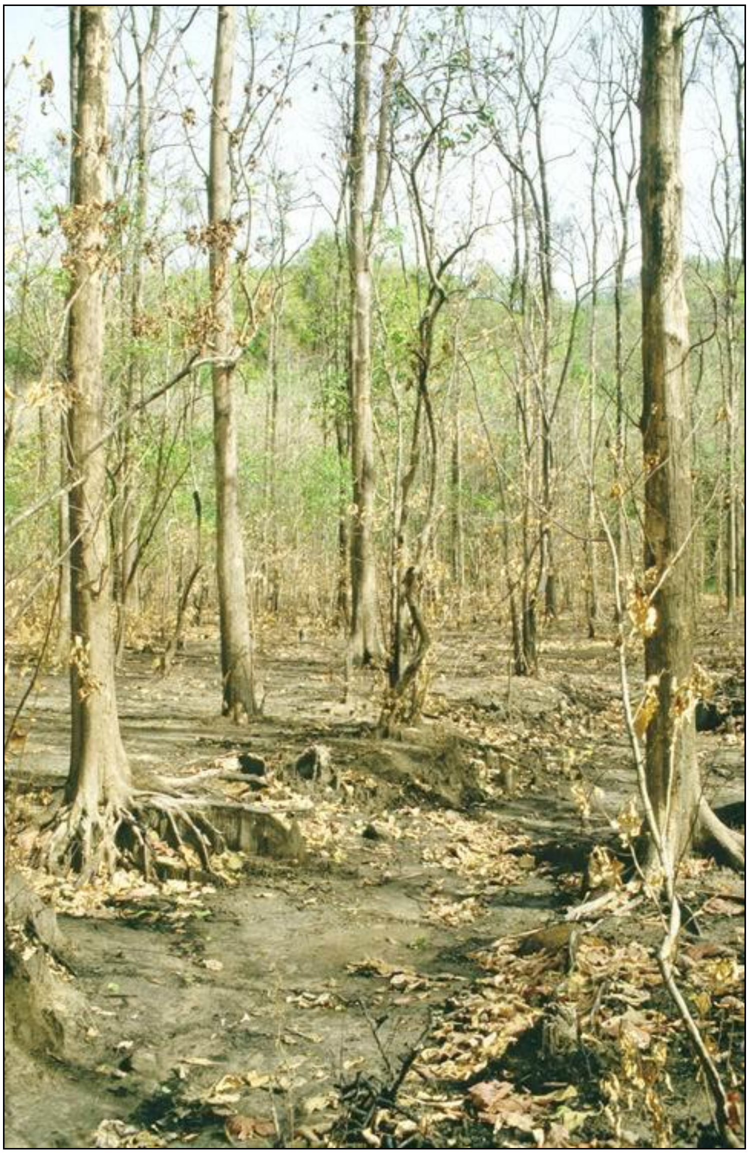

Figure 7. Teak (*Tectona grandis*) plantation in the State of Uttar Pradesh (India) annually affected by surface fires. The fires leave the teak trees largely unaffected and eliminate all competing vegetation. The depletion of litter layer prevents humus layer formation and leads to heavy erosion processes. Photo: GFMC.

The subtropical fire-climax pine forests are also the result of a long history of natural and anthropogenic fires. In North America, the belt of southern pines gradually stretches from the subtropical coastal regions along the Gulf of Mexico into the southern temperate forest region. Pines that may dominate or form exclusively pure stands, are in permanent competition with broadleaved tree species. Broadleaved trees in general, are less fire-tolerant than pine species. Thus the influence of regularly occurring natural fires caused by lightning, the historic fires set by the pre-Columbian Indian population, and later by the game hunting society, gave advantage to the genus *Pinus*, which proved to cope successfully with the fire environment. The mix of natural fires and anthropogenic influenced fire regimes was disturbed by the influential European dogma of fire exclusion, which inappropriately was imposed on North America. During the 1970s, public policies were modified aiming at the re-establishment of native natural and human-shaped fire regimes. This was approached through the reintroduction of prescribed burning practices, as well as allowing some wildfires to burn, within the fire management objectives.

In the tropical and subtropical regions, fire-climax pine forests provide a high degree of habitability and carrying capacity for humans. If used properly in time and space, fire creates a highly productive coniferous forest, which grants landscape stability and sustained supply of timber, fuelwood, resin, and grazing land. However, together with the effects of overgrazing (including mechanical disturbances, e.g. caused by trampling) and extensive illegal logging, the increasing occurrence of wildfires tend to destabilize the submontane pine forests and result in forest depletion, erosion and subsequent flooding of lowlands (Pancel and Wiebecke 1981; Fig. 8a and b).

Figures 8a and b. Young *Pinus khesyia* stand on a steep slope on Luzón, Philippines (left), and a pure open stands of *Pinus roxburghii* on the Himalayan south slopes of Uttar Pradesh (India) (right). Large tracts of these pine stands are subjected to severe erosion processes due to the effects of regular fires, overgrazing, browsing and trampling. Photo: GFMC.

2.1.4 Savannas and Open Woodlands

The various types of natural savanna formations are potentially of edaphic, climatic, orographic origin and additionally shaped by wildlife (grazing, browsing, and trampling) and fire (cf. Cole, 1986). Together with anthropogenic influences (e.g. livestock grazing, fuelwood cutting and other non-wood product uses), most tropical savannas are shaped by regularly occurring human-made fires (Fig. 9). The interactions of wildlife, humans and fire in the prehistoric climate and landscapes as described by Schüle (1990), are of significant importance in the development of tropical savannas. Modern synoptic analyses of savanna ecosystems have always regarded fire as an important function.[3]

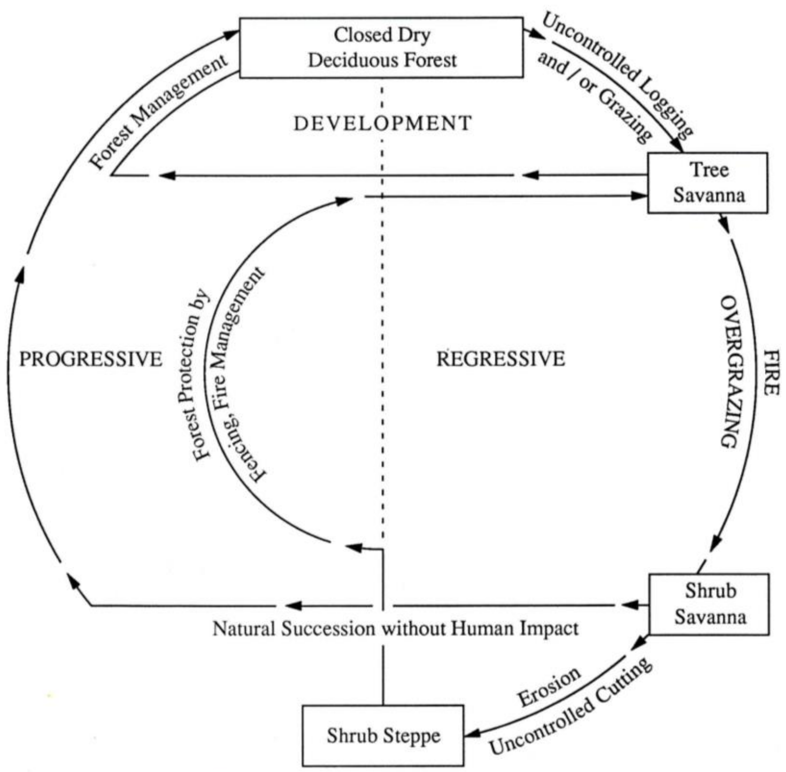

Figure 9. Generalized scheme of closed dry deciduous forest degradation and rehabilitation as induced by uncontrolled fire and grazing (regressive development) and protective measures (progressive development) (modified after Verma, 1972).

A tremendous variety in physiognomy of the savannas occurs throughout the tropics of Africa, America and Asia. A common feature, however, is the grass stratum, which is an important surface fuel of the open savanna woodlands (tree savannas) and the predominant or exclusive fuel in the grass savannas (grasslands), and in the ecotones between ecosystems defined as forests. From the point of view of fire ecology, the distinction between a savanna ecosystem and an open forest could be based on the potential fuel availability. In a savanna, the grass stratum would be the exclusive or predominant fuel, whereas in open deciduous forests the fuels carrying a fire should predominantly be tree leaf litter and other downed woody materials from the tree layer.

[3] The following monographs contain numerous bibliographical sources on savanna fires: Tall Timbers Research Station (1972), Huntley and Walker (1982), Booysen and Tainton (1984), Cole (1986) or van Wilgen et al. (1997).

Fuel availability (aboveground biomass density of the grass stratum) per area unit varies with the different bioclimatic and phytogeographic savanna zones (Menaut et al., 1991). In the arid zone of West Africa (Sahel), aboveground biomass ranges between 0.5 and 2.5 t ha^{-1}, in the mesic Sudan zone between 2 and 4 t ha^{-1}, and in the humid Guinea zone up to 8 t ha^{-1}. Fire frequency largely depends on fuel continuity and density. Thus, savannas with relatively high and continuous loads of flammable grasses, such as the Guinean savannas, are subjected to shorter fire-return intervals as compared to the arid savannas (Fig. 10). Burning efficiency depends on the moisture content of dead and live organic matter. Fires occurring in the early dry season generally consume less of the aboveground biomass than those at the end of the dry season.

Figure 10. Many of the tropical humid savannas are long-term stable fire climax ecosystems. The photograph shows a humid "Guinean" savanna type in Côte d'Ivoire (West Africa) which are subjected to regular fire influence. The extreme fire tolerance of palms (here: *Borassus aethiopum*) is a pantropical phenomenon (see also Fig. 2). Photo: GFMC.

2.1.5 Fires in Tropical Planted Forests

Forest plantations in the tropics are established for three main purposes. First, afforestations are planned to support the demands of local population such as for timber, fuelwood, non-wood forest products, silvopastoral and other agroforestry systems. Second, afforestations are part of landscape rehabilitation or environmental protection measures, for example planting of greenbelts and plantations to encounter the impacts of wind, erosion, and desertification.

The third objective of afforestation activities is to establish industrial plantations for cash crops, mainly timber, pulpwood or oilseeds. Only a minor part of the industrial plantations is afforested with indigenous species. Most species planted are fast growing exotics among which *Pinus* spp. and *Eucalyptus* spp. are the genera most widely used.

Litter production in plantations of fast growing species is extremely high and often is not in equilibrium with decomposition. The monoculture structure of plantations and the exclusion of other forest uses, lead to accumulation of surface fuels (thick layers of needles/leaves, downed woody debris, shed bark strips) and aerial fuels (draped fuels: shed needles intercepted by branches / twigs) (Fig. 11 and 12).


Figures 11 and 12. A typical fuel load of needles in a 9-year-old *Pinus ellliottii* plantation. Note the ladder (aerial) fuels and the lack of understory. Fazenda Monte Alegre, Paraná, Brazil (left). Surface fuel load in a 15-year-old *Pinus taeda* plantation after third thinning. Same location in Brazil as Figure 11 (right). Photos: GFMC.

Within their natural range both genera have developed forest formations largely shaped by natural and human-made fires. The role of regularly occurring fires was to suppress fire-sensitive vegetation and to favor the formation of pure stands of fire-resistant pines and eucalypts. Exclusion of fire from the fire-climax ecosystems generally leads to build-up of fuels and extreme wildfire hazard (high-intensity stand replacement fires).

During the past decades, almost all industrial exotic forest plantations in the tropics were established without considering and introducing recurrent fire as a basic element of stabilizing the biological disequilibrium in fuel dynamics. Consequently, many of these plantations are highly susceptible to high-intensity stand replacement fires.

The introduction of prescribed fire into tropical plantations (or: the restoration of fire into fire ecosystems that were transferred from their native fire environment into a management system in which fire originally had not been integrated) is still a challenging field of fire research and fire management policy (de Ronde et al. 1990; Goldammer and de Ronde, 2004; cf. paragraph 3.4).

2.1.6 Other Environmental Impacts of Tropical Fires

Since the 1990s increasing attention has been given to the impact of tropical fires on regional and global-scale environmental processes, e.g. the role of tropical fires in biogeochemical cycles and especially in the chemistry of the atmosphere (cf. syntheses by Goldammer, 1990, 2013a; Levine, 1991, 1996; Crutzen and Goldammer, 1993). A recent estimate of the magnitude of tropical plant biomass burned in shifting agriculture, permanent deforestation, other forest fires and savanna fires, revealed that up to 5.1 billion tons of combusted plant biomass may result in an annual immediate (gross) release of carbon into the atmosphere in the magnitude of 8.4 billion tons of carbon dioxide (CO_2) and 400 million tons of carbon monoxide (CO) (Andreae, 2013). Table 1 shows that the amount of CO_2 emitted from fires affecting tropical savannas and forests corresponds to about one third of the total emissions from fossil fuel burning.

Though the amount of carbon remaining in the atmosphere (net release) is not known exactly, it is generally accepted that the net release of carbon into the atmosphere from plant biomass burning for permanent conversion of tropical forest into other land uses ("deforestation"), amounts to ca. one billion tons per year.

Although the emissions from tropical vegetation fires are primarily CO_2, many by-products of an incomplete combustion process, which play an important role in atmospheric chemistry and climate, are emitted as well (Crutzen and Andreae, 1990). Much of the burning is concentrated in limited regions and occurs mainly during the dry season, resulting in levels of atmospheric pollution that rival those in the industrialized regions of the developed world. These environmental consequences of tropical fires demonstrate that this natural force, increasingly induced by humans, is influencing ecosystem processes on a scale that goes far beyond the site where fire is applied.

Table 1. Global annual plant biomass combusted by fire and the emitted amounts of CO_2 and CO released in the late 1990s (in mass of species per year; millions of tons per year) compared to the CO_2 and CO emissions from fossil fuel burning. Note: This table is an extract of a more comprehensive compilation of global annual emission of selected pyrogenic species in the late 1990s (Andreae, 2013).

	Savanna and grassland	**Tropical forest**	**Extra-tropical forests**	**Biofuel burning**	**Charcoal making**	**Charcoal burning**	**Agri-cultural residues**	**Total**	**Fossil fuel burning**
Million tons burned	3 160	1 330	640	2 824	152	38	496	8 600	---
CO_2	5 257	2 162	1 006	4274	73	98	723	13 600	23 100
CO	197	134	68	242	12	8.4	46	710	278

3 Fire Management

The description of fire ecology of some selected tropical vegetation types, coupled with other ecological implications of tropical biomass burning, demonstrate that a general and overall valid statement on the role of fire cannot be made. On the one hand, it is clear that fire in the tropics has been used by humans for millennia in successfully cultivating and maintaining valuable forests and open savanna landscapes of high sustainability and carrying capacity. On the other hand, in recent years, fire has become the most destructive and omnipresent agent in tropical vegetation.

The tropical forest land manager is challenged to carefully investigate the very specific (real) and potential role of fire in his area of responsibility, to determine the allowable extent to which fire is compatible with other management and conservation objectives, and to transfer this knowledge into an integrated fire management system (Fig. 13).

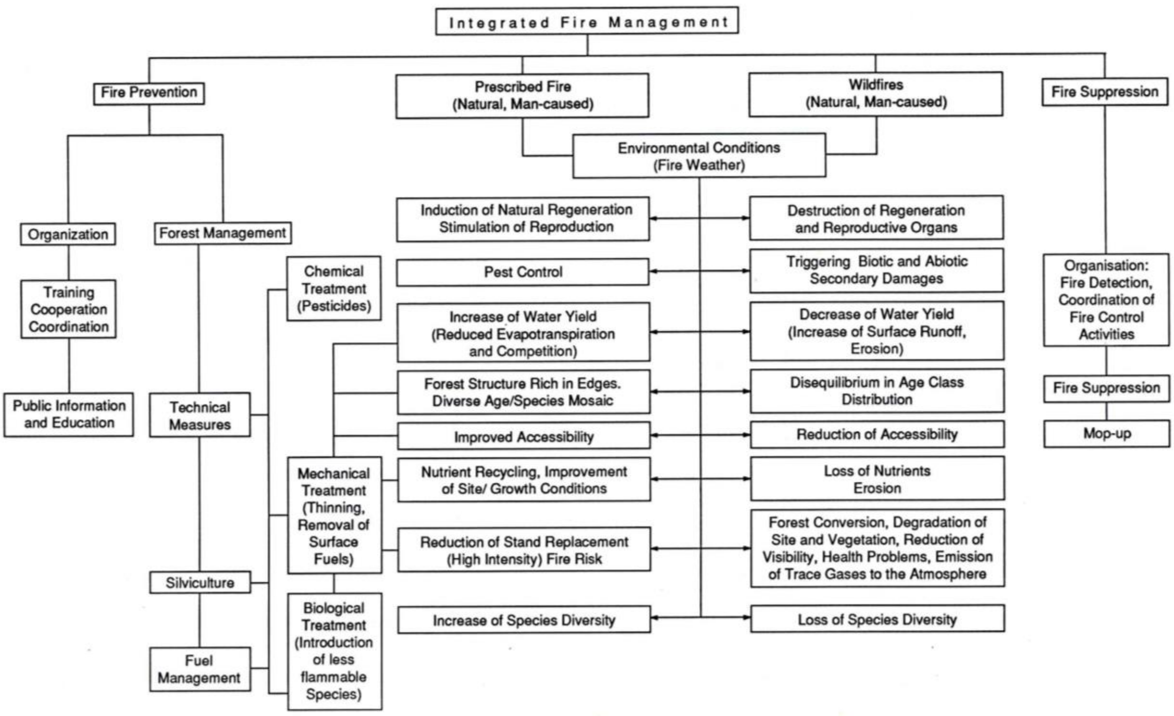

Figure 13. Schematic diagram of components, objectives and considerations of Integrated Fire Management system.

Fire Management Guidelines developed by international organizations provide more detailed guidance and suggestion for comprehensive approaches in fire management (ITTO, 1996; FAO, 2006). To avoid redundancy, it is suggested to consult these guidelines, which are available online.[4]

[4] See comprehensive web page of the Global Fire Monitoring Center (GFMC) with links to all fire management guidelines: http://gfmc.online/literature/fire-management.html

These guidelines provide, among other things, guidance to principles and strategic actions that are not addressed in this chapter:

- Principles
  - Social and cultural
  - Economic
  - Environmental
  - Institutional

- Strategic actions
  - Fire and resource management planning
  - Fire management in natural or protected areas and reserves
  - Fire awareness and education
  - Fire danger rating and early warning systems
  - Fire preparedness, including technical training
  - Pre-fire-season activities
  - Fire detection, communications and dispatching
  - Initial attack/action
  - Large-fire suppression and management
  - Managing multiple incidents
  - Burned area restoration and rehabilitation
  - Monitoring and assessment

3.1 Fire Management Options – Some Basic Considerations

A brief review of tropical fire regimes, revealed the different functional roles of fire in tropical ecosystems and the variation of sensitivities and adaptations to fire, including fire dependence of some ecosystems. Given the magnitude wildfires and land-use fires globally, which may affect up to 600 million hectares annually (Mouillot and Field, 2005), among which savanna ecosystems of Africa and South America may account for more than the half of the global area burned, fire management planning must be based on a realistic basis and give priorities to the most vulnerable ecosystems. In principle, there are three basic options for fire management planning; the following three basic considerations and possible fire management options in tropical forestry will be highlighted. The ecological and economic implications of these options are summarized in a general scheme provided in Table 2. The integrated fire management option embraces all possible treatments as listed in the table (fire exclusion, integration of uncontrolled but tolerable or desired wildfires, and application of prescribed fire).[5]

Fire Exclusion: Equatorial rain forests in general, are extremely fire sensitive and require the strict exclusion of fire if conservation or management objectives are not to be jeopardized. This also applies to forest plantations that are stocked by fire-sensitive tree species, or tropical peat-swamp forests. In these cases, fire management requires consequent fire prevention and control approaches and the availability of an efficient fire protection organization.

[5] Due to lack of space in the Tropical Forestry Handbook the reader is referred to comprehensive monographs and manuals that cover the basics in fire behavior, fire management, fire suppression methods and technologies, e.g. Brown and Davis (1973), Luke and McArthur (1978), Chandler et al. (1983), Pyne et al. (1996), Goldammer, and de Ronde 2004; Heikkilä et al. (2007). A short glossary of fire management terms is found in Appendix 2. For online glossaries see GFMC web page: http://gfmc.online/literature/glossary.html

Table 2. Ecological, economic and management aspects of integrated fire management options in various tropical forest and other sub-forest types Source: Goldammer (1993), modified

	Ecological and Economic Aspects of Fire	**Deciduous Broadleaved Forests (e.g. *Tectona grandis, Shorea robusta*)**	**Coniferous Forests (e.g. *Pinus* spp.)**	**Industrial Plantations (e.g. *Pinus* and *Eucalyptus* spp.)**	**Silvopastoral Systems (e.g. open pine forests with grazing)**	**Grass Savannas (e.g. extensively grazed wildlands)**
Fire Exclusion	Ecological Impacts	High diversity of species, habitats and niches. High water-retaining and soil protection capability	Replacement of coniferous species by less fire-tolerant broadleaved species. Pines only on dry shallow and disturbed sites. Overall increase of species diversity. High water retaining and soil protection capability	High risk of uncontrolled high-intensity stand-replacement wildfires due to fuel accumulation	Undesirable increase of species not suitable for grazing purposes. Replacement of grass stratum by succession	Progressive successional development toward brush/tree savannas or forest. Promotion of less fire-tolerant species
	Economic and Management Implications	Economic wood production difficult because of high diversity of species. Increase of non-wood forest products.	Economic wood production difficult because of high species diversity	Wood production feasible. Extreme high risk of destruction of plantations by wildfire	Only possible if intensively grazed and mechanically cleared	Not feasible
Uncontrolled Wildfires	Ecological Impacts	Selection of fire-resistant/tolerant tree species. Opening of forest formation	Retreat of fire-sensitive species and favoring of fire resistant pines. Opening of forests. Stand replacement fires. Forest degradation	Stand-replacement fires	Uncontrolled selective fire pressure. Maintenance of openness	Maintenance of a wildfire climax. Uncontrolled selection of fire adapted plants
	Economic and Management Implications	Species composition and relevant management & marketing opportunities get out of control	Tendency to degradation and loss of productivity	Management objectives jeopardized if no efficient fire prevention and control system available	Possible long-term degradation and loss of productivity	Productivity depends on savanna type and other degradation factors involved
Prescribed Fire (integrated Fire Management)	Ecological Impacts	Controlled selection of tree species. Advantageous for stimulation and harvest of selected non-wood forest products	Controlled favoring of desired fire-tolerant species. Reduction of stand-replacement fire risk	Maintenance of desired monostructure of plantations. Reduction of stand-replacement fire risk. Increase of vitality	Controlled promotion (stimulation) of desired tree and fodder plant species	Controlled promotion of desirable grass/herb layer and tree/blush regeneration
	Economic and Management Implications	An Integrated Fire Management System requires availability of relevant ecological background knowledge, trained personnel, and infrastructural facilities to prevent and control undesired wildfires and conducting safe prescribed burning operations				

Integrated Fire Management: The application of an integrated fire management approach requires a thorough understanding of the impacts of fire in a specific tropical forest type. It requires the capability to actively manage all fire situations, e.g. to prevent and suppress all undesirable fires, to take advantage of the benign effects of fire to obtain resource management goals by prescribed burning, and to define and control the threshold between the desired and undesired effects of uncontrolled natural and human-caused fires. In many regions of the tropics and subtropics, the effects of fire on ecosystem properties and stability, including carbon sequestration capacity, may vary depending on the seasonality of fires. For instance, fires burning at the peak or at the end of the dry season are generally more severe and destructive due to extreme fire weather and accumulated fuels; whereas fires burning in the early dry season may have less intensity and severity and thus cause less damage to the ecosystem.

No Fire Management (Uncontrolled Wildfire Occurrence): There are vast areas of tropical and subtropical open deciduous and semi-deciduous forests, grass, bush and tree savannas that are burning on a large scale, annually or in short-return intervals of two or more years. Burning patterns (timing of burning, burning frequency) follow traditional land treatment practices or are subjected to chance, and in some regions are also caused by lightning. In many places there may be no alternatives but to let these fires burn due to a lack of fire management capabilities, access, infrastructure and (suppression) funding. As mentioned before, the uncontrolled fire regimes of many fire-climax savanna and forest landscapes may be tolerable as long as no additional degradation factors interfere, e.g. excessive grazing. However, the introduction of integrated fire management in many places, based on the active participation of local rural communities, may increase the productivity and sustainability of the vegetation. For instance, progressive developments from savannized vegetation toward a higher tree cover or rehabilitation of forest cover, could be reached by implementing the principles of Integrated Fire Management. This also has implications on the sequestration of terrestrial carbon.

Methods and technologies for implementing either the fire exclusion policy or an integrated fire management system are described in the following sections of fire prevention, fire suppression, prescribed burning, fire management organization, legislation and policies.

3.2 Fire Prevention

The prevention of forest fires and other wildland fires embrace a wide range of measures that either modifies the fuels present – or within the fire-threatened resources so that spread and intensity of fires is hampered. Thereby, fires can be controlled by the technical means available (fuel management), or the human-caused ignition sources can be reduced.

3.2.1 Fuel Management

The most important fuels in forests, which need to be treated, are the surface fuels. Surface fuels – the grass-herb stratum, shrubs – are the main carrier of the horizontal spread of fire. Fuels comprising understory trees and “aerial fuels” determine the potential for building-up the vertical development of a surface fire, i.e. a crown fire. Aerial fuels are defined as all combustibles not in direct contact with the ground, e.g. foliage, twigs, understory tree crowns, which may carry a surface fire up to the crowns ("ladder fuels").

The treatment of these fuels either concentrates on buffer zones (firebreaks or fuelbreaks designed to break up large continuous forested areas), or is practiced inside of the forest stands to be protected.

Firebreaks

The construction of firebreaks and fuelbreaks around and inside of a forest complex is a common method of separating fuels (interruption of fuel continuity). A firebreak is a line of a width up to several meters on which all combustibles are removed and the mineral soil is exposed. The objective of firebreak construction is to segregate, stop, and control the spread of a wildfire. The width of the firebreak varies with fuel loads and expected spotting behaviour (fires jumping over the firebreak). Since fires may easily cross over firebreaks of up to several dozen meters, it is often extremely uneconomical to establish and to maintain such large and unproductive strips of land. Furthermore, firebreaks in steep terrain are subjected to erosion during the rainy season.

Fuelbreaks with agricultural crops

The concept of a fuelbreak is different: Fuelbreaks are generally wide (up to several hundred meters) strips of land on which flammable vegetation is modified so that fires burning into them can be more readily controlled. In the tropics, it has been demonstrated successfully that fuelbreaks can be maintained economically by agricultural or agro-silvopastoral land uses.

Agricultural and pastoral land uses usually involve intensive soil treatment and the removal of aboveground biomass so that less flammable ground cover is available. A general recommendation for species to be planted on agricultural fuelbreaks cannot be given because of the specific site and climate conditions required. However, some basic principles should be observed. The design of agricultural fuelbreaks should be according to the suitability of sites for growing agricultural crops. The selection, treatment and harvest of crops should observe the seasonality of fire danger, e.g. the removal of flammable plant debris prior to a period of high fire danger. The integration of millet cultivation (e.g. *Pennisetum glaucum*, a millet species largely planted as staple food throughout Africa and Asia) on fuelbreak strips may serve as an example for specific harvest planning. The edible parts of millet are usually harvested at the beginning of the dry season, and the remaining biomass (highly flammable stem with leaves) is left on the site until the end of the dry season. In this case it would be required, by contracting the farmer, so that the removal of all aboveground biomass has to be finalized before the beginning of the fire season.

If sites are suitable, it is preferable to grow creeping plants such as various legumes or groundnuts, which will not carry any surface fire due to intensive soil treatment and low and/or spaced growth.

Pastoral and silvopastoral fuelbreaks

The integration of grazing is another method of reducing the flammability of the surface fuels on treeless strips and on "shaded fuelbreaks" (grazing under wide-spaced tree overstory). The grazing resources on the treeless fuelbreaks may occur naturally or may need to be seeded if suitable grass species are not available locally. The impact of "prescribed grazing" (Goldammer, 1988) and the browsing of brush and tree succession keeps the total fuel loading down. If grazing and/or browsing is selective, e.g. by leaving certain grass and brush species unaffected, additional mechanical treatment or the use of prescribed burning is necessary in order to further reduce the surface fuel loads. Pastoral fuelbreaks may include firebreaks, for example small strips along each side of the fuelbreak; these firebreaks are mandatory if prescribed fire is applied for fuelbreak maintenance (see below). The spatial concept of open (treeless) rangeland strips follows the same basic patterns as provided in Figure 14.

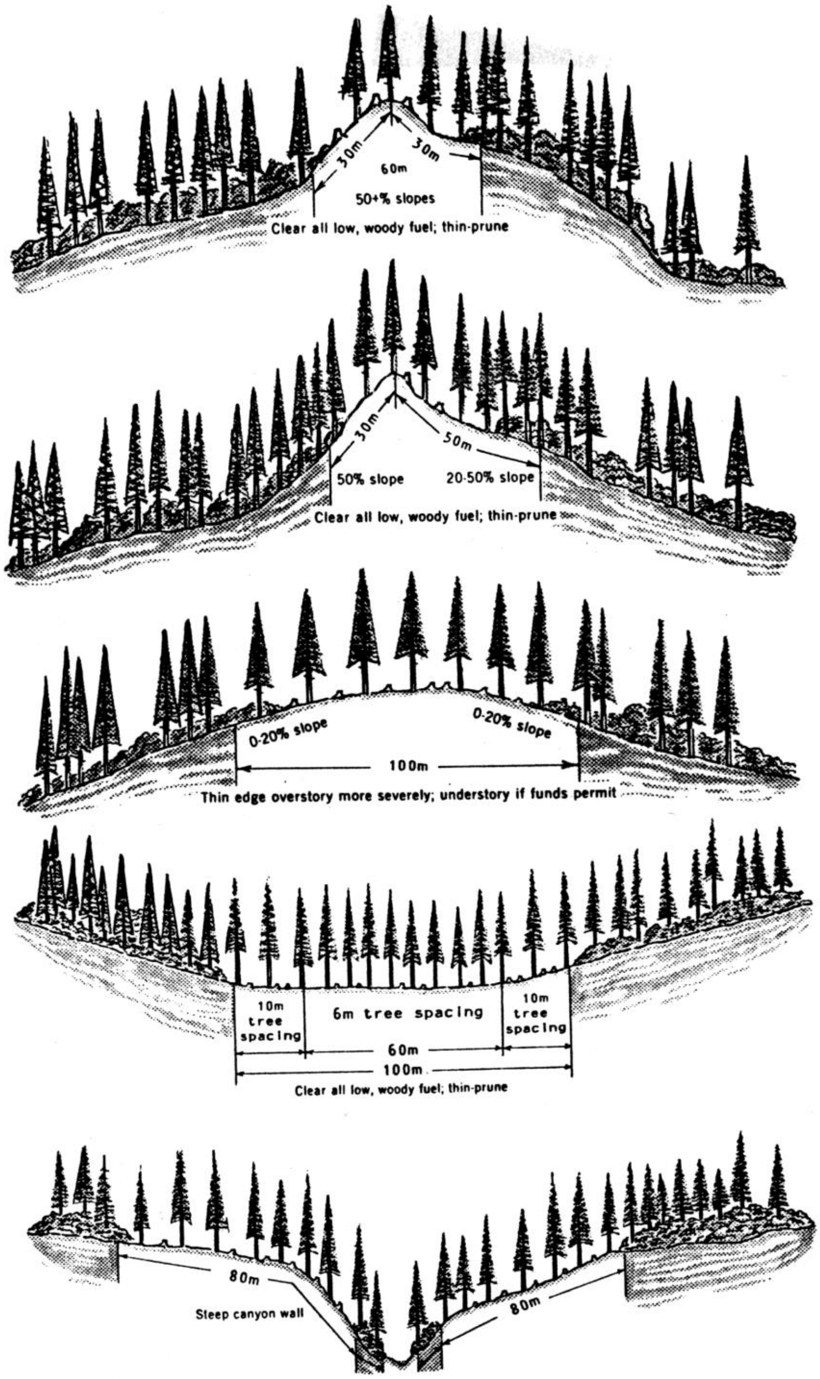

Figure 14. Generalized spatial concept of fuelbreak design in dependence of topography. This scheme has been developed for mixed conifer forests in the Sierra Nevada, California, but can be applied in other forest types and under different bioclimatic conditions. Source: Courtesy U.S. Forest Service (Green and Schimke, 1971).

Shaded fuelbreaks in principle are similar to the concept of silvopastoral systems. The idea of shaded fuelbreaks is to avoid the complete opening of a forest either by firebreaks or by treeless fuelbreaks. It involves a combination of timber production and animal husbandry management. Timber production is restricted to a relatively low amount of trees and depends on the species used, as well as the topography; low-density spacing produces solitary-type trees. Depending on the species involved and the timber production goals, these solitary trees may need to be pruned regularly (e.g. *Pinus* sp.). This spatial concept results in breaking the continuity of surface and aerial fuels, both vertically and horizontally.

Shaded fuelbreaks offer a variety of benefits both for pasture and forest management. For example, it reduces the heat stress of grazing animals or plant water stress due to wide spacing and reduced competition. The selection of tree and animal species to be used in an integrated silvopastoral system must be investigated carefully in order to avoid incompatibility of both uses, such as possible tree damages caused by animals, etc. In Figures 15 and 16 examples are given of what such shaded fuelbreaks inside of pine and eucalyptus plantations could look like.


Figures 15 and 16. The left photo shows a silvopastoral system (sheep grazing under *Pinus radiata*). Intensive pruning and removal of slash is required to provide sufficient light for grass growth and access for animals. Right: Open stand of *Eucalyptus globulus* in the North of Argentina. The effects of prescribed grazing and prescribed fire keeps the stand clean from fuel accumulation and considerably reduces the high-intensity wildfire risk. Photos: GFMC.

Fuelbreaks without any other land use

Fuelbreaks that are not utilized for agricultural land uses need to be structured in the same way as silvopastoral fuelbreaks. The removal of slash (thinning and pruning) requires mechanical treatment, by hand or by using shredding devices to cut the slash to small particles (chipping). These particles remain on-site for improvement of the humus layer formation. A compact layer of chipped fuels is generally less flammable. Surface fires creeping on such compact layers are generally easy to control. The slash can also be removed from the fuelbreaks and burned in piles. The use of prescribed fire on fuelbreaks follows the general concepts as described in paragraph 3.4.

Fuel management inside of the standing forest to be protected

The treatment of surface and aerial fuels inside a standing forest requires careful economic planning. Fuel reduction by mechanical means such as pruning, thinning, removal of understory vegetation, other surface fuels and slash thinning, is very labor and cost intensive.

Costs can be reduced if the biomass, which is to be removed, is utilized by the local population (e.g. for fuelwood).

Fuels inside of those forest and sub-forest types, which are adapted to low-intensity surface fires, can be treated by prescribed fire. Extensive information on techniques is available for conducting safe underburning of plantations in order to reduce the accumulation of fuels (cf. paragraph 3.4).

3.2.2 Integration and Cooperation with the Rural Population

Tropical forest fires and other wildland fires, are primarily caused by rural populations. An efficient fire prevention strategy therefore, requires an initial understanding of the cultural and socio-economic background of the tropical fire scene.

Socio-economic and cultural surveys on fire causes reveal that the most important reason for the careless use of fire is related to the fact that the rural population does not realize the economic and ecological benefits from forests and forest protection. Additionally, it is often recognized that rivalries and conflicts between forestry and agricultural land users provoke the intentional and careless setting of forest fires.

The tropical forest fire manager relies heavily on a positive relationship between the people in the rural space and his forest. Mutual confidence and public support can be created by participatory approaches, e.g. by employing people in the forestry sector, especially in fire prevention work (establishing and maintaining firebreaks and fuelbreaks, other fuel treatment). The integration of agricultural and grazing land-use into the fuelbreak system, as described before, can also create a high degree of confidence and even dependence (e.g. through a cost-free leasing of fuelbreak land).

Other measures that may stimulate cooperation in fire prevention are "non-fire bonus incentives". Such an incentive provides funding for villages (or other types of communities), if no fire occurs on specific lands and during specific times. Such programs however, must be accompanied by public information campaigns (e.g. through mass media, schools, churches).

Since the use of fire remains to be a vital factor in tropical land use systems, it is recommended that fire management extension services be offered. The extension service should provide information and training in safe and controllable burning techniques. With these techniques it would be possible to retain the fire within the intended area of application and to reduce the risk of human fatalities.

Figures 17 to 19 show examples of community involvement: Prevention messages, fire prevention planning at the community level, and cooperation of local farmers in the safe application of prescribed fire.

Concepts of participatory, local community-based fire management are increasingly being applied in many countries. Background information, case studies and outreach materials from all continents are available on a web portal.[6] These materials also include the "Guidelines on Defence of Villages, Farms and Other Rural Assets against Wildfires (Guidelines for Rural

[6] Community-Based Fire Management web portal of the Global Fire Monitoring Center (GFMC): http://gfmc.online/manag/cbfim.html

Populations, Local Communities and Municipality Leaders)". The guidelines, which were developed for the Balkan Region, provide easy-to-read advice for rural communities to prevent, be prepared for, and defend against wildfires threatening rural assets, human health and lives. The guidelines can be modified for the use in other regions.[7]

Figure 17. Fire prevention message involving local art in Namibia. Source: M. Jurvélius, former Namibia-Finland Forestry Programme.

[7] http://gfmc.online/manag/cbfim_11.html

Figure 18. Fire prevention planning in a local community in Mozambique. Photo: GFMC.

Figure 19. A prescribed slash-and-burn fire realized by a farmer in Jalapao, Brazil, with the assistance of the local fire crew, to ensure that the fire will not escape to the surrounding land. Photo: GFMC.

3.3 Fire Suppression

Most of the modern technologies for forest and other wildland fire suppression approaches have been developed in the industrialized countries. In many tropical countries, the lack of infrastructure, trained personnel and financial resources, constitute the major impediments for purchasing technologies. These more advanced approaches include but are not limited to: aerial firefighting assets (e.g. fixed-wing aircraft and helicopters for fire suppression and deployment of personnel by parachutes; helicopter attack crews), advanced extinguishants (chemical fire retardants and foam), and modern ground tankers (4-wheel drive multiple-purpose vehicles for rapid fire attack).

It has been recognized, however, that most of the average fire situations in many vegetation types of the world can be managed successfully simply by experienced professional and volunteer firefighters, or adequately trained rural community members. The success of ground crews depends on the availability of appropriate hand tools and personal protective equipment, and the provision of basic training in fire suppression and firefighter safety (Fig. 20 and 21).

Figures 20 and 21. Local community members equipped with personal protective equipment and backpack pumps fighting a surface fire in a sal (*Shorea robusta*) forest in the Terai, Nepal (left). Same community members setting a backfire (counter fire) in a sal forest (right). Photo: GFMC, Sundar P. Sharma.

The most important fire suppression hand tools are those for creating fire lines (principally the same concept as firebreaks) and for extinguishing a surface fire front or fires jumping (spotting) over the control lines with fire swatters or small amounts of water (e.g. by using backpack pumps). Tools designed for cutting (removal of grass, brushes, and small trees), hacking (removal of grass swards and brushes), and scraping/digging/raking (removal of litter layer and other debris for creating a mineral soil strip), are the main hand tools for fire line construction.

The simplest and most portable water-pumping device is the backpack pump. It consists of a collapsible bag or tank (plastic, rubber) that contains up to 20 liters of extinguishants (usually water, but also chemical retardants or a foaming agent). A hand-operated pumping device with a nozzle (adjustable for straight stream or spray) allows an extremely economic use of the liquid. Backpack pumps, operated by a skilled firefighter, are the simplest, efficient, flexible and economical, of all the water-pumping options – especially suitable for extinguishing fires spotting over fire lines and low-intensity surface fires.

Drip torches or other local ignition devices, are often used for setting prescribed fires in open land systems or under canopies, or for setting backfires, which are “counter fires” intentionally set to halt an approaching wildfire by starving the main fire of fuel. The use of backfires is a technique successfully applied by experienced fire teams throughout the world, but may be dangerous and detrimental when used by inexperienced personnel. In the rural societies of the tropics, many agriculturists have considerable empirical knowledge in backfire application. Fire safety training, however, in the use of backfiring and prescribed burning techniques (cf. following paragraph) is a mandatory part of extension programs for the rural population involved in any fire use and fire management activities.

For details on fire suppression tactics, the reader is kindly referred to the fire management training handbooks, which are quoted above.[8] Meanwhile, some online resources for the training of wildland firefighters have become available. The *EuroFire Competency Standards and Training Materials*, which were developed by the Global Fire Monitoring Center (GFMC) originally for the training of European fire and rescue service personnel, are now available in more than ten languages.[9] Figures 22 to 24 provide examples and illustrations for the safe use of prescribed fire (see paragraph 3.4) and backfiring.

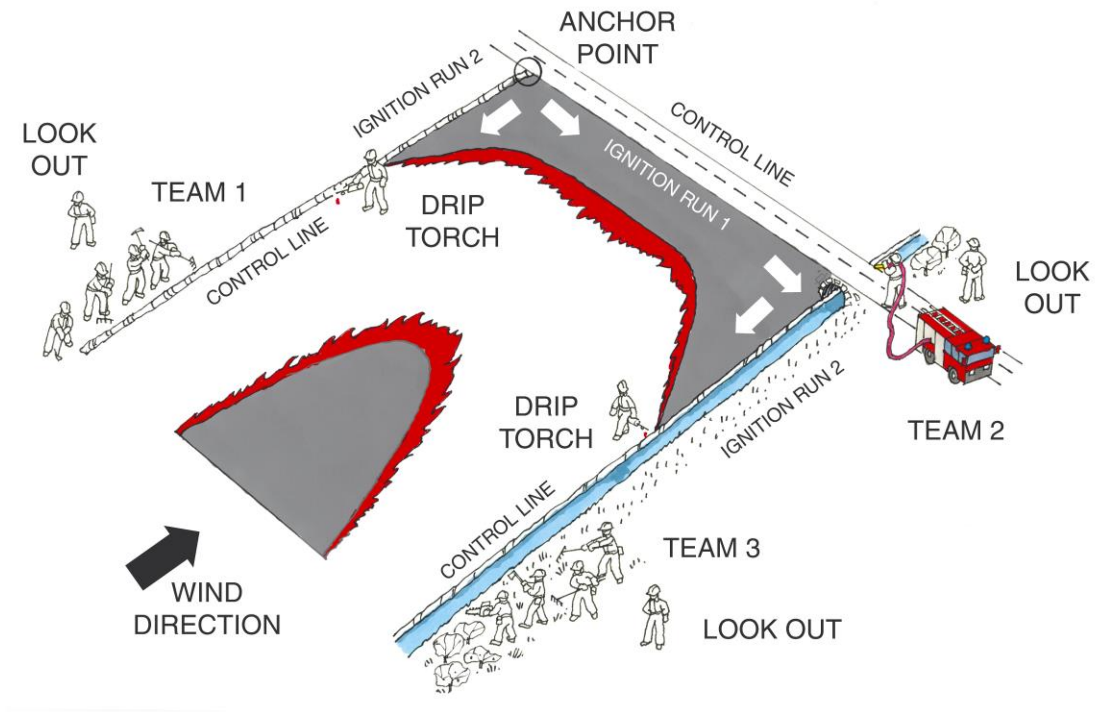

Figure 22. Example of EuroFire Training materials (I): Illustration of safe backfiring (counter firing) technique. Source: GFMC, EuroFire.

[8] See footnote 5.
[9] EuroFire website: http://www.euro-fire.eu/

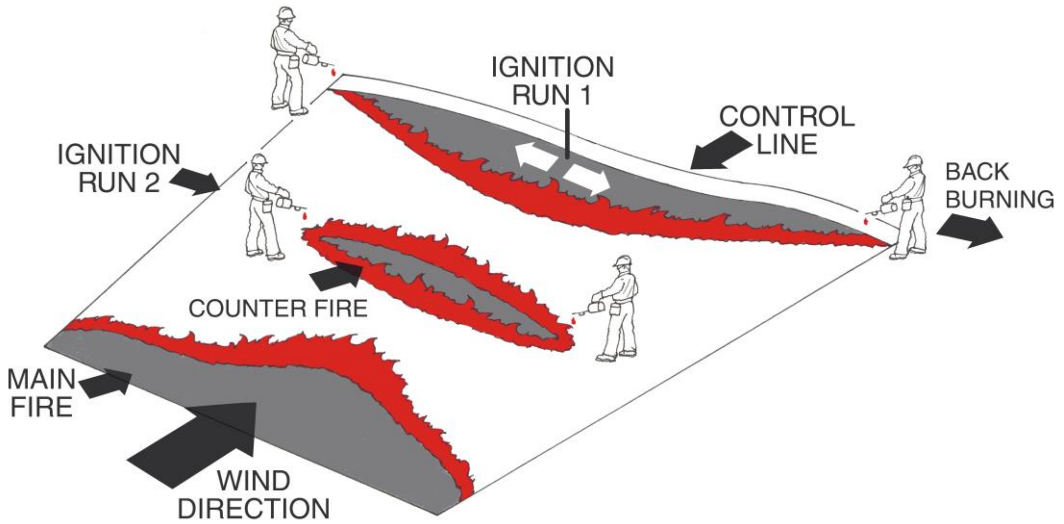

Figure 23. Example of EuroFire Training materials (II): Illustration of safe backfiring (counter firing) technique. Source: GFMC, EuroFire.

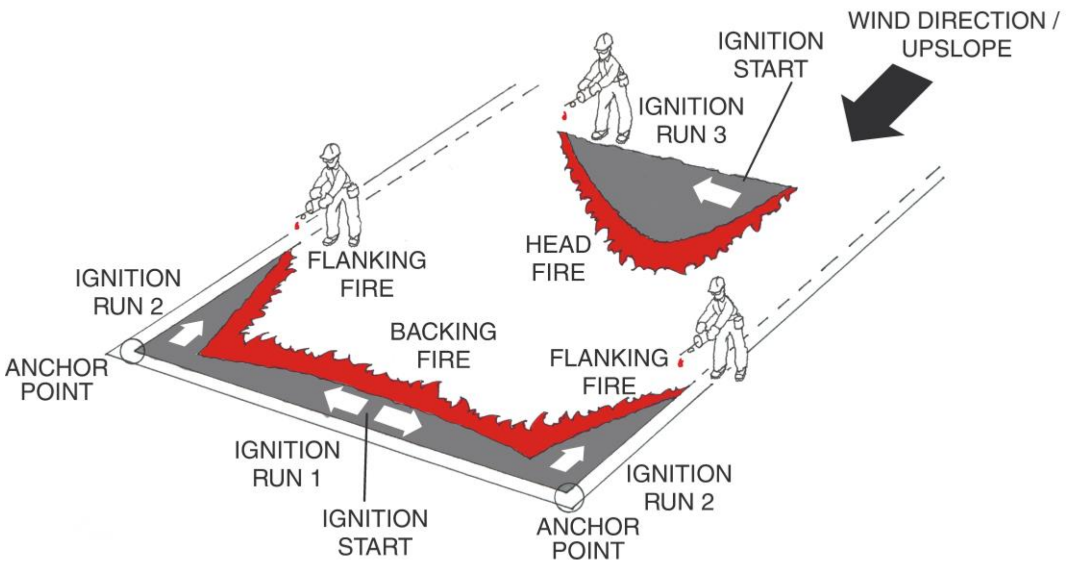

Figure 24. Example of EuroFire Training materials (III): Illustration of safe prescribed burning. Source: GFMC, EuroFire.

3.4 Prescribed Burning

The characteristics of some tropical fire-climax forests and sub-forest formations, coupled with the pressure of uncontrolled fires on most tropical vegetation types, require a careful approach in integrated fire management. The introduction of prescribed fire in many cases is mandatory if the productivity of these ecosystems were to be endangered by fire exclusion or by the occurrence of detrimental uncontrolled fires.

Prescribed burning is the controlled application of fire to wildland fuels in either their natural or modified state, under specific environmental conditions, which allow the fire to produce the fireline intensity and rate of spread required to attain planned resource management objectives. The principles of integrated fire management (Fig. 13) and the ecological, economic and management aspects of fire management options in tropical vegetation types (Tab. 2), show the broad variety of management objectives to be attained through prescribed burning. In tropical countries, the methods of prescribed burning are often referred to as "early burning". This term somewhat expresses the fact that a fire is intentionally set by the forest manager in the early dry season because its effects are to prevent the comparatively more serious effects of a fire occurring uncontrolled during the peak dry season.

It is impossible to cover in detail the possible prescribed burning principles, the objectives and the relevant techniques for all tropical sub-forest and forest types. More detailed information on prescribed burning in grasslands and savannas can be further assessed in syntheses by van Wilgen et al. (1990) and Trollope (1999).

Extensive expertise is available on prescribed burning in forest management in industrial pine plantations (e.g. the comprehensive summary by de Ronde et al. [1990]). The objectives of prescribed burning in pine plantations are summarized in Table 3 in which information is given in addition to Figure 2 and Table 2. In the context of this chapter, most important is the use of prescribed fire in underburning forests to temporarily reduce the hazardous build-up of dead fuels on the forest floor. This, in turn, reduces the risk of more damaging high-intensity wildfires. Low-intensity prescribed fires do not only reduce the surface fuels, but also speed up the recycling of nutrients into a form usable by the trees. The interval between fuel reduction burns, depend on several factors including species, fuel accumulation rates, values at risk, and wildfire risk.

The safest technique for underburning plantations is using a backing fire.[10] A backing fire must be started along a downwind baseline such as a road or a plow line and allowed to back into the wind or downslope. Wind keeps the flames bent over and cools the air on top of the flaming front, thus reducing the danger of crown scorch or the development of a crowning fire. The preferred prescribed burning wind-speed range between 2 and 5 $km \cdot h^{-1}$. The preferred relative humidity (RH) for prescribed burning varies from 30 to 50%. RH strongly influences the fine fuel moisture content, which is the most important parameter affecting prescribed fire behavior. For a successful burn, the fuel moisture content of the litter layer should not be below 7% and above ca. 30-35% (de Ronde et al., 1990).

Most expertise in prescribed underburning, is available for natural and man-made pine and eucalyptus forests (Fig. 25 and 26). Much of this expertise can also be transferred to the conditions of the tropical deciduous and semi-deciduous forest formations (see paragraph 2.1.2).

Extensive knowledge is available in the use of prescribed fire to maintain or restore open savanna “fire ecosystems” (see literature quoted in paragraph 2.1.4). Figures 27 and 28 show the use of traditional local ignition methods for setting a prescribed fire in a tree-grass savanna in East Africa (Kenya) and the systematic application of fire in a fire management unit, where the fire is controlled by unit boundaries (natural boundaries or roads) and monitored from the air.

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[10] Detailed information and description of other burning techniques is given by Wade and Lunsford (1989) and de Ronde et al. (1990)

Table 3. Potential objectives for the use of prescribed fire in management of industrial pine plantations. Source: Goldammer (1993), modified

Objectives	Target	Desired Effects	Undesired effects or potential hazards	Possible Substitution
Wildfire hazard reduction	Thinning or post-harvest slash, forest floor (raw humus), aerial fuels, rank understory	Reduce potential wildfire intensity and severity, remove surface and ladder fuels, reduce understory stature	Stand/tree damage (crown, bole, or roots)	Partial (mechanical treatment/removal by hand, shredding, piling and burning outside of stand, pruning)
Site preparation for natural regeneration or planting	Forest floor, post-harvest slash, undesired vegetation	Expose mineral soil (improve germination), increase seed fall	Encroachment, sprouting, or germination of undesired plants	Partial (herbicides to kill undesired vegetation)
Improve accessibility	Thinning of post-harvest slash, rank understory	Improve access for silvicultural operations, esthetics (recreation)	Reduction of understory stature	Partial (herbicides to kill undesired understory)
Increase growth/yield	Raw humus layer (forest floor), understory plants	Enhance nutrient availability; reduce competition for moisture, sun and nutrients	Loss of nutrients (leaching), erosion	Fertilization and herbicides
Alter plant species composition	Weeds and other undesirable vegetation	Promote desired species	Increase in weed germination/production of undesirable seeds	Herbicides
Pest management	Pests and diseases and their habitats	Eliminate spores, eggs, individuals, and breeding material	Fire-induced tree stress, increased susceptibility to secondary pests	Pesticides
Silvopastoral land use	Slash; forest floor; mature, unpalatable growth; competing vegetation	Create/improve conditions for desired ground cover		Mechanical removal of dead fuels and vegetation
Improve fire protection	Surrounding buffer zone, fuel breaks and fire breaks	Reduce spread and intensity of wildfires (outside of stands)		

Figures 25 and 26. Prescribed underburning of understorey ground vegetation and accumulated debris in a pine plantation (*Pinus radiata*) in South Africa with a fire backing into the wind (left). Prescribed underburning of pine plantations in a 9-year-old *Pinus taeda* stand in the State of Paraná, Brazil (right). Note that draped fuels (dead branches with hanging dead needles) have been removed up to a height of ca. 2 m. Photos: GFMC.

Figure 27. Start of a prescribed fire in an Eastern African (Kenya) tree-grass savanna using traditional ignition device. Photo: GFMC.

Figure 28. Prescribed fire in a tree-grass savanna in Kenya taking advantage of safe burning techniques, utilization of roads as firebreaks / control lines and fixed-wing aircraft for aerial safety patrol. Photo: GFMC.

Logging Debris Burning and Smoke Management

Another application of prescribed fire in the tropics is burning logging debris from clearcuts of degraded natural vegetation, which are prepared for either planting or converted for other land uses. Burning logging slash on open clearcuts also requires less experience because there is no overstory that needs to be protected. However, the amount of aboveground biomass burned in forest conversion or clearcut fires, is considerably higher than the amount of biomass combusted by underburning.[11] Precautions are needed in order to avoid (1) uncontrolled spread of fire (escaping fires) into areas not intended to be burned and (2) formation of hazardous near-ground smoke concentrations.

Both safety hazards can be controlled by burning techniques (ignition and burning patterns) and by observation of other factors that influence fire behavior, such as the spatial arrangement of fuels, fuel moisture, fire weather, etc. Two basic burning patterns are available for logging-debris disposal by fire, broadcast burning (use of the ring fire pattern) and pile or windrow burning.

The problem of escaping fires can be solved largely by constructing firebreaks around the area to be burned (beforehand) and to use ignition patterns, (e.g. the ring fire technique), that would drive the fire into the center of the burn area. The ring fire technique (also referred to as center or circular firing) is useful on clearcut areas where a hot fire is desired to reduce the logging debris as completely as possible and to kill any unwanted vegetation prior to planting. As with the backing fire technique, the downwind control line is the first line to be ignited. Once the baseline is secured, the entire perimeter of the area is ignited so the flame fronts will all converge toward the center of the plot. One or more ”dotting” fires are often ignited in the center of the area and allowed to develop before the perimeter of the burning block is ignited. The convection generated by these interior fires creates indrafts that help pull the outer circle of fire toward the center, thereby reducing the threat of slop-overs or heat damage to adjacent stands.

This technique is very important from the smoke management point of view. In the past years forest conversion fires have created considerable problems in near-surface air pollution. This was mainly due to stable atmospheric conditions and poor burning techniques, e.g. pile and windrow burning.[12] The objective of piling logging debris before burning is to prolong fire residence time thereby increasing the consumption of large materials. In practice, however, the piling of heavy fuels tends to mix up large amounts of topsoil (usually due to use of heavy machinery), which creates a moist pile/windrow interior, where fuels hardly dry at all and oxygen for complete combustion is consequently lacking. The result is a fire that continues to smolder for days and weeks and creates considerable problems in near-ground air quality.

It is therefore recommended to generate a strong convection column by using the ring fire technique in order to inject the smoke column into higher altitudes. However, attention must be given to the potential problem of generating spot fires in the adjacent fire-prone terrain. Strong

[11] Total fuel loads after clearcut of tropical rain forests may amount as much as 150 t ha^{-1} and needs to be burned as complete as possible by high-intensity fires, whereas the surface fuels inside of standing forests range between 2 and 10 t ha^{-1} and need to be burned with low-intensity fires in order to avoid damages of the standing trees.

[12] Logging slash in many cases is piled and windrowed before burning because of problems in igniting and completely burning large fuels (heavy logs) in discontinuous fuel beds. This technique also offers safety for conducting the burn.

convective columns can carry aloft burning or glowing materials and generate new fire starts after they fall out downwind.

Prescribed Burning Plans

Although detailed burning prescriptions for tropical forests are not yet available, many of the principles and considerations of prescribed burning in industrial pine and eucalyptus plantations can be used for planning. A successful prescribed fire is one that is executed safely and is confined to the planned area, burns with the desired intensity, accomplishes the prescribed treatment, and is compatible with resource management objectives. Prescribed fire planning should be based on the following factors (de Ronde et al., 1990):

- Physical and biological characteristics of the site to be treated
- Land and resource management objectives for the site to be treated
- Known relationships between pre-burn environmental factors, expected fire behavior, and foreseeable fire effects
- The existing art and science of applying fire to a site
- Previous experience from similar treatments on similar sites
- Smoke impact from health and safety standpoint

3.5 Fire Safety on Contaminated Terrain

Aside from fire management personnel safety (cf. paragraph 3.3), and the safety of prescribed burning operations (cf. paragraph 3.4), the tropical fire manager must also observe safety problems arising from fires burning on terrain contaminated by industrial/chemical deposits and remnants of armed conflicts (i.e. land mines and unexploded ordnance). These problems are common in many tropical countries of Asia and Africa and in other regions, notably Europe, where numerous injuries and fatalities have been recorded as consequence of explosions triggered by wildland fires (Goldammer, 2013b). Competent authorities should request special advice for fire management on dangerous terrain.

4 Fire Management Policy and Organization

The development of a national fire management policy and relevant legislation and regulations constitute important prerequisites for informed and coordinated fire management activities in a country and for to which the fire manager should refer. A fire management policy needs to address all vegetation types:

- Natural vegetation including forests and non-forest ecosystems
- Plantation forests
- Protected areas
- Wetlands (peat lands)
- Agricultural lands
- Pasture lands (rangelands)
- Abandoned (formerly cultivated) lands
- Vegetated lands contaminated by industrial and chemical waste and other pollutants

For the development of a cross-sectoral, consent-based fire management policy, some countries have established National Inter-Agency Fire Management Committees or Advisory Boards in which the main line ministries, other public administrations and civil society organizations are represented. These may include:

- Ministry of Environment (responsible for all environmental issues potentially affected by fire, including atmospheric and transboundary impacts of fire emissions; climate change)
- Ministry responsible for forestry (or national forest agency)
- Ministry of Agriculture (with regards to fire use in the agricultural and / or rangeland management)
- Ministry of Interior (or Emergency Situations or Civil Protection) (responsible for the fire and rescue services and emergency situations)
- Ministry of Public Health (protection of population from adverse effects of smoke pollution)
- Ministry of Foreign Affairs (cross-boundary fires, international protocols)
- Ministry of Defense (assistance in wildfire emergency situations)
- Civil society organizations (NGOs, representatives of local communities, agricultural associations, land / forest owners, …)

Main themes to be addressed in a national policy may include, but are not limited to:

- **Research, information and analysis:** Establishment of a national unit of competence in fire management that will assist all participating agencies and other stakeholders in joint implementation of the policy, e.g. by creating the position of a "National Rural Fire Management Cell" (or Officer).
- **Legal framework and institutional responsibility:** Review and update of the legislative and regulatory framework to define responsibilities and obligations of government agencies, stakeholders of civil society, particularly local communities and individual land owners and land users, in fire management planning, capacity building, fire prevention, preparedness and response.
- **Reduction of fire hazard, risk and vulnerability, and prevention of fires:** Implement systematically technical fire prevention measures in forests and other lands, notably agricultural, pastoral, and abandoned lands. Public awareness on the negative consequences of forest fires and the need for active participation in fire prevention, notably at the level of local rural communities located in fire-prone regions and for the defense of rural assets against fires, must be prioritized.
- **Preparedness: Provisions to improve fire response and safety:** Provide appropriate training of firefighters and other personnel of agencies responsible for forest fire suppression, including volunteers. This will ensure competency and efficiency of actors responsible for firefighting. The establishment of wildfire early warning systems will provide and disseminate warnings of periods of high fire danger and thus allow preparedness and early alerts at national and local levels.
- **Response: Fire suppression:** Ensure that specialized forest fire suppression units/sub-units are available in regions of high fire risk and that they be equipped appropriately. Land management authorities (e.g., agencies responsible for forestry, protected areas and agricultural lands), must provide budgets for training and equipping specialized fire management teams in areas of high fire risk.

- **Post-fire measures:** Reduce the threats and consequences of secondary effects of wildfires (e.g. site impoverishment due to erosion or lack of regeneration potential, reduction of water-holding capacity, increase of surface runoff and risk of flash floods, mudslides/landslides or rock fall).
- **International cooperation in fire management:** Sharing of knowledge in fire science and management and active participation in regional and global networks will ensure that countries take advantage of the state-of-the-art expertise available at international level.

5 Concluding Remarks

In this chapter, the complexity and ambiguity of phenomena and problems associated with fire use and wildfires affecting tropical forests, other tropical ecosystems and land-use systems, have been highlighted. The socio-economic and cultural conditions in the tropical forest environment are decisive for shaping tropical fire regimes. Forest managers and other land resource managers all around the tropics are facing tremendous pressures posed by humans and fire. This chapter recognizes the need to better understand fire-induced processes and to develop adequate strategies for harmonizing both the benefits of fire, as well as for addressing the detrimental impacts of many of these fires.

Finally, this chapter has highlighted basic processes, phenomena and solutions, and poses a number of challenging tasks for fire managers to undertake. The complexity of interactions between land use and other human activities, tropical vegetation characteristics, climate and climate change may require expert assistance in capacity building in fire management at national and local level. Apart of the quoted fire management guidelines and textbooks the Global Wildland Fire Network through the participating 14 Regional Wildland Fire Networks may offer opportunities to draw of the experience of countries in the tropics that have been more advanced than others.[13] The International Wildfire Preparedness Mechanism (IWPM) facilitates the exchange of knowledge and expertise in fire management globally.[14]

[13] The Global Fire Monitoring Center (GFMC) (http://gfmc.online/) acts as Secretariat of the Global Wildland Fire Network, which can be accessed on the internet: http://gfmc.online/globalnetworks/globalnet.html

[14] IWPM website: http://gfmc.online/iwpm/index-7.html

Appendix: Wildland Fire Management Terminology

Most of the wildland fire management terms defined in the following are taken from the United Nations Wildland Fire Management Terminology (FAO 1986).

Aerial Fuels — The standing and supported forest combustibles not in direct contact with the ground and consisting mainly of foliage, twigs, branches, stems, bark, and vines.

Backfire — A fire set along the inner edge of a control line to consume the fuel in the path of a forest fire and/or change the direction of force of the fire's convection column. Note: Doing this on a small scale and with closer control, in order to consume patches of unburned fuel and aid control-line construction (as in mopping-up) is distinguished as burning out = firing out, clean burning.

Broadcast Burning — Allowing a prescribed fire to burn over a designated area within well-defined boundaries for reduction of fuel hazard, as a silvicultural treatment, or both.

Bump-up Method — (=move-up, step-up, functional) A progressive system of building a fire line on a wildfire without changing relative positions in the line. Work is begun with a suitable space between workers such as 5 m. Whenever one worker overtakes another, all of those ahead move one space forward and resume work on the uncompleted part of the line. The last worker does not move ahead until the work is complete in his space. Forward progress of the crew is coordinated by a crew leader.

Center Firing — A method of broadcast burning in which fires are set in the center of the area to create a strong draft; additional fires are then set progressively nearer the outer control lines as indraft builds up so as to draw them in toward the center.

Control a Fire — To complete a control line around a fire, any spot fires there from, and any interior islands to be saved; the control lines; and cool down all hot spots that are immediate threats to the control line, until the line can reasonably be expected to hold under foreseeable conditions.

Counter Fire — Fire set between main fire and backfire to hasten spread of backfire. Also called draft fire. The act of setting counter fires is sometimes called front firing or strip firing. In European forestry synonymous with backfire.

Crown Fire — A fire that advances from top to top of trees or shrubs more or less independently of the surface fire. Sometimes crown fires are classed as either running or dependent, to distinguish the degree of independence from the surface fire.

Drip Torch — A hand-held apparatus for igniting prescribed fires by dripping flaming fuel on the materials to be burned. The device consists of a fuel fount, burner arm, and igniter. The fuel used is generally diesel or stove oil with gasoline added.

Early Burning Prescribed burning early in the dry season before the leaves and undergrowth are completely dry or before the leaves are shed, as an insurance against more severe fire damage later on.

Firebreak Any natural or constructed discontinuity in a fuel bed utilized to segregate, stop, and control the spread of fire or to provide a control line from which to suppress a fire.

Fire Danger Rating A fire management system that integrated the effects of selected fire danger factors into one or more qualitative or numerical indices of current protection needs.

Fire Hazard A fuel complex, defined by volume, type condition, arrangement, and location, that determines the degree both of ease of ignition and of fire suppression difficulty.

Fire Management All activities required for the protection of burnable forest values from fire and the use of fire to meet land management goals and objectives.

Fire Retardant Any substance except plain water that by chemical or physical action reduces the flammability of fuels or slows their rate of combustion, e.g., a liquid or slurry applied aerially or from the ground during a fire suppression operation.

Forest Residue The accumulation in the forest of living or dead mostly woody material that is added to and rearranged by human activities such as forest harvest, cultural operations, and land clearing.

Fuelbreak Generally wide (20 - 300 meters) strips of land on which the native vegetation has been permanently modified so that fires burning into them can be more readily controlled. Some fuelbreaks contain narrow firebreaks which may be roads or narrower hand-constructed lines. During fires, these firebreaks can quickly be widened either with hand tools or by firing out. Fuelbreaks have the advantages of preventing erosion, offering a safe place for firefighters to work, low maintenance, and a pleasing appearance.

Ladder Fuels Fuels which provide vertical continuity between strata. Fire is able to carry from surface fuels into the crowns of trees or shrubs with relative ease and help assure initiation and continuation of crowning.

Mass Fire A fire resulting from many simultaneous ignitions that generates a high level of energy output.

Mopping up (= mopup) Making a fire safe after it has been controlled, by extinguishing or removing burning material along or near the control line, felling snags, trenching logs to prevent rolling, etc.

One Lick Method A progressive system of building a fire line on a wildfire without changing relative positions in the line. Each worker does one to several "licks", or specified distance to make room for the worker behind.

Preattack Planning Within designated blocks of land, planning the locations of fire lines, base camps, water supply, sources, helispots, etc.; planning transportation systems, probable rates of travel, and constraints of travel on various types of attack units; and determining construct particular fire lines, their probable rate of line construction, topographic constraints on line construction, etc..

Prescribed Burning Controlled application of fire to wildland fuels in either their natural or modified state, under specified environmental conditions which allow the fire to be confined to a predetermined area and at the same time to produce the intensity of heat and rate of spread required to attain planned resource management objectives.

Prescribed Fire A fire burning within prescription. The fire may result from either planned or unplanned ignitions

Shaded Fuelbreak Fuelbreaks built in timbered areas where the trees on the break are thinned and pruned to reduce the fire potential yet retain enough crown canopy to make a less favorable microclimate for surface fires.

Smoke Management The application of knowledge of fire behaviour and meteorological processes to minimize air quality degradation during prescribed fires.

Surface Fire Fire that burns only surface litter, other loose debris of the forest floor, and small vegetation.

Values-at-Risk Any or all of the natural resources or improvements which may be jeopardized if a fire occurs.

Wildfire Any fire occurring on wildland except a fire under prescription.

Wildland/Residential Interface That line, area, or zone where structures and other human development meets or intermingles with undeveloped wildland or vegetative fuels.

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