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Tropical Wild-land Fires and Global Changes:
Prehistoric Evidence, Present Fire Regimes, and Future Trends

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The impact of tropical wild-land fires and other biomass burning on the environment is receiving increasing attention by atmospheric sciences. Earlier models and calculations of the trace gases released by the combustion processes involved in forest conversion and other land-use practices (Crutzen et al., 1979; Seiler and Crutzen, 1980; Crutzen et al., 1986; Crutzen and Andreae, 1990) showed that these emissions contribute considerably to the total annual global release of greenhouse gases and a net carbon flux to the atmosphere. Contributions to this volume reflect the growing interest in this subject (Andreae, Chapter 1).

Wild-land fires, however, are not a recent phenomenon. As fire history reveals, northern boreal and circumpolar ecosystems and many of the temperate and mediterranean forest biomes have been shaped by fire since prehistoric times (Kozlowski and Ahlgren, 1974; Wright and Bailey, 1982; Wein and MacLean, 1983). Large-scale wildfires in Northeast Asia such as the conflagrations in Siberia and Northeast China during 1987 were reported early in this century and have been documented in fire history (Shostakovich, 1925; Goldammer and Di, 1990). Fahnestock and Agee (1983) additionally have emphasized the importance of smoke produced by prehistoric wildfires.

Recent synoptic and multidisciplinary approaches to tropical wild-land fire ecology prove that natural fires and widespread human burning practices within the tropics have also greatly influenced vast areas of vegetation throughout all tropical biota during historic and prehistoric times (Goldammer, 1990b).

This chapter points out that wild-land fires in the tropics have existed for a long time, that fire has shaped and changed the forest and other vegetation, and that fire regimes are undergoing changes—in the past, today, and, most likely, in the future. Wild-land fires are related to disturbances by nature and by humans. Natural disturbances may be characterized as of short duration, such as the effects of lightning, drought, and hurricanes; other natural disturbances may be long-term processes, such as climatic fluctuations. Anthropogenic disturbances have not changed basically throughout human history. They are all related to forest conversion, slash and burn agriculture, hunting and grazing, and other wild-land uses (Bartlett, 1955, 1957, 1961; Goldammer, 1988). The difference between the past and today's fire scene, however, is the growing extent of fire-affected vegetation due to population pressure and accelerating degradation of vegetation cover. The future fire scenarios are largely determined by the human-induced feedback mechanisms between biosphere and atmosphere. Trace gases from tropical biomass burning are different from gases emitted by decay of plant life and play a significant role in the acceleration of change in the tropical biosphere and in the atmosphere.

Prehistoric Evidence

Global climatic changes throughout geological periods are drastically reflected by the fluctuations of the atmospheric CO_2 content and the temperature revealed by the Vostock ice core data for the past 160,000 years (Barnola et al., 1987, 1989). These climatic changes have largely influenced the development and biogeography of the tropical biotas which were subjected to migration both in area of distribution and altitude and to species extinction. Flenley (1979) suggests in his geological history of the rainforest that the tropical rainforests could not have developed as ecosystems undisturbed through extreme long periods as suggested by the classical school of tropical forest ecology (Richards, 1952; Whitmore, 1975); instead, large areas have carried savanna-type vegetation during the Quaternary (Pleistocene) due to cooler and more arid climatic conditions at that time (Prance, 1982).

Palynological reestablishment of tropical vegetation history in most cases has underestimated valuable fire history information, although valuable data on charcoal are generally available. New evidence about the ability of early hominids to use fire begin-

ning about 1.5 million years ago (Brain and Sillen, 1988) suggests that fires must have played a similar role in the fluctuating or transition savannas of the Pleistocene, as could be shown for historic times. Australia's Prequaternary and Quaternary fire history seems to have received sufficient attention (Kemp, 1981; Singh et al., 1981), which is lacking in the lower latitudes in the Americas, Africa, and Asia.

The lack of radiometric data in the present tropical moist rainforest area can be explained by flooding and erosion processes (Colinvaux, 1989), by the change of river beds, and by the most likely rapid turnover of organic material, including charcoal in tropical soils. Occasional observations of charcoal under primary rainforests have been underestimated in their ecological significance until very recently. The ^{14}C dating of Amazon rainforest charcoal revealed abundant fires up to about 6000 years before present (B.P.) and reflect both human activities and climatic oscillations during the period of postglacial climate stabilization in the Holocene (Sanford et al., 1985; Saldarriaga and West, 1986).

Radiometric dates from modern primary rainforests in eastern Borneo, however, indicate that fire already must have occurred during the peak of the last glacial period (Wisconsin-Würmian glaciation) about 18,000 B.P. In their investigations in East Kalimantan (Indonesia), Goldammer and Seibert (1989, 1990) found charcoaled remnants of trees and dipterocarp seeds under primary dipterocarp rainforest. These fires presumably have been ignited by burning coal seams stretching along or near the forest surface. Thermoluminescence dating of burned clay on top of extinguished coal seams found in the intermix with active coal fires, revealed subsurface fires back to about 13,000 to 15,000 B.P.; ongoing investigations (Goldammer, unpublished data) of burned clay tend to date the fires back to about 50,000 years B.P.

The evidence of prehistoric fires in today's rainforest biomes requires an interpretation beyond its immediate impact. The occurrence of fires may have fulfilled an ecological function (or task) during evolutionary or phylogenetic processes and related time scales. What was the role of fire in the development of the rainforest? Provided that the rainforest refugia (forest islands) theory has more substantial evidence than it has received criticism (Haffer, 1969; Simpson, 1972; Simpson and Haffer, 1978; Prance, 1982; Beven et al., 1984; Connor, 1986; Salo, 1987), one of the important functions of fire was between the refugia. The main postulate of the refugia theory is that diversification of species took place in rainforest patches isolated from each other. The forest refugia were separated by savanna vegetation and a seasonal climate with distinct dry fire seasons. The gene flow (seed dispersal, pollination) between the refugia was interrupted by "fire corridors," resulting in locally restricted diversification processes—one possible mechanism of the high species diversity in tropical rainforests.

In addition to that Darwinistic explanation of fire in evolutionary processes, another interpretation of the role of fire in diversification exists. In those primary rainforests where prehistoric charcoal was found, it must be distinguished whether the fuel affected by fire was originated in savanna biome or in a forest environment. The Borneo findings of Goldammer and Seibert (1989) showed that the analyzed charcoal was remnant from a dipterocarp forest. How and why could a forest burn which can be characterized as moist rainforest?

Fires in moist rainforests must have occurred because of brief climatic disturbances, not because of a climate change in the sense of thousands or ten thousands of years. Climatic oscillations of short duration (interannual climatic variability) are a possible explanation for periodic flammability of the moist rainforest biomes. The rainforest fires of 1982 to 1983 in Borneo, which affected a total of more than 5×10^6 hectares (ha) of primary dipterocarp forests, secondary and peat swamp forests in East Kalimantan (Indonesia), and the Malaysian territory of the island, are a striking example (Goldammer and Seibert, 1990). An extended drought triggered by the El Niño–Southern Oscillation (ENSO) event predisposed the rainforest to the fires set by shifting cultivators which largely spread into the surrounding forest lands. Such rainforest fires are not a recent phenomenon. Goldammer and Seibert (1990) showed that similar events had happened during ENSO droughts over the past 100 years. The collected fire data from prehistoric and presettlement times may be the result of a unique coincidence of periodic droughts (such as ENSO-related) and the permanent availability of fire sources (burning coal seams). In all other places lightning has been the main source of fire. Hurricane damage may also result in availability of flammable rainforest fuels. This has recently been demonstrated by the impact of Hurricane Gilbert on rainforests in Cancun (Yucatan, Mexico) in 1987 which were ready to burn after drying in 1989 (90,000 ha burned). Open questions are size (extent of burned area) and frequency of ancient rainforest fires. Prehistoric fire mapping is one of the upcoming challenges in tropical fire ecology.

The function of periodic fires which were limited in

size can be interpreted in two ways. The direct impact of lightning and lightning fires creates gaps (canopy openings) in the rainforest. These gaps are important elements for the regeneration and the dynamics of restructuring the rainforest (gap dynamics). In an undisturbed forest the pioneers and many other species would have been replaced by a few dominant *climax* species. Disturbances may be considered as basic elements for the theory of diversification through instability (Connell, 1978; Hubbell, 1979; Picket and White, 1985; Hubbell and Foster, 1986). Again, this theory is controversial to the Clementsian school of ecology (Clements, 1916). Clementsian climax postulates the explanation of species richness in tropical rainforests through stability over evolutionary time scales (Ashton, 1969, 1988; MacArthur, 1972; Whittaker, 1977).

One more evolutionary role of fire in rainforests may be added. Rainforest islands as diversification centers are mainly sought in climate-induced refugia or topographic features (isolated mountains) providing separation from neighboring gene pools. The process of forming of such islands within vast areas of closed rainforest may be performed by fire. Wildfires usually burn irregular patterns which create a mosaic of burned and unburned patches. This phenomenon is entirely explored in the temperate and boreal zones and explains the existence of diverse forest landscapes with diversity in stand ages and species composition. Similar effects of fire islands have been observed after the recent rainforest fires in Borneo (Goldammer and Seibert, 1990). This phenomenon becomes more visible in today's fire savannas of Western Africa where fire has shaped distinct, abrupt edges between rainforest patches and the surrounding pyrophytic vegetation. These fire-induced rainforest islands in a rainforest climate may have served, and may continue to serve, as centers of development of new varieties and even new species.

The role of fire in savanna and deciduous forest ecosystems is different from its role in rainforest biomes. Seasonal climate and seasonal vegetation are predisposing elements for the regular occurrence of fires. In many cases it is therefore difficult to determine whether natural fires or edaphic, orographic, and climatic conditions—or all of these elements combined—are the driving forces in shaping a savanna biome. Batchelder and Hirt (1966) suggested that the anthropogenic fire influence on tropical vegetation dates back to about 12,000 years B.P. Various documented examples on savanna formation support this assumption, such as the savannas of Rajastan (India), which were formed with the beginning of mesolithic grazing practices about 10,000 years B.P. (Jacobson, 1979). Maloney (1985) suggested that deforestation of landscape in Sumatra goes back 18,000 years. The savanna (monsoon) forests of Kampuchea are explained by the influence of fire on the dipterocarp forest for 2000 years (Wharton, 1966). On the other hand, as mentioned earlier, fire has been used by humans for more than 1.5 million years. Where and when was the beginning of the anthropogenic fire (and subsequently grazing) influence on tropical vegetation?

Paleofire regimes have varied with the influence of climate and man. Therefore a general picture cannot be drawn of the possible fire scene in the prehistoric past. However, a tentative prehistoric fire world during the last Pleistocene glaciation is shown in Figure 10.1. The map shows the postulated rainforest ref-
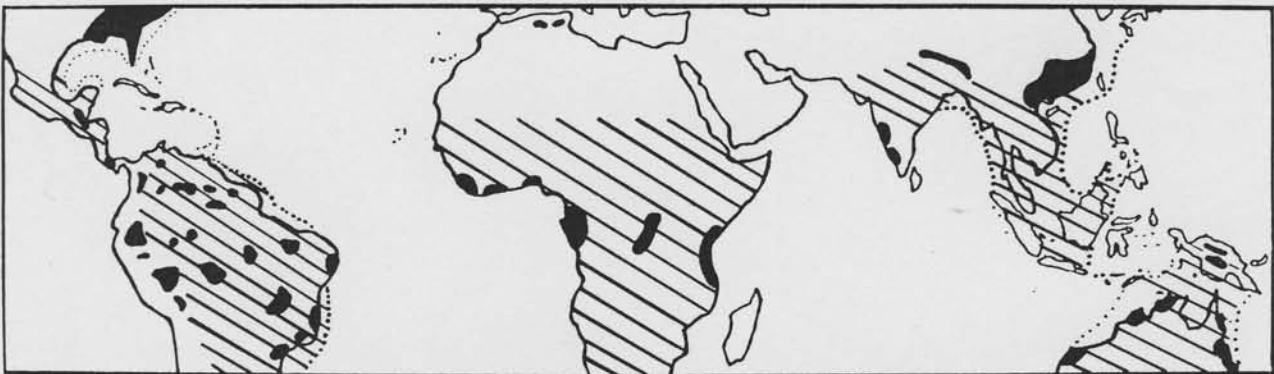

Figure 10.1 Suggested schematic distribution of fire-prone and of nonflammable vegetation types in the tropics during the peaks of glacial periods of the Pleistocene. Solid areas show tropical and adjoining forest refuges according to Prance (1982). Hatched areas between forest refuges illustrate the possible distribution of seasonal savanna-type vegetation characterized by short-return-interval fire regimes.

uges as compiled by Prance (1982), which are surrounded by vast areas of probably seasonal and drier vegetation subjected to fire in short return intervals.

Present Fire Regimes

After today's tropical climate became stabilized about 8000 to 10,000 years B.P., the rainforest reached its distribution and size as found by the early explorers and scientists. Alexander von Humboldt described the overall picture of the rainforest as damp, humid, and not flammable (Goldammer, 1990a). This impression was kept alive by tropical ecologists until very recently.

Recently, however, tropical fires have become visible through satellite imagery and have entered the calculations of climate modelers. In a satellite imagery such as the AVHRR a ground fire on a grassland with low fuel load, low emission and energy release may look completely similar to a slash and burn fire in which 50 to 100 times an amount of biomass is burned and a completely different bouquet of trace gases is released. Fires and fire regimes thus need to be classified and distinguished for a better understanding of the processes involved, ranging from the terrestrial ecological impact to the questions of trace gases and global carbon fluxes.

The characterization of fire and the general role and impact of fire in the environment can be classified as different fire regimes. A general model of tropical fire regimes proposed by Goldammer (1986b; see also Mueller-Dombois and Goldammer, 1990) is characterized by return interval, intensity and origin of fire, and main vegetation features. The main categories are related to anthropogenic and ecological gradients (sociocultural and ecological frame of landscape). From the seven fire regimes distinguished, four main types of tropical fire environments can be derived for the context of interest of this volume—rainforest fires, fires in deciduous forests and other open tree formations, tropical pine forest climax, and tropical savanna and grassland fires.

Rainforest Fires

Normally, fires do not regularly affect the tropical perhumid rainforest biomes. Natural disturbances locally may change the existing conditions which are unfavorable for fire—e.g., high humidity, fuel moisture, and lack of available surface fuels—eventually in return intervals up to hundreds of years. At present, human-caused fires are occurring more frequently and becoming a determining phenomenon of tropical

rainforest development. While the traditional system of slash-and-burn agriculture has been following a fallow cycle (corresponding to a fire return interval), present fire use overwhelmingly is related to conversion of rainforests to other permanent land uses (e.g., Malingreau and Tucker, 1988; Fearnside, 1990). Depending on weather conditions and burning skill, only a part of the above-ground biomass is consumed at the first burn. Subsequent burns usually follow, but sometimes the remaining biomass is left for decomposition and the agricultural crops are planted in between. In the case of conversion of forest to grazing lands (pastures) the same area will be reburned repeatedly, in many cases annually, until remnant woody vegetation, resprouting capability, and seed bank are eliminated (Watters, 1960, 1971; Peters and Neuenschwander, 1988).

The global extent of shifting cultivation fires and the rates of forest conversion are not known precisely. According to estimates of the Food and Agricultural Organization (FAO) (FAO, 1982, 1985; Lanly, 1985) about 500 million people were involved in shifting agriculture within the tropics during the early 1980s. It was estimated that shifting cultivation and its degraded forms at that time affected about 240×10^6 ha of closed forest and about 170×10^6 ha of open forest, totaling about 21% of the tropical forest area. The assessments on the extent of deforestation (in the sense of permanent forest conversion to other land use) in which fires are usually involved have a broad range, thus reflecting the lack of reliable information. The estimates of Crutzen and Seiler (1980) give a range of annually burned or cleared area of 21 to 62×10^6 ha due to shifting agriculture; other estimates are somewhat lower (Detwiler et al., 1985; Houghton et al., 1985; Myers, 1980, 1989). The most recent estimates of Myers (1989) still show an annually cleared area of 13.8×10^6 ha and a present net deforestation rate of 1.8% of rainforests in 28 investigated tropical countries.

A distinct feature of primary or closed rainforest fires is that they are used to remove woody vegetation from a specific and limited site. Because repeated disturbances result in increasing the flammability of rainforests and reducing them to savannas, the fires tend to escape from shifting cultivation plots and spread into the surrounding forest lands. Wildfires in vegetation characterized by uniformity of fuels, species, desiccating behavior, and climatic seasonality (fire season) tend to recur in shorter and more regular intervals. These fires shape uniform landscape patterns (larger fire mosaics) and are characteristic for

the tropical deciduous forests and other open tree formations, including the savanna biomes.

Fires in Deciduous Forests and Other Open Tree Formations

With increasing distance from the perhumid equatorial zone, the extent of regular or irregular droughts and wildfire occurrence is increasing. With decreasing precipitation and an increase of duration of drought periods, the tropical forest formations gradually develop toward semievergreen ecotones and finally to dry deciduous forests (Legris, 1963; Hegner, 1979). The distinction between these forest types and the general term *savanna*, which often includes open tree formations, is not clear (Hegner, 1979). Deciduous forests characterized by open understory and regular fire influence are sometimes designated as both forest formations and as savannas. One example is the *monsoon forests* of continental Southeast Asia, which are also referred to as *savanna forests* or *savannas* (Cole, 1986; Stott, 1988a, 1988b; Stott et al., 1990). This confusion of terminology has created problems in distinguishing and mapping tropical fire ecosystems and fire regimes which are the base of global models in trace gas emissions from biomass burning (e.g., Hao et al., 1990; other contributions in this volume).

In this chapter the term *forest* is used as long as trees are dominant landscape elements and are involved in the interactive processes between fire and vegetation. The main fire-related characteristics of these formations are seasonally available flammable fuels (grass-herb layer, shedded leaves) and adaptive mechanisms which allow the grass layer, other understory plants (shrub layer), and the overstory (tree layer) to survive and furthermore 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, etc.) (Goldammer, 1991). These features are characteristic elements of a *fire ecosystem.*

During the dry season the deciduous trees shed the 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 generally ranges between 5 to 10 tons ha^{-1}. The fires are mainly set by forest users (graziers, nonwood forest product collectors). The forests are usually fired in order to remove dead plant material, to stimulate grass growth, and to facilitate or improve the harvest of other forest products (Goldammer, 1988). The fires usually develop as surface fires of moderate intensity (usually less than 400 kw m^{-1} according to Stott, 1988b) and tend to spread over large areas of forested lands. The tree layer is generally not affected by the flames, although crowning may occur earlier in the dry season when the leaves are not yet shed. In some cases fires may affect the same area twice 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, 1991). The size of these fires is usually larger than the intended area of impact. This is mainly due to the uniformity of available fuels.

Dry deciduous forests and moist deciduous forests are occurring on about 250×10^6 ha and 530×10^6 ha, respectively (Lamprecht, 1986; Windhorst, 1974). No reliable information exists on the extent of recurring fires in these areas. Goldammer (1986a) estimated that in Burma between 3 to 6.5×10^6 ha of forests annually are affected by fire. A recent report from Thailand contains similar figures for the predominating dipterocarp monsoon forests of about 3.1×10^6 ha per year (Royal Forest Department, Thailand, 1988). The analysis of historic information from British India reveals that during the last century and early this century almost all Indian deciduous forests were reported to burn every year (Goldammer, 1991). Figure 10.2 shows the global area of distribution of tropical deciduous and monsoon forests potentially burning in short-return intervals of between one and five years.

The ecological impact of the yearly fires on the deciduous and semideciduous forest formations is significant. The fire strongly favors fire-tolerant trees which replace the species potentially growing in an undisturbed environment. Many of the monsoon forests of continental Southeast Asia would be reconverted to evergreen rainforest biomes if the man-made fires were eliminated. Such phenomena have been observed in Australia where the aboriginal fire practices and fire regimes were controlled and rainforest vegetation started to replace the fire-prone tree-grass savannas (Ellis, 1985). The 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 controversial discussions about the traditional fire control policy in British Indian Forestry for a long time (Pyne, 1990; Goldammer, 1991).

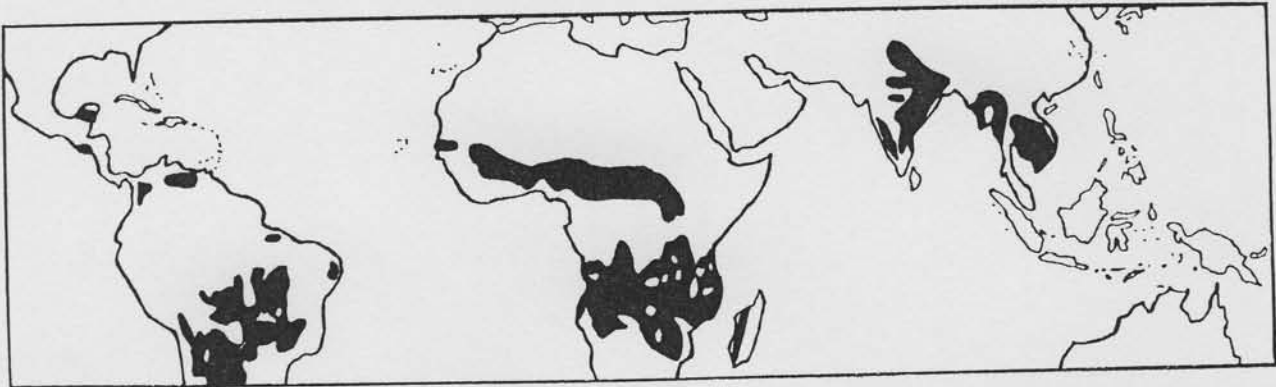The fire climax deciduous forests are not neces-

Figure 10.2 Present distribution of deciduous and monsoon forests in the tropics and adjoining regions which are affected by regular short-return-interval fires (solid areas). The boundaries given in this map are rough and may overlap with savanna biomes (Figure 10.4).

sarily in an ecologically stable condition. The long-term impact of the frequent fires is considerable erosion because of the removal of the protective litter layer just before the return of the monsoon rains. The erosion rates under standing deciduous forests regularly affected by fire may exceed 60 tons yr^{-1} (Goldammer, 1987).

Tropical Pine Forest Fire Climax

Approximately 105 species of the genus *Pinus* are recognized. From the main center of speciation in Central America and Southeast Asia some species extend into the tropics (Critchfield and Little, 1966; Mirov, 1967). The pines are largely confined to the zone of lower montane rainforest. They are usually found on dry sites and require 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. The fire ecology of tropical pines has been described for Southern Asia (Goldammer and Peñafiel, 1990) and for Central America (Munro, 1966; Koonce and González-Cabán, 1990); there are no pines occurring naturally between the tropics of Africa and in the whole of the Southern Hemisphere except Sumatra.

Besides the pioneer characteristics, most tropical pines show distinct adaptations to a fire environment (bark thickness, rooting depth, occasionally sprouting, flammability of litter) (Goldammer and Peñafiel, 1990). The tropical pure pine forests of Central America and South Asia in most places are the result of a long history of regular burning. Fire-return intervals have became shorter during the last decades and range between one to five 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 outside of the potential area of occurrence in a nonfire environment (Munro, 1966; Kowal, 1966; Goldammer and Peñafiel, 1990). However, together with the effects of overgrazing (including trampling effects) and extensive illegal fuel-wood cutting, the increasing pressure of wildfires tends to destabilize the submontane pine forests resulting in forest depletion, erosion, and subsequent flooding of lowlands. Like in the tropical deciduous forests the fires are mainly set by graziers but also spread from escaping shifting cultivation fires and the general careless use of fire in the rural lands.

These tropical fire climax pine forests are occurring throughout Central America, the midelevations of the Himalayas, throughout submontane elevations in Burma, Thailand, Laos, Kampuchea, Viet Nam, Philippines (Luzón), and Indonesia (Sumatra) (Goldammer, 1987). The extent of the annually burned pine forest lands is not known. Figure 10.3 shows the area of natural distribution of pines within the tropics and the adjoining regions which are greatly influenced by the tropical climate and similar socio-ecological and cultural conditions.

Tropical Savanna and Grassland Fires

The various types of natural savanna formations are potentially of edaphic, climatic, orographic, or fire (lightning fire) origin and are influenced by wildlife (grazing, browsing, trampling). Together with anthropogenic influences (e.g., livestock grazing), fuel-wood cutting, and other nonwood product uses, most tropical savannas are shaped at present mainly by
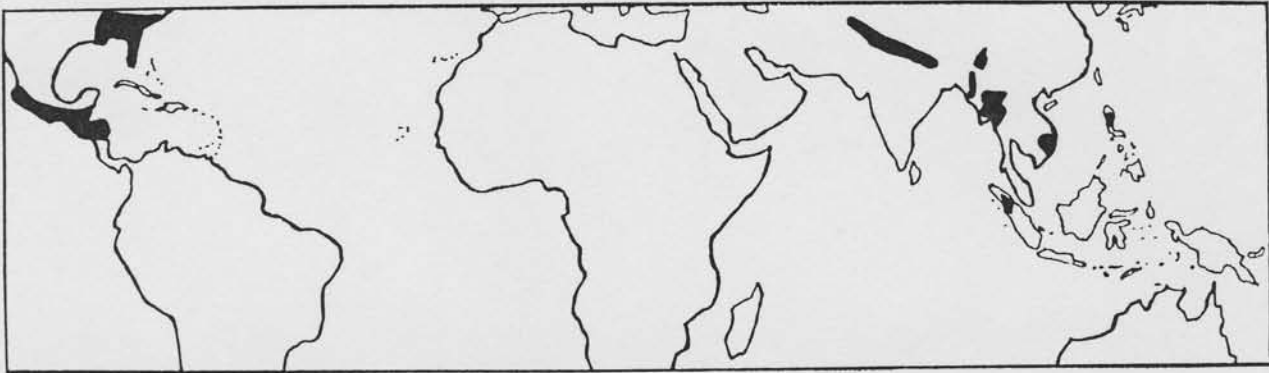
Figure 10.3 Area of natural and anthropogenic fire climax pine forests (*Pinus* spp.) within the tropics and adjoining regions (solid areas). These pine forests are characterized by occurrence of short-return-interval fires.

regularly occurring man-made fires. The impact of these fires became so dominant that only complete exclusion of fire and the other man-made influences would allow us to recognize the locally prevailing nonanthropogenic driver of savannization.

The role of fires in savanna ecosystem dynamics was recognized early. A publication of the German Colonial Service (Busse, 1908) describes the origin and impact of man-made forest fires and the importance of these fires for the rural savanna culture. The interactions of wildlife, man, and fire in the prehistoric climate and landscapes as highlighted by Schüle (1990) are of significant importance in the development of tropical savannas. Modern synoptic approaches toward an integrated savanna ecology have always considered fire as a major functional force (e.g., Tall Timbers Research Station, 1972; Huntley and Walker, 1982; Cole, 1986; Pätzold, 1986; these monographs contain numerous bibliographical sources on savanna fires).

There is a tremendous variety in physiognomy of the savannas occurring throughout the tropics of Africa; North, Central, and South America; and Asia. A common feature, however, is the grass stratum as the ground layer within the open savanna woodlands (tree savannas) or as the exclusive element in the grass savannas (grasslands) and in the ecotones between. From the point of view of fire ecology and biomass burning, the definition of a savanna ecosystem and its distinction from open forests should be based on the potentially available wild-land fire fuel. In this context savannas are defined as those ecosystems in which the grass stratum is the exclusive or predominant wild-land fire fuel; open deciduous forests, on the other hand, should predominantly be characterized by available fuels from the tree layer (leaf litter).

The available fuel (biomass density) per hectare depends on the net primary phytoproduction and varies between 0.5 and 2.5 tons ha^{-1} in the dry savannas of the Sahel and up to 8 tons ha^{-1} in the moist savannas of Guinea (Menaut, this volume, Chapter 17). The susceptibility of savannas to extended fires depends on fuel continuity and density (Imort, 1989). Accordingly, the fire frequency varies between about one and five years depending on the spareness and required minimum accumulation of flammable plant material.

The total global area of tropical savannas annually affected by fire and the total global biomass burned are not known. Figure 10.4 shows the present extent of tropical savannas potentially affected by short-return-interval fires. The overlap of areas with the distribution of open deciduous forests (Figure 10.2) is due to uncertainties in definitions and boundaries and the ecotonal characteristic of vegetation. Another uncertainty is the continuously progressing transition of flammable savannas to nonflammable ecotypes (desertification), which reduces the extent of area affected by fire. In a pantropical savanna fire mapping we found that savannas occur on a total of 2.6×10^9 ha, of which up to 1.5×10^9 ha may be affected by fire each year. This upper limit of frequently burned-over savannas corresponds to a value of 7.9×10^9 g of biomass (dry matter) combusted annually and a prompt release of about 3.5×10^9 g of carbon to the atmosphere (Goldammer and Weiss, 1991). Thus savanna fires contribute to approximately 65% of the total of about 5.5 Pg of prompt annual carbon release (upper potential limit) to the atmosphere by tropical
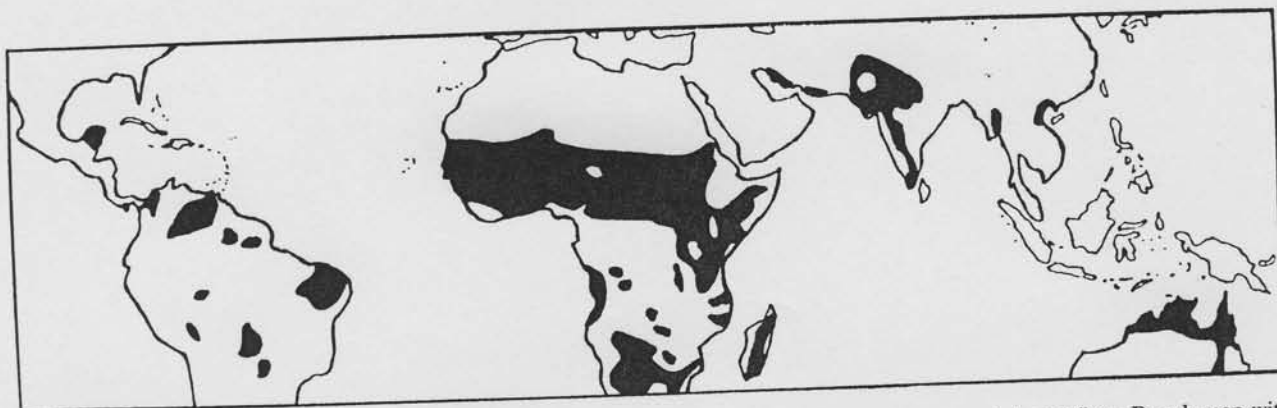
Figure 10.4 Distribution of tropical savanna biomes (solid areas) which are affected by short-return-interval fires. Rough map without distinction between the various savanna types (such as dry or moist savanna biomes).
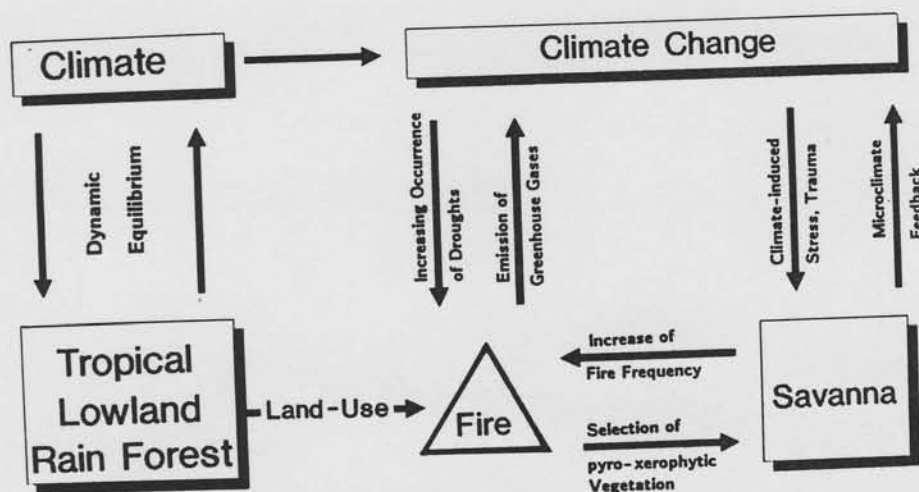

Figure 10.5 Feedback mechanisms between savannization of tropical forests, fire, and climate change (Goldammer, 1990a).

and subtropical vegetation fires (Goldammer and Weiss, 1991).

Future Trends

A future scenario of the extent of tropical fires and fire regimes can be derived from the suggested paleo-fire information and today's knowledge of tropical fire ecology. The process of expected change of the earth's vegetation cover induced by humans follows two different pathways. The first pathway is the large-scale dimension of savanna conversion, forest conversion, and depletion of vegetation cover (e.g., desertification) of the tropical biota through all kinds of human activities. These direct impacts induce the secondary pathway. Forest depletion, savannization, and the combustion processes involved result in a change of the physical and chemical environment.

Reduction and change of characteristics of vegetation cover result in change of evapotranspiration and albedo, thus consequently leading to changes in climate. The change of the water cycle, surface heating, and radiation regime may result in a drier and eventually warmer environment. Additionally the emission of trace gases through biomass burning contributes to the greenhouse effect and accelerates global warming (Figure 10.5).

Although the models on tropical greenhouse climate are still preliminary, there is sufficient evidence in trends to predict the future tropical wild-land fire scenario. Depending on political measures, the process of deforestation of the tropical rainforest may be finished soon due to either one of two reasons—because nothing will be left anymore (the worst-case scenario) or because legal restrictions will keep some of the rainforest and other closed forest formations
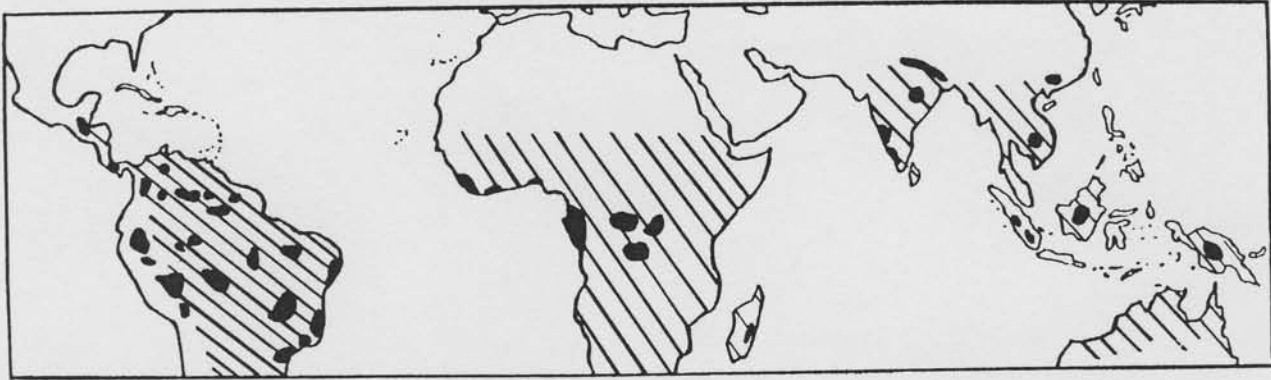
Figure 10.6 Possible distribution of fire-prone and of fire-protected tropical vegetation in a 2 × CO_2 climate. Hatched areas show large-scale degraded vegetation (savannized) regularly affected by short-return-interval fires. Solid areas tentatively show protected refuges (biosphere reserves), which may serve as gene-pool reserves and as source of forest expansion in a posthuman environment.

protected as reserves. Assuming that rainforest reserves will be maintained, a future tropical wild-land fire scenario in a 2 × CO_2 climate could look quite similar to the late Quaternary conditions (Figure 10.1 and Figure 10.6). The forest reserves (corresponding to the Pleistocene refuges) will be kept free from humans and fire. Between the refuges the non-agricultural vegetation will be largely degraded toward pyrophytic and xerophytic (tree-) savannas and characterized by short-return-interval fires.

However, there are differences between the paleo-fire scenario and the 2 × CO_2 fire scenario. One distinction is the available land mass bearing savanna fire climaxes. During the Pleistocene the total area of lowland savanna formations was larger due to the lowered global sea surface level and the exposure of the shelves. Under the 2 × CO_2 climate the available land mass may even be smaller because of a possible rise in sea level due to global warming. The other distinction is the fire climate. The tropical paleofire climate was cooler and drier than today, and the 2 × CO_2 climate will be warmer than today, with regional and local extremes in weather patterns (droughts, hurricanes).

Conclusions

Wildfires have been an integrated factor of the natural environment of Earth for millions of years. Evidence of ancient wildfires is given by fusain (fossil charcoal) embedded in the coal seams of the carboniferous period (Francis, 1961; Komarek, 1973). During geological time scales the role of fires in ecosystem processes was always interdependent with climate patterns and characteristics of the atmosphere. Car-

bon fixation and carbon release of the terrestrial biota occurred in and probably were triggers of the cyclic patterns of the glacial and the interglacial periods.

Since the beginning of burning fossil carbon sources in the mid-nineteenth century man has added a new driving force into global climate changes. Both the human-caused conversion of terrestrial biomass and the combustion of the buried fossil carbon storage will lead to an accelerated process of global change in the near future. The responses of the terrestrial tropical biota are not yet entirely predictable. However, from the past and present tropical fire regimes it can be concluded that wild-land fires will continue to burn in the future. Negative impacts of fires need to be encountered by integrated fire-management systems. Fire policies must be targeted to provide vegetational cover to protect the soil productivity and to maintain or increase the overall carbon storage of land biomass. Thus, forest or vegetation management strategies are needed which consider a global perspective in environmental policies.