PERSPECTIVES: ECOLOGY

Forests on Fire

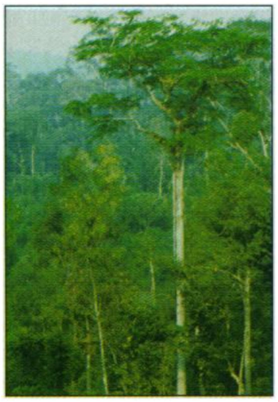
Johann G. Goldammer

The world's tropical forests are disappearing, but it is not easy to understand the complexities of how this is happening. The initial critical disturbance that triggers forest depletion is often obscured by the subsequent, more destructive events. Two reports on pages 1829 and 1832 in this issue (*1, 2*) and a recent paper in *Nature* (*3*) demonstrate that fire (together with logging) increases the vulnerability of tropical forests to future burning. These results, presented by a U.S.-Brazilian consortium (*3*), indicate that the devastating impact of small-sized logging operations and low-intensity surface fires in drought- and logging-stressed Amazonian forests has been underestimated. One of the reports in this week's *Science* explains why (*2*): Fire, an indicator of human intervention in tropical rainforests, is a major driving force in the depletion and savannization of tropical forests (*2*).

Destruction by fire. This series of photographs illustrates fire-induced conversion of a lowland tropical rainforest in East Kalimantan, Indonesia (*10*) to savanna.

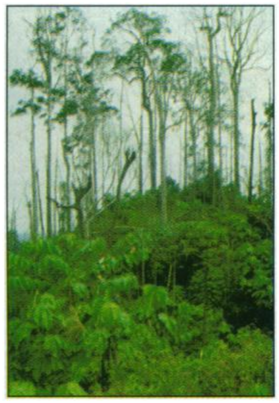
These reports are particularly timely because of the recent massive fires in Indonesia during the El Niño–Southern Oscillation (ENSO). The cumulative damaging effects of human forest occupation, forest clearing by fire, and extreme drought caused by interannual climate variability such as ENSO interact to destroy tropical forests. With the likely increase in the frequency and severity of ENSO as a consequence of increasing greenhouse gas concentrations (*4*), the stage is set for an increasing number of fires and, consequently, for more forest destruction.

These studies highlight a severe problem in our analysis of tropical deforestation and point the way toward a solution. The data from these studies were obtained by vegetation plot and fire behavior studies and multitemporal analyses of high-resolution satellite imageries. They paint a much bleaker picture of the severity of the deforestation problem than we had from previous inventories and remote sensing tool application (Landsat, NOAA AVHRR, SPOT). The application of these remote sensing methods over large areas either did not adequately quantitate small disturbances or subcanopy effects of fire that lead to forest depletion (*3*), or classified forests partially damaged by fire as "deforested" (*2*). Thus, present estimates of deforestation based on superficial evaluation of spaceborne information are likely to be superficial and are therefore of limited value. Only concrete numbers such as those presented in these two case studies (*2, 3*) will be able to focus attention on a potentially disastrous problem.



1980. Pristine lowland rainforest in Eastern Borneo dominated by trees of the dipterocarp family.

1982. Initial surface fire in the same forest, which has been selectively cut since 1980.



1985. Three years after the initial fire. Most trees are killed by the surface fire, some by drought stress, but some trees are still standing.

Scientists have been aware of the detrimental impact of fire on deforestation and the urgent need for action since a forum was convened in Germany 10 years ago. Because fire is an important traditional tool in the management of land, however, it cannot simply be banned (*5, 6*). In 1992, a large series of experiments clarified the role of vegetation fires and domestic fuelwood burning on seasonal tropospheric ozone formation in the tropics (*7, 8*). Nevertheless, little general notice was taken of the steadily increasing fire problem in the equatorial forest belt until the severe fire and smoke episodes of 1997

Toward a New Fire Schism?

Integrated fire management practices increasingly depend on a balance between natural and human-caused fires. In a broad range of ecosystems, fire is considered necessary for regeneration and recycling—for example, in savannas, grasslands, seasonal tropical forests, some temperate forests, most of the northern circumpolar boreal coniferous forests, and the Mediterranean-climate brushlands (such as the Californian chaparral, the South African *Fynbos*, or the Mediterranean *Macchia*). Human fire suppression at certain stages of ecosystem development may lead to the buildup of combustible materials. Once ignited, the resulting high-intensity fires are difficult to control. Prescribed burning and prescribed natural fires in many of these ecosystems, sometimes together with mechanical treatment, imitate natural fire regimes. These procedures reduce fuels, create barriers, and limit intensity and spread of the inevitable wildfires, because the fuels already have been burned under controlled conditions. The validity of this fire and fuels management approach is now questioned by Keeley *et al.* (*1*). By analyzing a fire history database for the Californian brushlands, they conclude that fire suppression and rotational burning had no effect on the occurrence of large fires. This report will stir a hot—and crucial—debate on the utility of fire suppression as integrated fire management philosophy moves into the last unexplored corners of the globe. The boreal forest of Russia, covering more than a billion hectares, is one of the most prominent candidate regions. Legal and financial restrictions and the polemics around emissions from vegetation fires will additionally contribute to what is sure to be a polarized debate.

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and 1998 in Asia and the Americas. Today, vast tropical rainforest areas have already been opened up by commercial and subsistence land clearing. A large swath of rainforest in South America and Southeast Asia has been affected by its first big (initiating) fire in 1998, the galvanizing event from which more violent, frequent, and destructive fires will follow.

1995. Thirteen years after the initial fire. More standing trees have died and collapsed. The undergrowth is dominated by pioneer tree species (predominantly *Macaranga* spp.). This secondary succession becomes highly flammable in extremely dry years.

1998. A second fire. The tree layer, including the postfire secondary succession, is almost completely killed by a high-intensity fire.

1998. Final stage of fire-induced savannization of the rainforest in a nearby site. The area is dominated by an aggressive invading grass species (*Imperata cylindrica*).

The last 2 years have seen an increase in the willingness of international agencies to address the fire problem. The Global Fire Monitoring Center (GFMC) was established in 1998 for continuous worldwide monitoring, archiving, and information distribution and to form a link between science, users, and policy-makers (*9*). One of the major objectives of the GFMC is to provide a balanced view on fire and to assist in the clarification of detrimental and beneficial effects of fire and their implications for fire management. The report by Keeley *et al.* (*1*), questioning one of the prime tenets in fire management policy, is an important contribution toward this end (see box on previous page). An interagency task force on fire is urgently needed to follow up on the requirements laid out by the UN Convention on Climate Change and the UN Commission for Sustainable Development. The initiative of the World Bank to establish a Consultative Group for Global Disaster Reduction in June 1999 is an important step toward a concerted global fire program.

References and Notes

1. J. E. Keeley, C. J. Fotheringham, M. Morais, *ibid.*, p. 1829.
2. M. A. Cochrane *et al.*, *Science* **284**, 1832 (1999).
3. D. C. Nepstad *et al.*, *Nature* **398**, 505 (1999).
4. A. Timmermann *et al.*, *ibid.*, p. 694.
5. J. G. Goldammer, Ed., *Fire in the Tropical Biota. Ecosystem Processes and Global Challenges* (Springer-Verlag, Berlin, 1990); the Freiburg Declaration on Tropical Fires, as released by the conference participants in May 1989, is included in Appendix I (pp. 487–489). See also P. J. Crutzen and J. G. Goldammer, Eds., *Fire in the Environment: The Ecological, Atmospheric, and Climatic Importance of Vegetation Fires* (Dahlem Workshop Reports, Environmental Sciences Research Report 13, Wiley, Chichester, UK, 1993).
6. *Protecting the Earth. A Status Report with Recommendations for a New Energy Policy*, vols. I and II (German Bundestag, Bonn, 1991).
7. See the newsletter *IGACtivities* (no. 15, December 1998) for a summary of the International Global Atmospheric Chemistry (IGAC) Biomass Burning Experiment (BIBEX). The BIBEX home page is maintained at the Max Planck Institute for Chemistry (http://hermes.mpch-mainz.mpg.de/~bibex).
8. For the results of the Southern Tropical Atlantic Regional Experiment (STARE: TRACE-A and SAFARI), see *J. Geophys. Res.* **101**, 23519 (1996); B. van Wilgen, M. O. Andreae, J. G. Goldammer, J. Lindesay, Eds., *Fire in Southern African Savannas. Ecological and Atmospheric Perspectives* (Univ. of Witwatersrand Press, Johannesburg, 1997).
9. The GFMC (www.uni-freiburg.de/fireglobe) is supported by the German Foreign Office and cosponsored by the UN Food and Agricultural Organization (FAO)/Economic Commission for Europe (ECE) Team of Specialists on Forest Fire, International Decade for Natural Disaster Reduction (IDNDR), UNESCO, and the World Bank.
10. J. G. Goldammer, B. Seibert, W. Schindele, in *Dipterocarp Forest Ecosystems: Towards Sustainable Management*, A. Schulte and D. Schöne, Eds. (World Scientific, Singapore, 1996), pp. 155–185.

PERSPECTIVES: ATMOSPHERIC SCIENCE

Vertical Couplings

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The conventional approach to studying the global atmosphere is to divide the atmosphere into the troposphere, stratosphere, mesosphere, and thermosphere (see figure), horizontal layers which are defined by the temperature-altitude profile of the atmosphere (*1*). Many characteristic dynamical and chemical processes distinguish these layers, but the boundaries between them are far from impermeable. Studies over the past decade have revealed that strong chemical, dynamical, and radiative coupling exists between them. It is becoming increasingly clear that the global atmosphere must be considered as an integrated system if we are to understand the relative roles of natural and anthropogenic effects on Earth's changing atmosphere. Recent research presented at a Chapman Conference held in Annapolis, Maryland (*2*), highlighted the importance of atmospheric coupling across the stratopause (at an altitude of about 50 km), the region that marks the transition between the stratosphere and mesosphere, together known as the middle atmosphere.

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It is now well established that anthropogenic pollutants such as chlorofluorocarbons (CFCs) released in the troposphere cause depletion of stratospheric ozone on a global scale (*3*). Effects attributable to other anthropogenic pollutants have also been predicted to occur but are less well established. Middle atmosphere model results presented by Guy Brasseur (National Center for Atmospheric Research) predict that increasing levels of atmospheric carbon dioxide—associated with global warming in the troposphere as a result of an enhanced greenhouse effect—should, in contrast, lead to global cooling of the middle atmosphere (*4, 5*). This is a robust prediction and is based on the fact that CO_2 is not only an efficient absorber of infrared radiation but also an efficient emitter. At stratospheric altitudes and above where infrared emission from CO_2 can "escape" to space because of the low atmospheric density at these heights, dramatic atmospheric cooling is expected. Tropospheric climate models generally predict a 1° to 4°C increase in the tropospheric temperature in a doubled-CO_2 scenario. Corresponding middle atmospheric models for the same scenario predict a 10° to 20°C decrease in middle atmospheric temperatures (*5*).

Such a large middle atmospheric signal of global temperature change suggests that the atmospheric effects of increasing lev-