Fire in the Earth System

David M. J. S. Bowman,[1]* Jennifer K. Balch,[2,3,4]*† Paulo Artaxo,[5] William J. Bond,[6]
Jean M. Carlson,[7] Mark A. Cochrane,[8] Carla M. D'Antonio,[9] Ruth S. DeFries,[10] John C. Doyle,[11]
Sandy P. Harrison,[12] Fay H. Johnston,[13] Jon E. Keeley,[14,15] Meg A. Krawchuk,[16]
Christian A. Kull,[17] J. Brad Marston,[18] Max A. Moritz,[16] I. Colin Prentice,[19] Christopher I. Roos,[20]
Andrew C. Scott,[21] Thomas W. Swetnam,[22] Guido R. van der Werf,[23] Stephen J. Pyne[24]

Fire is a worldwide phenomenon that appears in the geological record soon after the appearance of terrestrial plants. Fire influences global ecosystem patterns and processes, including vegetation distribution and structure, the carbon cycle, and climate. Although humans and fire have always coexisted, our capacity to manage fire remains imperfect and may become more difficult in the future as climate change alters fire regimes. This risk is difficult to assess, however, because fires are still poorly represented in global models. Here, we discuss some of the most important issues involved in developing a better understanding of the role of fire in the Earth system.

Over the past decade, a surge in the incidence of large, uncontrolled fires has occurred on all vegetated continents, irrespective of national fire-fighting capacity or management tactics (*1*–*5*). These episodic fires have high economic costs. The fires in Southeast Asia's tropical forests related to the 1997–1998 El Niño–Southern Oscillation (ENSO) event, for example, resulted in economic costs near $U.S. 8.8 to 9.3 billion, of which a conservative estimate of $U.S. 1 billion was from adverse health effects of smoke haze (*6*). During the same period, more than 20 million ha burned in Latin America, causing an estimated $U.S. 10 to 15 billion in damages (*4*). The ubiquity of such large fires calls into question our capacity for fire control and highlights our limited understanding of fire's causes, effects, and feedbacks.

There is growing awareness of the deleterious effects of such uncontrolled fires on biodiversity, human health, and the economy (*2*). However, there remains a serious lack of knowledge about fire's fundamental role in Earth system processes, as well as an insufficient appreciation of fire's interaction with anthropogenic global environmental change. For example, though the Intergovernmental Panel on Climate Change (IPCC) report concluded that global climate change will increase the risk of extreme fire events (*7*), its assessment did not quantify potential fire-climate feedbacks. In order to achieve a better understanding of fire, it must be understood as an integral Earth system process that links and influences regional and global biogeochemical cycles, human activity, and vegetation patterns. Failure to develop a coordinated and holistic fire science will slow efforts to adapt to changing fire regimes and manage fire.

Fire in Earth History

Fossil charcoal indicates that wildfires began soon after the appearance of terrestrial plants in the Silurian [420 million years ago (Ma)] (*8*). Combustion occurs when atmospheric O_2 concentrations are above 13%, and variation in O_2 levels correlates with fire activity throughout Earth history (*8*) (Fig. 1). Many Permian coals contain large quantities (70%) of charcoal during a period when atmospheric oxygen was thought to have exceeded 30%, making even moist vegetation flammable (*8*). Counterintuitively, the burial of decay-resistant charcoal and organic matter following postfire erosion may have increased oxygen levels and caused long-term reduction of atmospheric carbon dioxide levels (*9*). Fire also influences the geological cycling of other elements, such as phosphorus, by volatization and leaching (*10*).

Fire's occurrence throughout the history of terrestrial life invites conjecture that fire must have had pronounced evolutionary effects on biotas. However, the evolution of adaptations to fire remains a difficult topic to explore because traits that increase the rate of occurrence of fire, or of recovery following burning, are not unambiguously the result of natural selection by fire regimes (*11*) (table S1). Nonetheless, flammable vegetation types leave distinct signatures in the fossil record, chronicling changes in their abundance and geographic range. For example, tropical grasses produce large quantities of fine, aerated fuels that become highly flammable during dry periods, and their C_4 photosynthetic pathway produces organic matter characteristically depleted in ^{13}C. Stable isotope analyses of carbon in sediments have shown that tropical savanna biomes simultaneously spread in Asia, Africa, and the Americas, approximately 7 to 8 Ma, coinciding with a substantial spike in charcoal in marine sediments (*12*). It has even been suggested that fire led to the expansion of savannas due to climate feedbacks that created hotter, drier conditions that favored savannas (*13*).

Humans and Fire

The spread of highly flammable savannas, where hominids originated, likely contributed to their eventual mastery of fire (*14*). The hominid fossil record suggests that cooked food may have appeared as early as 1.9 Ma (*15*), although reliable evidence for controlled fire use does not appear in the archaeological record until after 400,000 years ago, with evidence of regular use much later (*16*). The routine domestic use of fire began around 50,000 to 100,000 years ago (*17*), which may have influenced the evolution of human tolerance to air pollution (*18*), and hunter-gatherers used fire to reduce fuels and manage wildlife and plants beginning tens of thousands of years ago (*19*).

In recent history, the ongoing transition from subsistence to industrial economies is typified by the conversion of forests into agricultural or pastoral landscapes through the use of fire. For example, fire-resistant tropical rainforests are rapidly being cleared with fire in agricultural frontiers (*20*) (Fig. 2). Conversely, in the developed world, suburban sprawl into rural and natural landscapes, where people and their dwellings are juxtaposed with flammable vegetation types, is accompanied by substantial fire-suppression efforts (*21*). Worldwide, fire is used to minimize fuel hazard, maintain habitat quality, and stimulate forest and pasture regeneration. Despite human use of fire to achieve economic and ecological benefits (*22*), fire remains an unreliable tool, often evading control, particularly during extreme drought events (*3*, *23*). This imperfect mastery of fire manage-

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[1]The University of Tasmania, Hobart, TAS 7001, Australia. [2]National Center for Ecological Analysis and Synthesis, Santa Barbara, CA 93101, USA. [3]Yale University, School of Forestry and Environmental Studies, New Haven, CT 06511, USA. [4]Woods Hole Research Center, Woods Hole, MA 02543, USA. [5]Universidade de São Paulo, Instituto de Física, CEP 05508-900, São Paulo, Brazil. [6]University of Cape Town, Department of Botany, Cape Town, South Africa. [7]University of California, Department of Physics, Santa Barbara, CA 93106, USA. [8]South Dakota State University, Geographic Information Science Center of Excellence, Brookings, SD 57007, USA. [9]University of California, Environmental Studies Program and Department of Ecology, Evolution & Marine Biology, Santa Barbara, CA 93106, USA. [10]Columbia University, Ecology, Evolution and Environmental Biology, New York, NY 10027, USA. [11]California Institute of Technology, Department of Control and Dynamical Systems, Pasadena, CA 91125, USA. [12]School of Geographical Sciences, University of Bristol, Bristol BS8 1SS, UK. [13]University of Tasmania, Menzies Research Institute, Hobart, TAS 7001, Australia. [14]U.S. Geological Survey, Western Ecological Research Center, Sequoia-Kings Canyon Field Station, Three Rivers, CA 93271, USA. [15]University of California, Department of Ecology and Evolutionary Biology, Los Angeles, CA 90095, USA. [16]University of California, Ecosystem Sciences Division, Department of Environmental Science, Policy, and Management, Berkeley, CA 94720, USA. [17]Monash University, School of Geography and Environmental Science, Melbourne, VIC 3800, Australia. [18]Brown University, Department of Physics, Providence, RI 02912, USA. [19]QUEST, Department of Earth Sciences, University of Bristol, Bristol BS8 1RJ, UK. [20]Ohio State University, Department of Anthropology, Columbus, OH 43210, USA. [21]Royal Holloway University of London, Department of Earth Sciences, Egham, Surrey TW20 0EX, UK. [22]The University of Arizona, Laboratory of Tree-Ring Research, Tucson, AZ 85721, USA. [23]VU University, Faculty of Earth and Life Sciences, Department of Hydrology and Geo-environmental Sciences, 1081 HV, Amsterdam, Netherlands. [24]Arizona State University, School of Life Sciences, Tempe, AZ 85287, USA.

*These authors contributed equally to this work.

†To whom correspondence should be addressed. E-mail: balch@nceas.ucsb.edu

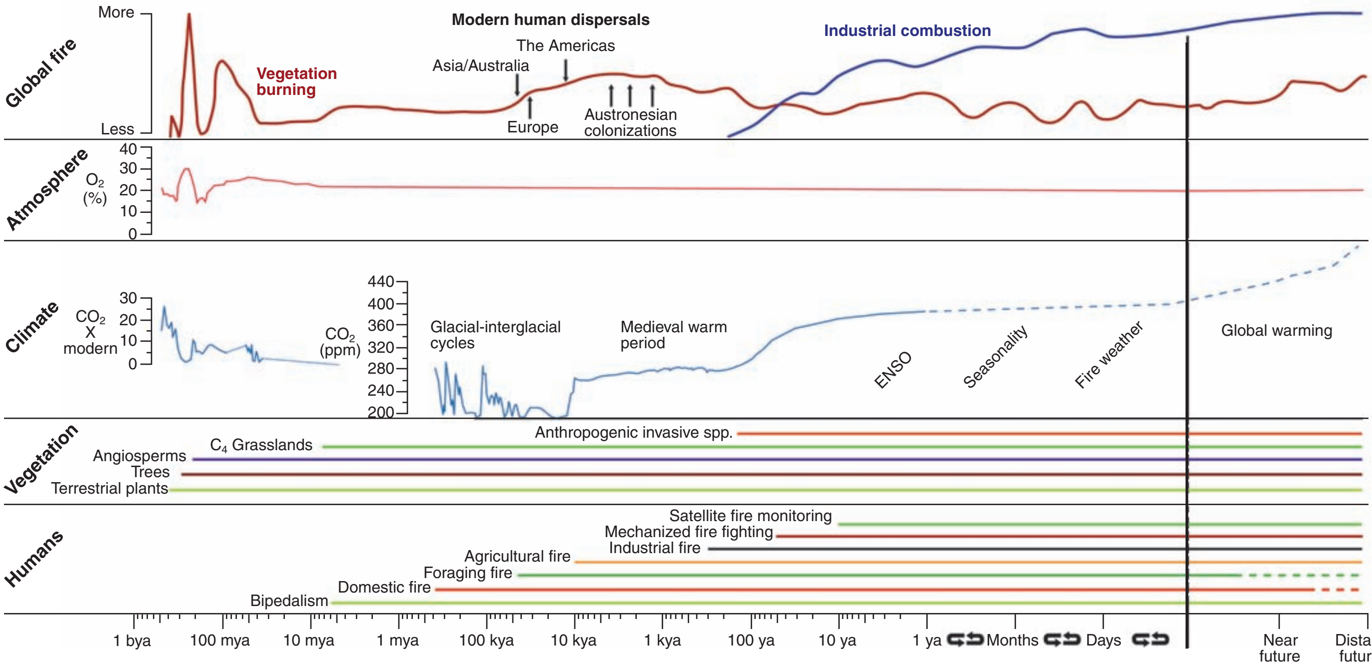

Fig. 1. Qualitative schematic of global fire activity through time, based on pre-Quaternary distribution of charcoal, Quaternary and Holocene charcoal records, and modern satellite observations, in relation to the percentage of atmospheric O_2 content, parts per million (ppm) of CO_2, appearance of certain vegetation types, and the presence of the genus *Homo*. (See supporting online text for data sources used.) Dotted lines indicate periods of uncertainty.

ment raises the unsettled issue of whether humans or climate are more important in determining fire patterns.

Distribution and Diversity of Fire

Earth is an intrinsically flammable planet owing to its cover of carbon-rich vegetation, seasonally dry climates, atmospheric oxygen, and widespread lightning and volcano ignitions. Yet, despite the human species' long-held appreciation of this flammability, the global scope of fire has been revealed only recently by satellite observations available beginning in the 1980s (*24*) (Fig. 2). This record shows a strong association between high fire activity and areas of intermediate primary production, particularly in tropical savannas (*25*). However, the satellite record does not adequately capture fire activity in ecosystems that have long (>100-year) fire intervals, nor in cases in which fire behavior is highly variable. Satellite products that provide those data on area burned, fire intensity, and completeness of combustion are still being developed (*26*).

Fires burn with different intensities and frequencies, resulting in a wide variety of ecological effects. To capture this diversity, ecologists define the "fire regime" on the basis of a range of variables including fuel type (ground, surface, and crown), temporal nature (rate of spread, seasonality, and frequency), spatial pattern (size and patchiness), and consequences (impacts on vegetation and soils) (*27*). The association of plant species having distinct reproductive and survival strategies with different fire regimes suggests that fire is a potent biological filter (table S1) influencing biomass production, vegetation distribution, and thus the risk of fire. Indeed, a notable feature of fire's distribution is the broad correlation between vegetation formations and fire regimes (*28*). Furthermore, fire can sometimes explain the presence of alternate ecosystem states within the same climatic zone (*28*).

Vegetation transitions can occur when fire regimes are altered substantially beyond historical norms, owing to changes in ignition sources or fuel mass, and variations in structure caused by fire protection, grazing, or the spread of invasive plants. For example, nonflammable tropical rainforests, evergreen woodlands, and arid shrublands can abruptly convert to highly flammable plant communities with increasing anthropogenic ignitions and fine fuels from invasive grasses (*29*). Fire protection, by contrast, promotes dense regrowth and closed woodlands. In the southwestern United States, this has led to an associated switch from surface to crown fires (*30*). Human landscape management is implicated in these fire regime transitions, yet underlying climate patterns also alter fire behavior.

Climate and Human Drivers of Fire

Analyses of historical meteorological data and national fire records show the primacy of climate in driving large regional fires, e.g., via antecedent wet periods that create substantial herbaceous fuels or drought and warming that extend conducive fire weather (*1*). Additionally, dendrochronological and observational analyses show tight coupling between high fire activity and interannual- and decadal-scale climate oscillations (*31*, *32*). For example, fire occurrence increases during the La Niña phase of the ENSO in the southern United States and Patagonia, Argentina (*25*, *33*), whereas a marked increase in fire activity occurs in tropical rainforests during El Niño phases (*34*). Sedimentary charcoal records also show a strong link between climate and fire activity, with reduced fire in cold intervals and increased fire in warm intervals, regardless of whether humans were present (*35*). However, charcoal records do show a reduction in fire after ~1870 C.E. in most regions, apparently in response to agricultural intensification and introduced animal grazing (*36*).

Abrupt changes in fire activity during island colonization offer insight into human influence on fire, beyond background climate conditions. For example, the colonization of the southern island of New Zealand by the Maori about 700 to 800 years ago was characterized by widespread destruction of forests by burning, causing the loss of half of the island's temperate rainforests (*37*). Likewise, it has been argued that fire usage during the late Pleistocene colonization of Australia triggered a series of megafaunal extinctions and vegetation changes (*38*).

Fire, Carbon, and Climate

Humans and climate both play a role in determining fire patterns and, in turn, fire influences the climate system via the release of carbon. Fires accelerate the natural cycle of primary production and respiration. In a world without fire, more carbon would be stored in woody vegetation (*39*). If climate and fire regimes equilibrate, then fire-induced atmospheric CO_2 emissions are balanced by uptake from surviving vegetation or via regeneration. The individual contributions of landscape fires, biomass combustion for domestic and industrial uses, and fossil-fuel combustion to total carbon emissions remain difficult to separate. Currently, all sources of fire (landscape and biomass) cause CO_2 emissions equal to 50% of those stemming from fossil-fuel combustion (2 to 4 Pg C year^{-1} versus 7.2 Pg C year^{-1}) (*7*, *40*, *41*). Of the fire-related emissions, we estimate that burning related to deforestation, a net CO_2 source, contributes about 0.65 Pg C year^{-1} (supporting online material). In contrast, the regrowth of vegetation and the production of black carbon (which is a by-product of burning, with a long residence time in soils) are sinks of atmospheric CO_2 and may be expanded with targeted management (*42*).

Between 1997 and 2001, biomass burning accounted for about two-thirds of the variability in the CO_2 growth rate (*34*, *43*). During the 1997-1998 ENSO-related drought event, Indonesian peat fires contributed an estimated 0.8 to 2.6 Pg C (*3*), while Amazon forest fires committed 0.024 to 0.165 Pg C to the atmosphere from just understory fires (*23*). These deforestation-related fires contribute substantially to the global burden of greenhouse gases, and the associated global warming that they will cause is projected to increase extreme fire weather (*1*), leading to further spikes of carbon emissions (*44*).

Fire also influences climate by releasing atmospheric aerosols and changing surface albedo. An appreciable fraction of biomass-burning emissions consists of black carbon aerosols that have strong solar radiation absorption properties, and may have the strongest effect on global warming after CO_2 (*45*). Regionally, smoke plumes inhibit convection, and black carbon warms the troposphere, thereby reducing vertical convection and limiting rain-cloud formation and precipitation (*46*). Locally, fire heats the surface by reducing albedo. However, albedo may increase over longer time periods owing to larger exposure of snow following boreal fires, or replacement of dark forests with brighter pastures and croplands following deforestation. Indeed, aerosol and surface albedo effects could even cancel each other [e.g., (*47*)].

Fire influences most radiative forcing components and has a substantial positive feedback on the climate system. We estimate that global CO_2 emissions from deforestation fires alone contribute up to ~19% of the total increased radia-

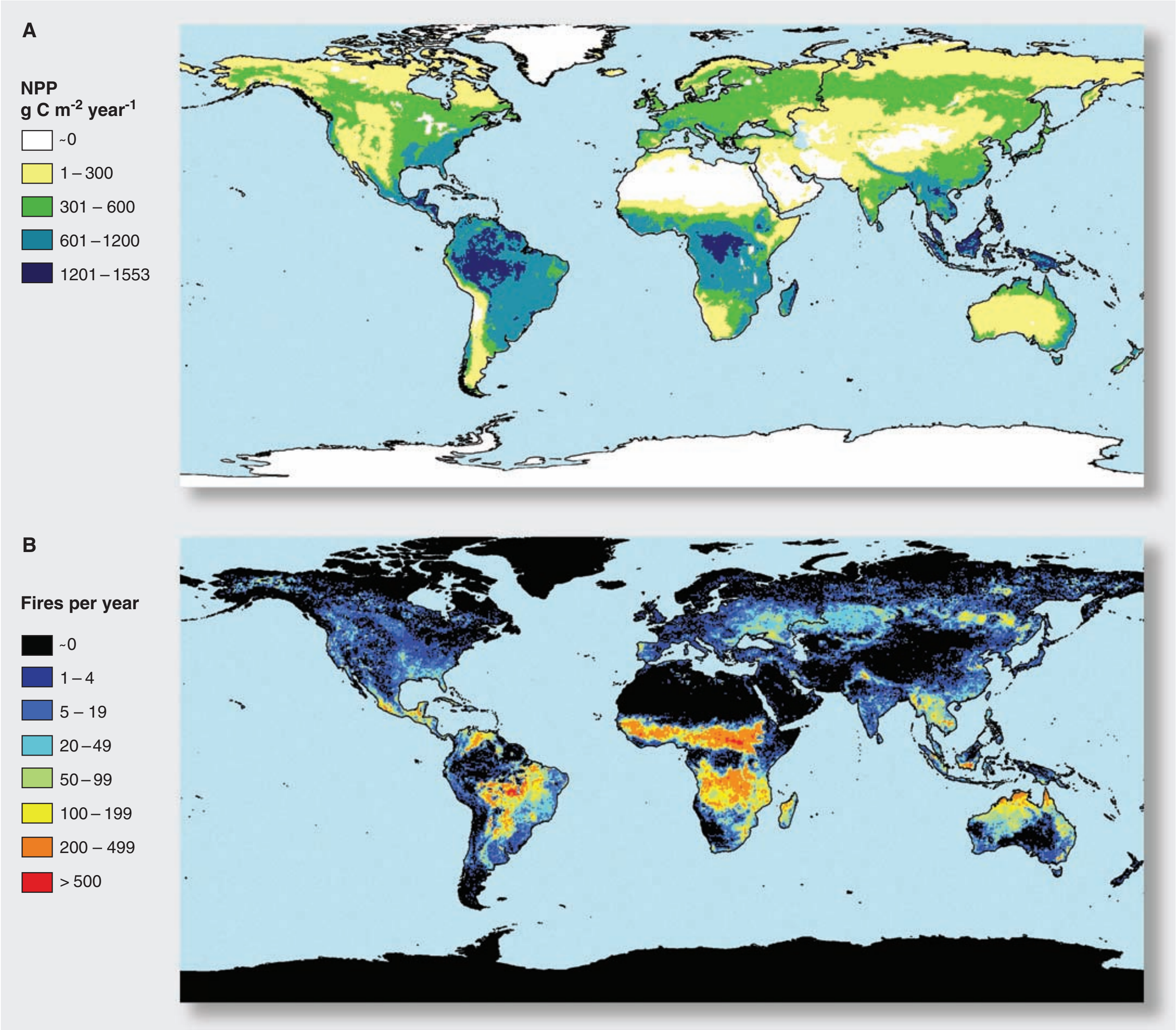

Fig. 2. Current pyrogeography on Earth, illustrated by (**A**) net primary productivity (NPP, g C m^{-2} year^{-1}) (*40*) from 2001 to 2006, by 1° grid cells; and (**B**) annual average number of fires observed by satellite (*49*).

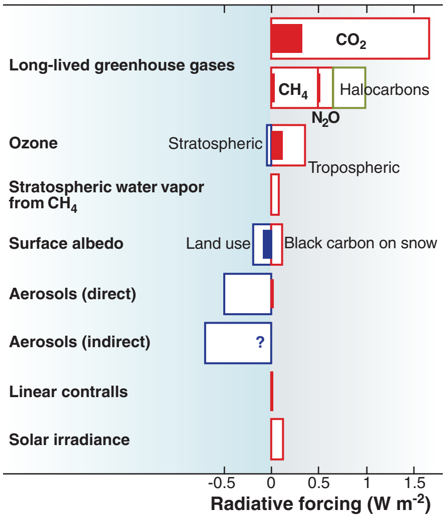

Fig. 3. Estimated contribution of fire associated with deforestation to changes in radiative forcing compared to 1750 C.E. (*7*), assuming a steady state for other fire emissions. The shaded inner bar (blue indicates cooling; red, warming) is the estimated fire contribution to the total radiative forcing of individual agents identified by the IPCC (unshaded, outlined bar) (*7*). Several assumptions had to be made to estimate these contributions, and more interdisciplinary research is needed to reduce uncertainties, especially for ozone, albedo, and the complicated effect of aerosols.

tive forcing since preindustrial times, following IPCC definitions (*7*) (Fig. 3 and supporting online text). The positive and negative fire-related contributions of the other radiative forcing components are assumed to cancel each other. Excluding deforestation fires, we also assume that fire-related emissions over the long term are at a steady state because of the natural successional cycle. Improved estimates of the climate forcing of fire must address fire's complex web of interactions with other radiative forcing components and must resolve how fire activity and land-cover change have varied through the industrial period.

Fire Feedbacks

At the flame front, fire instantaneously links the atmosphere, biosphere, and hydrosphere via the release of heat, gases (notably water vapor), and matter. The composition of these products is influenced by fuel type, moisture content, and combustion type (smoldering versus flaming), which in turn is influenced by temperature and available oxygen. At the landscape scale, fire responds predictably to variation in fuel types, vegetation structure, topographic features, and weather conditions. At regional and global scales, the interaction of fire with vegetation types and human land use results in characteristic fire regimes. Climate conditions are a fundamental driver of fire spread, and fire-induced emissions influence future climate scenarios and fire weather.

Simulations using physiologically based global vegetation models suggest that forests would at least double in extent in the absence of fire, particularly in the flammable savanna biome (*39*). The difference between simulated and observed vegetation distribution highlights the importance of including fire in terrestrial ecosystem modeling. Indeed, some global carbon and dynamic global vegetation models explicitly include fires (*34*, *48*).

Conclusions

Progress in understanding fire on Earth has been hampered by cultural aversions to accepting fire as a fundamental global feature and disciplinary parochialism (*19*, *22*). An Earth system perspective is essential to understanding how fire has developed throughout Earth history, and teasing apart the direct and indirect interactions between humans and fire. Understanding global trends in fire activity demands greater development of fire regime mapping, as well as global modeling approaches that are more sophisticated than the current generation. Such an integrated perspective is necessary and timely, given that a diversity of fragmented research programs have identified the pervasive influences of fire on the Earth system. Indeed, future IPCC assessments of anthropogenic global climate forcing should include specific analyses of the role of fire.

References and Notes

1. A. L. Westerling, H. G. Hidalgo, D. R. Cayan, T. W. Swetnam, *Science* **313**, 940 (2006).
2. D. J. Lohman, D. Bickford, N. S. Sodhi, *Science* **316**, 376 (2007).
3. S. E. Page *et al.*, *Nature* **420**, 61 (2002).
4. UNEP, *Spreading Like Wildfire—Tropical Forest Fires in Latin America and the Caribbean: Prevention, Assessment and Early Warning* [United Nations Environment Programme (produced by M.A. Cochrane), Panama, 2002].
5. G. G. Forsyth, B. W. van Wilgen, *Koedoe Afr. Protected Area Conserv. Sci.* **50**, 3 (2008).
6. J. Schweithelm, D. Glover, T. Jessup, in *Indonesia's Fire and Haze: The Cost of Catastrophe,* D. Glover, T. Jessup, Eds. (International Development Research Centre and the Institute of Southeast Asian Studies, Ottawa and Singapore, 1999, reprinted 2006).
7. IPCC, *Climate Change 2007: The Physical Science Basis*, Contribution of Working Group I to the Fourth Assessment Report of the IPCC (Cambridge Univ. Press, Cambridge, 2007).
8. A. C. Scott, I. J. Glasspool, *Proc. Natl. Acad. Sci. U.S.A.* **103**, 10861 (2006).
9. R. A. Berner, D. J. Beerling, R. Dudley, J. M. Robinson, R. A. Wildman, *Annu. Rev. Earth Planet. Sci.* **31**, 105 (2003).
10. T. M. Lenton, *Glob. Change Biol.* **7**, 613 (2001).
11. D. W. Schwilk, B. Kerr, *Oikos* **99**, 431 (2002).
12. J. E. Keeley, P. W. Rundel, *Ecol. Lett.* **8**, 683 (2005).
13. D. J. Beerling, C. P. Osborne, *Glob. Change Biol.* **12**, 2023 (2006).
14. L. Ségalen, J. A. Lee-Thorp, T. Cerling, *J. Hum. Evol.* **53**, 549 (2007).
15. R. W. Wrangham, J. H. Jones, G. Laden, D. Pilbeam, N. Conklin-Brittain, *Curr. Anthropol.* **40**, 567 (1999).
16. P. Karkanas *et al.*, *J. Hum. Evol.* **53**, 197 (2007).
17. O. Bar-Yosef, *Annu. Rev. Anthropol.* **31**, 363 (2002).
18. S. M. Platek, G. G. Gallup, B. D. Fryer, *Med. Hypotheses* **58**, 1 (2002).
19. S. J. Pyne, *Fire: A Brief History* (Univ. of Washington Press, Seattle, 2001).
20. F. Mouillot, C. B. Field, *Glob. Change Biol.* **11**, 398 (2005).
21. D. Theobald, W. Romme, *Landsc. Urban Plan.* **83**, 340 (2007).
22. S. J. Pyne, *Int. J. Wildland Fire* **16**, 271 (2007).
23. A. Alencar, D. C. Nepstad, M. C. V. Diaz, *Earth Interact.* **10**, 1 (2006).
24. O. Arino, J.-M. Rosaz, P. Goloub, *Earth Obs. Q.* **64**, 1 (1999).
25. G. R. van der Werf, J. T. Randerson, L. Giglio, N. Gobron, A. J. Dolman, *Global Biogeochem. Cycles* **22**, GB3028 (2008).
26. K. Tansey *et al.*, *Geophys. Res. Lett.* **35**, L01401 (2008).
27. W. J. Bond, J. E. Keeley, *Trends Ecol. Evol.* **20**, 387 (2005).
28. D. M. J. S. Bowman, *Australian Rainforests: Islands of Green in a Land of Fire* (Cambridge Univ. Press, Cambridge, 2000).
29. C. M. D'Antonio, P. M. Vitousek, *Annu. Rev. Ecol. Syst.* **23**, 63 (1992).
30. C. D. Allen *et al.*, *Ecol. Appl.* **12**, 1418 (2002).
31. T. Kitzberger, P. M. Brown, E. K. Heyerdahl, T. W. Swetnam, T. T. Veblen, *Proc. Natl. Acad. Sci. U.S.A.* **104**, 543 (2007).
32. T. W. Swetnam, *Science* **262**, 885 (1993).
33. T. Kitzberger, T. W. Swetnam, T. T. Veblen, *Glob. Ecol. Biogeogr.* **10**, 315 (2001).
34. G. R. van der Werf *et al.*, *Science* **303**, 73 (2004).
35. M. J. Power *et al.*, *Clim. Dyn.* **30**, 887 (2008).
36. J. Marlon *et al.*, *Nat. Geosci.* **1**, 697 (2008).
37. M. S. McGlone, J. M. Wilmshurst, *J. Quat. Sci.* **14**, 239 (1999).
38. G. H. Miller *et al.*, *Science* **309**, 287 (2005).
39. W. J. Bond, F. I. Woodward, G. F. Midgley, *New Phytol.* **165**, 525 (2005).
40. G. R. van der Werf *et al.*, *Atmos. Chem. Phys.* **6**, 3423 (2006).
41. M. O. Andreae, P. Merlet, *Global Biogeochem. Cycles* **15**, 955 (2001).
42. J. Lehmann *et al.*, *Nat. Geosci.* **1**, 832 (2008).
43. R. L. Langenfelds *et al.*, *Global Biogeochem. Cycles* **16**, 1048 (2002).
44. J. B. Marston, M. Oppenheimer, R. M. Fujita, S. R. Gaffin, *Nature* **349**, 573 (1991).
45. V. Ramanathan, G. Carmichael, *Nat. Geosci.* **1**, 221 (2008).
46. M. O. Andreae *et al.*, *Science* **303**, 1337 (2004).
47. J. T. Randerson *et al.*, *Science* **314**, 1130 (2006).
48. V. K. Arora, G. J. Boer, *J. Geophys. Res. Biogeosci.* **110**, G02008 (2005).
49. L. Giglio, I. Csiszar, C. O. Justice, *J. Geophys. Res. Biogeosci.* **111**, G02016 (2006).
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Supporting Online Material

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SOM Text
Table S1
References

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