Global Change Biology (2005) **11**, 398–420 doi: 10.1111/j.1365-2486.2005.00920.x

Fire history and the global carbon budget: a $1^{\circ} \times 1^{\circ}$ fire history reconstruction for the 20th century

FLORENT MOUILLOT and CHRISTOPHER B. FIELD
Department of Global Ecology, Carnegie Institution of Washington, 260 Panama Street, Stanford, CA 94305, USA

Abstract

A yearly global fire history is a prerequisite for quantifying the contribution of previous fires to the past and present global carbon budget. Vegetation fires can have both direct (combustion) and long-term indirect effects on the carbon cycle. Every fire influences the ecosystem carbon budget for many years, as a consequence of internal reorganization, decomposition of dead biomass, and regrowth. We used a two-step process to estimate these effects. First we synthesized the available data available for the 1980s or 1990s to produce a global fire map. For regions with no data, we developed estimates based on vegetation type and history. Second, we then worked backwards to reconstruct the fire history. This reconstruction was based on published data when available. Where it was not, we extrapolated from land use practices, qualitative reports and local studies, such as tree ring analysis. The resulting product is intended as a first approximation for questions about consequences of historical changes in fire for the global carbon budget. We estimate that an average of 608 Mha yr^{-1} burned (not including agricultural fires) at the end of the 20th century. 86% of this occurred in tropical savannas. Fires in forests with higher carbon stocks consumed 70.7 Mha yr^{-1} at the beginning of the century, mostly in the boreal and temperate forests of the Northern Hemisphere. This decreased to 15.2 Mha yr^{-1} in the 1960s as a consequence of fire suppression policies and the development of efficient fire fighting equipment. Since then, fires in temperate and boreal forests have decreased to 11.2 Mha yr^{-1}. At the same time, burned areas increased exponentially in tropical forests, reaching 54 Mha yr^{-1} in the 1990s, reflecting the use of fire in deforestation for expansion of agriculture. There is some evidence for an increase in area burned in temperate and boreal forests in the closing years of the 20th century.

Keywords: fire history, global change, global fires

Received 4 May 2004; revised version received 30 November 2004 and accepted 15 December 2004

Introduction

With the exception of deserts and sparsely vegetated lands, fires occur in almost all biomes (Mack *et al*., 1996). The development of satellite remote sensing has dramatically enhanced the monitoring of fires at the global level (Kasischke & Penner, 2004), although further developments are still needed to accurately calculate yearly burned areas, especially at the global scale (Boschetti *et al*., 2004). Many models predict fire regimes from an empirical humidity index, plus fuel biomass (Thonicke *et al*., 2001). These approaches contribute little, however, to quantifying burned areas before the start of the satellite era. Ecosystem models that represent fire typically have little or no access to anthropogenically driven changes in fire regimes, including effects of ignition, suppression, and prevention. The models that include anthropogenic factors are mostly quite coarse, estimating area burned and carbon and pollutant emissions (Seiler & Crutzen, 1980), based on the needs of the local population, fire return interval, and agricultural practices. However; only partial data are available before the 1960s (FAO, 2001, Pyne, 2002).

Until recently, studies on global fires aimed to quantify present trace gazes by fuel combustion (Crutzen & Andreae, 1990, Hoelzemann *et al*., 2004, Ito & Penner, 2004, Tansey *et al*., 2004), but analyses of the global carbon budget generally ignored fires (Houghton, 2003). The general assumption was that fires have no net effect on a steady-state world, where

Correspondence: Florent Mouillot, IRD UR 060 CLIFA, CEFE/CNRS, 1919 route de Mende, 34293 Montpellier Cedex 5, France, e-mail: mouillot@cefe.cnrs.fr

losses because of combustion in some places were compensated by gains because of biomass accumulation in others (Crutzen & Andreae, 1990). This steady state view is relevant only if total carbon release from fires is constant over time. If it is not, then fire can generate a carbon source or sink. A trend of increasing combustion through time generates a net source of carbon, while a trend of decreasing combustion causes a sink (Chen *et al*., 2000, Tilman *et al*., 2000). In addition to the direct emissions (Crutzen & Andreae, 1990), fires can also have a long-term indirect effect on the global carbon cycle, as ecosystem responses to past fires can generate both sources and sinks (Field & Fung, 1999). Every fire influences the carbon budget for many years, with effects from, decomposition of killed biomass, regrowth of vegetation, vegetation succession, and equilibration of soil organic matter. A complete assessment of the current and future consequences of fire for the carbon cycle depends on a global map of burned areas over the time scale of the ecosystem responses, up to several centuries for some forest ecosystems. The importance of a long-term perspective for carbon cycle studies is well established for land use. Several efforts have already addressed land use changes since the 18th century (Ramankutty & Foley, 1999, Goldewijk, 2001), mainly by linking cultivation to human population increase.

For recent fires, we have the capacity to observe global fire activity from space at a range of spatial resolutions (Eva & Lambin, 1998a, Dwyer *et al*., 2000, Arino *et al*., 2001, Schultz, 2002, Giglio *et al*., 2003, Kasischke *et al*., 2003, Van der Werf *et al*., 2003, Simon *et al*., 2004). Several sensors have been used for rapid and efficient detection of fires, from the landscape to the global level (Levine, 2000). These sensors use a variety of methods to estimate burned areas, including interpretation of smoke, unusually hot surface temperatures, and fire scars (Eva & Lambin, 1998b).

Historical information on fires is very incomplete. Human population size provides a starting point for accessing fires related to deforestation, but it is less useful for estimating forest fires ignited by other sources or fires in grasslands and shrublands. Through the twentieth century, record keeping on fires gradually improved, but the data are still far from comprehensive. Given the potential importance of changes in fire regime for the current and future carbon budget, we developed a fire history that synthesizes a number of different kinds of historical data, mostly at the country scale. The data are too inconclusive to support a fire reconstruction with high quantitative accuracy, but they are sufficient to support an analysis of broad trends and patterns. In that spirit, we synthesized historical records to produce a realistic spatial and temporal interpretation of global fire history for the twentieth century. Our approach starts by developing an estimate of burned areas for the 1980s, based on fire statistics and global remote sensing studies. We then worked backward in time, reconstructing a historical trend by integrating fire statistics, plus spatial and temporal interpolations and extrapolations. The resulting product is intended to provide a starting point for asking questions about consequences of historical changes in fire for the global carbon budget and the composition of the atmosphere.

Materials and methods

Fire database

Our database of recent fires combines three components. One is the within state or country distribution of recent fires activity, from the Along Track Scanning Radiometer (ATSR) satellite sensor (Arino *et al*., 2001). The second is published fire data, at the national or regional scale. The third is interpolation and smoothing, to minimize the impact of errors from differences in standards and reporting, and to estimate fires for areas without data.

As a source of information on the distribution of fires within states and counties, we used data from the ATSR, a 1 km resolution sensor for environmental monitoring in the visible and infrared wavebands (Arino *et al*., 2001). ATSR has a swath width of 512 km, allowing resampling every 3 days at equator. The satellite cycle is 35 days. The ATSR-2 thermal channel (3.7 μm) is very sensitive to radiation emitted at temperatures from 500 to 1000 K, especially with night-time acquisitions, which are typically used for fire mapping. The use of night-time data complicates the task of mapping high-latitude fires, because the fire season corresponds to the shortest night length (Kasischke *et al*., 2003). Monthly fire products from 1995 to the present are publicly available at http://shark1.esrin.esa.it/ionia. The information in this atlas provides the spatial pattern of fire activity, but not burned area. As a reference year for spatial pattern, we selected for each $1^\circ \times 1^\circ$ pixel, the year with the largest number of fires, from the period 1997–2000. We estimated the fire risk, on a continent-by-continent basis, on pixels that did not burn during 1997–2000, based on the assumption that fire risk declines linearly with distance from a pixel that did burn during this time.

We developed a global estimate of area annually burned from state and national data (Appendix A). We collected all of the available data as they were found in the literature, and rejected the ones with obvious errors in official statistics (Kasischke *et al*., 2000). The data we used are from studies based on a range of methods, including field observations as well as interpretation of aerial photographs and satellite data. The data sources for Appendix A are official statistics (forestry services, fire fighter reports), FAO estimates, and scientific surveys. This uncorrected global estimate has four kinds of limitations. The first is that it provides data for many, but not all, countries. Second, sharp contrasts at regional and national borders suggest differences in source data or interpretation, including remotely sensed data (Fraser *et al*., 2000, Levine, 2000, Garcia-Haro *et al*., 2001). Third, the quality and quantity of fire data drops rapidly as a function of time before present. Before the satellite era, most of the available information is based on aerial photography, field measurements, or fire-fighter reports. Fourth, the fire statistics vary greatly in what they report and how much detail they provide. At a global or regional level, remote sensing studies report all sources of fires without differentiation. Official reports often consider only a subset of the total area burned and may or may not classify fires based on intent (intentional, accidental or natural), land ownership (private or public), or vegetation type (forest or shrubland/grassland).

The best-documented fires in our database are 'Wildfires'. This class includes both 'forest fires' and shrubland/grassland fires – called 'other lands' in the FAO statistics. Fires on other lands are not, however, always included in the statistics. This is particularly the case in boreal and tropical areas, where fires on other lands burn on a regular basis and involve little biomass, which recovers quickly. Unfortunately, the definition of a forest is not entirely consistent among countries and through time. For example, FAO defines an area as forest if it has trees at least 5 m tall with a cover of more than 10%, whereas others use a 30% threshold. 'Prescribed fires' are generally not included in official reports, as they are supposed to be controlled, should not lead to firefighter intervention, and are often used in deforestation or landscape clearing. 'Agricultural fires' (the burning of agricultural wastes, like sugar cane in South America, rice in Asia, or wheat in temperate countries) impact large areas but are not considered in our analysis, because of the combination of limited statistics and their generally nonsignificant impact on the long-term global carbon budget. To compare our fire product with a global fire product, our estimates of burned area would need to be augmented with estimates for prescribed and agricultural fires, perhaps based on land use maps (Goldewijk, 2001).

To address the limitations in the available information, we made two kinds of adjustments to the data. First, for areas with no data, we assumed that the fraction of the area annually burned is equal to that of the nearest area within the same biome for which we have data. This hypothesis was built on analyzing accurate statistics for Europe (temperate vs. Mediterranean), USA, Canada, and Africa. In cases where there were sharp contrasts at borders, we treated these as reflecting differences in reporting, and we assigned the higher value to both sides of the border. The implications of these corrections are detailed in Appendix A.

We compiled data on a yearly basis when available, so we could calculate a standard deviation (SD) for each 10-year interval and represented in Fig. 2.

Historical reconstruction and interpolation

From a representation of burnt areas for the 1980s and 1990s, we built the temporal trend backwards to the beginning of the century, based on the approach developed by Ramankutty and Foley (1999). For regions with fire statistics, we used those.

Some of the regions without quantitative statistics had useful amounts of qualitative information, from a variety of different sources. Much of the qualitative information on fire histories comes from tree-ring reconstructions (Swetnam, 1993, Burrows *et al*., 1995, Kitzberger *et al*., 2001). These provide strong constraints on temporal trends, even though they do not provide information in terms of burned area. Tree-ring reconstructions of fire histories are based on analyses of hundreds of widely distributed fire-scarred trees among a region. Burrows *et al*. (1995), however, point out that scars represent only the effects of the relatively high intensity subset of all fires. Low intensity prescribed fires, for example, may not be recorded as a scar. This method is also useless in case of very high intensity fires that kill every tree or for shrubland/grassland fires. Additional information on fire histories can be obtained from the distribution of stand age in contemporary stands (Kurz *et al*., 1995, Chen *et al*., 2000). We also took qualitative information from historical writings on fire regime or land use. Finally, the trajectory of land use change is an important constraint on fire used in deforestation. The qualitative information was especially useful for estimating whether the prevalence of fire increased or decreased for a given decade and region. The yearly rates of change were deduced either by the difference between burned areas at these two periods when knowing (or deducing) them, or by setting an empirical yearly rate of change compared with other regions with accurate data. Whatever the method used, both rates of changes and deduced burnt areas were compared – and eventually adjusted – to similar biomes and regions having experienced a similar process for an ultimate homogeneity in the database.

For regions without historical fire data, we used the following approach. For large countries without sub-national statistics or information, we scaled historical trends in fire by vegetation type (DeFries & Twonshend, 1994). For countries with no historical data, we assumed that the fire trends in each country were the same as those in nearby countries with comparable social systems and levels of economic development. This approach has been used in land use change reconstruction (Goldewijk, 2001) and is supported by the long-term fire time series available for Europe and North America.

Deforestation

Deforestation is a major contributor to vegetation fires in the tropics. It is usually assumed that the area deforested, quantified with remote sensing or aerial photography, is the same as the area burned. The actual area burned is, however, probably substantially larger. At least two processes contribute to this. First, burning efficiency is so low that burning is typically repeated 3–4 times to clear an area sufficiently for planting (Seiler & Crutzen, 1980). Second, more than half of the areas deforested in the past have been replaced by relatively flammable, savanna-like, abandoned land (Houghton, 1994). In addition, Nepstad *et al.* (1999) conclude that the actual burned area in a tropical forest is at least twice as large as the observed deforested areas. We estimate the burned area B for each year i as half of the cumulative surface deforested until the present (p), divided by r, the fire return interval, plus five times the total amount of area deforested yearly (D)

$$B_p = 0.5 \sum\nolimits_{i=1}^{p} \frac{D_i}{r} + 5D_p. \qquad (1)$$

The second term represents the sum of the burning for deforestation + land burned but not deforested + 3 reburnings. We validated this algorithm against an accurate spatial gradient of burned areas from savannas to tropical forest in Amazonia and then applied it to all tropical forests.

Mapping

Based on the fire statistics on burned areas B (in ha) in each region in each year i, and the area of this region S (ha), the burned fraction F is $F(i) = B(i)/S$. Based on the global data sets based on remote sensing at $1^\circ \times 1^\circ$ resolution (Arino *et al.*, 2001, Giglio *et al.*, 2003), an increase in the burned area of a region is usually correlated with an increase in the number of pixels with fire activity, rather than an increase in the burned area within each pixel. We calculated the probability $P(x, i)$ of a fire in a pixel x in year i with

$$P(x,\ i) = A(x)(1\mathrm{e}^{(-1.5F(y))}), \qquad (2)$$

where $A(x)$ is the ATSR fractional fire activity for a pixel x, calculated as

$$A(x) = \frac{n(x)}{\Sigma_{j=1}^{k} n(j)}, \qquad (3)$$

where $n(x)$ is the number of fires in pixel x from the 1997–2000 ATSR data set, and k is the number of pixels in the entire region. Each pixel x is considered 'fire prone' (x^*) if a random number between 0 and 1 is lower than $P(x, i)$. Effectively, this is a mechanism for capturing the observation that high fire frequency areas remain in the same place over time. For the historical data, we inserted additional year-to-year among-pixel variability in fire locations through introducing $\pm 10\%$ variability in $A(x)$. This did not lead to a regional interannual variability, but a spatial variability in the distribution of fires within these regions.

To generate historical fire maps, we merged the estimate of total burned area B, with the spatial map, distributing the burned area within each region to each pixel (x^*), in proportion to $A(x^*)$, the ATSR fractional fire activity for the selected fire prone pixels (x^*). The final output is a $1^\circ \times 1^\circ$ map of percentage of burned area of each pixel for each year of the 20th century.

Results

The reconstructed historical fire maps present areas burned as 10-year averages from 1900 to 2000 (Fig. 4). Trends in burned area since 1900 for the 14 world regions – based on country boundaries and biomes in Fig. 1 – are in Fig. 2. Burned areas, contributions to the global burned area, and the fire return interval are given in Table 1. We also illustrated in Table 2, the accuracy of the data set and the main causes of fire along the century.

Consistent with Mack *et al.* (1996), we found no reports on fires in deserts (Sahara, Antartica, Greenland), wetlands, or Tundra (Table 1). Fires are generally absent at latitudes poleward of 70°N and 70°S (Fig. 3). They progressively increase towards the tropics and drastically drop at the equator. We estimate that an average 608 million hectares per year ($\mathrm{Mha\,yr^{-1}}$) burned at the end of the 20th century. This has been increasing gradually since the 1950s. Around 86% ($522\,\mathrm{Mha\,yr^{-1}}$, Table 1) of the fires occur in the tropical savannas and grasslands (55.7% in Africa, 15.5% in South America, and 9.5% in Australia, and 6.2% in South Asia for the 1990s). Forest fires represent only 11% of the yearly burned area (9% in the tropics, 1% in the boreal forest, and 0.9% in the temperate forest), but

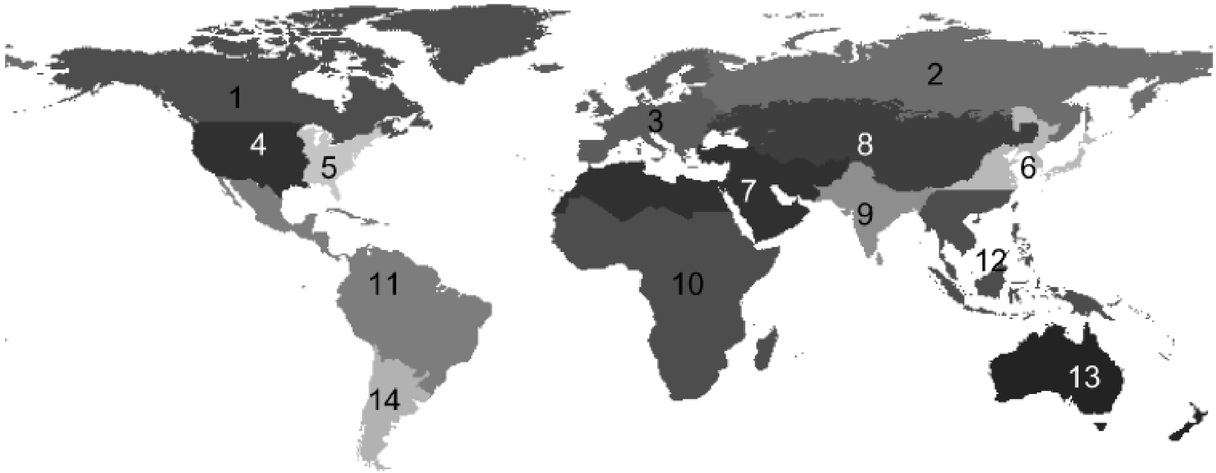

Fig. 1 Map representing the 14 regions of the world chosen to present the fire statistics. They are assumed to be homogeneous according to their political history. The text refers to some internal subdivision according to vegetation types. NB, the boundaries between the regions usually follow country boundaries. We preferred biome boundaries for large countries like Russia and China covering different vegetation types.
1, North America (boreal); 2, Russia (boreal); 3, Europe; 4, USA (west Mississipi); 5, USA (East Mississipi); 6, East Asia; 7, Middle East and Northern Africa; 8, Central Asia; 9, South Asia; 10, Africa (sub-saharian); 11, Central and Northern South-America; 12, South East Asia; 13, Australia/New Zealand; 14, Southern South-America.

involve more biomass. In general, burned area decreased throughout the century at higher latitudes but increased in the tropics. Forest fire in temperate ecosystems burned 70.7 Mha yr^{-1} (13.18%) from 1900 to 1920, mostly in the boreal forest and the temperate forests of the new European settlements. This decreased to 15.2 Mha yr^{-1} (3.06%) in the 1960s as a consequence of fire suppression policies and the development of efficient fire fighting. Since then, fires in temperate forests have continued to decrease, falling 11.2 Mha yr^{-1} by the end of the 20th century. Meanwhile, burned area increased exponentially in tropical forests, reaching 54 Mha yr^{-1} in the 1990s, driven largely by the fire-processed deforestation for the expansion of agriculture. Near the end of the 20th century, there is some evidence of an increase in the burned area of temperate forests (Fig. 2), perhaps reflecting fuel accumulation since the initiation of effective fire prevention in North America and changes in landscape management in Mediterranean Europe.

In the following section, we discuss spatial aspects of these historical patterns.

Fires in the tropics

The tropics cover northern South-America, Africa, India, South-East Asia, and Northern Australia, with a total land area of 4400 Mha. Two main vegetations types (Hansen *et al.*, 2000, IPCC, 2001) are broad leaf evergreen rainforest (1832 Mha, 13.42% of land surface) and wooded grassland savannas (2589 Mha and 18.96%). The savanna biome has the highest fire risk of any zone in the world, combining sufficient primary production to generate substantial amounts of fuel with hot dry periods when the vegetation is highly flammable.

Africa. African savanna (1184 Mha, or 48% of global savannas) is the region with the largest area of recent fires, burning an average of 311 Mha yr^{-1} in the 1980s. Our estimate is the lower estimate from the continental study by Barbosa *et al.* (1999); burned areas could be up to 60% higher.

Within the African savanna, the part in the northern hemisphere combines large areas burned (240 Mha yr^{-1}) and low interannual variability (CV = 16%). The Southern and Eastern regions experience higher variability. Fires burn 70 Mha yr^{-1}, but with interannual variability higher than in the North (CV = 50%). These two regions also have contrasting trajectories of fire history. Since the 1950s, when 95 Mha yr^{-1} burned, fires in the southern and eastern less populated region, particularly in South Africa, Botswana, and Zimbabwe, have tended to decrease, probably as a consequence of fire prevention. The northern region may have experienced a slight increase in fires, perhaps as a result of an increasing human pressure. In this region, the relatively low interannual variability suggests that fires are largely set and controlled by humans as a land management tool, almost independently of climate conditions. The increase in land use by a growing

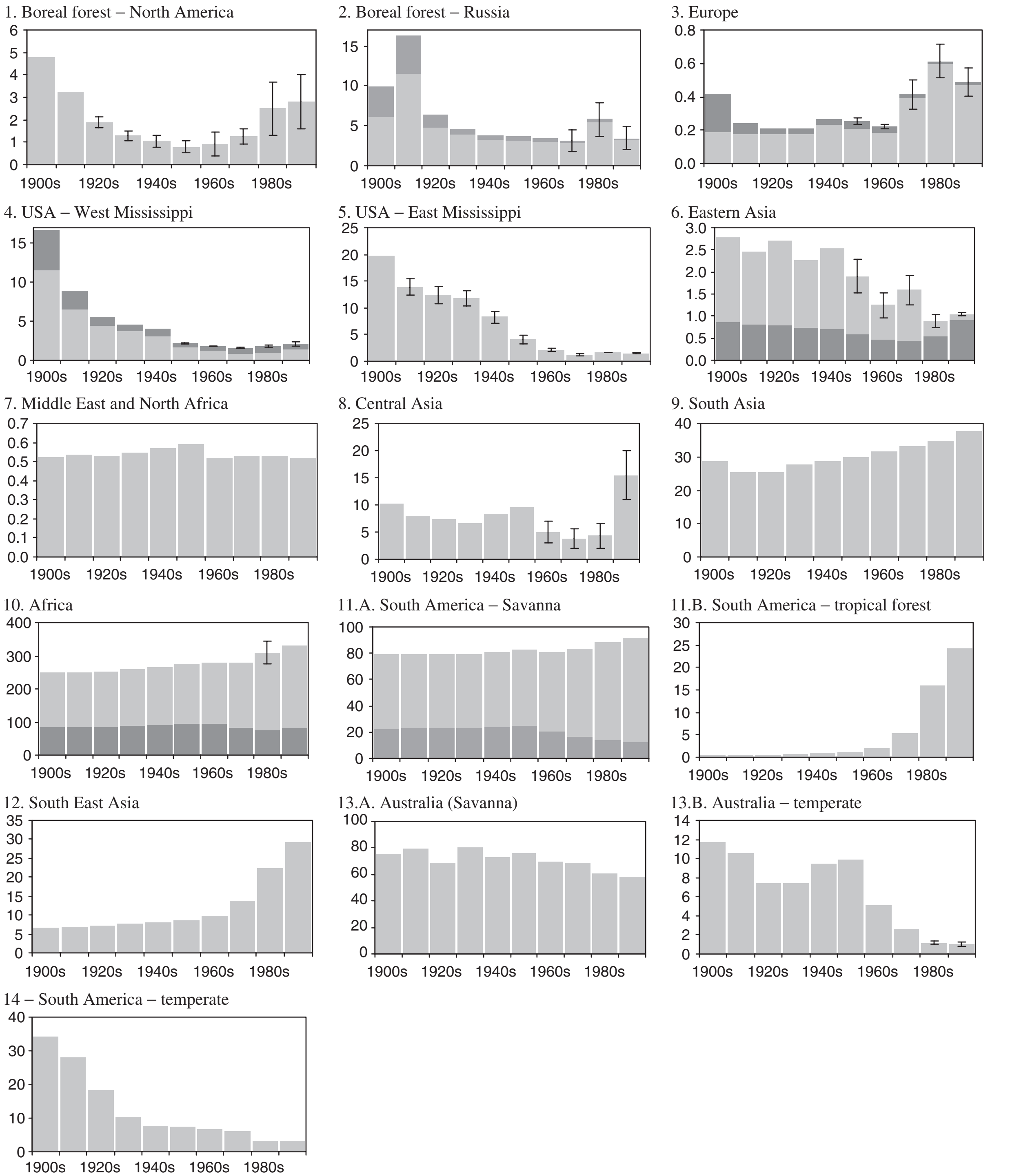

Fig. 2 Temporal trend of burned areas (in Mha), averaged by decades for the 14 regions showed in Fig. 1. Sub-regions have been shown for Europe (Northern Europe in dark grey, Mediterranean Europe light grey), USA west (North light grey, south dark grey), Asia (North Korea dark gray), Africa (southern and eastern, dark gray), South America (coastal brazil, dark gray).

population might have increased the number of ignitions, but may have decreased fire size as a result of landscape fragmentation and lower fuel biomass, leading overall to a slight increase.

Fires in the African tropical forest burned a relatively small area, probably reflecting low to modest human activity. Deforestation occurred mostly in savanna rather than forest (Ramankutty & Foley, 1999). African

Table 1 Surface (S, Mha) and percentage cover (%) of the 14 regions presented in Fig. 1

				1900–1910			1910–1920			1920–1930			1930–1940		
		S	%	B	%	FRI	B	%	FRI	B	%	FRI	B	%	FRI
Boreal forest		1689	11.69	18.6	3.47	91.0	24.3	4.52	69.5	10.0	2.06	169.7	6.5	1.31	259.3
1	N. America	601	4.16	4.8	0.90	124.8	3.2	0.60	185.2	1.9	0.39	316.1	1.3	0.26	467.7
2	Russia	1088	7.53	13.8	2.57	79.1	21.0	3.92	51.7	8.1	1.66	135.1	5.2	1.05	208.1
Temperate forest		789	5.46	51.0	9.54	15.5	49.5	9.22	15.9	29.2	6.03	27.1	26.1	5.24	30.2
3	Europe	265	1.83	0.4	0.08	615.7	0.3	0.05	1054.8	0.2	0.05	1213.5	0.2	0.04	1216.0
4&5	N. America	485	3.36	36.5	6.82	13.3	36.5	6.79	13.3	18.0	3.73	26.9	16.4	3.29	29.6
6	E. Asia	187	1.29	2.8	0.52	67.6	2.4	0.46	76.3	2.7	0.56	69.0	2.3	0.46	82.3
13B	Australia	117	0.81	11.8	2.20	9.9	10.6	1.97	11.1	8.4	1.74	13.9	7.4	1.49	15.8
Temperate grasslands		1699	11.76	26.7	5.00	63.5	21.7	4.03	78.4	10.9	2.26	155.5	11.9	2.38	143.1
7	Middle East	792	5.48	0.5	0.10	1517.6	0.5	0.10	1489.6	0.5	0.11	1500.6	0.5	0.11	1453.0
8	Central Asia	709	4.91	10.2	1.91	69.5	8.1	1.51	87.7	7.3	1.51	97.1	6.6	1.33	107.0
15	S. America	198	1.37	16.0	3.00	12.4	13.0	2.43	15.2	3.1	0.64	63.9	4.7	0.94	42.1
Savanna/Grassland		2589	17.92	431.0	80.61	6.0	433.7	80.78	6.0	425.6	87.98	6.1	445.0	89.34	5.8
9	South Asia	284	1.97	28.7	5.37	9.9	25.3	4.72	11.2	25.4	5.26	11.2	27.7	5.55	10.3
10	Africa	1184	8.19	247.7	46.33	4.8	250.0	46.57	4.7	252.3	52.16	4.7	257.4	51.68	4.6
11A	S. America	666	4.61	78.9	14.76	8.4	79.2	14.75	8.4	79.1	16.35	8.4	79.5	15.96	8.4
13A	Australia	455	3.15	75.6	14.15	6.0	79.2	14.75	5.7	68.8	14.22	6.6	80.4	16.15	5.7
Tropical forest		1832	12.68	7.4	1.38	248.0	7.7	1.44	236.9	8.1	1.67	226.2	8.6	1.73	212.2
10	Africa	520	3.60	0.4	0.07	1468.1	0.4	0.07	1453.4	0.4	0.07	1438.9	0.4	0.07	1411.7
11B	S. America	991	6.86	0.5	0.09	2087.7	0.5	0.09	2029.9	0.5	0.10	2017.6	0.6	0.13	1573.0
12	SE Asia	321	2.22	6.6	1.23	49.0	6.9	1.28	46.6	7.2	1.50	44.3	7.6	1.53	42.1
Never burned areas		5850	40.49	0.0	0.00	na	0.0	0.00	na	0.0	0.00	na	0.0	0.00	na
0	Tundra	950	6.58	0.0	0.00	na	0.0	0.00	na	0.0	0.00	na	0.0	0.00	na
0	Wetlands	350	2.42	0.0	0.00	na	0.0	0.00	na	0.0	0.00	na	0.0	0.00	na
0	Desert	4550	31.49	0.0	0.00	na	0.0	0.00	na	0.0	0.00	na	0.0	0.00	na
TOTAL		14448	100.00	534.7	100.00	–	536.9	100.00	–	483.7	100.00	–	498.1	100.00	–

(Continued)

Table 1. (Contd.)

	1940–1950			1950–1960			1960–1970			1970–1980			1980–1990			1990–2000		
	B	%	FRI	B	%	FRI	B	%	FRI	B	%	FRI	B	%	FRI	B	%	FRI
	5.4	1.08	312.6	4.9	0.94	341.6	4.9	0.98	347.0	4.7	0.94	359.6	8.7	1.57	194.8	6.5	1.07	260.7
1	1.0	0.21	575.1	0.8	0.15	756.9	0.9	0.18	656.8	1.3	0.25	477.4	2.5	0.45	240.5	2.8	0.46	215.4
2	4.4	0.87	249.7	4.1	0.79	262.2	4.0	0.79	275.3	3.4	0.69	316.5	6.2	1.11	176.3	3.7	0.61	295.0
	24.4	4.88	32.4	18.1	3.43	43.6	10.3	2.08	76.4	7.0	1.41	112.1	5.5	0.99	144.2	5.7	0.94	137.9
3	0.3	0.06	958.2	0.3	0.05	1013.4	0.2	0.05	1116.4	0.4	0.09	608.6	0.6	0.11	429.3	0.5	0.08	541.5
4&5	12.3	2.47	39.3	6.3	1.20	76.8	3.9	0.79	123.3	2.9	0.57	169.5	3.4	0.62	140.8	3.6	0.60	134.2
6	2.5	0.51	73.6	1.9	0.36	98.2	1.2	0.25	150.1	1.6	0.32	117.7	0.9	0.16	212.0	1.0	0.17	179.9
13	9.5	1.90	12.3	9.9	1.87	11.8	5.2	1.04	22.7	2.6	0.52	45.2	1.1	0.21	102.2	1.1	0.18	109.4
	12.7	2.54	133.9	13.2	2.50	128.6	8.7	1.75	195.1	7.2	1.44	235.6	8.1	1.47	209.0	19.4	3.20	87.7
7	0.6	0.11	1398.2	0.6	0.10	1437.9	0.5	0.10	1516.0	0.5	0.11	1500.4	0.5	0.10	1498.3	0.5	0.09	1524.3
8	8.5	1.70	83.5	9.6	1.81	74.1	5.1	1.02	139.5	3.8	0.76	186.9	4.3	0.78	163.3	15.5	2.55	45.8
15	3.6	0.73	54.6	3.1	0.59	63.9	3.1	0.62	63.9	2.9	0.58	68.5	3.3	0.59	60.7	3.4	0.56	58.6
	447.8	89.62	5.8	481.8	91.21	5.4	461.8	92.79	5.6	462.3	92.33	5.6	492.7	88.97	5.3	520.1	85.86	5.0
9	28.8	5.76	9.9	29.9	5.67	9.5	31.5	6.32	9.0	33.1	6.60	8.6	34.8	6.29	8.2	37.7	6.23	7.5
10	265.4	53.12	4.5	274.3	51.93	4.3	279.6	56.19	4.2	277.2	55.37	4.3	309.1	55.82	3.8	332.6	54.91	3.6
11	80.8	16.17	8.2	101.0	19.12	6.6	81.3	16.34	8.2	83.2	16.61	8.0	88.4	15.97	7.5	91.9	15.18	7.2
13	72.8	14.57	6.2	76.6	14.50	5.9	69.4	13.94	6.6	68.9	13.75	6.6	60.3	10.89	7.5	57.8	9.55	7.9
	9.4	1.88	195.1	10.1	1.92	180.5	12.0	2.40	153.3	19.5	3.89	94.1	38.8	7.01	47.2	54.1	8.93	33.9
10	0.4	0.08	1369.3	0.4	0.07	1328.2	0.4	0.08	1288.4	0.4	0.08	1224.0	0.5	0.09	1021.4	0.6	0.09	939.0
11	1.0	0.19	1042.5	1.2	0.23	831.4	1.9	0.37	533.2	5.3	1.05	188.8	15.9	2.87	62.3	24.3	4.01	40.8
12	8.1	1.61	39.8	8.6	1.62	37.5	9.7	1.95	33.1	13.8	2.75	23.3	22.4	4.04	14.3	29.2	4.83	11.0
	0.0	0.00	na	0.0	0.00	na	0.0	0.00	na	0.0	0.00	na	0.0	0.00	na	0.0	0.00	na
0	0.0	0.00	na	0.0	0.00	na	0.0	0.00	na	0.0	0.00	na	0.0	0.00	na	0.0	0.00	na
0	0.0	0.00	na	0.0	0.00	na	0.0	0.00	na	0.0	0.00	na	0.0	0.00	na	0.0	0.00	na
0	0.0	0.00	na	0.0	0.00	na	0.0	0.00	na	0.0	0.00	na	0.0	0.00	na	0.0	0.00	na
	499.7	100.00	–	528.2	100.00	–	497.6	100.00	–	500.7	100.0	–	553.8	100.0	–	605.7	100.0	–

The table also shows the average yearly burned area (B, Mha yr^{-1}), by decades, the percentage it represents within the global burned area (%), and the corresponding Fire Return Interval (FRI, in years). Results are presented by region, and summed by biomes.
na, not applicable.

Table 2 Reliability (four classes: 'very poor' (!!), 'poor' (!), 'good' (*) and 'accurate' (**)) and data sources (statistics (S), remote sensing (R), interpolation (I) or extrapolation (X)) of the global fire data set

		1900–1910			1910–1920			1920–1930			1930–1940			1940–1950		
Boreal forest		Reli.	Proc.	Data	Reli.	Proc.	Data	Reli.	Proc.	Data	Reli.	Proc.	Data	Reli.	Proc.	Data
1	N. America	!	N	I	!	N	I	!	N	I	*	N	S	*	N	S
2	Russia	!	N,s	X	!	N,s	X	!	N,s	X	!	N,s	X	!	N,s	X
Temperate forest																
3	Europe	!	Sn	X	!	Sn	X	!	N	X	!	N	I	*	N	Is
4&5	N. America	!!	CN	I	!	CN	Ix	!	CN	I	!	Nc	Is	*	N	Is
6	E. Asia	!!	N	X	!!	N	X	!!	N	X	!!	N	X	!	N	I
13B	Australia	!!	Nd	X	!!	Nd	X	!!	Nd	X	!!	Nd	X	!	N	I
Temperate grasslands																
7	Middle east	!	cn	X	!	cn	X	!	cn	Is	!	cn	Is	!	cn	Is
8	Central asia	!!	Nc	X	!!	Nc	X	!!	Nc	X	!!	Nc	X	!!	Nc	X
15	S. America	!!	CN	X	!!	CN	X	!!	CN	X	!!	CN	X	!!	CN	X
Savanna/Grassland																
9	South Asia	!!	CN	X	!!	CN	X	!!	CN	X	!!	CN	X	!!	CN	CN
10	Africa	!!	CN	X	!!	CN	X	!!	CN	X	!!	Cn	X	!!	Cn	X
11A	S. America	!!	CN	X	!!	CN	X	!!	CN	X	!!	CN	X	!!	CN	X
13A	Australia	!!	CN	X	!!	CN	X	!!	CN	X	!!	CN	X	!!	CN	X
Tropical forest																
10	Africa	*	Sn	I	*	Sn	I	*	Sn	I	*	Sn	I	*	Sn	I
11B	S. America	*	n	I	*	n	I	*	n	I	*	n	I	*	n	I
12	SE Asia	!	Sn	X	!	Sn	X	!	Sn	X	!	Sn	X	!	Sn	X

		1950–1960			1960–1970			1970–1980			1980–1990			1990–2000		
Boreal forest		Reli.	Proc.	Data	Reli.	Proc.	Data	Reli.	Proc.	Data	Reli.	Proc.	Data	Reli.	Proc.	Data
1	N. America	*	N	S	**	N	S	**	N	S	**	N	S	**	N	S
2	Russia	*	N	S	*	N	S	*	N	S	**	N	RS	*	N	S
Temperate forest																
3	Europe	*	N	S	**	N	S	**	N	S	**	N	S	**	N	S
4&5	N. America	*	N	SI	**	N	S	**	N	S	**	N	S	**	N	S
6	E. Asia	*	N	S	*	N	S	*	N	S	*	N	S	*	N	S
13B	Australia	*	N	S	*	N	S	**	N	S	**	N	S	**	N	S
Temperate grasslands																
7	Middle east	!	cn	Is	!	cn	Is	!	cn	Is	*	cn	Si	*	cn	Si
8	Central asia	!	CN	Ix	*	Nc	Si	*	Nc	Si	*	Nc	Si	*	Nc	Si
15	S. America	!!	Cn	X	!	Nc	I	!	Nc	Is	*	Nc	Si	*	Nc	Si
Savanna/Grassland																
9	South Asia	!!	CN	X	!!	CN	X	!!	CN	I	!	CN	Si	!	CN	Si
10	Africa	!!	Cn	X	!	Cn	X	*	Cn	I	**	Cn	R	*	Cn	I
11A	S. America	!!	Cn	X	!!	Cn	X	!!	Cn	X	*	Cn	I	*	Cn	I
13A	Australia	!!	Cn	X	!	Cn	X	!	Cn	X	*	Cn	X	**	Cn	RS
Tropical forest																
10	Africa	*	Sn	I	*	Sn	I	*	SD	I	*	DS	I	*	DS	I
11B	S. America	*	n	I	*	Dn	I	*	DC	I	*	DC	I	*	DC	I
12	SE Asia	!	Sn	X	!	Sn	X	!	SD	X	!	DS	X	*	DS	I

Fires are classified according to their causes along the century: Natural fires (N) are either accidental or caused by lightings or other natural sources; 'deforestation' (D) is used for direct (burning of the forest itself) or indirect (reburning, or secondary forest burning) effects of forest clearing on the fire regime. 'Clearing' (C) is used for recurrent fires affecting vegetation for grazing or fuel reduction (hunting, fire prevention. . .). 'shifting cultivation' (S) is used for fires affecting regrowing forests on abandoned cultivations where farmers moved to another place when the land became exhausted. We used capital letters for the dominant processes.

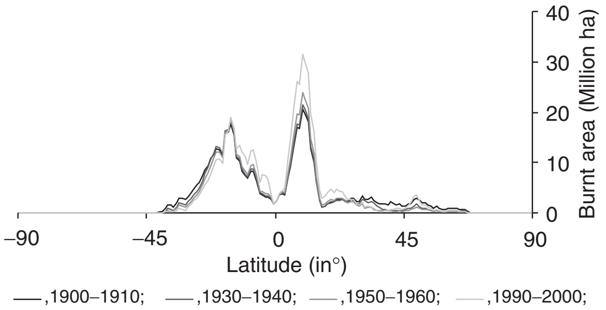

Fig. 3 Latitudinal distribution of burnt areas for the periods 1900–1910, 1930–1940, 1960–1970, and 1990–2000.

tropical forest covers mainly Zaire, which experienced a 1.2% increase in burned areas per year, over the last half of the century.

South and Central America. Savannas in South America cover an area of 380 Mha, mainly in the eastern part of Brazil, most of Bolivia, northern Mexico, Paraguay, and Venezuela. They are subjected to frequent fires despite lower human pressure than African savannas. 125 Mha burned annually in South American savannas in the 1980s. In this ecosystem type, fires are extensively used in landscape clearing for cattle grazing. Since the 1960s, fires have increased dramatically in the Brazilian Cerrado as a result of deforestation and agricultural development of the central plateau. In contrast, burning has decreased along the Brazilian coastline since the 1970s, reflecting the pattern of long-standing human settlement and a recent switch to permanent agriculture. Fires have also decreased in northern Mexico, a consequence of fire prevention in connection with permanent agriculture.

Over the last century, fires have increased dramatically in the forested parts of South America, a series of landscapes in which fires are an infrequent element of the natural disturbance regime. Deforestation contributed to this increase in two ways, both through its direct use in clearing land and also through replacing the existing vegetation with a more flammable grassland/shrubland community. Fires were essentially absent from the Amazon Basin before the 1960s but became significant between 1975 and 1980, when deforestation doubled from the rate in the 1960s. Burning rapidly increased in the 1980s, reaching 18 Mha yr^{-1}, particularly in the 'arc of deforestation' along the south-eastern edge of the Amazon Basin and Bolivia (sensu Cochrane *et al.*, 1999). In Mexico and Central America, which cover a smaller area, deforestation began earlier, in the 1930s, when population growth and changes in agricultural policies increased the pressure for agricultural land. The rate of deforestation reached 7 Mha yr^{-1} in the 1990s.

In the absence of published data, we estimated burned areas in South and Central America from deforested area based on the algorithm described in Eqns (1)–(3). This approach produced a reasonable transition between the forest and savanna biomes for the 1980s and 1990s and indicating that the interpolation method might be satisfactory for application throughout the tropics.

South Asia. South Asia covers an area of 400 Mha, with grasslands and savannas as the dominant biomes. South Asia, with a dense population, has a long-standing history of fire use for landscape clearing and shifting cultivation. Fires are common, burning 35 Mha yr^{-1} in the savanna/grassland regions, and 3 Mha yr^{-1} in the forest. Based on the ATSR 'hot spots' used in this study, vegetation fires in India are relatively evenly distributed, but with less activity in the Ganges floodplain, with its dense cultivation and human habitation. The conclusion that fires are less frequent in the Ganges floodplain than in surrounding regions contrasts with the pattern in TRMM satellite data (Van der Werf *et al.*, 2003). This discrepancy highlights the challenge in using global products based on different sensors. Much of the contrast between the two estimates may be a consequence of the sensitivity of the TRMM data set to low intensity agricultural fires that do not register as fires in the night-time ATSR data set. The temporal trajectory of burned areas decreased slightly from 1900 to the 1920s as a result of forest conservation policies of colonial governments. Burned areas then returned to the levels of 1900 and continued to increase in response to population growth and an increase in shifting cultivators (Pyne, 1994).

Australia. Almost all vegetation types in Australia are fire prone, with the exception of North Queensland's tropical rainforest (Pyne, 1991). The climate of Australia is characterized by extreme year-to-year variability, so that even the arid interior can carry extensive fires following wet years, which favor the development of continuous fuels (Dixon *et al.*, 1996). Average fire return intervals range from 2 to 3 years in northern Australia to 10 years in drier central Australia, with some of the control reflecting aboriginal burning practices.

The current fire frequency in Central and Northern Australia (total area = 455 Mha) is typical of that for tropical regions. Low population density, the maintenance of some aboriginal fire practices, and the absence of significant changes in land use led to a temporal trajectory of only slight decreases in the burned areas dropping from 66 to 58 Mha yr^{-1} over the last several decades. Human intervention to protect grazing areas probably contributed to this decrease. The southern part of Australia, covered by temperate forest, will be discussed further.

South-east Asia. Savannas, characterized by a high fire frequency, cover a small portion of South-east Asia. Most of the demand from a growing population for increased agricultural land has led to deforestation of tropical forest (Hao & Liu, 1994, Ramankutty & Foley, 1999). Early in the century; fires burned 10 Mha yr^{-1}, mostly in the savannas. Burning increased rapidly in the 1970s as a result of forest clearing and the conversion of forest into more flammable savanna vegetation, reach 38 Mha yr^{-1} in the 1990s. During extreme climate anomalies such as El Nino years (82–83 or 97–98), fires tend to be much more widespread in tropical forest, leading to high interannual variability.

Fires in Central Asia and the Middle East

Grassland steppes cover 709 Mha in central Asia, including parts of Ukraine, Kazakhstan, Mongolia, Northern China, and Southern Russia. These regions are very fire-prone, a consequence of a strong summer drought and use for extensive grazing. In the 1990s, burned areas increased from 3.79 to 15.5 Mha yr^{-1} because of decreased investments in fire management following the dissolution of the USSR. Earlier in the century, fires burned an average 7 Mha yr^{-1}, peaking at 10 Mha yr^{-1} in the 1950s during a period of cropland expansion in which 100 Mha were cleared in 10 years (Ramankutty & Foley, 1999).

The drier, sparser steppes of the Middle-East experience a very low fire occurrence with only 0.5 Mha yr^{-1} (0.1%) burning annually. Most of this is distributed along the Mediterranean coast and around irrigated valleys. This value was stable throughout the 20th century, with very few changes in land use practices in this region.

Boreal forests

Boreal forest covers 600 Mha in North America and 1088 Mha in Eurasia. This biome is not heavily exploited by humans, and climate is still the principal driver of fire in this biome in both Canada and Russia (Flannigan *et al.*, 1998). Although 60% of ignitions are anthropogenic, most or the large fires are natural (Eastwood *et al.*, 1998). The development of fire fighting technologies played a key role in limiting wild fires during the 20th century. In Canada, fires burned 5 Mha yr^{-1} at the beginning of the century but no more than 0.8 Mha yr^{-1} in the 1950s. This increased to an average of 2.8 Mha yr^{-1} during the 1990s, with a high interannual variability (SD = 2.4 Mha). Fires in Canada occur mostly in the mid-latitudes, South of the tundra and North of the temperate broadleaf forest, with some variation from province to province.

In Russia, burning decreased from 6.8 Mha yr^{-1} at the beginning of the century to 3.1 Mha yr^{-1} in the 1970s. This was the consequence of active fire suppression, beginning in the 1920s, improved fire prevention methods in the Far East, and abandonment of the shifting cultivation in western-Russia. Large fire events are associated with drought (Ivanova, 1998). During the most extreme fire year of the century (1915), fires burned 181 Mha. Only 14 Mha of these, however, were crown fires. Surface fires dominate the fire regime in Russia, a major contrast with the crown fires that are most common in Canada. Burned area has increased since the 1980s, probably a reflection of decreased funding for fire fighters. Fires occur mainly in the southern part of Far East Russia, within the taiga forest at the border with China and Mongolia.

Forests in Scandinavian countries are generally highly accessible and intensively managed. As a result, large forest fires are almost completely absent. Total burned area currently averages 0.0025 Mha yr^{-1} (Stocks, 1996). At the beginning of the 20th century, fires in the Scandinavian countries burned 0.2 Mha yr^{-1}, mainly in association with swidden agriculture (shifting cultivation) (Parviainen, 1996).

Temperate forest

The temperate zone includes most of the 'developed' countries, where human activities, especially fire prevention, dramatically modified natural fire regimes throughout the 20th century. The fire regime in this region is far from natural control by fuel biomass and climate. Instead, the abundance and distribution of fires is strongly influenced by factors like population density, landscape pattern, prescribed fire, and fire prevention policies. All of these changed dramatically between 1900 and 2000, particularly in regions where human settlement is relatively recent.

Europe. Burned area in Europe is negligible, currently about 0.62 Mha yr^{-1} (0.11%), in comparison with that of other continents (FAO, 1999). As a result of a long history of permanent agriculture, a high population and land use density, and rainfall evenly distributed throughout the year, fires have never been important in northern Europe. Burned area was 0.02 Mha yr^{-1} in 1900 and fell gradually to the current pattern of total fire exclusion. Southern Europe (Albania, Italy, France, Greece, Portugal, Spain, and the former Yugoslavia) has a significant dry season, making it much more fire-prone. Despite increased investments in fire prevention, fires in southern Europe increased from 0.2 Mha yr^{-1} in the 1960s to more than 0.6 Mha in the 1980s. It is unlikely that climate was responsible for this change, as the neighboring middle-eastern countries have not followed the same trend, despite being in the similar climatic areas. Much of the increase is a result of the relatively recent establishment of forest and shrubland on abandoned land, reflecting changes in agricultural policy (Moreira *et al*., 2001, Mouillot *et al*., 2003) and rural population, which in Mediterranean countries decreased from 22.5 million in 1980, to 12 million in 1996.

USA. The fire regime in the United States changed significantly in the 20th century (Pyne, 1982). As statistics were available by states, we did not use vegetation types for the US but considered two large regions. West of the Mississippi River, the conservative estimate is that fire in 1900 burned about 14 Mha yr^{-1}, mostly in the forests of the Rocky mountains (North) and grasslands of the Great Plains (South and East) (Fig. 4). Forests of the Rocky Mountains experienced recurrent ground fires. Fire prevention became a significant factor at different times in different parts of the country. Its effects were relatively by the late 19th century in the Northeastern US, ca. 1930 in the Southeast, and ca. 1910 in the West. Fire prevention was so successful that in the South East, only 1.29 Mha yr^{-1} burned in the 1970s. The area was 1.3 Mha in the West, with an additional 3 Mha yr^{-1} in the agricultural landscapes (Leenhouts, 1998). Since the 1970, fires have tended to increase in the West, especially in the Rocky Mountains. This may be a consequence of fuel accumulation during 40 years of continuous fire prevention.

Australia. Wild fires in Australia burned between 0.053 and 1.061 Mha yr^{-1} of temperate forest over the period 1956–1996. This is a decrease from earlier areas and also a negligible part of total Australian fires, which are mostly on savannas. Managed burning has a long history in Australia. Prior to the consolidation of European traditions, aboriginal burning in much of the country was probably similar to that the aboriginals currently practice in North Australia (Cheney, 1995). Aboriginals in Australia managed a sophisticated fire regime, burning areas only at times when fires did little damage. European settlement led to a change in the fire regime over much of the country. In Southwestern Australia, light annual burnings were replaced by

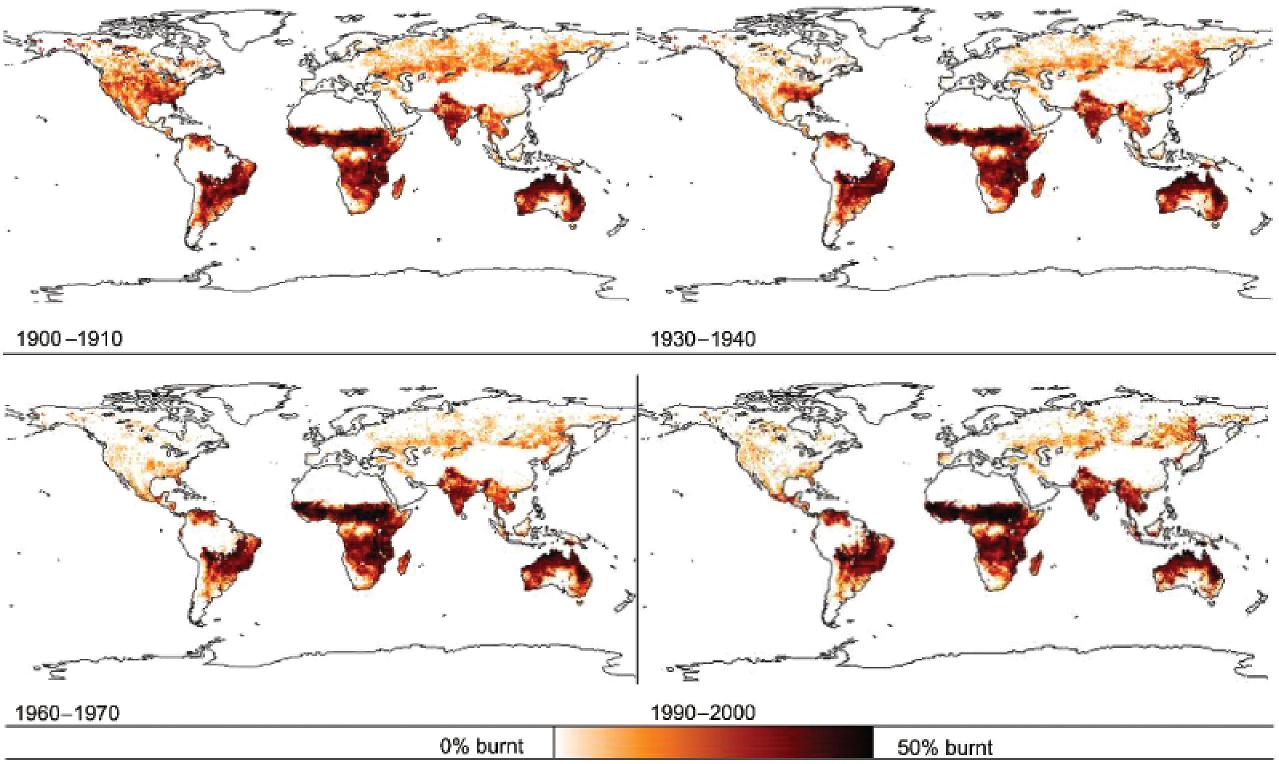

Fig. 4 $1^{\circ} \times 1^{\circ}$ maps of burned area (% of cell burned) for the periods 1900–1910, 1930–1940, 1960–1970, and 1990–2000.

larger fires every 3–4 years. Widespread fire, burning about 12 Mha yr^{-1} persisted until 1920 or as long as it was widely used for clearing bush. After 1920, the policy switched to 'complete protection' or 'fire exclusion', decreasing the burned area to an average 7 Mha yr^{-1} in the 1930. This change in policy induced a rapid recovery of understory vegetation, leading to an increase in major fires and an increase in area burned to 10 Mha yr^{-1} in the 1940s. Despite extensive policies to diminish the dangers from bushfires, major changes occurred only in the 1950s. Since then, burning for grazing has continued to decrease.

South America. Fires in Argentina and Chile burned an average 3.5 Mha yr^{-1} in the 1990s, mostly in the Northern savannas and grasslands that cover most of the region. This fire regime was relatively stable throughout the 20th century, with continuing landscape clearing for cattle grazing. Fire prevention began in Argentina between the 1910s and the 1930s. At that time, 23 Mha yr^{-1} burned.

Eastern Asia. Fire is relatively uncommon in East Asia, a region characterized by a high population density, as well as extensive agriculture and grasslands. Forests cover a limited portion of the area, mainly in Northern China, and North Korea. Fires burned an average of 0.8 Mha yr^{-1} in the 1980s, with 0.35 Mha yr^{-1} in China, and 0.55 Mha yr^{-1} in North Korea. Earlier in the century, burned area were larger, reaching 2 Mha yr^{-1} in China, and 0.8 Mha yr^{-1} in the other countries of the region. Japan and South Korea experienced decreases in burned area from fire prevention, parallel the case in the other developed countries. Fires increased in North Korea in the 1990s (1 Mha yr^{-1}), probably as a consequence of decreased investments in fire fighting expenditures.

Conclusion

The global fire history discussed here is based on yearly statistics, plus interpretation of qualitative data, interpolation, and extrapolation. The resulting product should be viewed as a spatially explicit best guess, subject to a number of caveats and uncertainties. We managed to present a critical overview of the data available at this time, identified the major caveats, and offered a best guess of the global fire history, in a spatially explicit manner.

These results highlight the large contribution of grassland and savanna fires to the global total, representing more than 86%. In forested regions, fires in the early decades of the 20th century were concentrated in the temperate latitudes. Since the 1970s the center of forest fire activity has switched to the tropics, with continuing pressure from deforestation.

The task of translating burned areas into global carbon budgets is fraught with challenges. These range from uncertainty about vegetation types to challenges in estimating combustion factors. This database must be coupled with vegetation type maps to know how much biomass is affected, and how much of this biomass is actually combusted and emitted in the atmosphere. Still, this database should be a useful tool for estimating the effects of fire on the 20th century carbon budget. Useful estimates will include not only the carbon emitted to the atmosphere during fire events, but also the carbon dynamics reflecting decomposition and regrowth, as well as potential combustion in future fires. This kind of long-term analysis of fires and their consequences is only beginning to appear in carbon balance studies. Future challenges include improving both the estimates of burned area and fire intensity.

References

Achard F, Eva HD, Stibig HJ *et al.* (2002) Determination of deforestation rates of the world's humid tropical forests. *Science*, **297**, 885–1080.

Adamoli J, Sennhauser E, Acero JM *et al.* (1990) Stress and disturbance: vegetation dynamics in the dry Chaco region of Argentina. *Journal of Biogeography*, **1990**, 491–500.

Arino O, Simon M, Piccolini I *et al.* (2001) *The ERS-2 ATSR-2 world fire atlas and the ERS-2 ATSR-2 world burnt surface atlas project*. Eighth ISPRS Conference on Physical Measurements and Signatures in Remote Sensing, Aussois, France.

Arkhipov VA, Goldammer JG, Khaidarov KA *et al.* (2000) Overview on forest fires in Kazakhstan. *International Forest Fire News*, **24**, 43–48.

Barber CV, Schweithelm J (2000) *Forest Fires and Forestry Policy in Indonesia's Era of Crisis and Reform*. World Resources Institute, Washington DC, USA. 84pp.

Barbosa PM, Stroppiana D, Gregoire JM (1999) An assessment of vegetation fire in Africa (1981–1991): burned areas, burned biomass, and atmospheric emissions. *Global Biogeochemical Cycles*, **13**, 933–950.

Barney RJ (1971) Wildfires in Alaska-some historical and projected effects and aspects. In: *Fire in the Northern Environment – A symposium* (eds Slaughter CW, Barney RS, Hansen GM), pp. 51–57. USDA Forest Service, Fairbanks, Alaska.

Barrett SW, Arno SF, Menakis JP (1997) *Fire Episode in the Inland Northwest (1540–1940) Based on Fire History Data*. USDA Forest Service, Gen.Tech.Rept.INT-GTR-370, intermountain research station, Ogden, UT, USA. 17pp.

Barton AM (2002) Intense wildfire in southeastern Arizona: transformation of a Madrean Oak-Pine forest to Oak woodland. *Forest Ecology and Management*, **165**, 205–212.

Boschetti L, Eva HD, Brivio PA *et al*. (2004) Lessons to be learned from the comparison of three satellite-derived biomass burning products. *Geophysical Research Letters*, **31**, 501.

Bran D, Lopez C, Ayesa J *et al*. (2001) *Evaluacion de areas afectadas por incendios de campos en el verano 2000/01 en el noreste Rionegro (Argentina) – In Spanish*. INTA, Bariloche, Argentina.

Bravo S, Kunst C, Gimenez A *et al*. (2001) Fire regime of a Elionorus muticus Spreng. Savanna, Western Chaco region, Argentina. *International Journal of Wildland Fire*, **10**, 65–72.

Brown PJ, Manders PT, Bands DP (1991a) Prescribed burning as a conservation management practice: a case history from the Cederberg Mountains, Cape Province, South Africa. *Biological Conservation*, **56**, 133–150.

Brown PM, Ryan MG, Andrews TG (2000) Historical surface fire frequency in Ponderosa pine stands in research natural areas, central Rocky Mountains and Black Hills, USA. *Natural Areas Journal*, **20**, 133–139.

Brown S, Gillespie AJR, Lugo AE (1991b) Biomass of tropical forests of south and south east Asia. *Canadian Journal of Forest Science*, **21**, 111–117.

Burrows ND, Ward BG, Robinson AD (1995) Jarrah forest fire history from stem analysis and anthropological evidence. *Australian Forestry*, **58**, 7–16.

Burrows WH, Henry BK, Back PV *et al*. (2002) Growth and carbon stock change in Eucalyptus woodlands in North-eastern Australia: ecological and greenhouse sink applications. *Global Change Biology*, **8**, 769–784.

Cahoon DRJ, Stocks BJ, Levine JS *et al*. (1994) Satellite analysis of the severe 1987 forest fires in northern China and southern Siberia. *Journal of Geophysical Research*, **99**, 627–638.

Chen J, Chen W, Liu J *et al*. (2000) Annual carbon balance of Canada's forests during 1895–1996. *Global Biochemical Cycles*, **14**, 839–849.

Cheney NP (1995) Bushfires – An integral part of Australia's environment. Year Book Australia. ABS catalogue No 1301.0.

Clark JS (1988) Stratigraphic charcoal analysis on petrographic thin sections: application to fire history in Northwestern Minnesota. *Quaternary Research*, **30**, 81–91.

Cochrane MA (2002) Spreading like wildfire: tropical forest fires in Latin America and the Caribbean, prevention, assessment and early warning. UNEP (web.rolac.unep.mx/dewalac/eng/fire_ingles.pdf).

Cochrane MA, Alencar A, Schulze MD *et al*. (1999) Positive feedbacks in the fire dynamic of closed canopy tropical forests. *Science*, **284**, 1832–1835.

Cochrane MA, Laurance WF (2002) Fire as a large scale edge effect in Amazonian forests. *Journal of Tropical Ecology*, **18**, 311–325.

Conard SG, Ivanova GA (1997) Wildfire in Russian boreal forests – potential impacts of fire regime characteristics on emissions and global carbon balance estimates. *Environmental Pollution*, **98**, 305–313.

Crutzen PJ, Andreae MO (1990) Biomass burning in the tropics: impact on atmospheric chemistry and biogeochemical cycles. *Science*, **250**, 1669–1677.

DeFries RS, Twonshend JRG (1994) NDVI-derived land cover classification at global scales. *International Journal of Remote Sensing*, **15**, 3567–3586.

Delmas RA, Loudjani P, Podaire A, Menaut JC (1996) Biomass burning in Africa: an assessment of annually burned biomass. In: *Global Biomass Burning. Atmospheric, Climatic and Biospheric Implications* (ed. Levine JS), pp. 127–132. The MIT press, Cambridge, MA, USA.

Dixon B, Bouma W, Cheng P, LeCornu J, Morgan P, Wilson S (1996) The Atmosphere. In *Australia: the State of the Environment 1996*. Taylor R (Ed.), CSIRO Publishing, Collingwood, Australia.

Dixon RK, Krankina ON (1993) Forest fires in Russia: carbon dioxide emissions to the atmosphere. *Canadian Journal of Forest Research*, **23**, 700–705.

Donnegan JA, Veblen TT, Sibold JS (2001) Climatic and human influences on fire history in Pike National Forest, central Colorado. *Canadian Journal of Forest Research*, **31**, 1526–1539.

Dwyer E, Pinnock S, Gregoire JM *et al*. (2000) Global spatial and temporal distribution of vegetation fire as determined from satellite observations. *International Journal of Remote Sensing*, **21**, 1289–1302.

Eastwood JA, Plummer SE, Wyatt BK (1998) The potential of SPOT – Vegetation data for fire scar detection in boreal forests. *International Journal of Remote Sensing*, **19**, 3681–3687.

Elvdige CD, Baugh KE (1996) Survey of fires in Southeast Asia and India during 1987. In: *Global Biomass Burning. Atmospheric, Climatic and Biospheric Implications* (ed. Levine J.S.), pp. 663–670. The MIT Press, Cambridge, MA, USA.

Eva H, Lambin EF (1998a) Burnt area mapping in Central Africa using ATSR data. *International Journal of Remote Sensing*, **19**, 3473–3497.

Eva H, Lambin EF (1998b) Remote sensing of biomass burning in tropical regions – sampling issues and multisensor approach. *Remote Sensing of Environment*, **64**, 292–315.

FAO (1999) Forest fire statistics: 1996–1998. *Timber Bulletin*, **52**, 1–19.

FAO (2001) Global forest fire assessment, 1990–2000, Rome.

Fearnside PM (1993) Deforestation in Brazilian Amazonia: the effect of population and land tenure. *Ambio*, **22**, 537–545.

Field CB, Fung IY (1999) The not-so-big US carbon sink. *Science*, **285**, 544–545.

Flannigan M, Bergeron Y, Engelmark O *et al*. (1998) Future wildfire in circumboreal forests in relation to global warming. *Journal of Vegetation Science*, **9**, 469–476.

Fox J (2002) Land use and land cover changes in Montane mainland southeast Asia. www-cger.nies.jp/LUGEC/proceedings/13)jefferson%20fox.pdf.

Fraser RH, Li Z, Cihlar J (2000) Hotspot and NDVI differencing synergy (HANDS): a new technique for burned area mapping over boreal forest. *Remote Sensing of Environment*, **74**, 362–376.

Fule PZ, Covington WW (1996) Changing fire regimes in Mexican pine forests. *Journal of Forestry*, **94**, 33–38.

Garcia-Haro FJ, Gilabert MA, Melia J (2001) Monitoring fire-affected areas using Thematic Mapper data. *International Journal of Remote Sensing*, **22**, 533–549.

GBA (2000) Global Burnt Area. (http://www.grid.unep.ch/activities/earlywarning/preview/ims/gba/).

Giglio L, Kendall JD, Mack R (2003) A multi-year active fire dataset for the tropics derived from the TRMM VIRS. *International Journal of Remote Sensing*, **24**, 4505–4525.

Gill AM, Moore PHR, McCarthy MA *et al*. (1997) *Contemporary Fire Regimes in the Forests of Southwestern Australia*. CSIRO, Australia Environment, Canberra.

Goldammer JG, Furyaev VV (1996) Fire in ecosystems of boreal Eurasia: ecological impacts and links to the global system. In: *Fire in Ecosystems of Boreal Eurasia* (eds Goldammer JG, Furyaev VV), pp. 1–20. Kluwer Academic Publishers, Dordrecht, the Netherlands.

Goldammer JG, Stocks BJ (1999) Eurasian perspective of fire: dimension, management, policies, and scientific requirements. In: *Fire, Climate Change and Carbon Cycling in the Boreal Forest*. Kasischke ES, Stocks BJ. (Eds.), Ecological studies 138. Springer-Verlag, Berlin, Germany, 49–65 pp.

Goldewijk KK (2001) Estimating global land use change over the 300 years: the HYDE Database. *Global Biogeochemical Cycles*, **15**, 417–433.

Hansen MC, DeFries RS, Townshend JRG *et al*. (2000) Global land cover classification at 1km spatial resolution using a classification tree approach. *International Journal of Remote Sensing*, **21**, 1331–1364.

Hao WM, Liu M-H (1994) Spatial and temporal distribution of tropical biomass burning. *Global Biogeochemical Cycles*, **8**, 495–503.

Haripriya GS (2003) Carbon budget of the Indian forest ecosystem. *Climatic Change*, **56**, 291–319.

Hoelzemann JJ, Schultz MG, Brasseur GP *et al*. (2004) Global Wildland Fire Emission Model (GWEM): evaluating the use of global area burnt satellite data. *Journal of Geophysical Research-Atmospheres*, **109** D14 S04.

Houghton RA (1994) The worldwide extent of land-use change. *Bioscience*, **44**, 305–313.

Houghton RA (1996) Biomass burning from the perspective of the Global Carbon Cycle. In: *Global Biomass Burning, Atmospheric, Climatic and Biospheric Implications* (ed. Levine JS), pp. 321–325. The MIT press, Cambridge, MA, USA.

Houghton RA (2003) Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management. *Tellus*, **55B**, 378–390.

Houghton RA, Skole DL, Nobre CA *et al*. (2000) Annual fluxes of Carbon from deforestation and regrowth in the Brazilian Amazon. *Nature*, **403**, 301–304.

Hudak AT, Wessman CA (2001) Textural analysis of high resolution imagery to quantify bush encroachment in Madikwe Game reserve, South Africa, 1955–1996. *International Journal of Remote Sensing*, **22**, 2731–2740.

Hurtt GC, Pacala SW, Moorcroft PR *et al*. (2002) Projecting the future if the US carbon sink. *Proceedings of the National Academy of Sciences of the United States of America*, **99**, 1389–1394.

IPCC (2001) Climate Change 2001: the scientific basis. eds Houghton JT, Ding Y, Griggs DJ, Noguer M, Van Der Linden PJ *et al*.), Cambridge University Press, Cambridge.

IFFN: International Forest Fire News. Online publications from the ‘FIRE GLOBE: global fire monitoring center’ http://www.fire.uni-freiburg.de/iffn/iffn.htm

Ishikawa Y, Krestov PV, Namikawa K (1999) Disturbance history and tree establishment in old-growth *Pinus koraiensis*-hardwood forests in the Russian far East. *Journal of Vegetation Science*, **10**, 439–448.

Ito A, Penner JE (2004) Global estimates of biomass burning emissions based on satellite imagery for the year 2000. *Journal of Geophysical Research-Atmospheres*, **109** D14 S05.

Ivanova GA (1998) The history of forest fire in Russia. *Dendrochronologia*, **16–17**, 147–161.

Joshi V (1991) Biomass burning in India. In: *Global Biomass Burning. Atmospheric, Climatic, and Biospheric Implications* (ed. Levine JS), pp. 185–193. The MIT press, Cambridge, MA, USA.

Kasischke ES, Christensen Jr. NL, Stocks BJ (1995) Fire, global warming, and the carbon balance of boreal forests. *Ecological Applications*, **5**, 437–451.

Kasischke ES, Hewson JH, Stocks B *et al*. (2003) The use of ATSR active fire counts for estimating relative patterns of biomass burning-a study from the boreal forest region. *Geophysical Research Letters*, **30**, 1969.

Kasischke ES, Penner JE (2004) Improving global estimates of atmospheric emissions from biomass burning. *Journal of Geophysical Research-Atmospheres*, **109**, 1–2.

Kasischke ES, Stocks BJ, O’Neil K *et al*. (2000) Direct effects of fire on the boreal forest carbon budget. In: *Biomass Burning and its Inter-relations with the Climate System* (eds Innes JL, Beniston M, Verstraete MM), pp. 51–68. Kluwer Academic Publishers, Dordrecht, the Netherlands.

Kipfmueller KK, Baker WL (2000) A fire history of a subalpine forest in South-Eastern Wyoming, USA. *Journal of Biogeography*, **27**, 71–85.

Kitzberger T, Swetnam TW, Veblen TT (2001) Inter-Hemispheric synchronic of forest fires and the El Nino Southern Oscillation. *Global Ecology and Biogeography*, **10**, 315–326.

Kurz WA, Apps MJ, Bekema SJ *et al*. (1995) 20th century carbon budget of Canadian boreal forests. *Tellus (B)*, **47**, 170–177.

Lambin EF, Ehrlich D (1997) The identification of tropical deforestation fronts at broad spatial scales. *International Journal of Remote Sensing*, **18**, 3551–3568.

Laurance WF, Albernaz AKM, Schroth G *et al*. (2002) Predictors of deforestation in the Brazilian Amazon. *Journal of Biogeography*, **29**, 737–748.

Lavoue D (2000) *Transport vers la region arctique de l’aerosol carbone emis par les feux de biomasse des regions boreales et temperees*. University Paris VII, Paris, France 267pp.

Leenhouts B (1998) Assessment of biomass burning in the conterminous United States. *Conservation Ecology*, **2**, 1–25 (online: http://www.consecol.org/vol2/iss1/art1).

Levine JS (2000) Global biomass burning: a case study of the gaseous and particulate emissions released to the atmosphere during the 1997 fires in Kalimantan and Sumatra, Indonesia. In: *Biomass Burning and its Inter-Relationship with the Climate System* (eds Innes JL, Beniston M, Verstraete MM), pp. 15–31. Kluwer Academic Publishers, Dordrecht.

Liew SC, Lim OK, Kwoh K *et al*. (1998) *A study of the 1997 fires in south East Asia using SPOT quicklook mosaics*.International Geoscience and Remote Sensing Symposium, Seattle, WA, USA, 3pp.

Loope LL, Gruell GE (1973) The ecological role of fire in the Jackson Hole area, Northwestern Wyoming. *Quaternary Research*, **3**, 425–443.

Mack F, Hoffstadt J, Esser G *et al*. (1996) Modelling the influence of vegetation fires on the global carbon cycle. In: *Global Biomass Burning. Atmosphere, Climatic, and Biospheric Implications* (ed. Levine JS), pp. 150–159. The MIT press, Cambridge, MA, USA.

MacKenzie D, Peterson DL, Agee JK (2000) Fire frequency in the interior Columbia river basin: building regional models from fire history data. *Ecological Applications*, **10**, 1497–1516.

Madoui A (2002) Les incendies de forêt en algérie: historique, bilan et analyse. *Forêt Méditerranéenne*, **XXIII**, 23–29.

Makarim N, Arbai YA, Deddy A *et al*. (1998) *Assessment of the 1997 Land and Forest Fires in Indonesia: National Coordination*. United Nations Economic Commission for Europe and the Food and Agriculture Organisation of the United Nations, Geneva, Switzerland.

Malingreau JP, Stephens G, Fellows L (1985) Remote sensing of forest fires: kalimantan and North Borneo in 1982-1983. *Ambio*, **14**, 314–321.

Minnich RA (1998) Landscapes, land use and fire policy: where do large fires come from? In: *Large Forest Fires* (ed. Moreno JM), pp. 133–158. Backhuys, Leiden.

Molion LCB (1996) Amazonia: burning and global climate impacts. In: *Global Biomass Burning. Atmospheric, Climatic, and Biospheric Implications* (ed. Levine JS), pp. 547–562. The MIT press, Cambridge, MA, USA.

Moore JL, Howden SM, MacKeon GM *et al*. (2001) The dynamics of grazed woodlands in southwest Queensland, Australia, and their effect on greenhouse gas emissions. *Environmental International*, **27**, 147–153.

Moreira F, Rego FC, Ferreira PG (2001) Temporal (1958–1995) pattern of change in a cultural landscape of Northwestern Portugal: implications for fire. *Landscape Ecology*, **16**, 557–567.

Mouillot F, Ratte JP, Joffre R *et al*. (2003) Some determinants of the spatio-temporal fire cycle in a mediterranean landscape (Corsica-France). *Landscape Ecology*, **18**, 665–674.

Myers N (1991) Tropical forest: present status and future outlook. *Climatic Change*, **19**, 3–32.

Nepstad DC, Verissimo A, Alencar A *et al*. (1999) Large scale impoverishment of Amazonian forests by logging and fire. *Nature*, **398**, 505–508.

Parviainen J (1996) The impact of fire on Finnish forests in the past and today. In: *Fire in Ecosystems of Boreal Eurasia* (eds Goldammer JG, Furyaev VV), pp. 55–64. Kluwer Academic press, Dordrecht, the Netherlands.

Pausas JG (2004) Changes in fire and climate in the eastern Iberian Peninsula (Mediterranean basin). *Climatic Change*, **63**, 337–350.

Prasad VK, Kant Y, Gupta PK *et al*. (2002) Biomass burning and related trace gas emissions from tropical dry deciduous forests of India: a study using DMSP-OLS data and ground-based measurements. *International Journal of Remote Sensing*, **23**, 2837–2851.

Pyne SJ (2002) *Fire: A Brief History*. University of Washington Press, Washington.

Pyne SJ (1982) *Fire in America: A Cultural History of Wildland and Rural Fire*. Princeton University Press, Princeton.

Pyne SJ (1991) *Burning Bush: A Fire History of Australia*. Henry Holt and Company, New York.

Pyne SJ (1994) Nataraja: India's Cycle of Fire. *Environmental History Review*, **18**, 1–20.

Pyne SJ (1997) *Vestal Fire: An Environmental History, Told Through Fire, of Europe's Encounter with the World*. University of Washington Press, Washington.

Quadri della Torre G (2002) *Incendios forestales y deforestación en México: Una perspectiva analítica*. Consejo Coordinador impreserial, Mexico.

Ramankutty N, Foley J (1999) Estimating historical changes in global land cover: croplands from 1700 to 1992. *Global Biogeochemical Cycles*, **13**, 997–1027.

Rawson R, Rees B (1982) A summary of forest fire statistics, 1972–73 to 1980–81. Forest commission, Victoria, Australia.

Ringrose S, Chipanshi AC, Matheson W *et al*. (2002) Climate- and human-induced woody vegetation changes in Botswana and their implications for human adaptation. *Environmental Management*, **30**, 98–109.

Schellhaas MJ, Nabuurs GJ, Schuck A (2003) Natural disturbances in the European forests in the 19th and 20th centuries. *Global Change Biology*, **9**, 1620–1633.

Scholes M, Andreae MO (2000) Biogenic and pyrogenic emissions from Africa and their impact on the global atmosphere. *Ambio*, **29**, 23–29.

Schultz MG (2002) On the use of ATSR fire count data to estimate the seasonal and interannual variability of vegetation fire emissions. *Atmospheric Chemistry and Physics*, **2**, 387–395.

Schulze ED, Lloyd J, Kelliher FM *et al*. (1999) Productivity of forests in the eurosiberian boreal region and their potential to act as a carbon sink-a synthesis. *Global Change Biology*, **5**, 703–722.

Seiler W, Crutzen PJ (1980) Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning. *Climatic Change*, **2**, 207–247.

Setzer AW, Pereira MC (1991) Amazonia biomass burning in 1987 and estimate of their tropospheric emissions. *Ambio*, **20**, 19–22.

Sheriff RL, Veblen TT, Sibold JS (2001) Fire history in high elevation subalpine forests in the Colorado front Range. *Ecoscience*, **8**, 369–380.

Shvidenko A, Goldammer JG (2001) The forest fire situation in Russia. *International Forest Fire News*, **24**, 41–59.

Shvidenko AZ, Nilsson S (1999) Extent, distribution, and ecological role of fire in Russian forests. In: *Fire, Climate Change, and Carbon Cycling in the Boreal Forest* (eds Kasischke ES, Stocks BJ), pp. 132–150. Springer, New York.

Simon M, Plummer S, Fierens F *et al*. (2004) Burnt area detection at global scale using ATSR-2: the GLOBSCAR products and their qualification. *Journal of Geophysical Research-Atmospheres*, **109**, D14 S02.

Skole D, Tucker C (1993) Tropical deforestation and habitat fragmentation in the Amazon: satellite data from 1978 to 1988. *Science*, **260**, 1905–1910.

Skole DL, Chomentowski WH, Salas WA *et al*. (1994) Physical and human dimensions of deforestation in Amazonia. *Bioscience*, **44**, 314–322.

Stocks BJ (1996) The extent and impact of forest fires in Northern circumpolar countries. In: *Global Biomass Burning. Atmospheric, Climatic, and Biospheric Implications* (ed. Levine J.S.), pp. 197–202. The MIT press, Cambridge, MA, USA.

Swetnam TW (1993) Fire history and climate change in giant Sequoia Groves. *Science*, **262**, 885–889.

Swetnam TW, Betancourt JL (1990) Fire-Southern oscillation relations in the southwestern United States. *Science*, **249**, 1017–1020.

Swetnam TW, Betancourt JL (1998) Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. *Journal of Climate*, **11**, 3128–3147.

Tansey K, Gregoire JM, Stroppiana D *et al*. (2004) Vegetation burning in the year 2000: global burned area estimates from SPOT VEGETATION data. *Journal of Geophysical Research-Atmospheres*, **109**, D14 S03.

Thonicke K, Venevsky S, Sitch S *et al*. (2001) The role of fire disturbance for global vegetation dynamics: coupling fire into a Dynamic Global Vegetation Model. *Global Ecology & Biogeography Letters*, **10**, 661–677.

Tilman D, Reich P, Phillips H *et al*. (2000) Fire suppression and ecosystem carbon storage. *Ecology*, **81**, 2680–2685.

Van der Werf GR, Randerson JT, Collatz J *et al*. (2003) Carbon emissions from fires in tropical and subtropical ecosystems. *Global Change Biology*, **9**, 547–562.

Wang X, Feng Z, Zhuang YH (1996) Forest fires in china: carbon dioxide emissions to the atmosphere. In: *Global Biomass Burning Atmospheric, Climatic and Biospheric Implications* (ed. Levine JS), pp. 771–779. The MIT press, Cambridge, MA, USA.

Weber MG, Flannigan MD (1997) Canadian boreal forest ecosystem structure and function in a changing climate: impact on fire regimes. *Environmental Review*, **5**, 145–166.

Woods P (1989) Effects of logging, drought, and fire on structure and composition of tropical forests in Sabah, Malaysia. *Biotropica*, **21**, 290–298.

Zaizhi Z (2001) Status an perspectives on secondary forests in tropical China. *Journal of Tropical Forest Science*, **13**, 639–651.

Zhang P, Shao G, Zhao G *et al*. (2000) China's forest policy for the 21rst century. *Science*, **288**, 2135–2136.

Zhang YH, Wooster MJ, Tutubalina O *et al*. (2003) Monthly burned area and forest fire carbon emission estimates for the Russian Federation from SPOT-VGT. *Remote Sensing of Environment*, **87**, 1–15.

Appendix A

We summarize here the references we used to rebuild the fire history, and the different methodologies we used to extrapolate missing values. The data set (maps and statistics) is available online at http://globalecology.stanford.edu/DGE/CIWDGE/CIWDGE.HTML and http://www.cefe.cnrs-mop.fr/fe/staff/Florent_Mouillot.htm

Africa

The major source of information is the study from Barbosa *et al*. (1999) for the 1981–1990 period, for all the African countries (referenced as region 10, Fig. 2). Among the two scenarios proposed in that study, we chose the lowest values, in comparison with previous estimates (Hao & Liu, 1994, Houghton, 1994, Delmas *et al*., 1996, Scholes & Andreae, 2000), and the 2000–2001 remotely sensed estimations (GBA, 2000, FAO, 2001). No information before 1981, to our knowledge, exists for African countries. We interpolated backwards burned surfaces based on land cover changes and human intervention in fire setting: (i) for the northern hemisphere part of Africa, we related population growth – and the subsequent human pressure by extensive subsistence agriculture – to a fire increase (Lambin & Ehrlich, 1997, Ramankutty & Foley, 1999). We used the 25% increase rate for the 1975–2000 period (overall leading to a + 1% year^{-1}) proposed by Crutzen & Andreae (1990) and Delmas *et al*. (1996), decreasing down to 0.5% year^{-1} for the 1950–1975 period and 0.1% year^{-1} before that, based on the land use change dynamic in the region (Ramankutty & Foley, 1999). ii) for the southern hemisphere part, we set a fire decrease based on fire ecosystem conservation policies since the 1950s (Brown *et al*., 1991a), and substantial woody encroachment observed in the area (Hudak & Wessman, 2001, Ringrose *et al*., 2002). Tourism in natural parks has been considered as a better source of benefits than extensive grazing, and protected cultivated lands have expanded (Ramankutty & Foley, 1999). We fixed a burnt area for the 1900–1955 period in accordance with the one obtained for the northern part of Africa at this period. Then, we linearly interpolated the burnt areas between 1955 and 1981 (date after which we have available data) for all the southern hemisphere countries (Mozambique, Namibia, South Africa, Zambia, Zimbabwe), as well as the Eastern-African countries where tourism is well developed (Tanzania, Kenya). The resulting decrease obtained from this interpolation reached the rate of −1.5% year^{-1}.

We deduced the trend for fires in the tropical forest (mostly covering Zaire) from Achard *et al*. (2002) and Lambin & Ehrlich (1997), where 0.85 Mha yr^{-1} have been deforested between 1990 and 1997. We set a burnt area at 0 Mha yr^{-1} in 1960 and linearly interpolated between the two dates. We calculated the subsequent burnt surfaces following the algorithm used for tropical forests and described in 'Mapping'.

South America

The sources are as follow: FAO statistics in Hao & Liu (1994) and Cochrane (2002) for general statistics in South-America in the 1980s. Data from the SEcretaria del Medio Ambiante y Recursos NATurales (SEMARNAT) (http://www.semarnap.gob.mx), CENCIF (Centro National de Control de Incendios Forestales) and (FAO, 2001) have been used for Mexico (1970–2000). We observed that the spatial representation of the SEMARNAT statistics available by states for Mexico, produced an unrealistic low fire frequency, compared with the neighboring regions of California, New Mexico and Arizona (USA), and remote sensing studies. We suspect these data to be as underestimated as the data obtained in Argentina from the same Agency. We corrected the data in the same proportion as the underestimation found for Argentina ($\times$ 3). Before the 1970s, the fire history in Mexico actually followed the same fire prevention process as in the south-western US (Fule & Covington, 1996, Barton, 2002), but in a lesser extent compared with California (Minnich, 1998). We fixed a fire regime for the beginning of the century in Northern Mexico, matching the fire regime obtained for California, New Mexico and Arizona (USA). The rate of change obtained between 1900 and 1970 lead to a 50% decrease, accurately lower than the 80% decrease observed in the western US states.

For Brazil, we used the studies of Skole & Tucker (1993) and Skole *et al*. (1994) for the spatial and temporal history of fires. Before 1970, most of the conversion of savanna (Cerrado) into cultivated/grazed areas had occurred in Southern Brazil and along the coast. We considered two zones: (i) the coastal range, experiencing a fire increase until the 1970s, followed by a fire decrease and (ii) the central plateau, experiencing a continuous increase until now because of government policies to stimulate agricultural development (Laurance *et al*., 2002). Without any further information on the importance of the fire decrease, we chose the $-1.5\%\ \mathrm{year}^{-1}$ rate observed in southern Africa. Regarding the fire increase in the central plateau, (Houghton, 1996) estimated a 25% increase from 1945 to 1970, and a 50% increase of fire-prone grasslands. We finally chose a 50% increase of in burnt areas in the Brazilian savanna biome between 1970 and 2000 ($2\%\ \mathrm{year}^{-1}$)-which is, to our knowledge, accurately higher than the $1\%\ \mathrm{year}^{-1}$ rate observed in Northern Africa-, $1\%\ \mathrm{year}^{-1}$ between 1945 and 1970, and 0.5% before 1945. We considered this rate to be actually a fair assumption, as Central Brazil has been experiencing a faster growing human pressure compared with the long lasting fire regime in Africa. In turn, we fixed, at first, a fire return interval in the Cerrado at 4.5 years for the 1980s (Seiler & Crutzen, 1980), and interpolated forwards at a rate of $2\%\ \mathrm{year}^{-1}$, and backwards at the rate of successively 2%, 1%, and $0.5\%\ \mathrm{year}^{-1}$. We used the same pattern for the neighboring countries (Bolivia, Paraguay).

Within the tropical forest of South America, forest fires because of deforestation are not taken into account in statistics (Quadri della Torre, 2002). Then, we derived burned areas from deforestation values (procedure described in 'Mapping'), as fires are an infrequent element of the Amazon natural disturbance regime (Cochrane *et al*., 1999). The data sources from the 1960s to the 1990s for deforestation in Amazonia are as follows, including census data and remote sensing studies:

Area deforested *($\mathrm{Mha\,yr}^{-1}$)*	*Year*	*References*
1.18		Hao & Liu (1994)
2–3	1966–1975	Seiler & Crutzen (1980)
1.36	1975–1980	Skole & Tucker (1993)
1.12–2.7	1978–1998	Brazilian Space Agency in Houghton *et al*. (2000)
2.1	1978–1988	INPE http://www.grid.inpe.br/ + (Skole & Tucker, 1993) + (Skole *et al*., 1994)
5–8	1985–1990	Myers (1991)
4	1987	Setzer & Pereira (1991)
2.8	1988	INPE http://www.grid.inpe.br/
2.1–5	1989	Molion (1996)
1.9	1988/1989	Fearnside (1993)
1.4	1989/1990	
1.1	1991	
1.49	1993–1994	SEMARNAT + (Nepstad *et al*., 1999)
2.9	1994–1995	
1.8	1995–1996	
1.81	1996	INPE http://www.grid.inpe.br/
1.28	1997	
3–4	1990s	Cochrane & Laurance (2002)
2.5	1990s	Achard *et al*. (002)

The significant deforestation in the Amazon began between 1975 and 1980, when deforestation might have doubled (Crutzen & Andreae, 1990), and followed afterwards an exponential increase (Skole *et al*., 1994). Before 1960, deforestation in Amazonia has been documented as negligible (Houghton *et al*., 2000), so we interpolated linearly deforested areas between 1960 and 1975, and we calculated the subsequent burnt surfaces following the algorithm used for tropical forests and described in 'Mapping'.

For Mexico, we retained that more than 0.5 Mha are deforested every year in the 1990s (CENCIF). The deforestation followed a constant increase since the 30's, when the need in agricultural land started to increase because of population growth, and postrevolution agricultural policies were installed (Quadri della

Torre, 2002). We used a linear trend for deforestation interpolation, from 0 in the 1930s to 0.5 Mha yr^{-1} in 1990. This trend was used as a general model for the Central American countries, but we considered a recent decrease in the 1990s regarding the fire statistics available for Nicaragua (FAO, 2001). We calculated the subsequent burnt surfaces following the algorithm used for tropical forests and described in 'Mapping'.

South Asia

The sources for India, Nepal and Sri Lanka are FAO, 2001.

For India, additional sources are as follows for the 1980s:

Burned area (Mha yr^{-1})			
Savanna	*Forest*	*Year*	*References*
1.39	0.28		Hao & Liu (1994)
	0.13–0.4		Skole & Tucker (1993)
37–80			Pyne (1994)
12.2	1		Pyne (1994)
	1.45	1995	FAO (2001)
	3.73		
12.2#			Joshi (1991)
9.47#			
		1981	
	0.26	1968–1972	Joshi (1991)
	0.98	1985–1986	
	0.97	1986–1987	
	1.05	1987–1988	
	3.74	1985–1986	
1.012			Haripriya
		1985–1988	(2003)
		1980–1985	
0.11			
1			Elvdige & Baugh (1996)

Regarding the heterogeneity in the data set, we retained the intermediate value of 35 Mha from (Pyne, 1994) critical review and estimations from the Environmental Information Center (EIC, USA) (http://www.cleantechindia.com/eicnew/NatForestProg/pressure.htm).

To our knowledge, and despite the main concern about fires in India found in the literature, no long-term statistics exist for South Asia, except qualitative notes. The temporal trend of fire frequency is described as slightly decreasing until the 1920s, because of the colonial forest policies to protect lands from fires, followed by a recovery of the initial fire pattern and a continuous increase because of the need in cultivation as a response to population growth (Pyne, 1994, Prasad *et al.*, 2002). Then, from the 35 Mha obtained for the 1990s, we extrapolated backwards at a conservative fire increase of 0.6% $year^{-1}$ until the 1930s (slightly lower than the 1% $year^{-1}$ in Northern Africa because of a long land use history but a higher population density). From Indian statistics, extrapolations to Pakistan have been performed proportionally to the country surface area.

Australia

The sources are as follows for the Australian Savanna: the Australian National Greenhouse Gas Inventory (NGGI), 2000 (http://www.greenhouse.gov.au/inventory/) for the 1994–1999 period and the FAO data for the 1998–2000 period (GBA, 2000, FAO, 2001). We compared these data with previous general estimations (Hao & Liu, 1994, Cheney, 1995), as well as the highest value observed for the year 1974 (Dixon *et al.*, 1996). In absence of any big land use change within the Australian savanna (Ramankutty & Foley, 1999), and a still low population density, fires have slightly decreased along the 20th century, because of some human intervention to protect some grazing areas (Burrows *et al.*, 1995, 2002, Moore *et al.*, 2001). We interpolated burnt areas backwards from the 1990s downto the 1950s according to the same 1% $year^{-1}$ rate, slightly lower than the one obtained for southern Africa.

The main sources of information for forest fires in temperate Australia are FAO statistics delivered by states for the 1956–1996 period (FAO, 2001), despite their authors point out that some changes in the methodology along the process have occurred. Longer-term information is also available for South Western Australia for the 1915–1996 period (Gill *et al.*, 1997), and Victoria for the 1972–1981 period (Rawson & Rees, 1982), showing a significant decrease in fire frequency along the century. After a huge fire prevention policy in the 1930s, fires burnt again in the following decades because of important fuel build-up (Pyne, 1991). To reconstruct Australia's forest fire history, we interpolated burnt areas in temperate forest at the beginning of the century based on the present aborigines fire return intervals (Pyne, 1991). Then, we linearly interpolated burnt areas between the 1970s for which we have accurate statistics, and the effective year of change in the fire regime for which we have the aborigene's fire regime. This year of change was different in each state (Cheney, 1995): 1944 in Victoria, 1968 in New South Wales, 1961 in Western Australia, and 1967 in Tasmania.

South East Asia

Forests mainly cover South East Asia, and burned areas are closely related to deforestation. The sources are as follows for the most documented deforestation in the Indonesian forest in the 1990s:

Burned area (Mha yr^{-1})			
Savanna	*Forest*	*Year*	*References*
	2.4–3.6	1982–1983	Makarim *et al.* (1998)
	4.5	1982–1983	Malingreau *et al.* (1985)
3.7	0.56–0.85		
			Hao & Liu (1994)
	0.5	1991	
			Barber & Schweithelm (2000)
	4.9	1994	
0.5	2.7	1982–1983	
	1.7–2.5	1997	
			Levine (2000)
4.67	4.79	1997–1998	Barber & Schweithelm (2000)
	0.55–1.2		
			Skole & Tucker (1993)
	4.56	1997–1998	Liew *et al.* (1998)
	2.5	1990–1997	Achard *et al.* (2002)

Additional data for Malaysia (Woods, 1989, Brown *et al.*, 1991b), and Thailand for 1985–2000 (FAO, 2001) (http://www.oepp.go.th/projects/climate/comm/inventory, for deforestation), are also available. Deforestation in South-eastern Asia increased at a rate estimated to be between +1% and +8.8% year^{-1} in the 1980s (Seiler & Crutzen, 1980, Houghton, 1994, Barber & Schweithelm, 2000, Fox, 2002), the highest in the tropical zone, because of a huge population increase, and very few savanna available for agricultural expansion (Hao & Liu, 1994). We retained a conservative rate of 5% year^{-1}, and we used the tropical forest algorithm ('Mapping') to convert deforestation data into burnt areas. By using this algorithm on Indonesian deforestation data, and starting the deforestation process in the 1960s (Barber & Schweithelm, 2000), we reached the 4.9 Mha yr^{-1} estimated to have burnt in Indonesia in 1990, combining shifting cultivation and savanna/grassland fires (ALGAS 1997: Indonesian national greenhouse gas emissions inventory, http://netweb03.asiandevbank.org). Larger burnt areas are obtained during dry years. For the neighboring countries (Burma, Cambodia, Laos, Thailand, Viet-Nam), we extrapolated the temporal trend obtained for Indonesia proportionally to the size of the country, and based on country deforestation data from (Fox, 2002).

To our knowledge, no data are available for tropical southern China. Zaizhi (2001) points out that, even if natural wildfires are actually not frequent in tropical China, because of a humid climate, human induced fires occur in the secondary forests, and are not taken into account in the statistics. We retained Zaizhi's (2001) burning estimations for the year 1994 in secondary forest (0.276 Mha) and shifting cultivation (0.4 Mha), assumed to burn 3 times for a complete clearing as previously observed in the tropical forests. We extrapolated backwards forest fires in southern china using the same rate as the one observed in South-Eastern Asia, because of the increase in population density and, in turn, the need for decreasing the fallow period for shifting cultivation, (Zhang *et al.*, 2000, Zaizhi, 2001, Fox, 2002).

Central Asia

The sources cover mostly Mongolia for the period 1963–1997 (Mongolia fire update. Int. Forest Fire News No.15, 34–35.), updated for the year 2000 (GBA, 2000). Official statistics for Kazakhstan (1950–1998: (Arkhipov *et al.*, 2000)), Russian steppes (1990s by Shvidenko & Goldammer (2001) and Zhang *et al.*, (2003)) and China (1997–1998: Report on the State Of the Environment in China, 1999: http://www.sepa.gov.cn/soechina99/forest/forestdown.htm), might be highly underestimated in comparison with the Mongolian estimations and GBA, 2000 data. We made corrections by following the Mongolian database to provide a homogeneous pattern within the region.

We then assumed the Mongolian trend for the 1963–1997 period to be the model for the neighboring countries with the same biome, as suggested for the Chinese inner Mongolia (FAO, 2001). Before this period, fires may have burnt larger areas in absence of fire prevention and fire fighting policies, which only started between the 1920 and the 1950s (Goldammer & Stocks, 1999). We interpolated this fire decrease backwards from the 1960s at a rate of -1.5% year^{-1}, by comparison with the fire decrease in the grasslands of Southern Africa. By using this rate, we reached in 1900 an intermediate value of 10.2 Mha, in between the lowest value of 3.79 Mha observed in the 1970s and the extreme value of 15.5 Mha observed in the 1990s. We increased burnt areas in the 1960s in the Russian steppes because of landscape clearing for crop development (Ramankutty & Foley, 1999).

Canada

The sources are as follows: Canadian council of forest ministers, Compendium of Canadian forestry statistics (http://nfdp.ccfm.org/) for the 1970–1998 period, where data are available by province, a nation-wide database for the 1946–1998 period (Weber & Flannigan, 1997). We corrected incomplete statistics before 1946 (particularly for the northern territories) by estimates based on tree ring analysis and tree community composition as performed by Chen *et al*., (2000).

Russia

The sources are as follows: official statistics are available since 1961 (Shvidenko & Nilsson, 1999), but are highly underestimated, based on a comparison with the boreal forest of Canada (Kasischke *et al*., 1995, 2000), and observed fire return intervals (Conard & Ivanova, 1997). Kasischke *et al*. (2000) refer that the local forest officials use to under-report fires in Russia because of financial incentives provided to those regions that achieved a high fire suppression. Alternatively to underestimated official statistics which cover only controlled regions (Goldammer and Stocks, 1999), we used corrected data based on additional studies for the year 1987 (Cahoon *et al*., 1994, Stocks, 1996), for the 1980-1995 period (Dixon and Krankina, 1993), and averages for the 1980s (Schulze *et al*., 1999, Shvidenko & Goldammer, 2001, Zhang *et al*., 2003). Despite data are only available at the national level, Dixon and Krankina (1993) report that 61% of the burnt areas occur in the far east Russia, 34% in the east Siberian, whereas no more than 5% occur in Ural or West Siberia, supporting the use of ATSR data for this large country, overall leading to a higher fire frequency in the Far East (Ishikawa *et al*., 1999). To build the database, we divided the boreal forest part of the country into the western part, and the Eastern part, respectively, according to vegetation types 'needleleaf evergreen trees' and 'high latitude deciduous trees' or 'broadleaf deciduous trees' (DeFries & Twonshend, 1994).

We used historical records of fire use by humans in western Russia (Pyne, 1997), observed fire return intervals (Conard & Ivanova, 1997) and highest fire events (the year 1915 for example) (Goldammer & Furyaev, 1996, Ivanova, 1998, Lavoue, 2000) to estimate fire activity at the beginning of the century. Based on Conard and Ivanova (1997)'s estimates, we fixed the burnt areas at the beginning of the century to be 13 Mha. Actually, we used 10 Mha for 1900–1910, and 16 Mha for the 1910–1920 with the huge fire of 1915 that burnt more than 100 Mha (Goldammer & Furyaev, 1996). We linearly interpolated the decrease for the 1920–1950 period in eastern Russia, as a result of the soviet fire exclusion policy (Goldammer & Stocks, 1999). For the whole century, we kept using the same ratio (90–10%) as the one observed in the 1980s, to distribute fires between Eastern and Western Russia, respectively. However, we increased the proportion of fires occurring in Western Russia to 30% for the 1900–1910 period, and 20% for the 1910–1920 period, when fallow system of agriculture was still in use, and was progressively abandoned in the 1920s (Pyne, 1997, Lavoue, 2000).

Europe

The source for the 1980–2000 period are FAO (1999), FAO (2001), Schellhaas *et al*. (2003) for the Mediterranean countries since the 1960s. Data were compared with GBA (2000) estimations, and the State of the Environment for Georgia (http://www.grida.no/enrin/htmls/georgia/soegeor/english/forest/fexploit.htm). We used statistics for the 1980–1995 period in Latvia and Lithuania (FAO, 2001) as the model for the recent fire history in eastern Europe (Czech republic, Hungary, Poland, Romania, ex-Yugoslavia, Slovakia).

Longer-term statistics are available for Germany and Finland (FAO, 1999, Goldammer & Stocks, 1999, FAO, 2001). We used these data sets as a model for, respectively, the whole northern Europe and Scandinavia before 1960, and statistics for the 1874–2000 period in Spain for Mediterranean Europe (Pausas, 2004).

USA

The sources are as follows: US forest service. Forest fire statistics. Annual issues. Government printing office, Washington, DC for the 1926–1967 period, US forest service. Wildfire statistics. Annual issues. Government printing office, Washington, DC, for the 1968–1982 period, US forest service, 1988. Wildfire statistics. Government printing office, Washington, DC. For the year 1983, US forest service, 1992. 1984–1990 Wildfire statistics. Government printing office, Washington, DC. For the 1984–1990 period, and US forest service, 1998. Wildland fire statistics. Government printing office, Washington, DC, for the 1991–1997 period. These statistics have already been used in several studies (Swetnam & Betancourt, 1990, Tilman *et al*., 2000). For Alaska, we used data available from the 'Alaska fire Service' for the 1940–1997 period, and rough estimations for the 1900–1940 period (Barney, 1971). However, prescribed burnings (1.2 Mha yr^{-1} occurring in the South Eastern part, 0.8 Mha yr^{-1} in the western part) are not taken into account in the statistics and have been added as a constant value since the 1950s (Leenhouts, 1998, FAO, 2001).

We can deplore some obvious inconsistencies in the historical statistics for the western states compared with the general knowledge of the American fire history (Pyne, 1982). Statistics alone lead to an overall underestimation compared with other studies (Leenhouts, 1998, Hurtt *et al*., 2002).

For example, statistics for the southwestern states (Arizona, New Mexico) show a low fire regime at the beginning of the century increasing after the 1970s. However, fire scars studies tend to prove a large decrease in the fire frequency in these states since the beginning of the century (Swetnam, 1993, Swetnam & Betancourt, 1998). The northwestern statistics are more in accordance with the fire scar study performed by Barrett *et al*. (1997) or MacKenzie *et al*. (2000) in the interior Columbia basin (Washington, Oregon, Idaho, Montana, Wyoming). For this region particularly, the trend observed before 1926 on tree rings and not available in terms of statistics, has been used for the temporal interpolation. For instance, we extrapolated a peak of fires in 1920 and 1910, and we retained the hypothesis that fires were burning on a yearly basis, at the beginning of the century, the same surface as the large fires of 1988 and 1994. The use of this hypothesis lead to a general fire regime in accordance with the trend obtained for the neighboring Canadian boreal forest. Additional low intensity prescribed burnings might have occurred without any signal neither in the statistics, neither in the tree scars, and have not been considered in this study due their limited impact on the carbon budget.

Our main concern was about the Midwest states, where almost no fires have been registered during the 1940s, and swap to a high fire regime in the following years. Regarding that these states (Nebraska, Iowa, Kansas, N/S Dakota) were also the latest states to produce fire statistics, we considered these statistics to be accurate only after the 1960s. We then relied on local studies dating and describing fire suppressions, ca. 1920 in Colorado (Brown *et al*., 2000, Donnegan *et al*., 2001, Sheriff *et al*., 2001), ca. 1920–1930 in Wyoming (Loope & Gruell, 1973, Kipfmueller & Baker, 2000), or 1890–1910 in Minnesota (Clark, 1988). We fixed burnt areas at the beginning of the century according to the fire return intervals observed in other grassland biomes at this time, as southern US, Argentina and central Asia or present Brazil as stated in Pyne (1982). We then linearly interpolated burnt areas between the fire suppression date and 1960.

Argentina

The source is FAO (2001), and SEMARNAT for the 1980–1998 period. These data appeared to be low compared with local studies (Bran *et al*., 2001, Bravo *et al*., 2001) and national statistics from other agencies (Proyecto LEMU, http://orbita.starmedia.com/~lemuproyecto/not8.htm) estimating up to three times the official statistics. As a general comparison with other biomes and neighboring countries, we retained the highest value as the most accurate.

Regarding the temporal trend along the century, studies on tree scars (Kitzberger *et al*., 2001), land use (Adamoli *et al*., 1990), and land cover changes (Ramankutty & Foley, 1999) converge towards a strong fire suppression occurring since the 1930s. We then stated a fire activity at the beginning of the century in accordance with the one observed in the south-eastern US, and interpolated the temporal trend of the decrease along the century using the tree scars studies to reach the actual burnt areas in the 1980s.

Eastern Asia

The unique source for China is Wang *et al*. (1996) for the 1952–1995 period, and the state of the environment for the years 1997–1999 (http://www.sepa.gov.cn/soe-china99/forest/forestdown.htm). Average statistics are available for each Chinese province, providing a gross spatial distribution of fires, highlighting that most of the referenced fires occur in the northeastern part of china similar to the ATSR data for China. Regarding the relatively constant temporal trend observed between 1952 and 1970, and a burnt area in accordance with the fire regime in the neighboring Russian Far-east, we fixed burnt areas at the beginning of the century to be in the same order of magnitude as the one observed in 1950s.

The source for Japan and South Korea is FAO (2001), and the GBA (2000) for North Korea. We interpolated the North Korean fire history based on the Russian temporal pattern, and the Japanese and South Korean one, based on the western Europe pattern.

Middle East/North Africa

The sources are: Madoui (2002) for the 1876–1915 and 1958–2000 period for Algeria, IFFN No. 17-July 1997, p. 15–21 for Turkey, and IFFN, 25, July 2001 for Marocco during the 1960–1999 period corrected according to the GBA, 2000 database.

Additional data from GBA, 2000 were used for Algeria, Egypt, Iran, Iraq, and Turkey. The temporal trend was supposed to remain constant according to the long-term data obtained for Algeria.