

Global spatial and temporal distribution of vegetation fire as determined from satellite observations

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Abstract. Vegetation fires occur worldwide, all year round and inject enormous amounts of trace gases and particles into the atmosphere. Nonetheless, there is still great uncertainty as to the global spatial and temporal distribution of vegetation fires. Twenty one months of global, daily, daytime satellite data at 1 km resolution, from April 1992 to December 1993, were processed in order to determine the positions of active vegetation fires. Results from the first twelve months of the study period are presented here. This is the first time that such a global study has been carried out using a long time series data set and a single processing technique. The data set and results discussed provide much improved information on the spatial variability and the seasonality of vegetation fires. They will be of use in the global mapping and modelling of emissions due to biomass burning as well as in the study of the role of fire in land cover maintenance and change. We show that half of the fires detected were on the African continent and over 70% within the tropical belt. Fires were detected in more than 6% of 1 km² pixels, over land, during the 12-month period and savanna grasslands accounted for over one third of this area.

1. Introduction

Vegetation fire, whether caused naturally or by humans, is widespread and its occurrence depends on vegetation type and state, climatic and meteorological conditions and land use. From a global perspective human-made fires form by far the majority, whether accidental or deliberate (Levine 1992), although lightning-induced fire is responsible for the majority of burning in boreal regions (Stocks 1992). Human-made fires are closely related to land use and there are many reasons for setting them (Andreae 1992).

Over recent years the growing concern in scientific communities and among international policy makers about climate change and environmental degradation

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has highlighted the requirement for improved information on the dynamics of biomass burning at global scales. As a consequence, fire as an agent of change is now systematically investigated. Burning produces very large emissions of trace gases and aerosol particles, however, there is much uncertainty as to the quantities emitted (Crutzen and Andreae 1990), the plume trajectories (Cooke *et al.* 1996) and the consequences on the Earth's radiative budget and hence climate. The impact on the biogeochemical cycles of several elements such as P, Ca, Mn, Zn, Cl, Si and K, which are released during burning is, unknown. They may also act as cloud condensation nuclei, therefore affecting the mechanisms of cloud formation. This can have consequences on precipitation patterns at regional and global scales (Fishman *et al.* 1993). Fire practises are also of interest from the perspective of land use and potential land degradation. Fire is widely used as a tool in land management, but its misuse coupled with excessive grazing and unfavourable meteorological conditions can lead to soil erosion, changes in hydrological cycles, an increase in water runoff and modifications in the soil's nutrient status (Menaut *et al.* 1993, Maass 1995).

Due to the lack of information on the global distribution of vegetation fires, the spatial and temporal distribution of surface ozone has been used as a proxy for locating fire events and the burning season (Hao and Liu 1994). The method is recognized as being approximate and there is a strong need for improved maps of global biomass burning (Crutzen and Goldammer 1993, Hein *et al.* 1997). Satellite remote sensing is the only technology which allows consistent and extensive data collection at global scales. Its use for the detection and monitoring of active fires at local and continental scales has been developed over many years and a number of different sensors and systems, such as Landsat Thematic Mapper (TM) (Brustet *et al.* 1992), National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) (Setzer and Pereira 1991, Langaas 1992, Koffi *et al.* 1996), the Defence Meteorological Satellite Program (DMSP) satellite (Cahoon *et al.* 1992), and the Geostationary Operational Environmental Satellite (GOES) (Prins and Menzel 1994) have been exploited. The widespread use of AVHRR data for active fire detection is due to the presence of suitable thermal sensors on the instrument, the data produced being inexpensive and widely available, the existence of historical archives, daily coverage of the areas studied and a spatial resolution suitable for regional-scale studies (Kendall *et al.* 1997).

The Joint Research Centre of the European Commission has played an active part in the International Geosphere-Biosphere Programme (IGBP) Data and Information System (DIS) project to produce a Global Fire Product (GFP) (Dwyer *et al.* 1998). We have processed daily global coverage imagery for the 21 months from April 1992 to December 1993 to detect vegetation fires over the whole world. The processing strategy and implementation are described in Stroppiana *et al.* (2000). This paper discusses the spatial and temporal distributions of the detected fires during the 12-month period from April 1992 to March 1993. The regional patterns are highlighted and the main vegetation types affected by burning are identified.

2. Methodology

Most fires, depending on whether they are smouldering or flaming, burn at temperatures between 500 K and 1200 K. At these temperatures there is a very strong infrared emission at wavelengths of 3–5 μm . Fire detection using AVHRR data has traditionally depended on imposing fixed thresholds on the values recorded in channels 3 and 4, which operate at 3.7 μm and 10.8 μm respectively. The appropriate

thresholds are calculated empirically and depend on vegetation type, region and time of year. More recent methods using contextual algorithms compute relative thresholds based upon statistics calculated from neighbouring pixels. An adaptation of this method has been implemented in the processing system used here.

Firstly, a simple threshold test is applied pixel by pixel to both channels 3 and 4 in order to select those pixels that may contain a fire. A contextual test is then applied to these potential fires. This test involves the calculation of statistics on channel 3 and 4 pixels in a variable sized window, centred on the pixel under consideration. A potential fire pixel is confirmed as a fire pixel, if it is much warmer than the background pixels within the window.

The algorithm and processing system are explained in more detail in works by Stroppiana *et al.* (2000) and Flasse and Ceccato (1996). Modelling work shows that contextual algorithms provide the most consistent range of fire detectability across vegetation types and seasons and are therefore most appropriate for global applications (Giglio *et al.* 1999).

The data set used here was constructed as part of the IGBP's project to produce a 1 km resolution global land cover map from satellite imagery (Eidenshink and Faundeen 1994, Loveland and Belward 1997). For each day processed, the system ingests 2 gigabytes of data from tape, which represents the 5 channels of the raw AVHRR data for the 14 orbits covering all land areas of the globe. Firstly the data are geolocated using an orbit model obtained from the Colorado Center for Astrodynamics Research (CCAR) (Rosborough *et al.* 1994). The orbit model is typically accurate to ± 2 pixels. Then all ocean and large inland water bodies are masked out. A 'no-burn' mask is applied to exclude regions where the surface is of a type which does not support any significant vegetation fire. These masks significantly reduce the amount of data to be subsequently processed. A simple cloud detection algorithm based on that of Saunders and Kriebel (1988) is applied before finally testing the remaining pixels for the presence of hot sources using the algorithm outlined above.

The output from the fire detection system is a list of latitude and longitude positions of all fire pixels detected in one day. A fire pixel is any AVHRR image pixel in which a hot source has been detected. Both spatial and temporal compositing techniques can be used to generate gridded products at any desired resolution greater than 0.01° .

3. Results

3.1. *The yearly cycle of fire activity*

The fire detection algorithm used to process the data identifies image pixels which radiate more strongly than their neighbours in the infrared. These pixels are identified as fire pixels if they pass a series of tests. A total of 6.5 million fire pixels were detected in the 12 months of 1 km resolution AVHRR data analysed. However, these are not evenly distributed throughout the year. There is a peak in global fire activity in July and August. Activity then decreases slowly reaching a minimum in early November when the number detected is only 28% of those detected during the period of peak burning. From November, fire activity increases again reaching another lower peak in late December and January after which it reduces.

Independent validation of a global product such as this is not possible. Fires are ephemeral events and evidence of their passage may last a very short time, particularly in tropical ecosystems. The algorithm used for fire detection was chosen and

recommended to IGBP-DIS, as the most appropriate for global applications, by an international expert group (IGBP 1996). During the prototyping of the system, the results were compared with those from visual interpretation for a number of areas. From those pixels selected by the algorithm as fire, visual analysis confirmed that 85% were definitely fires (EOS 1995). Comparison of the performance of the contextual algorithm with multi-threshold algorithms for Africa led Eva and Flasse (1996) to favour the former. We have compared fire patterns with those derived from the same AVHRR data using regionally specific satellite data analysis methods for south-east Asia (Jones 1997), Africa (Arino and Melinotte 1995) and Brazil (Miranda *et al.* 1994). They are in close agreement. Differences in the absolute number of fires detected are due to the use of different algorithms. As part of the IGBP-DIS GFP verification procedure, adopted at the fire working group meeting in Toulouse in March 1998, feedback on the GFP will be sought from regional experts. This information will be combined with data from field studies in order to identify the shortcomings of the product. Areas where we believe anomalous detections occur are discussed below.

Cloud cover inhibits the detection of fires. Although the probability of ignition of a fire under heavy cloud is reduced (Moula 1996), it is still possible that burning occurs in cloudy conditions (Robinson 1992). Analysis of this data set shows that many tropical regions are cloud free for over 6 months of the year, while in equatorial, temperate and boreal regions cloud cover can persist for very long periods. Due to the lack of ground observations on fire presence in cloudy conditions, it is impossible to make any estimation of the number of fires not observed due to cloud.

3.2. Geographical distribution of vegetation fires

Figure 1 shows the location and number of vegetation fires detected over three-month periods in the year studied. 38% of all fire pixels were located in the Southern Hemisphere. Although only 26% of the global land surface is located south of the equator, much of it lies within or near the tropics, which is the area subject to most burning. 50% of all fire pixels detected were on the African continent. This large contribution of Africa to global biomass burning is in agreement with previously published material (Andreae 1992, Hao and Liu 1994). Most of the fires are set in the savanna regions. Reasons for burning are numerous and vary across the continent, but some of the more common are burning to remove unpalatable stubble and to initiate off-season regrowth of fresh shoots, clearing ground for crops, establishment of fire-breaks around settlements, removal of parasites, to drive game out of hiding and to make pathways accessible (Menaut *et al.* 1992). Figure 1 and figure 2(a) show that in Africa north of the equator, fire stretches in a band from Senegal to Ethiopia, the main burning season being from November to April with peak activity in late December and early January. Burning then shifts with the dry season to the Southern Hemisphere and from May through to early November it moves in a west to east direction across the continent (figure 2(b)). Southern Africa experienced a long drought in 1991–1992 which is believed to have resulted in reduced fire activity as the amount of fuel available for burning was much less than normal (Justice *et al.* 1996).

The temporal pattern of fire activity in Africa is illustrated in figure 3, which shows the month by which 50% of all fire pixels had been detected in a given cell. There is a progressively later onset of the fire season, linked with the passage of the dry season, from north to south in the Northern Hemisphere while there is a west

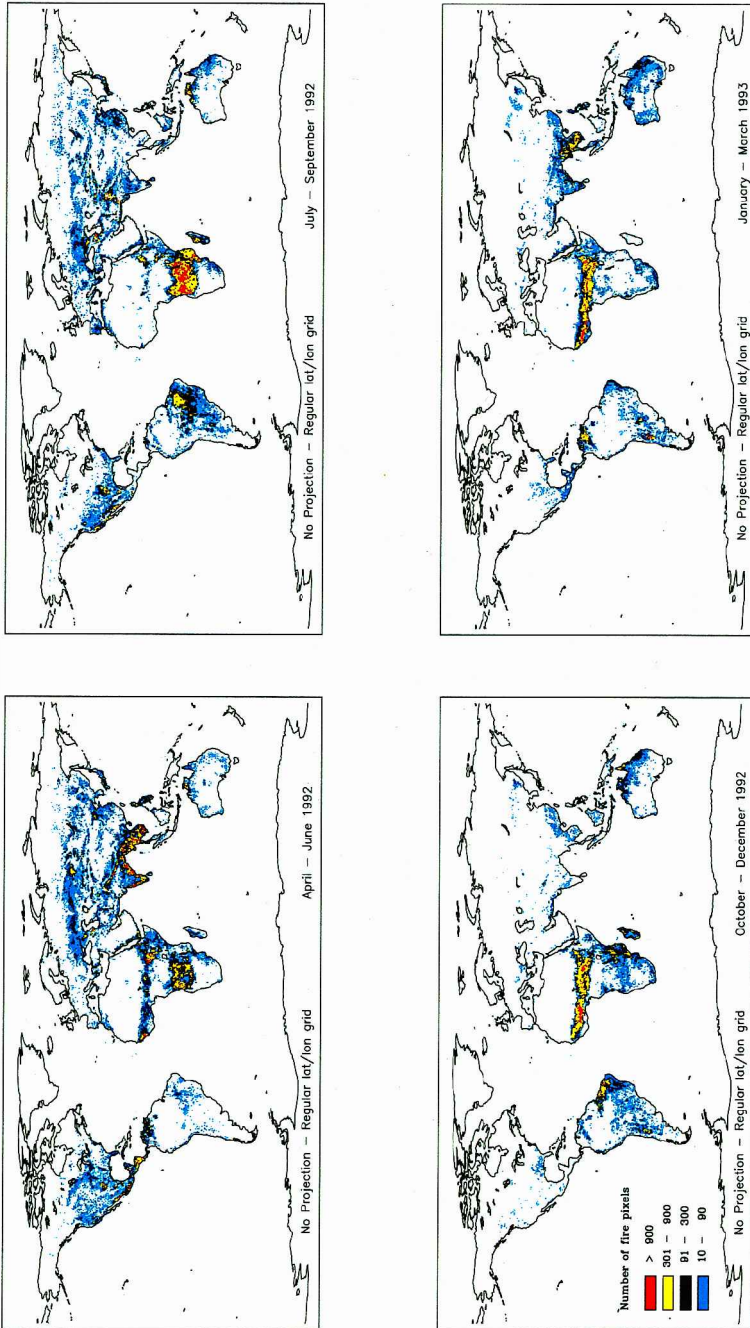


Figure 1. The number of fire pixels detected in cells of $0.5^\circ \times 0.5^\circ$ over 3-month periods is shown. Those cells containing less than ten fire pixels are not indicated as they unrealistically exaggerate the amount of burning in this type of representation.

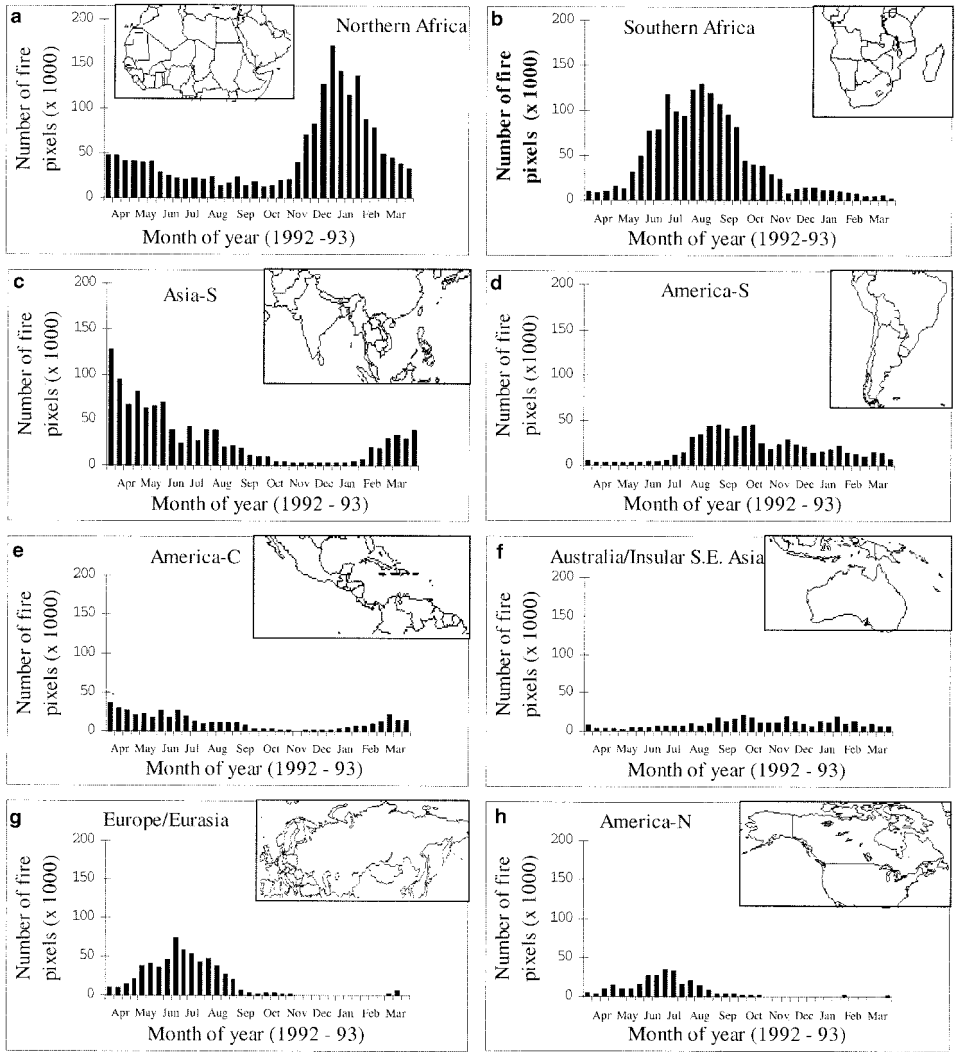


Figure 2. The world was divided into eight regions considering both land masses and the timing of the fire season. The number of fire pixels (in thousands) detected in each region for each 10-day period from 1 April 1992 to 27 March 1993 is shown.

to east movement south of the equator. This type of information can be extracted from the data set for any part of the globe.

In southern Asia there are three main regions of activity (figure 1 and figure 2(c)). In peninsular south-east Asia the fire season runs from late January to mid-May, with the highest activity being detected in early April. This late dry season burning is associated with forest areas and may be due to shifting cultivation, since the most efficient burns are achieved after prolonged drying of felled vegetation (Jones 1997). In eastern India and in particular in the Orissa province there is burning from late February with a peak in activity in early June, after which burning decreases very rapidly. According to Joshi (1992), 90% of the area affected by forest fire in India is in the Orissa province; however estimates of total fire occurrence in India are

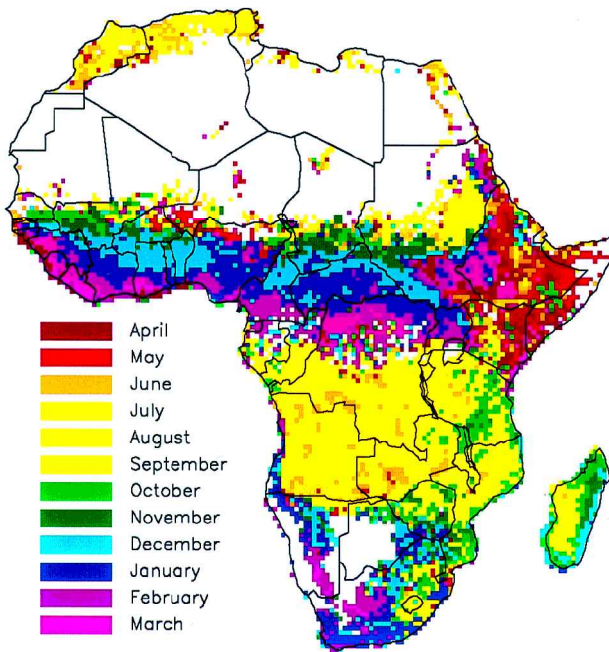


Figure 3. The month by which 50% of the fire pixels had been detected in Africa in each cell of $0.5^\circ \times 0.5^\circ$ is shown. The areas in white correspond to arid regions and were masked before fire detection. The timing of the fire season is useful in evaluating fire effects on vegetation and ecosystems and also in determining the direction in which emissions will travel.

widely varying. Fires detected on the slopes of the Himalayas are associated with graziers who annually burn the forest litter layer; this forms a very slippery surface and can be dangerous for cattle (Goldammer and Peñafiel 1990). The third region in which many fire events were detected is in eastern China; fire pixels can be detected in the plains drained by the Yangtze and Yellow rivers between late May and August. Burning of field residues from rice, wheat, maize and other crops is increasing in China as organic composts are replaced by chemical fertilisers and industry switches to fossil fuels (Zhuang *et al.* 1996). Some false detections due to Sun glint from water occur in this extensively irrigated area.

Burning in South America, south of the equator, begins in June, with peak activity remaining practically constant from late August to mid-October (figure 2(d)). Most of the burning takes place in the grasslands of north-east Brazil, where ranchers use fire in the management of grazing areas and small farmers burn crop residues. In September burning is most intense in the states of Mato Grosso and Rondonia, towards the border with Bolivia. These observations are in very good agreement with those of the Instituto Nacional de Pesquisas Espaciais (INPE) (Miranda *et al.* 1994). We also detected fire pixels in Argentina, on or near the lower slopes of the Andes, from November to early March. As this is during the austral summer, many of these may be spurious detections due to hot bare soil and the salt flats of the 'Salinas Grandes'.

In the Central American region, shown in figure 2(e)—which for the purposes of this study includes South American countries north of the equator—there is a south

to north migration in the burning pattern. In Venezuela and Colombia savanna burning starts towards the end of January reaching a peak in early April after which it dies off. Burning in Central American countries peaks about a month later and continues, with fires being observed in Mexico into early August.

Most of the burning events in Australia are in the savanna grasslands of Arnhem Land in the so-called 'Top-End' of the Northern Territory. These fires move in a west to east direction across the province from May to November (figure 2(f)). In the east in Queensland and along the southern coast, there is widespread low-level burning activity which reaches a peak in January and February. The location and timing of the fires detected are in good agreement with known fire patterns in Australia (Tapper *et al.* 1993). In insular south-east Asia, in particular in New Guinea and Borneo, burning occurs from August to November, with a high density of fire events observed in southern New Guinea. The widespread burning which occurred in these regions in 1997 and into 1998 was favoured by an abnormally long dry season which allowed fires to spread more easily and uncontrollably.

The Europe/Eurasia window (figure 2(g)) covers the largest geographical area of all the regions investigated. This region is characterized by a well defined fire season from April to September, outside of which very few fire events were detected. In the Mediterranean regions fire activity reaches a maximum at the end of July and beginning of August. A large band of fire stretches across Eurasia from the Black Sea to Lake Baikal and beyond, starting in early April and dying out towards the end of August. Here, fires are started by farmers to clear land and burn crop residues, and if not properly controlled can spread to nearby forested lands. In the more northern latitudes of Siberia there is widespread low-density fire activity in July and August. Fires due to lightning are frequent in the Taiga and are important in controlling forest regeneration and conditions (Cahoon *et al.* 1996, Goldammer and Furyaev 1996).

In North America most of the burning takes place over quite a short season between May and August (figure 2(h)). Although low-density burning is observed across the region there are three main areas of activity. The region of most dense activity runs through Kansas, Oklahoma and Texas where the peak activity is in late June and early July. Burning to clear agricultural fields is common practise in this area and fires have also been observed here by the GOES satellite (http://cimss.ssec.wisc.edu/goes/misc/fires_ok.html). Another band of fire activity stretches down the west coast from Washington state to California and into Arizona. As certain regions of these states are arid there may be some false detections due to hot soil. There is also a band of fire activity stretching from the Great Lakes up past Lake Winnipeg in Canada. This is a region of frequent fire activity as reported by the Canadian Forest Service (<http://fms.nofc.cfs.nrcan.qc.ca/cwfs/index.html>). There is a high inter-annual variability in burning. The number of fires reported in Canada in 1992 was about average, however the area of forest land burned was one of the lowest in the last 25 years (http://www.nrcan.qc.ca:80/cfs/proj/iepb/nfdp/frames2_e.htm). About ten times as many fires were detected in the US as compared with Canada. This is broadly in line with the figures reported by Stocks and Trollope (1993). Prescribed burning as a means of forest management is common in North America, however, the small proportion (~10%) of wildfires caused by lightning is responsible for about 90% of the area burned (Cofer *et al.* 1996).

3.3. Vegetation types affected by burning

The IGBP-DIS has been co-ordinating a project to produce a global land cover map at a resolution of 1 km using AVHRR data. This map has been recently made available and, although it is still undergoing verification and validation, it represents the highest resolution and most up-to-date map of global land cover available (Loveland and Belward 1997). Using the 25 class United States Geological Survey (USGS) legend supplied we determined the fire distribution among the different vegetation types. Almost 90% of all the fire pixels detected were found in eight vegetation types. Table 1 shows the percentage of dry land surface covered by each of these vegetation types, the proportion of each type affected by fire and the percentage of the Earth's land surface this represents. Although fires were detected in over 6% of 1 km land pixels in the course of the year, this does not mean that this much surface area was burned. Each fire pixel detected covers a surface area from approximately 1 km² to 12 km², depending on the sensor scan angle, and can contain one or more fires of unknown dimensions and intensity. The actual fire size and burn efficiency depends on the vegetation type, moisture loading and meteorological conditions at the time of burning. Area burned should not be extrapolated from the fire position data.

Savanna fires are predominant, accounting for the largest proportion of pixels containing fires. Broadleaf forest also experiences burning, with a larger proportion of deciduous forests affected than evergreens. Croplands, which are the third largest contributor, are often burned in order to remove residues after harvesting, as noted above. However, the impact of fire on the ecosystems or atmosphere cannot be simply inferred from the number of fires detected alone. For example, in boreal ecosystems, the annual number of fire events is quite small in terms of global activity, however, the amount of biomass, both above and below ground, that is consumed can be enormous, resulting in the release of carbon stocks that may have been accumulated over hundreds of years (Kasischke 1996).

Table 2 shows the regional distribution of burning for each of these eight

Table 1. Vegetation types affected by fire. The eight vegetation types, as defined in the IGBP-DIS land cover map, which showed the most fire activity account for 66% of the Earth's land surface. Varying amounts of each vegetation type were affected by fire, however, savanna burning was the most widespread.

Vegetation type	Per cent of global land surface	Per cent of 1 km ² vegetation pixels with fires	Per cent of global 1 km ² land pixels with fire
Savanna	11	19	2.1
Evergreen broadleaf forest	10	7	0.7
Deciduous broadleaf forest	5	13	0.6
Dryland crops and pasture	9	6	0.5
Shrubland	12	4	0.5
Cropland/woodland mosaic	7	7	0.5
Irrigated crops and pasture	3	14	0.4
Grassland	9	4	0.3

Table 2. Percentage of fire pixels in each region as percentage of total observed in each vegetation type.

	Northern Africa	Southern Africa	Southern Asia	South America	Central America	Australia/ Pacific	Europe/ Eurasia	North America
Savanna	51	27	4	3	5	8	1	1
Evergreen broadleaf forest	36	24	13	13	9	5	0	0
Deciduous broadleaf forest	0	78	11	3	6	0	1	1
Dryland crops and pasture	6	5	27	6	10	3	36	7
Shrubland	26	3	16	15	8	13	10	9
Cropland/woodland mosaic	9	30	11	36	2	0	11	1
Irrigated crops and pasture	1	0	85	0	3	1	8	2
Grassland	10	6	7	23	5	3	26	17

vegetation types, where the regions are as described previously. Over three quarters of savanna burning occurs on the African continent. In the evergreen forest domain 60% of the fires were observed in Africa while fires in the Central and South American regions contribute another 20%. Deciduous forest is dominated by fires in southern Africa. Dry cropland fires are mostly seen in the Eurasian and southern Asian windows, while burning in irrigated crop areas is almost exclusively confined to Asia. However, care must be taken in the interpretation of this last figure, as it is known that many false detections result from Sun glint from temporary water surfaces that have not been masked due to the lack of an appropriate digital data set. Grassland fires are seen in the more temperate regions of South America, North America and Eurasia. As the land cover map used is general, using only 25 classes to map the whole globe, some important details are masked. For example, the class mapped as deciduous forest in southern Africa is commonly known as miombo, which is open woodland dominated by small trees and shrubs and which is regularly burned.

4. Discussion

The production of a 21-month daily inventory of active vegetation fire occurrence and the analysis of a 12-month portion of it represents the first attempt to characterize one aspect of biomass burning on a global scale using direct observations of the phenomenon. Fires occur throughout the year but there is a strong spatial and temporal variability. Although the majority of fire events were observed in the tropics, much fire activity was also present in temperate and boreal regions. Accurate information at a sub-regional resolution on the timing and duration of the fire season is necessary in order to improve estimates of quantities of biomass consumed and correlate fire events with the emission and transport of gaseous products and particulates (Kim and Newchurch 1998).

Scholes *et al.* (1996) have shown, as part of the SAFARI-92 experiment in southern Africa, how fire counts as determined from AVHRR satellite imagery can be calibrated, using high resolution data, to areas burned and thus used to determine the quantity of biomass consumed. Their estimates are smaller than those calculated using

non-remotely sensed data, but they believe they are more realistic, even though fire counts are not as accurate as direct measurements of area burned. Research into determining suitable algorithms to detect and quantify burned areas using satellite data at regional and global scales is ongoing (Barbosa *et al.* 1998, Pereira 1998, Roy *et al.* 1998).

A number of international interdisciplinary projects have expressed a need for biomass burning related information. The GFP provides one piece of this complex jigsaw puzzle. The International Global Atmospheric Chemistry (IGAC) project needs information to quantify trace gas emissions and to determine their spatial and temporal patterns of occurrence (Scholes *et al.* 1996) and the impact of aerosols on the atmospheric radiation budget (Andreae 1997). Analysis of the role of fire in land cover maintenance and change is one of the research aims of the Land-Use and Land-Cover Change (LUCC) Project (IGBP 1995), while the Global Change and Terrestrial Ecosystems (GCTE) project looks at the role of fire as a disturbance factor in ecosystem dynamics (IGBP 1992). We are currently investigating the relationship between climatic conditions and fire patterns observed. This is an important first step in helping us to determine how current fire regimes may be modified under a changed climate.

Although remote sensing offers an unprecedented opportunity to carry out global monitoring, there are a number of limitations in fire detection using the AVHRR sensor alone. AVHRR imagery only represents a snapshot of the total number of fires which burn in any 24-hour period, fire counts may be either overestimated or underestimated due to confusion with hot surfaces and Sun glint from reflective surfaces such as water and clouds. Although flaming fires with fronts as short as 50 m can be detected, in general no information on the fire characteristics (e.g. size, temperature) is available. However, this single observation system approach will soon be qualitatively and quantitatively improved by combining global data sets of both active fires and burned areas from different Earth observing systems such as the Japanese Earth Resources Satellite (J-ERS) Synthetic Aperture Radar (SAR), the Along Track Scanning Radiometer (ATSR) data set from the European Space Agency (ESA) ERS, the VEGETATION instrument on SPOT, the Moderate Resolution Imaging Spectroradiometer (MODIS) data set from the Earth Observing System (EOS) and other small satellites specifically designed for fire detection.

Acknowledgments

The satellite data processed and analysed in this study were provided by the USGS EDC Sioux Falls (US) and ESA/ESRIN Frascati (Italy) in the framework of IGBP-DIS activities. The assistance of J. Eidenshink in securing the data is acknowledged. E.D. was supported by a doctoral grant from the European Commission's TMR programme.

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