SAFARI 2000 1-Degree Estimates of Burned Biomass, Area, and Emissions, 2000

Abstract

A new method is described for estimating the amount of monthly averaged biomass burned with spatial variations of 1 by 1 degree in southern Africa. Using this new method, emissions of trace gases and aerosols from open fires are estimated from burned areas, fuel load maps, combustion factors, and emission factors.

Global burned area data sets for the year 2000 (GBA2000) supplemented with the Along Track Scanning Radiometer (ATSR) fire count data sets have been employed to quantify the area burned at 1-km resolution by using a fractional vegetation cover map derived from satellite observations. To account for the spatial heterogeneity in main types of vegetation within each 1-km grid cell, fuel load maps have been developed from biomass density data sets for herbaceous and tree covered land together with fractional tree and vegetation cover maps. To represent the fire characteristics, land cover is classified into forests, woodlands, and grasslands, based on satellite-derived data sets for fractional tree cover. The combustion factor (CF) takes into account fuel composition, tree cover density, and the dryness of herbaceous vegetation for fires in forests, woodlands, and grasslands, respectively. The effect of variation in fuel conditions for grasslands on the combustion factor is derived from the percentage of green grass to total grass (PGREEN), which is related to satellite-based leaf area index (LAI) data for 1999 and 2000. In addition, the emission factors (EF) for grassland fires are designed to represent the spatial and seasonal variations associated with the fuel conditions by making use of the modified combustion efficiency. The emissions in southern Africa were analyzed using different techniques for calculating the combustion factors and emission factors for grassland fires. This analysis suggests the importance of accounting for the seasonal variation in both CF and EF in order to determine the appropriate temporal variations in emissions of trace gases and aerosols.

Annual amounts of total area burned and CO_2 emissions for southern Africa are

compared to those from other authors. The differences in emissions from biomass burning can be ascribed to different vegetation cover data sets and the assumed fuel load for woody vegetation rather than the area burned.

Background Information

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Project: SAFARI 2000

Data Set Title: SAFARI 2000 1-Degree Estimates of Burned Biomass, Area, and Emissions, 2000

Site: Southern Africa
Westernmost Longitude: -18
Easternmost Longitude: 56
Northernmost Latitude: 0
Southernmost Latitude: -36

Data Set Citation:

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Data File Information

This data set contains spatial and temporal estimates of trace gas and aerosol emissions from open fires in southern Africa for 8 separate data variables:

Acetic Acid (CH_3COOH)
Methanol (CH_3OH)
Methane (CH_4)

Carbon Dioxide (CO_2)
Carbon Monoxide (CO)
Formaldehyde (HCHO)
Non-Methane Hydrocarbons (NMHC)
Particulate Matter (less than 2.5 µm in diameter) ($PM_{2.5}$)

There are 3 different types of data files: monthly ASCII maps (.asc) and monthly ASCII map data files (.dat) for each variable for each modeled scenario; and a regional monthly emissions data file (.csv) which provides total monthly emissions estimates for each trace gas and $PM_{2.5}$. The model runs four different "scenarios" (labeled "Sc1", "Sc2", "Sc3", and "Sc4"), each having a different set of model output files. These "scenarios" are described in detail in the "Fuel Load Model" section of this document.

The monthly ASCII scenario maps (.asc) are on a 1 degree grid, and have 74 columns and 36 rows, with space-delimited ASCII numbers. The monthly ASCII scenario data files (.dat) are the map data in column format (the first 74 values are all 0-1S and progress from 18W to 56E, then next 74 values are the next line of the map, etc.). The emissions data file (emission_totals.csv) is a comma-delimited ASCII file containing total emissions for the region by variable by month.

File naming conventions are as follows:

"emi_scN_xxx_2000-08.asc" is the monthly ASCII map for August 2000 (kg) (74x36 pixels)
"emi_scN_xxx_2000-08.dat" is the monthly ASCII data file for August 2000 (kg)
"emi_scN_xxx_2000-09.asc" is the monthly ASCII map for September 2000 (kg) (74x36 pixels)
"emi_scN_xxx_2000-09.dat" is the monthly ASCII data file for September 2000 (kg)
"emission_totals.csv" is the monthly totals for August & September 2000 (Tg)

where "N" is the "scenario" number (1-4) and "xxx" is one of the following variable abbreviations:

- "ch3cooh" is acetic acid
- "ch3oh" is methanol

- "ch4" is methane
- "co2" is carbon dioxide
- "co" is carbon monoxide
- "hcho" is formaldehyde
- "nmhc" is non-methane hydrocarbons
- "pm" is particulate matter less than 2.5 µm in diameter

Method for Estimating Biomass Burning Emissions

The total amount of burned biomass (M_{ijt}) for open fires can be described by the following equation (Seiler and Crutzen, 1980):

$$M_{ijt} = \sum ([A]_{ijt} \times [B]_{ijt} \times [CF]_{ijt}) \qquad (1)$$

where A is the monthly (t) burned area (m^2) at location i and the fuel class j within a grid, B is the fuel load (kg m^{-2}) expressed on a dry mass (DM) basis, and CF is the fraction of available fuel which burns (the combustion factor). In this work, the fuel loads are differentiated between herbaceous and tree covered land even in each 1km grid of burned area (see below). Separate methods for calculating combustion factors are applied to grasslands, woodlands, and forests, respectively. The amount of biomass burned is used to estimate emissions of carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), non-methane hydrocarbons (NMHC), formaldehyde (HCHO), methanol (CH_3OH), acetic acid (CH_3COOH), and particulate matter less than 2.5 µm in diameter (PM).

Area Burned

The determination of the monthly burned area was based on new satellite remote-sensing techniques and procedures (Grégoire et al., 2003). The GBA2000 data were developed from a coalition of researchers working to develop estimates of burned area in different regions using the SPOT-VEGETATION S1 (one-day composite) imagery. Each group was responsible for the validation of their algorithm in their region. The global data for the year 2000 were provided on a 1 km x 1 km grid resolution each month. Each cell was specified as either burned ("1") or not burned ("0"). An assessment of the accuracy of the classification tree in GBA2000 shows that it performed very well at classifying the unburned areas

(Silva et al., 2003). However, it is understood that the small fires are not always detected in the GBA2000. In contrast, the Along Track Scanning Radiometer (ATSR) fire algorithm can detect small hot spots of order 0.1 ha for detection of a 600° K and 0.01 ha hot spot for an 800° K fire (Arino and Melinotte, 1998), although the total ATSR fire count is underestimated because it only detects fires at night (Arino and Plummer, 2001). In this work, the ATSR fire counts are used to compensate for the underestimation of fires in GBA2000.

Because the values of the burned area occurrence were given as either a "0" or "1" in each 1 km x 1 km area, the burned area detected by remote sensing includes any land covered by wood, grass, and bare ground within those cells. Additionally, the ATSR data set contains a number of events from heat sources other than vegetation fires. Therefore we accounted for the effects of bare ground on the area burned using a separate data set of fractional vegetation cover for each 1 km x 1 km grid:

$$[A]_{ijt} = [A']_{ijt} \times [Fc] \qquad (2)$$

where A' is the burned areas detected by satellite and Fc is the fractional vegetation cover. The available 1-km fractional vegetation cover was derived from the Advanced Very High Resolution Radiometer (AVHRR) Normalized Difference Vegetation Index (NDVI) data for 1992 - 1993, based on the annual maximum NDVI value for each pixel in comparison with the NDVI value that corresponds to 100% vegetation cover for each IGBP land cover type (Zeng et al., 2000).

Vegetation Cover Data Set

In order to estimate the fuels exposed to fires, vegetation cover was examined from three different tree cover data sets (referred to as TC1, TC2, and TC3), which were derived from different sources and methods (see Table 1).

Table 1. Summary of data sets and parameterizations used in the estimation of emissions.

Name [a]	Sources	Method	Year
TC1	DeFries et al., 2000	Linear mixture model + classification	1992-1993
TC2	Zhu and Waller, 2001	Modified linear mixture model	1995-1996
TC3	Hansen et al., 2003	Regression model	2000-2001
CF1	see Table 5 & 6	Compilation of measurements	
CF2	Hély et al., 2003	Exponential model + TC2	1995-1996
CF3	Hoffa et al., 1999	Linear regression model + LAI [b]	2000-2000
EF1	see Table 7	Compilation of measurements	
EF2	see Table 8	Linear regression model + LAI	2000-2000

[a] TC=Tree cover, CF=Combustion factor, EF=Emission factor

[b] Leaf area index from Myneni et al. (2001).

The first data set (TC1) used the AVHRR satellite data set for 1992 - 1993 (DeFries et al., 2000), the second (TC2) used AVHRR for 1995 - 1996 (Zhu and Waller, 2001), and the third data set (TC3) used the Moderate Resolution Imaging Spectroradiomter (MODIS) satellite data set for 2000 - 2001 (Hansen et al., 2003). TC1, which was a prototype of TC3, used a linear mixture model, based on spectral signatures of end-members or pure pixels of forest, grassland, and bare ground training, with some adjustments in regions where results were known to be biased (DeFries et al., 2000). It is difficult for the mixture model to distinguish the percentage tree cover at extreme high and low percentage tree cover. Thus, the tree cover range for TC1 in the original data set covered 0.1 to 0.8, with 0.1 representing tree cover less than or equal to 10% and 0.8 representing tree cover greater than or equal to 80%. For our comparison analysis, we simply used the indicated tree cover percentage. TC2, developed for the Forest Resources Assessment (FRA) 2000 report (Saket, 2001), was produced using temporal compositing of AVHRR NDVI and modified mixture analysis. TC3 employs continuous training data over the whole range of tree cover as opposed to a linear mixture model (Hansen et al., 2002). We also examined differences in the estimated forest area burned using the 1 km International Geosphere-Biosphere Programme (IGBP) land cover data set which was produced through a continent-by-continent unsupervised classification of 1 km AVHRR NDVI composites with ancillary data analysis (Loveland et al., 2000). This data covered 1992 - 1993.

In this work, the land cover type was classified into three classes: forests, woodlands, and grasslands, based on the percentage of tree canopy cover. Forests were defined as those regions with greater than 60% canopy cover, woodlands were defined as those regions with 40-60% canopy cover, and grasslands were defined as those areas with less than or equal to 40% canopy cover (Matthews, 1983; Hansen et al., 2000). The averaged tree cover data in the burned areas detected by the GBA2000 (A') for each vegetation cover type and each tree cover data set is shown in Table 2.

Table 2. Comparison of the average tree cover in burned areas detected by GBA2000 for three tree cover density data sets.

Vegetation Cover	Grasslands	Woodlands	Forests
Tree cover	0.0 - 0.4	0.4 - 0.6	0.6 - 1.0
TC1 (0.1 - 0.8) [a,b]	0.15	0.49	0.75
TC2 (0.01 - 1) [a,c]	0.08	0.50	0.78
TC3 (0 - 1) [a,d]	0.17	0.50	0.68
Average	0.13 ± 0.05 [e]	0.50 ± 0.004 [e]	0.74 ± 0.05 [e]
RSD [f] (%)	38	0.8	6.8

[a] Values in parenthesis represent the tree cover range of the original data set.
[b] DeFries et al. (2000)
[c] Zhu and Waller (2001)
[d] Hansen et al. (2003)
[e] Standard deviation.
[f] Relative standard deviation.

The average tree cover for grasslands differs by as much as 0.09 between the data sets, and the relative standard deviation (RSD) is high, i.e. 38%, while that for woodlands is similar in all three data sets. The tree cover in forests for TC3 is the smallest at 68%, in spite of the fact that the values for tree cover ranged from 0-100% in the original data set, unlike the data for TC1. Our area burned data set (GBA2000) represents the year of 2000, while the MODIS (TC3) tree cover data refers to October 31, 2000 to December 9, 2001. It is inevitable that the fractional tree cover in the tree cover data set derived from MODIS has been reduced compared to the actual tree cover for the GBA2000 time period, because some areas covered by trees were burned from January 2000 to October 2000. On the other hand, the TC2 data set probably represents higher tree cover than those from the year 2000, since it was developed from data for earlier time periods. It is difficult to classify TC1 as either too high or too low tree cover density, since it was developed without differentiating tree cover greater than 80% or less than 10%. As we shall see, the differences in tree cover from these data sets have important implications for the amount of forested area burned.

To illustrate the differences in area burned in different land cover types detected by GBA2000 (A') for different tree cover data sets, the annual area burned in grasslands, woodlands, and forests are compared for the three different tree cover maps in Table 3.

Table 3. Comparison of annual amounts of area burned (10^3 km^2 yr^{-1}) from different tree cover maps for sub-Saharan Africa.

Cover Type	TC1	TC2	TC3	IGBP [a]	Average	RSD (%)
Grasslands	1522	1795	1745	-	1690 ± 140	9
Woodlands	858	353	531	-	580 ± 260	44
Forests	29	262	133	70	130 ± 100	82

[a] IGBP land cover map for 1992 - 1993 (Loveland et al., 2000).

This table also compares the forest areas burned for the IGBP tree cover map (Loveland et al., 2000). The consistency of the area burned estimates for different land-cover categories varies significantly. Overall, the area burned in grasslands is the most consistent among the tree cover maps with a low RSD of only 5%, while woodlands and forests varied significantly with a high average RSD of 39% and 57%, respectively. The total forest area burned from the TC2 data set is substantially larger than that from TC3, by a factor of 2. The smaller forested area burned in TC3 could be associated with the fact that this data set was developed for the period October 31, 2000 to December 9, 2001, and, as such, would have smaller areas associated with forests if these forests burned prior to October 30, 2000. The total area classified as forests and as burned in TC1 is substantially smaller than in either TC2, TC3, or IGBP. Since the land cover determined for TC3 represents a new approach based on the MODIS instrument, it should provide an improved description of tree cover (Hansen et al., 2002). However, because of the time period for this data set, it could indicate the minimum area burned for forests in 2000. This discussion suggests that TC2 may be the most appropriate tree cover data set for use with burned areas in 2000. Therefore, the TC2 was used for our estimates.

Living Tree Biomass Density Data Sets

The potential biomass density of forests with a minimum of 10% crown cover for Africa was estimated using a weighted overlay of four input parameters: mean annual precipitation, a climatic index, elevation and slope, and soil depth and texture class (Brown and Gaston, 1995). Weighting factors were adjusted through an iterative process by comparing results to known localities. These spatial distributions of biomass density in Africa were obtained from Carbon Dioxide Information Analysis Center (CDIAC) at 5-km (Brown and Gaston, 1996). We separated the aboveground forest biomass into the biomass of leaves and above-stump woody biomass using the average ratios of foliage to above-stump tree biomass of 9.3% and 2.5% for evergreen and deciduous forests, respectively, determined for mid-Atlantic forests in the U.S. (Jenkins et al., 2001), because no data was available that was specific to areas of Africa. The median ratio of 5.9% between evergreen and deciduous forests was used for the leaf biomass of mixed forests.

Herbaceous Cover Biomass Density

Biomass density data for herbaceous cover (i.e. shrubs and grass) is derived from an estimate for the maximum standing biomass (excluding trees) in savannas. The following equation of biomass versus annual rainfall has been applied to obtain the amount of carbon release in Guinea savannas (Menaut et al., 1991).

$$(\text{Biomass}) = 4.9 \times 10^{-3} \times (\text{Annual rainfall}) - 0.58 \qquad (3)$$

This equation was used in this work to estimate the maximum biomass in herbaceous cover. Interannual variability in the aboveground production of grassland biomass was accounted for by using the monthly precipitation data from the Global Precipitation Climatology Project (GPCP) of the Laboratory for Atmospheres, NASA Goddard Space Flight Center (GSFC). This data set is available at a resolution of 0.5° x 0.5° and was used for the annual rainfall from 1999 to 2000 (Roads et al., 2003).

To evaluate the use of eq. (3) globally, we used data sets for the biomass density at 42 grassland sites distributed around the world (Gill et al., 2002). The average biomass density compiled by Gill et al. (2002) together with that estimated from eq. (3) and local long-term measurements of annual precipitation from these 42 sites is shown in Table 4.

Table 4. Comparison of biomass density (kg DM m-2) in grasslands.

	Gill et al. (2002)	Long-term mean [a]	2000 [b]
Average	0.291	0.244	0.425
Minimum	0.080	0.070	0.023
Maximum	0.933	0.582	1.338
Standard Deviation	0.156	0.124	0.265

[a] Biomass density calculated from the equation (3) and the long-term mean of precipitation obtained at each location (Gill et al., 2002).
[b] Biomass density calculated from the equation (3) and annual precipitation interpolated at each location from 0.5° x 0.5° grid (Roads et al., 2003).

We also show the estimated biomass density for 2000 at these sites based on the annual precipitation interpolated from the GPCP data set. The average biomass density calculated from the long-term mean precipitation at each location (0.244 ± 0.124 kg DM m^{-2}) is in good agreement with the measured biomass density (0.291 ± 0.156 kg DM m^{-2}). The average biomass density estimated from the precipitation in 1999-2000 is higher (i.e., 0.425 kg DM m^{-2}), which is associated with the interannual variations of the annual precipitation at each site. We conclude that this is a reasonable method for estimating the maximum herbaceous cover biomass density.

Fine Litter Fuel Load

Litter pool (also referred to as forest floor mass or littermass) is defined as recently fallen litter and decomposing organic matter above the mineral soil. The fine litter pools were obtained from a compilation of biomass density measurements for different vegetation types (Matthews, 1997). We distributed the pools from Matthews (1997) models 1D (as described in Table 6 from that paper) to the Matthews (1983) vegetation cover map which is available at a resolution of 1° x 1°. These values of fine litter masses were used to estimate fuel loads.

Coarse Woody Debris Fuel Load

Matthews (1997) employed the technique outlined in Harmon and Hua (1991) to estimate the pool of coarse woody debris (CWD), based on measured relationships between the CWD pools and live wood biomass. They report ratios of CWD to live wood biomass of 5% for tropical rainforests, shrublands, and grasslands, and ~20-25% for subtropical, temperate, and boreal forests. Here, we used the live tree biomass data set derived here and the Harmon and Hua (1991) ecosystem ratios of CWD to live tree biomass with the ecosystem map from Matthews (1983). These values of CWD were used to estimate fuel loads.

Soil Organic Carbon

Available data sets of soil organic carbon (SOC) density (kg C m^{-2}) for 0 - 30 cm depth range and for 0 - 100 cm depth range on a 1/2 by 1/2 degree global grid were obtained from the International Soil Reference and Information Centre (ISRIC). The data sets have been derived from version 1.0 of the World Inventory of Soil Emission Potential Database (WISE) profile database, linked to a 0.5 by 0.5 degree raster version of the FAO Soil Map of the World (Batjes, 1996). An average burned depth of 51 cm was assumed based on the field measurements reported by Page et al. (2002). It should be noted, however, that the depth of peat burned varied between 25 and 85 cm for the measurements analyzed by Page et al. (2002), so that the use of a single average depth for this factor introduces a degree of uncertainty. The values of SOC for 0 - 51 cm depth were interpolated from those for 0 - 30 cm and 0 - 100 cm using a log-log model, which captures the vertical distribution of SOC (Jobbágy and Jackson, 2000). On average, 60% of the total organic carbon in the upper 100 cm of soil is held in the first 30 cm, while 73% is in the first 51 cm.

Fuel Load Model

Fire behavior can be described by the following four types of propagation:

- Surface fires of aboveground fuels
- High-intensity crown fires of living trees or high intensity fires of felled trees
- Burning of pastures associated with land conversion
- Smoldering fires (i.e., oxygen-starved, inefficient consumption of the fuel) of dead and downed logs and ground-layer carbon (e.g., lichen, moss, and organic soil).

We use these categories of fire types to define the fuel load subject to burning in each 1 x 1 km grid.

In general, the low-intensity fires do not consume the biomass of live shrubs and trees in savanna ecosystem (Shea et al., 1996; Hoffa et al., 1999). Therefore, we conservatively assumed that the living tree components and coarse woody debris were not burned in grasslands. Moreover, living wood and dead wood more than 5 cm in diameter is not traditionally counted as part of the fuel load in savannas (e. g., Scholes et al., 1996a). In woodlands, large-diameter woody fuels were consumed by pasture-maintenance burns (Kauffman et al., 1998; Guild et al., 1998) and by the residual smoldering fires after a flaming front passes (Bertschi et al., 2003). Recently, fire mortality factors for coarse wood were introduced in estimates of the fuel load available to burn (van der Werf et al., 2003). Here, we consider 4 scenarios in estimating the long-term emissions from residual smoldering combustion of large logs in woodlands. First, we define the Residual Smoldering Factor (RSF) as the fraction of residual smoldering combustion of large wood that is burned as a result of residual smoldering combustion (Equations 5 and 6). In scenario 1 (Sc1) we assume that only the area associated with the ATSR fire counts is subject to long-lasting fires which consume large logs (RSF=1), while in scenario 2 (Sc2), all of the fires in all burned areas consume the coarse fuels. In addition, we define a tree felled factor (TFF). In scenarios 1 and 2, the TFF is equal to 1, meaning that all trees to be burned are assumed to be felled so that the coarse woody fuels include both the CWD defined above and the living trees that have subsequently been felled. As can be seen in Table 3, the burned area in grasslands determined by TC3, which represents the tree cover after October 31, 2000, is only slightly larger than that determined by TC2, which represents the tree cover in 1995-1996. If all other aspects of these two tree cover analyses were equal, this would mean that the tree-covered areas in woodlands were not completely converted to grasslands in the intervening years between 1996 and 2000. Therefore, it is unlikely that all of the trees in burned areas in woodlands were subject to clearing as assumed in Sc2. Scenarios 3 and 4 correspond to the assumptions for area subject to residual smoldering as in scenarios 1 and 2, but TFF was set to 0, which means that no trees are assumed to have been felled so that the coarse fuels that burn only include the CWD.

In forested regions, we assumed that fires could consume part of the living or felled trees. Therefore, our fuel load included some of this component (see below). In addition, in forests, fuel consumption of belowground fuels of organic soil carbon was included in all scenarios of Sc1, Sc2, Sc3, and Sc4, since this burning can be important (Page et al., 2002).

Based on this model, for each land cover type (grassland, woodland or forest), biomass density data were represented for the two vegetation cover types (herbaceous and tree cover) within each 1-km grid by the following five categories: Aboveground fine and coarse living tissue biomass, aboveground fine and coarse litter, and SOC. The biomass density data for each living fuel type was derived from available biomass data sets for each region, as described above. We developed living tree biomass data for woody and leafy parts, separately, while estimates for the living biomass density of grasslands were based on the relationship between rainfall and in-situ biomass density measurements (see above). Data sets for fine litter, CWD, and SOC were also available for southern Africa.

In order to account for the horizontal allocation of the biomass, fractional tree and herbaceous covered vegetation areas were separately estimated to derive the average biomass fuel load in each 1-km grid cell. The biomass densities of tree-covered regions were allocated to the fractional area associated with trees. The biomass density data of herbaceous covered areas predicted from the relationship between a rainfall and biomass density were distributed in the fraction of area not covered by trees and not counted as bare ground. Thus, the average fuel load ($[B]_{ijt}$) in each 1 km x 1 km cell was calculated from the fuel load for herbaceous cover ($[B]_{iht}$), the fine litter pool fuel load ($[B]_{if}$), the CWD ($[B]_{ic}$), the living wood fuel load ($[B]_{iw}$), the living leaf fuel load ($[B]_{il}$), and belowground fuel load ($[B]_{ib}$) in each land cover type according to:

Grasslands (Tc <= 40%):

$$[B]_{ijt} = Hc \times [B]_{iht} + Tc \times [B]_{if} \quad (4)$$

Woodlands (40% < Tc < 60%):

$$[B]_{ijt} = Hc \times [B]_{iht} + Tc \times \{[B]_{if} + [B]_{il} + RSF \times ([B]_{ic} + TFF \times [B]_{iw})\} \quad (5)$$

Forests (Tc > 60%):

$$[B]_{ijt} = Hc \times [B]_{iht} + Tc \times \{[B]_{if} + [B]_{il} + RSF \times ([B]_{ic} + [B]_{iw} + [B]_{ib})\} \quad (6)$$

- Sc1: RSF = 1 and TFF = 1 in only grid cells where ATSR fire counts are detected.
- Sc2: RSF = 1 and TFF = 1 in all grid cells.
- Sc3: RSF = 1 and TFF = 0 in only grid cells where ATSR fire counts are detected.
- Sc4: RSF = 1 and TFF = 0 in all grid cells.

where Hc is the fractional herbaceous cover (= Fc - Tc), Tc is the fractional tree cover, Fc is the fractional vegetation cover, and TFF represents whether the trees are felled or not. The fuel load maps were interpolated by the nearest-neighbor non-zero values in grid boxes where there was no data.

Combustion Factor

The combustion factor (CF) is the fraction of biomass exposed to fire that is actually consumed. The CF is mainly determined by fuel type, fuel spatial arrangement, and fuel moisture content. The CF for all fuel types in forests assumed an average combustion factor, and is described below. The CF in woodlands depends only on the tree cover fraction, while the CF in grasslands is a dynamic combustion factor that depends on the moisture condition of the fuel. We also examined two other assumptions for the CF in grasslands based on (1) an average CF for grasslands and (2) the tree cover fraction. The comparison of the use of these three assumptions in grasslands with measurements is used to argue for the need for methods to treat the effect of moisture and fuel arrangement on CF in woodlands and forests in the future.

Combustion Fraction in Forests

The average CF for herbaceous vegetation in forests is assumed to be 0.99 as determined for 13 field measurements of grassland fires in Africa (Shea et al., 1996). The average CF for fine and coarse fuels was estimated from field measurements of CF obtained from detailed studies in tropical rainforests as summarized in Table 5 (Fearnside et al., 1993, 1999, 2001; Carvalho et al., 1998, 2001; Guild et al., 1998; Araújo et al., 1999; Graça et al., 1999).

Table 5. Combustion factors for fine and coarse fuels in forests from various sources.

Study	Fine Fuels [a]	Course Fuels [b]	Aboveground Fuels
Fearnside et al., (1993)	1.00	0.26	0.29
Fearnside et al., (1999)	0.97	0.32	0.43
Fearnside et al., (2001)	0.68	0.26	0.30
Carvalho et al., (1998)	0.88	0.14	0.20
Carvalho et al., (2001)	0.92	0.26	0.33
Guild et al., (1998)	0.95	0.47	0.51
Araújo et al., (1999)	0.83	0.13	0.20
Graça et al., (1999)	0.96	0.29	0.36
Combustion Factor [c]	0.90 ± 0.10	0.27 ± 0.09	0.33 ± 0.10
RSD [d] (%)	12	40	32

[a] Litter and leaves.
[b] Wood such as branches and trunks.
[c] Averages of CF for fine fuels and coarse fuels were separately used in this study.
[d] Relative standard deviation.

Typically, the original forests are slashed and burned by property owners at these sites towards the end of the dry season. The CF for this vegetation was determined from the percentage difference in biomass before and after burning for fine fuels (such as litter and leaves) and for coarse fuels (such as wood) separately. These CFs for fine and coarse fuels are presented in Table 5. The combustion factor for fine dry fuels from these studies is relatively high at 0.90 ± 0.10. In contrast, the

CF for coarse fuels is low at 0.27 with a high RSD of 40%. Since the fuel loads for fine and coarse fuels are differentiated in our model, the average CF for fine fuels and coarse fuels were separately used to estimate the biomass burned in living tree biomass and litter in forests.

Because crown fires are not differentiated from slash fires in this work, the average CF summarized in Table 5 was compared with those measured in other fires. We find a weighted average CF of 0.33 ± 0.10 for total aboveground fuels. This is similar to the CF found in high consumption severity fires in the Alaskan boreal forest (French et al., 2003). This agreement indicates that a CF of order 0.3 may be representative of the large-area fires detected by remote sensing in most regions.

All of the soil organic matter for 0 - 51 cm depth in forested regions was treated as fuel loads. The CF for SOC was assumed to be 33.9% in peat-covered areas (Page et al., 2002).

The CF is influenced by the fuel conditions (moisture content, packing density). Methods for determining biomass burning that predict these conditions have the advantage of representing such parameters within each ecosystem and may therefore yield more accurate estimates of CF. However, because the amount of data available to estimate CF is so limited, we feel that this simple approach (using constant emission factors) is justified at the present time.

Combustion Fraction in Woodlands

Because the percentage tree cover controls the fuel type distribution in each pixel and, thus, influences fire propagation and intensity, Hély et al. (2003) developed an empirical relationship between CF and Tc based on dry season fires in Zambia and South Africa during the SAFARI 1992 campaigns and a fire in the Etosha National Park of Namibia. Here, we apply this relationship to herbaceous fuels, leaves, and fine litter in woodlands:

$$CF = \exp(-0.013 \times (Tc)) \quad (40\% < Tc > 60\%) \qquad (7)$$

Because this model was developed for fuel loads such as grass, litter, and small woody debris in southern Africa at the end of dry season, in applying it throughout the season, we are assuming that regional fuels in the burning seasons are sufficiently dry to ignore the dependency of CF on moisture content.

We used an average combustion factor for CWD (2.55 < diameter cm) in woodlands based on the field measurements summarized in Table 6 (Kauffman et al., 1998; Guild et al., 1998). An average value of 30% was used for our estimates of the burning of coarse woody fuels in woodlands.

Table 6. Combustion factors for coarse fuels in woodlands from various sources.

Study	Study Areas	Course Fuels [a]
Kauffmann et al. (1998)	Rondônia	0.09
Kauffmann et al. (1998)	Rondônia	0.28
Kauffmann et al. (1998)	Pará	0.61
Guild et al. (1998)	Pará	0.20
Combustion Factor [b]	-	0.30 ± 0.20
RSD [c] (%)	-	66

[a] Wood such as branches and trunks.
[b] Averages ± standard deviation.
[c] Relative standard deviation.

Combustion Factor in Grasslands

The combustion factor in grasslands can be determined from the percentage of green grass to total grass (PGREEN) which accounts for the seasonal and spatial variation in CF (Hoffa et al., 1999). In this work, PGREEN was estimated from the LAI as derived by Myneni et al. (1997) from the maximum NDVI value in global composites of the NOAA/NASA Pathfinder AVHRR Land data set. The derivation of LAI used an algorithm that incorporates results from a three-dimensional radiative transfer model and a six biome classification scheme (Myneni et al., 1997). The data set of monthly averaged LAI at 16-km resolution was available from 1999 to 2000.

It was assumed that the maximum LAI of the monthly averages in the growing season represented the total grass available to burn within a season. Then, the parameter PGREEN was estimated from the ratio of the LAI of the monthly averages to the maximum monthly average LAI over the growing season. The relationship between PGREEN and CF derived in Hoffa et al. (1999) was applied to herbaceous fuels and fine litter in grasslands:

$$CF3 = - 213 (PGREEN) + 138 \qquad (Tc <= 40\%) \qquad (8)$$

We limited CF3 to the range from 0.44 to 0.98 to avoid any extrapolation beyond measured values for grassland fires.

We also explored the range of estimates associated with assuming (1) an average CF in grasslands (taken as 0.99 as above for herbaceous cover in forest) and (2) the method used for determining the CF for herbaceous cover in woodlands, Eq. 7. These three methods in grasslands are designated CF1 (for the constant value), CF2 (for the values based on Eq. (7)), and CF3 (for the value based on Eq. (9).

Emission Factor

The total emissions of gases and particles are calculated from the following,

$$Q (X) = M \times EF (X) \qquad (9)$$

where X is chemical species and EF is the emission factor in gram species per kilogram of dry matter burned. The emissions factors for fuels in woodlands and forests assumed an average emission factor, designated here as EF1. To account for the type of combustion (e.g., flaming and smoldering fires), we used an approach based on relating the emission factor to the combustion efficiency of the fuel in grassland fuels (designated EF2). We compared these results in grasslands to a result using average emission factors for savanna and grasslands recommended in Andrea and Merlet (2001) and Yokelson et al. (2003).

Emission Factors Used for Woodlands and Forests

Measurements of EFs in different regions were reviewed and tabulated by Andreae and Merlet (2001). The averaged EFs for CO_2, CO, CH_4, NMHC, and $PM_{2.5}$ for savanna and grasslands from Table 1 in that paper were applied to our woodland vegetation cover types (except for the emission factors associated with smoldering fires of coarse fuels), while those for HCHO, CH_3OH, and CH_3COOH were taken from recent measurements (Yokelson et al., 2003). Those from tropical forests in Table 1 from Andreae and Merlet (2001) were applied to our forests except for the smoldering fires of SOC. Emission factors for CO_2, CO, CH_4, HCHO, CH_3OH, and CH_3COOH from smoldering fires of coarse fuels in woodlands and SOC in forests were taken from those measured for logs and organic soils, respectively (Bertschi et al., 2003). These EFs are summarized in Table 7.

Table 7. Emission factors from various sources.[a]

Species	CO_2	CO	CH_4	NMHC	HCHO	CH_3OH	CH_3COOH	$PM_{2.5}$
Woodland	1613	65	2.3	3.4	1.06	1.17	2.42	5.4
CWD in Woodlands	1454	158	23.2	8.3 [b]	3.48	8.09	8.43	13.1 [b]
Tropical Forest + CWD	1580	104	6.8	8.1	1.4	2	2.1	9.1
SOC in Forests	1436	112	9	8.7 [c]	0.49	1.07	1.43	9.80 [c]

[a] Andreae and Merlet (2001); Bertschi et al. (2003); Yevich and Logan (2003); Yokelson et al. (2003).

[b] EF determined from the measurements summarized by Andreae and Merlet (2001) and used here for woodlands and the ratio of emissions of CO for CWD determined by Bertschi et al. (2003) and Andreae and Merlet (2001) emissions of CO in woodlands.

[c] The EF was determined from the measurements summarized by Andreae and Merlet (2001) and used here for forests and the ratio of emissions of CO for CWD determined by Bertschi et al. (2003) and Andreae and Merlet (2001) emissions of CO in forests.

Emission Factors in Grasslands

Emission factors are expected to change with season due to the nature of the combustion. Fuels are moister during the early part of the season causing more smoldering combustion. The amount of smoldering combustion can be estimated from the modified combustion efficiency (MCE), which is the ratio of CO_2 emitted to the sum of CO and CO_2, because emissions of the products of incomplete combustion (PIC), such as CO, are relatively larger during smoldering combustion (Ward and Radke, 1993). The MCE can be related to PGREEN by (Hoffa et al., 1999):

$$MCE = -0.286\,(PGREEN) + 1.019 \quad (Tc <= 40\%) \tag{10}$$

The range for MCE in grasslands was limited to 0.908 to 0.966.

Here, we used a linear regression to relate compound-specific emission factors to MCE based on field measurements for savanna and grassland fires in Africa, Australia, and Alaska (Hurst et al., 1994a, b; Andreae et al., 1996; Ward et al., 1996; Goode et al., 2000; Shirai et al., 2003; Sinha et al., 2003; Yokelson et al., 2003). Thus, our linear model is based on data from a wide variety of independent fire measurements varying from tropical to boreal zone fuels. The number of measurements (n) ranges from 11 to 27.

$EF(CO_2) = 2134\,(MCE) - 311.2$	(n=27)	(11)
$EF(CO) = -1134\,(MCE) + 1135$	(n=27)	(12)
$EF(CH_4) = -51.8\,(MCE) + 50.253$	(n=26)	(13)
$EF(NMHC) = -45.96\,(MCE) + 46.358$	(n=17)	(14)
$EF(PM_{2.5}) = -86.67\,(MCE) + 85.985$	(n=11)	(15)

When EF of three species of CO_2, CO, and CH_4 were measured for the same fires by both Gas Chromatography on Canister Samples (CG/C) (Sinha et al., 2003) and Airborne Fourier Transform Infrared Spectroscopy (AFTIR) (Yokelson et al., 2003), the AFTIR values were used in this work. In addition, the equations for HCHO, CH_3OH, and CH_3COOH were taken from Yokelson et al. (2003).

$EF (HCHO) = - 44.196 (MCE) + 43.003$ (16)

$EF (CH_3OH) = - 33.321 (MCE) + 32.407$ (17)

$EF (CH_3COOH) = - 74.696 (MCE) + 72.583$ (18)

Comparison of Dynamic and Average EFs in Grasslands

In addition to the dynamic EF for grasslands described above, we also examined the use of the average EF determined by Andreae and Merlet (2001) and Yokelson et al. (2003) in grasslands. Table 8 shows the globally and seasonally averaged estimates of the EF for CO_2, CO, CH_4, NMHC, HCHO, CH_3OH, and CH_3COOH, and $PM_{2.5}$ for grassland fires.

Table 8. Comparison of average emission factors for grasslands.

Species	EF1 This Study	EF2 Andreae and Merlet (2001)	EF2 Yokelson et al. (2003)
CO_2 (g-CO_2 kg-DM^{-1})	1694	1613	1703
CO (g-CO kg-DM^{-1})	69.4	65	71.5
CH_4 (g-CH_4 kg-DM^{-1})	2.16	2.3	2.19
NHMC (g-NMHC kg-DM^{-1})	3.17	3.4	-
HCHO (g-HCHO kg-DM^{-1})	1.47	0.26 - 0.44	1.06
CH_3OH (g-CH_3OH kg-DM^{-1})	1.09	1.3	1.17
HAc [a] (g-CH_3COOH kg-DM^{-1})	2.37	1.3	2.42
$PM_{2.5}$ (g-$PM_{2.5}$ kg-DM^{-1})	4.54	5.4	-

[a] Acetic acid

The average emission factors from the compilation of Andreae and Merlet (2001) and measurements of Yokelson et al. (2003) used for the regression model here are also shown. As shown there, the emission factors for CO_2, CO, CH_4, NMHC are in good agreement within 10%, but the emission factor of HCHO which is based on the data of Yokelson et al. (2003) was out of the range of Andreae and Merlet (2001). These results suggest that the modeled relationship between EF and MCE can be used to estimate the emissions for grasslands globally, but that further work may be needed to define the appropriate emission factor for HCHO.

Results and Discussion

The combustion factors used in woodlands and grasslands in this work were primarily based on field experiments in southern Africa. Here, our estimates are described and evaluated by comparison with measurements in southern Africa.

Emissions from Southern Africa

Table 9. Comparison of annual amounts of areas burned and CO_2 emissions from open fires in southern Africa from different studies.

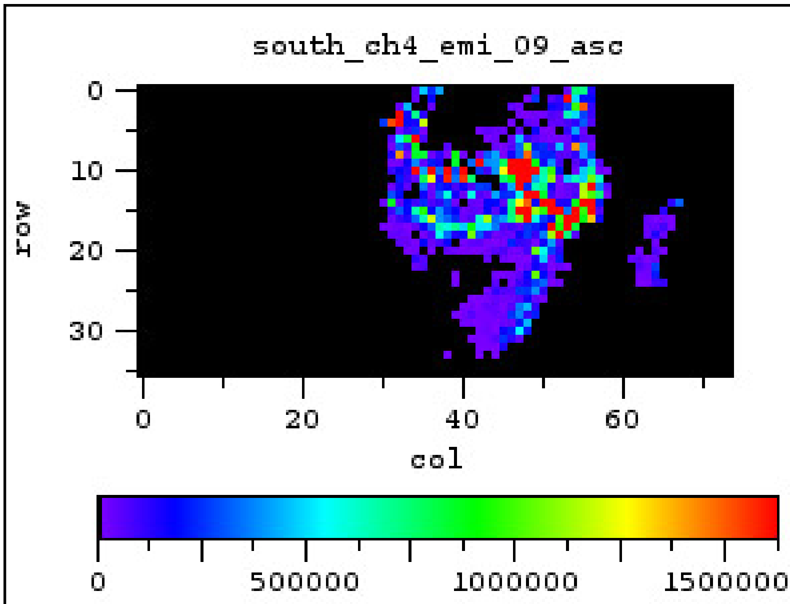
Study	Areas burned (10^3 km^2 yr^{-1})	Emissions (Tg CO_2 yr^{-1})	Emissions per unit area (TgCO_2 km^{-2})
This work	999	1644 - 2188 [a] (1639 - 1786)[b]	1.65 [c]
Hao et al. (1990)	-	1508	-
Scholes et al. (1996a, b)	1680	324	0.19
Barbosa et al. (1999)	1540	748	0.49
Justice et al. (2002)	-	1525	-
van der Werf et al. (2003)	1160	1702 [d]	1.47
Average	1345 ± 318	1242 ± 568 [a]	-
RSD (%)	24	46	-

[a] Statistics were estimated by using Sc1.
[b] Values in parenthesis represent the Scenarios 3 and 4.
[c] Value from Scenario 1.
[d] Estimated from the carbon emissions in van der Werf et al. [2003] assuming 90% is CO_2.

Our annual amounts of total area burned and $COCO_2$ emissions for Southern Africa are compared to those from other authors in Table 9. The estimates for emitted $COCO_2$ for southern Africa based on the Sc1 and Sc3 are in better agreement with previous estimates than those of Sc2 and Sc4. To examine differences based on fuel load, we also show the amount of CO_2 emitted per unit area burned. These differences in biomass burned per unit area can be ascribed to different vegetation cover data sets and the assumed fuel load for woody vegetation. For example, living wood and dead wood more than 5 cm in diameter were not counted as part of the fuel load that might burn in the lowest case (Scholes et al., 1996a), while above ground woody biomass as well as coarse woody debris were included in our estimates of the fuel load that might burn in woodlands [based on measurements by Kauffman et al. (1998), Guild et al. (1998), and Bertschi et al. (2003)] and in the estimate by van der Werf et al. (2003) in Table 9. Clearly, further work is necessary to quantify both the total woody biomass associated with the vegetation cover data sets and the conversion process from live woody biomass to slashed fuel loads available to burn for modeling total emissions and the CWD that burns.

Examples of the output from this data set are provided below

1-Degree Estimates of Biomass Burning Emissions, Southern Africa, September 2000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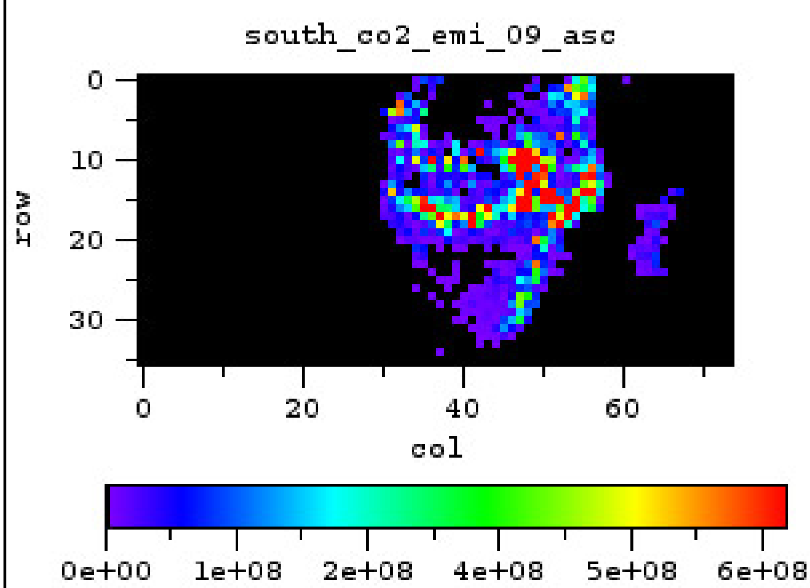
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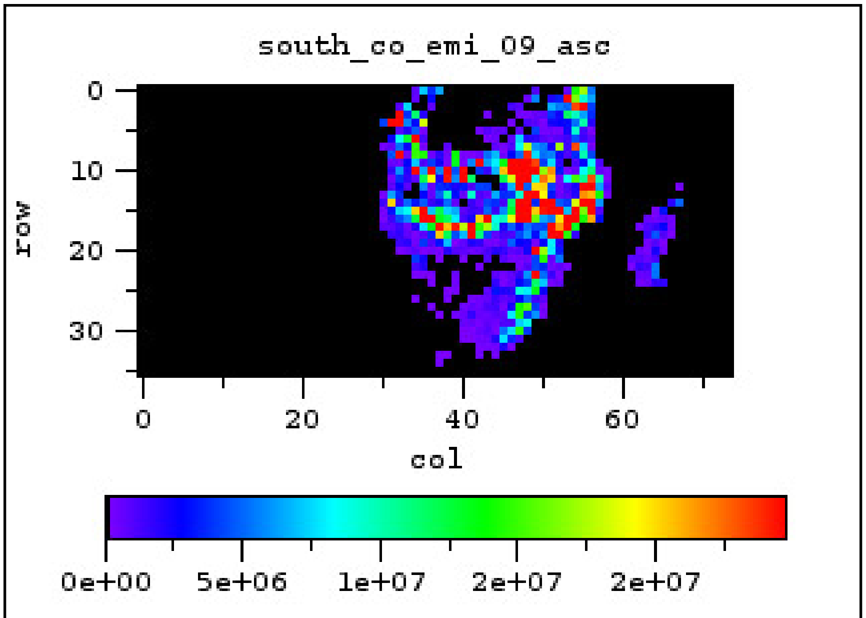
6e+08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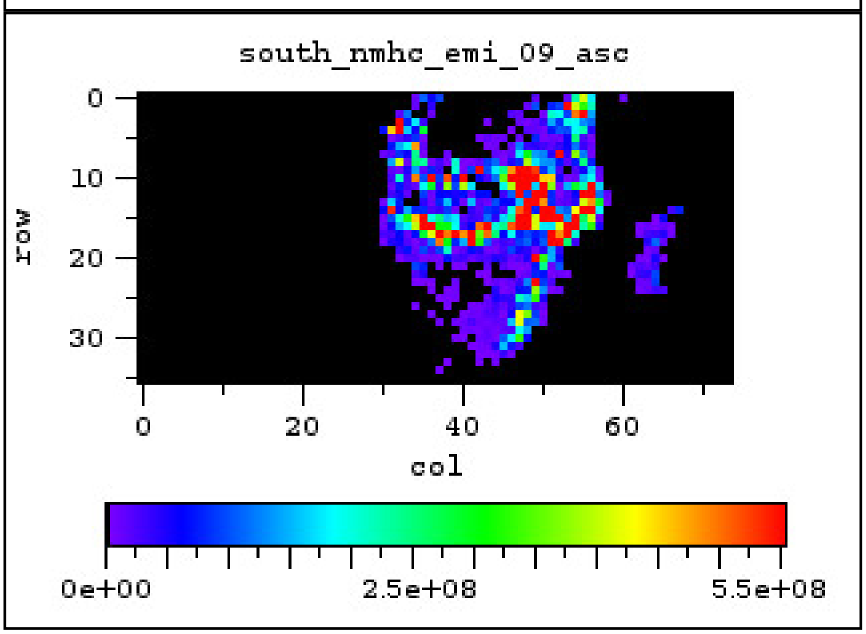
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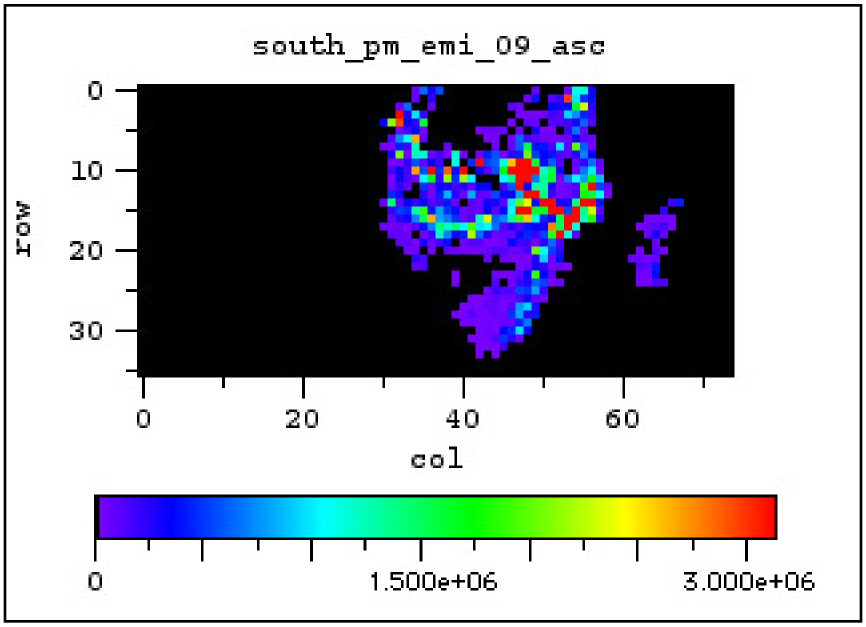

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