Emissions from Fire in Sub-Saharan Africa: the Magnitude of Sources, Their Variability and Uncertainty

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Abstract

About half of the global gas and particle emissions to the atmosphere resulting from the burning of biomass originate from sub-Saharan Africa. There are four principal pathways: wildfires, the use of biomass fuels for energy, burning associated with deforestation, and the burning of agricultural residues. The total amount of biomass consumed by all four pathways is estimated from a review of many studies to be around 1400 Tg dry matter per year, with a 95% confidence interval of 1,200 to 1,600 Tg DM/y. Of this about 57% is consumed by wildfires, 36% for domestic and industrial energy, and around 3% each as in-field combustion associated with land use change and agricultural residue burning. While the overall emissions are relatively well-constrained (an uncertainty of around ±14%, about the same size as the interannual variability) by convergence between bottom-up and top down measures, the contribution from individual sources, and of individual pyrogenic trace gases, remains much less certain.

Key words: burned area, fuel load, pyrogenic emissions

1. Introduction

Africa has been called 'the fiery continent' because of the extent of vegetation which burns every year (Fig. 1). Up to half of the global pyrogenic (fire-derived) emissions to the atmosphere have been estimated to originate in Africa (Barbosa *et al*., 1999; Korontzki *et al*., 2003), and these emissions have a substantial effect on the atmospheric composition both regionally and globally. The main extent of the fires is in the seasonal savannas north, south and east of the Congo Basin rainforests, but fires are also prominent in montane grasslands, seasonal wetlands and winter-rainfall thickets. Vegetation wildfires are not the only pyrogenic emission sources in Africa. The vast majority of Africans use biomass-based fuels for domestic and light-industrial or commercial energy, in the form of fuel wood, charcoal or dried dung. A portion of these biomass fuels originates in land clearing activities, and a further portion from agricultural residues. Although the rate of land clearing ('deforestation') in Africa has thus far been lower than has been recorded in South America and South-East Asia, the contribution of emissions from land clearing could increase in future. Agricultural residues are largely channelled into fodder or other uses in Africa, but in-field burning remains a small source of pyrogenic emissions.

The many ecological, atmospheric and social issues associated with fire in Africa have attracted much research over the past decades. Nevertheless, there are still widely divergent estimates of the area burned annually, the amount of fuel consumed, and the quantities of gases and aerosols emitted to the atmosphere as a consequence.

The uncertainty in the estimates has the following three sources:

1. The burned area and the fuel load are characterised by high inter-annual variability, largely associated with variation in the rainfall during the growing season immediately prior to the dry period in which the fire occurs. African savannas occupy a subtropical zone that is characterised by unusually high inter-annual rainfall variability – coefficients of variability of around 30% are typical. Some of the variation is associated with global climate modes such as El Niño and the Southern Oscillation. Contrary to the widely- held notion that dry periods are associated with more fire, both the burned area and the fuel consumed in savannas and grasslands are higher in fire seasons following an above-average rainfall year (Archibald *et al*., 2009).
2. The inclusion of different source terms in the various inventories. Some deal only with fires in savannas, while others also include fires in grasslands, shrublands, forests, wetlands, Mediterranean thickets (*fynbos*) and croplands. Most provide data for unconfined wildfires only (in reality, the overwhelming majority of 'wild' fires in Africa are ignited by people, as part of formal or informal land management practices). The emissions from the

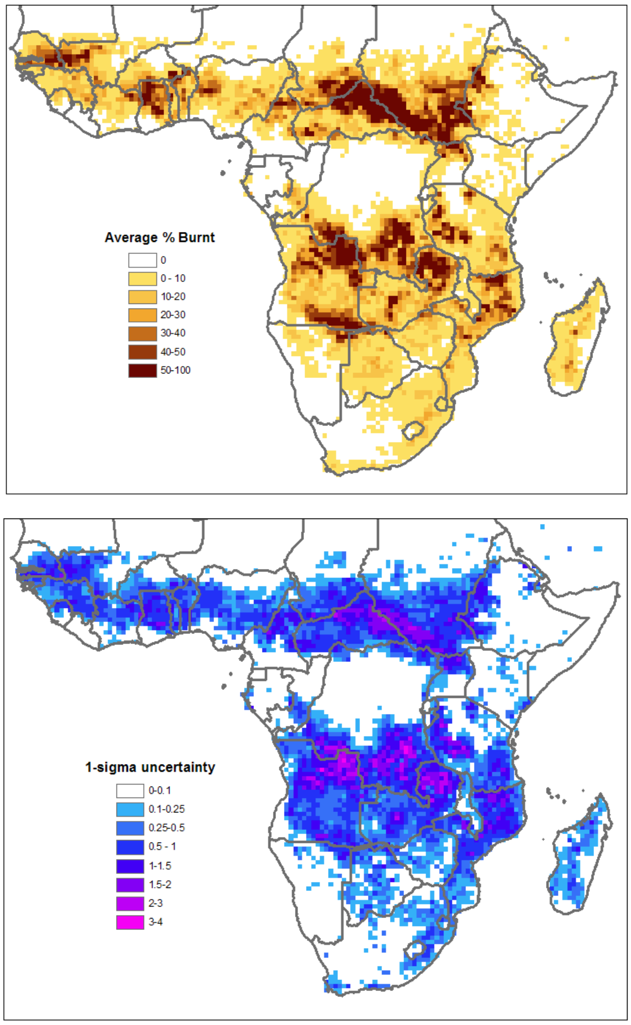

Fig. 1 Map of average burned area fraction in sub-Saharan Africa over twelve years, and associated uncertainty (1-σ) derived from the GFED3 dataset (Giglio *et al.*, 2010) at 0.5 degree resolution. The unburned area around the equator is rainforest, too wet to burn on a widespread basis.

burning of fuel wood and the production and burning of charcoal are typically studied by different groups of researchers and published in different sets of literature. Furthermore, they tend to be expressed on a national or subnational basis, rather than as spatially-gridded databases.

3. There are inherent (but usually unquantified) errors in all the estimates. The sample sizes are often small and not randomly distributed, and the parent populations are not normally distributed, making the risk of bias high. Many estimates depend on national statistics, which are of highly variable quality.

The objectives of this paper are to:

1. Critically review published estimates of the amount of biomass burned annually in Africa, considering the four main combustion pathways; and
2. Estimate their range of uncertainty and inter-annual variability.

The paper focuses on sub-Saharan Africa including Madagascar (SSA), an area of 25.434 million km^2. This zone is culturally and ecologically more coherent than geographic Africa as a whole. Biomass burning is a much less widespread phenomenon in North Africa.

2. The Four Main Ways in Which Biomass is Burned in Africa

2.1 Wildfires

Wildfires in Africa occur predominantly in savannas (including deciduous woodlands), with minor contributions from arid shrublands, sclerophyllous thickets (*fynbos* in South Africa), reedy or grassy wetlands and montane grasslands. Almost all are human-ignited, but few within formal land management plans. In the absence of human ignition, lightning ignition is also effective.

The first continental-scale estimates of area burned in Sub-Saharan Africa (SSA) were produced in the 1990s. These initial attempts used the extent of various land cover types and expert-based estimates of the mean fire return periods, spatially extrapolated using satellite-detected active fire observations (Hao *et al.*, 1990; Delmas. *et al.*, 1991). Later attempts provided these estimates spatially (Scholes. *et al.*, 1996; Hao & Lui, 1994), but at coarse resolution (5 degree).

Barbosa *et al.* (1999) derived burned area from the visible and near-infrared channels of the advanced very high resolution radiometer (AVHRR), rather than the thermal channels used for active fire detection. This allowed for more accurate burned area estimation. The 5-km-resolution data were validated against a sample of Landsat TM images (30 m resolution), and the accuracies were estimated to be around 70%. This multi-year study was able to assess inter-annual variability in burning. More recent satellite-derived datasets have improved in accuracy (see Section 3.1) and estimate that on average, Africa as a whole contributes about 70% (~2500*10^3 km^2) to the global burned area of ~4000*10^3 km^2 (Tansey *et al.*, 2008).

Relative to other parts of the world, Africa has quite a low interannual variability in burned area, around 12% (Giglio *et al.*, 2010, see also Van der Werf *et al.*, 2006). This is attributed to the fact that there are always enough sources of ignition and the grass fuel regrows very quickly after burning (Archibald *et al.*, 2009). The within-year seasonal variability is high, but because the area that burns in northern-hemisphere Africa is nearly the same in extent as that which burns in the southern hemisphere, the high local seasonality balances out at an all-Africa scale. Because such a large area burns in Africa every year, even this modest inter-annual variability has an observable impact on global-scale carbon budgets (Williams *et al.*, 2007).

The patterns of interannual variability in burned area in African savannas are different from those displayed in systems dominated by crown-fire regimes. This is because fire spread in African savannas is limited by the *amount* of fuel, rather than the *dryness* of the fuel. Thus burned area decreases in times of drought, and increases in fire seasons following a period of higher rainfall

(Archibald *et al.*, 2010a; Van der Werf, 2004).

Other new insights into burning in Africa relate to the spatial pattern of fire, and the role of humans in determining it (Archibald *et al.*, 2010b). Many parts of southern, eastern and western Africa have relatively high rural population densities. The people use the landscape intensively for agriculture and cattle grazing, activities which decrease and fragment the fuel load. Thus fires are unable to spread as easily as they would in less densely populated landscapes. In the densely populated regions the burned area consists mainly of many small fires. A multi-year analysis reveals that it is typically the same parts of the landscape that burn again and again, while other patches, habitually more heavily-used, remain unburned (Fig. 2). This observation explains why the landscape-scale burned area fraction, as estimated by remote sensing, is typically smaller than the inverse of the fire return time as observed on the ground, especially if the latter estimates are provided from anecdotal evidence rather than systematic fire scar mapping.

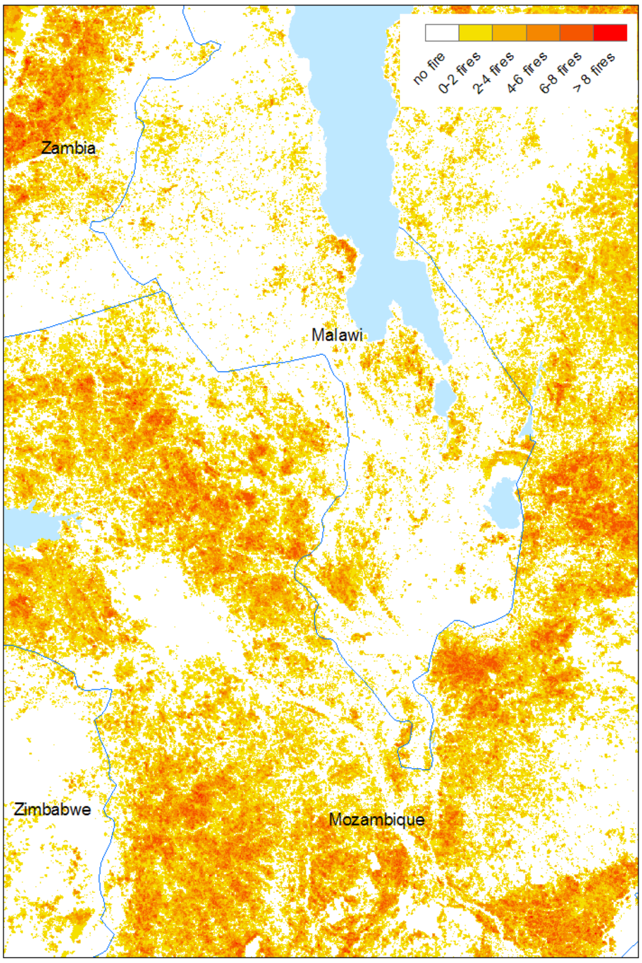

Fig. 2 Number of fires over an eight-year period in a heavily-utilised rural landscape in Malawi. The patches of the landscape that burn do so repeatedly, but most of the landscape remains unburned. This means that using fire return times to estimate burned area becomes problematic: the Mean Return Interval (MRI) for fires in Malawi is 3-4 years (Archibald, 2010) which would produce a burned area estimate of 20-30%. In reality, less than 10% burns every year.

2.2 Burning of agricultural residues

With some notable exceptions – such as sugar cane and cotton – in-field burning of crop residues is not a widespread practice in Africa. Crop residues are generally too valuable as forage for livestock, cropland mulches or domestic fuel to be 'wasted' through in-field burning, although accidental cropland fires do occur. In the case of sugar cane, the dense, dry 'slash' is burned prior to harvest to provide easier access for manual harvesting, suppress hazards such as snakes, and concentrate the sugar. The practice is in decline as mechanical harvesting increases and densely-populated areas encroach on cane fields. Cotton crop residue is burned post-harvest in some areas to control pests.

A major review on crop residue burning was conducted by Yevich and Logan (2003). They concluded that 173 Tg/year of residues (dry matter; DM) were produced in SSA, of which 47 Tg/y was used as biofuels and 48 Tg/y was burned in the field. No uncertainty estimates are provided, but given the sources used and the assumptions made, the uncertainties must be broad – perhaps ±50%.

The residues from plantation forests tend not to be noted by either the agricultural sector reviews or the forestry sector reviews. Plantation forests (typically *Pinus* and *Eucalyptus* species) generate biomass-burning emissions via three pathways. Firstly, the branches pruned during the growing cycle and the leaves and small branches that remain after felling are often burned to reduce the risk of uncontrollable wildfires breaking out in the accumulated fuel. Secondly, plantation forests occasionally burn by accident or as a result of arson. Thirdly, mill waste such as bark, sawdust and unmarketable off-cuts are burned, in one of three ways: in boilers at the sawmill to generate heat and electricity; as biofuel by-products for domestic use; or through uncontrolled smouldering of waste dumps. Plantation forests in SSA cover an area of 7.235 million ha (FRA, 2010), with the largest single area in South Africa (1.763 million ha, one third designated for pulp). In the South African case (Muller *et al.*, 1999), 200-230 g/m^2 of residues are generated in-plantation at the time of harvest (after a 10 to 20 year rotation) and the equivalent of a further 440 to 790 g/m^2 of waste is generated at the mill. Extrapolating these values to all of SSA suggests a residue stream of 3.1 to 4.9 Tg/y from plantation forests. The bulk of this plantation residue is burned as domestic or industrial fuel.

2.3 Combustion associated with land use change (deforestation)

Most land cover change in Africa occurs in savannas and forests, both of which cases qualify as 'deforestation.' Some of this change is at very-small-patch scales, or does not result in complete tree removal ('degradation') and is thus not easily detected using remote sensing. Achard *et al.* (2002), using coarse-resolution satellite images, estimated the net tropical humid forest deforestation rate in Africa over the period from 1990 to 1997 to be 0.71 million ha/y (0.36%/y), with a 95% confidence interval ± 0.31 Mha/y. The 'net' deforestation consisted of 0.85 ± 0.3 Mha/y of clearing of forests (0.43%/y) balanced by 0.14 ± 0.11 Mha/y of regrowth (0.07%/y). Achard *et al*. (2002) estimated that a further 0.39 ± 0.19 Mha of humid forest was degraded during the same period (0.21%/y). Duveiller *et al*. (2008), for the period 1990-2000 and applying a 3% systematic sample based on high-resolution satellite images in the Congo River basin only, estimated a net deforestation rate of 0.15%/y, consisting of a deforestation rate of 0.21 ± 0.05%/y and a regrowth rate of 0.05 ± 0.01%/y. They further estimated a degradation rate of 0.15 ± 0.03%/y and a recovery from degraded to dense forest of 0.6 ± 0.2%/y. The FAO's Forest Resources Assessment (FRA, 2001), based on a combination of satellite-derived and country-provided data, estimated a net deforestation rate 0.34%/y (1.2 million ha/y) for the whole of Africa for the decade of the 1990s. Brink and Eva (2009) applied a systematic 1% sample of high-resolution images over all of Africa and Madagascar for 1975 and 2000, to estimate a mean annual net loss rate for humid forests to be 0.64 Mha/y (which translates to a 0.18%/y rate in the Congo basin, for comparison with the above estimates). The net loss rate in dry forests was 2.26 Mha/y and in savannas, 2.2 Mha/y.

Citing Brown (1997) for estimates of aboveground biomass and adding 20% for roots, Achard *et al*. (2002) estimate African moist forests to have a carbon density of 17,900 gC/m^2, acknowledging that the uncertainty range could be as high as ± 60%. A series of assumptions regarding the various fates of this biomass following clearing (*e.g*., emitted as CO_2 at the time of harvest, presumably mostly through burning; subsequently emitted over a ten-year period, by decomposition of residue left *in situ*; emitted from harvested material removed from the site (mostly domestic burning); and decreased by the rate of re-accumulation of carbon on site) led to an estimate that about 57 TgC/y was emitted as a result of deforestation (excluding degradation, and only in humid forests) in Africa in the 1990 to 1997 period. Brink and Eva (2009) adjusted these values to 94 TgC/y from moist forests and 79 TgC/y from dry forests, and considered that the amounts resulting from savanna clearing were 'negligible.' The carbon content of savannas varies greatly, depending on the rainfall, soil clay percentage and tree cover, but we conservatively estimate 2,000 gC/m^2 aboveground, which means that if the same decay rates apply as for forests, savannas amount to a non-negligible emission stream of 36 TgC/y. We assume that most of this (perhaps 80%) is actually burned as biomass fuel, and it is accounted for there.

2.4 Biomass burned for energy

Fuel wood and charcoal remain the main energy source for the majority of households in Africa. It is estimated that 93%-94% of rural households in SSA and 58%-73% of urban households are reliant on either fuel wood or charcoal as their primary energy source (Bailis, 2005; IEA, 2006). Over 90% of urban households use charcoal in Kenya, Tanzania, Mozambique and Zambia (IEA, 2002). Estimating the total fuel and charcoal use in Africa remains difficult due to data constraints (Amos, 1999; IEA, 2008; Arnold *et al*., 2003). FAO conducted numerous fuel wood assessments during the 1970s and early 1980s, in response to the so-called "fuel wood crisis," but research interest waned during the later 1980s and 1990s (Arnold *et al*., 2003, 2006). There has been a recent revival of interest in the topic, inspired by the contribution of fuel wood to total energy use and as a driver of deforestation (Arnold *et al*., 2003, 2006; Zulu, 2010; World Bank, 2009). No recent synthesis has attempted a total wood fuel use estimate. A number of independent estimates suggest that approximately 90% of all wood extraction in Africa, including wood extraction from timber-harvesting in tropical forests, is used for fuel wood or charcoal (FAO, 2006; FRA, 2010).

3. Issues Relating to the Accuracy of Estimates

3.1 The area of land that burns

As the spatial resolution and sensitivity of satellite data products improved, so too did the algorithms used to identify burn scars, and several global burned area datasets have become available in the last decade. These include: the 1 km L3JRC product (Tansey *et al*., 2008); 1 km GLOBCARBON product (Plummer *et al*., 2006); the 500 m MCD45A1 product (Roy *et al*., 2008); as well as the GFED3 product (Giglio *et al*., 2010) which integrates various satellite fire data to a 0.5 degree grid. Validations of these products against Landsat TM data indicate that accuracy (defined as the percentage of correctly classified pixels) has increased to over 90%. The MODIS MCD45A1 and the GFED3 product perform significantly better than the others – although some vegetation types (for example surface fires underneath dense tree canopies) remain problematic (Roy & Boschetti, 2009; Giglio *et al*., 2009 and 2010; Tsela *et al*., 2010).

Giglio (2010) has performed the most comprehensive error analysis so far, and produced burned area maps with associated uncertainty estimates by integrating several different remotely-sensed products. Giglio's methods for calculating uncertainty varied depending on the type of data, but in general uncertainty coefficients for different parts of the globe and different months were determined through accuracy assessment against high-resolution images. These monthly uncertainties were then squared and summed to produce an overall uncertainty estimate for each grid cell. This method estimates uncertainties for Africa in the order of ±3% of the area burned for each pixel. Roy (2008) used a different method to assess the accuracy of similar products and found coefficients of determination (R^2) of 0.74, indicating substantial room for improvement in burnt area accounting. Despite this residual uncertainty, it appears that on average, Africa as a whole contributes about 70% ($\sim 2500*10^3$ km^2) to the global burned area of $\sim 4000*10^3$ km^2.

3.2 The biomass density that can potentially burn

The amount of aboveground biomass per unit area at a given location, the fraction of this which is potentially combustible because it is dry and within the reach of the flames, and the amount that actually burns given the weather at the time of the fire are three different things, though often mixed together in the literature. Particularly in savannas, which are the main vegetation type that burns in Africa, over 80% of the biomass is in the form of the stems of woody plants. Savanna fires are ground fires, largely burning the dead dry grass and leaf litter, sometimes igniting standing or fallen dead trees, and singeing the leaves of evergreen shrubs within the flame zone. The tree canopies are typically leafless during the fire season and the canopies of the few evergreen trees may be scorched, but are mostly too far above the flame zone to sustain combustion. The fires are insufficiently intense to ignite living stems. The potentially-combustible fuel, which we define as the sum of the live and dead standing grass and herbs, the shrub leaves up to a height of about 3 m, and the litter, twigs and downed logs on the ground surface, ranges from under 20 g/m^2 (below which fires tend to fail to propagate) to over 1,000 g/m^2, depending on:

- the productivity of the system, which is mostly a function of rainfall and soil fertility;
- the fraction tree cover (trees suppress grass and forb growth);
- the length of the period since the last fire; and
- the fraction of the production that is consumed by herbivores or people (Scholes *et al*., 1996).

Estimates of fuel load in Africa that are based on models of primary production (*e.g*., Van der Werf *et al*., 2003, 2006) tend to give estimates that are substantially higher than the average measured values. For instance, Van der Werf *et al*. (2006) suggest grass biomass estimates of ~580 g/m^2 for southern Africa, whereas a database of observed fuel loads in this region. Figure 3 indicates that a large portion of this landscape has fuels loads < 400 g/m^2.

Field measurements of fuel loads are labour-intensive. Here we report on a database of 60 fuel load measurements taken across a range of savanna and woodland environments in southern Africa at the beginning of the dry season. At each site many replicate samples of grass were clipped and weighed, and litter and twigs were collected and weighed separately. The quadrat samples were averaged for each site to produce estimates of fine, coarse, and woody fuels, with estimation 95% confidence

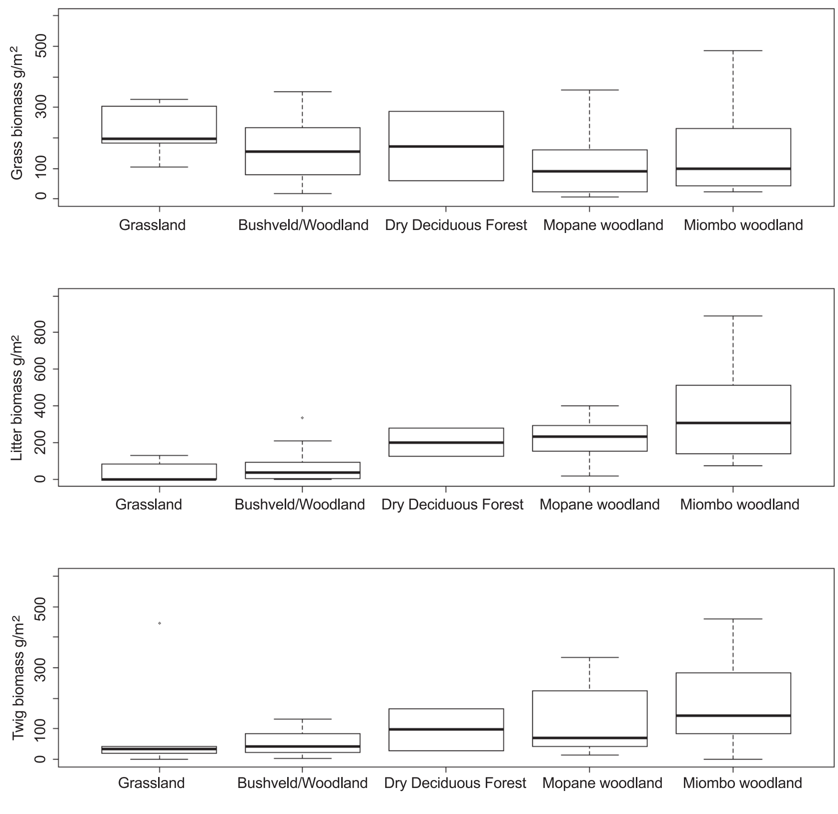

Fig. 3 Biomass of grass, litter and twig fuels for different vegetation types in southern Africa in order of generally increasing tree fraction cover. Data represent summaries from ~60 field measurements across southern Africa. Mean annual rainfall for the sites in each vegetation type: grassland – 740 mm, bushveld/woodland – 720mm, dry deciduous forest – 641 mm, mopane woodland 616mm, miombo woodland, 885 mm. Bushveld/woodland is a low(~5m tall), deciduous woodland, often dominated by trees from the family Combretaceae. Mopane woodland is a 2-10 m tall deciduous woodland highly dominated by Colophospermum mopane. Miombo woodland is a tall (~10 m) deciduous woodland containing many species, but typically dominated by trees from the genus Brachystegia.

ranges at a site level of around ±10%. The data are summarised by vegetation type to give an indication of the variability across the region (Fig. 3).

3.3 Combustion completeness

Combustion completeness is the fraction of the potentially combustible fuel that actually burns. It depends on the moisture content of the fuels (Hely *et al.*, 2003) and the intensity of the fire, and varies for each fuel type (Fig. 4). Combustion completeness ranges from nearly 100% in dry standing dead grass, to under 50% for slightly damp litter layers. It is not independent of fuel load, since the more fuel that becomes entrained in the fire, the more energy is released, igniting the wetter and coarser fuels and increasing the height range exposed to fire.

Monitoring of the energy released by fires provides an independent way of estimating the amount of fuel combusted. The instantaneous Fire Radiative Power (FRP) can be measured using the thermal channels of polar-orbiting earth observation satellites. Integrating this signal over the fire duration requires the use of coarser-resolution geostationary weather satellites, and yields Fire Radiative Energy (FRE), which is proportional to amount of fuel combusted (Kaufman *et al.*, 1998; Wooster *et al.*, 2003). The constant of proportionality differs somewhat from the energy content of the fuel, because corrections need to be made for the failure to detect small fires (<100 MW) and the attenuation of some of the radiated energy by the atmosphere, including complete blocking in the presence of clouds. Since the total amount of fuel combusted is the product of the area burned, the fuel load and fire completeness, the fuel loads can be calculated if the burned area is known and the completeness is estimated.

Using this logic, Roberts *et al.* (2005) estimated that for several large regions in southern Africa, the fuel combusted in forest, woodland (savanna), and open savanna or grassland fires was 490 ± 150, 270 ± 200 , and 150 ± 90 g/m^2 (± 1 SD), respectively. Ellicott *et al.*

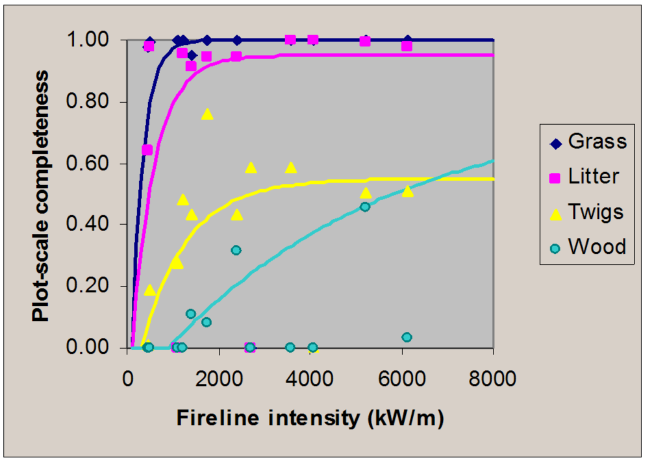

Fig. 4 Combustion completeness in different categories of fuel observed in savanna fires in southern Africa (data from Shea *et al.*, 1996). The fireline intensity is the rate of energy release along the burning edge of a fire.

(2009), using the FRE approach, assessed the biomass burned in Africa to be between 716 to 881 Tg DM/y, which translates to an average combusted fuel load of 279 to 344 g/m^2. These values are consistent with the measured fuel loads (taking into account combustion completeness, Shea *et al.*, 1996; and Fig. 4 in this paper) and the lower range of modelled fuel loads (Scholes *et al.*, 1996).

3.4 The amounts and sources of wood used as fuel

Household fuel use patterns vary substantially across Africa. The BEST 1994 study (Amous, 1999) found the use rate to be 1.4 Mg per capita in tropical southern Africa, while in West Sahelian Africa (where fuel wood is less available) 0.7 Mg per capita was used, and in North Africa only 0.2 Mg per capita (Amos, 1999). Bailis *et al.* (2005) found national per capita fuel wood consumption to range from less than 0.2 to over 1.5 Mg per capita in individual SSA countries. In urban areas, a shift from fuel wood to charcoal has been widely documented. For instance, it was found that in Bakoma and Mali, the proportion of charcoal-using households rose from under 5% in 1975 to close to 60% by 2000, as users swopped from wood to charcoal (Girard, 2002) In Dar-es-Salaam, Tanzania, urban charcoal use rose from 47% in 2001 to 71% in 2007 (World Bank, 2009). Considering the rapid urbanisation in most African countries, this represents a huge growth rate in total urban charcoal consumption. Households typically use more than one energy source, with the more expensive fuels used for lighting, and biomass-derived fuels used for cooking. Charcoal remains the principle energy source for the poor in most sub-Sahara African cities, though its use is relatively rare in South Africa, Botswana, Namibia and Zimbabwe. Some countries, such as Tanzania and Kenya, have attempted to ban charcoal from cities, but this has been ineffective and simply created an illegal charcoal trade, making the collection of charcoal use statistics more difficult (Mugo & Ong, 2006).

It is commonly accepted that the transition from traditional to modern fuels is strongly related to the level of economic development (Reddy, 1982; Cooke *et al.*, 2001). This suggests that fuel wood and charcoal dependence is likely to be a feature of African energy systems for the foreseeable future, especially given recent hikes in fossil fuel prices (Miranda *et al.*, 2010). Together with an estimated annual population growth rate of 2.5% in SSA (PRB, 2009), this suggests that total fuel wood and charcoal use will increase rather than decrease in the future (IEA, 2006; Arnold *et al.*, 2006; Broadhead *et al.*, 2001; World Bank, 2009).

Charcoal production in Africa tends to be performed in primitive earth-mound kilns, achieving an 8% - 15% energy conversion efficiency. It is acknowledged that skilled charcoal makers may achieve a substantially better efficiency (Kalumiana & Shakachite, 2003; Yigard, 2002; Pereira, 2001; Paddon, 1988). Green wood is typically used in the kilns, reducing charcoaling efficiency and increasing the emissions of volatile organic carbon compounds. Stove efficiency can also greatly alter the amount of charcoal needed to prepare a meal. Traditional charcoal stoves are estimated to have an efficiency of about 15%, while improved stoves reach 35%. By comparison, cooking on the traditional “three stone fireplace” has 5% - 10% efficiency (WEC, 1999). The higher efficiency of charcoal stoves when used for cooking can compensate for the inefficiencies during the charcoaling process. Though there have been many initiatives to promote improved charcoal stoves, it is probable that most households still use inefficient traditional hearths and stoves.

Charcoal production and fuel wood collection have different impacts on forested areas. During charcoal production, areas are totally cleared of all woody vegetation, including large trees. In contrast, rural fuel wood collection tends to target dead wood or smaller trees (Mugo & Ong, 2006).

The FAO bases its estimates of wood use in SSA either on data supplied by national forestry departments, or on models based on estimates of population and consumption patterns (Arnold *et al*., 2003). Because wood is collected directly by the household or through informal trade, and charcoal is produced and traded through the informal sector, governments tend to have poor data on the quantity of wood and charcoal used (Arnold *et al*., 2003; Mugo & Ong, 2006). In some countries permits are required for charcoal production, and the countries report on the permits issued, but in many cases there is an illicit trade that may far exceed the formal trade. The wood and charcoal trade is huge, with some studies suggesting that fuel wood and charcoal trade represents the single biggest market for a rural (including agricultural) commodity in countries such as the Congo, Kenya, Tanzania and Malawi (Sepp, undated; World Bank, 2009; Schure, 2009).

An alternative approach to quantifying the production and trade in fuel wood is to do detailed household fuel-use studies and to extrapolate this data to the national or regional level. This gives a more rigorous estimate, but is an expensive and methodologically complex process. Ideally, household fuel-use should be tracked over an entire year to understand seasonal variations, and over the entire country to establish spatial variations. Few countries have the resources to do this. These consumption-side studies suggest that fuel wood and charcoal use may be far higher than the supply-side studies indicate. For instance, a study of charcoal use in Tanzania suggested that total charcoal use was one million tons of charcoal, requiring 30 million m^3 of wood. This is approximately twice the FOA estimate for charcoal use in this country.

In 1999 FAO (Amous, 1999) attempted to consolidate available Africa-wide fuel wood use estimates based on FAO, IEA and other data sources (see summary data in Table 1). This study highlights many of the uncertainties surrounding the FAO and other available data sources. Updated FAO data are available for 2005 (FAO, 2010), but remain based on estimates submitted by countries and are likely to suffer from the same data problems identified by Amous (1999). IEA produces annual estimates of total biomass usage, expressed in million tonnes oil equivalent (Mtoe). Since a tonne of oil equivalent represents 41.868 GJ of energy, and the energy content of fuel wood is about 17 MJ/kg, 1 Mtoe is equivalent to about 2,460 kg of dry fuelwood. The IEA estimate is derived from a number of data sources and its origin is poorly documented (Amous, 1999). The IEA 2002 world energy outlook estimated that Africa in year 2000 had a total fuel wood demand of 254 Mtoe (*i.e*., 625 Tg wood), of which 71% was for residential energy use. Bailis *et al*. (2005), using a combination of FAO and IEA data, suggest that the household sector of SSA used 470 Tg of fuel wood in 2000. Other studies have suggested that household wood fuel use contributes about 80% of total wood fuel use (Amous, 1999). As can be seen from Table 2, estimates of total wood fuel demand range widely among studies, but are in the region of 500 Tg/y in recent years, with an

Table 1 Burned area estimates for sub-Saharan Africa.

Reference	Year	Method	Scale	No of years	Burned area SH (km^2x10^3)		Burned area NH (km^2x10^3)		Burned area ALL (km^2x10^3)		Uncertainty
					mean	range	mean	range	mean	range	
Scholes	1996	Calibrated AVHRR active fires	5 degree	1	1684	--	--	--	--	--	Estimated at 30%
Barbosa	1999	AVHRR burn scars	5km pixel	8	1541	(1005-1918)	2390		3931	(2564-4894)	Tested against Landsat data: ~30% misclassification
Silva	2003	SPOT burn scars	1km pixel	1	960	--	--	--	--	--	Regressed against Landsat estimates: on average ~40% of the variance not explained
Simon	2004	ATSR-2 burn scars	1km pixel	1	--	--	--	--	1210*	--	Regressed against Landsat estimates (by Roy, 2009): 49% of the variance not explained
Giglio	2006	Calibrated MODIS active fires		4	810	(753-840)	1359	(1255-1532)	2163	(2051-2372)	Uncertainty estimates based on Landsat accuracies and summed over time period: ~3% per 0.5 degree pixel
Ito	2007	VIRS active fires	0.5 degree	8	2300	--	--	--	--	--	
Roy	2009	MODIS burn scars	500m pixel	8	1171	(915-1292)					Regressed against Landsat estimates: 25% of the variance not explained
Giglio	2010	MODIS burn scars, VIRS active fires, ASTR active fires	0.5 degree	12	1252	(1126-1531)	1310	(1144-1524)	2562	(2317- 3018)	Uncertainty estimates based on Landsat accuracies and summed over time period: ~2% per 0.5 degree pixel ~ 321 km^2x10^3 in total

SH = Southern Hemisphere, NH = Northern Hemisphere, ALL = sub-Saharan Africa
* High errors of omission reported

annual growth rate of around 1.5% and an uncertainty range of around 62 Tg/y (±15%). These predictions are probably conservative given the rapid increases in charcoal use that have been observed in a number of urban centres recently (World Bank, 2009).

3.5 The emissions which result from biomass burning

The emissions from biomass burning, which include a range of gases (some of which are important greenhouse gases such as CO_2 and CH_4, and others are reactive and contribute to the formation of tropospheric ozone) and fine particles (also called as aerosols), have been widely studied in Africa, amongst others in the SAFARI 94 and SAFARI 2000 campaigns in southern Africa and the DECAFE and EXPRESSO campaigns in West Africa. Andeae and Merlet (2001) provide a comprehensive synthesis of emission factors from Africa and elsewhere; Marufu *et al*. (2000) quantify emissions from domestic fires; Bertschi *et al*. (2003) provide information for smouldering logs; and Janhall *et al*. (2009) update the information regarding particles. The emissions are typically initially determined as changes in the molar ratios of various constituents of the atmosphere relative to their concentration in uncontaminated air. The 'delta molar ratios' are then converted to 'emission factors' (EF, g/kg DM fuel burned) for more convenient application. The latter step requires a number of assumptions regarding the chemistry of the fuels and the combustion conditions. The uncertainly range is small for CO_2 (perhaps ±5%) but is suggested to be up to ±30% for CH_4 , CO, NO_x, N_2O, non-methane hydrocarbons and particulate matter (Langmann *et al*., 2009), but can be reduced through several strategies. The carbon content of dry biomass is fairly consistently between 0.41 (grass) and 0.45 (wood). The emission factors for products of incomplete oxidation (such as methane and non-methane hydrocarbons and aerosols) tend to have a strong negative linear relationship with the 'Modified Combustion Efficiency' (MCE, $\Delta CO_2/(\Delta CO_2+\Delta CO)$), which approaches a value of 1.0 for the flaming combustion typical of fine, dry fuels such as grass, and may be as low as 0.7 for smouldering wood or peat (Wooster, 2011). If it is possible to estimate the MCE from the fuel type and combustion conditions, much of the variability in emission factors can be removed (and, by definition, all of the uncertainty in the emission factors for CO_2 and CO, if the MCE estimate is perfect). Emissions of nitrogenous and sulphur-containing gases scale linearly with the N and S content of the fuel, so if these can be estimated, the uncertainties in the NO_x, N_2O and SO_x emission factors can be greatly reduced.

Table 2 Summary of Africa-wide wood fuel use estimates. Charcoal and fuel wood data are combined to give total wood fuel. A charcoal production efficiency of 165 kg charcoal per m^3 fuel wood is assumed (Amous, 1999), and a wood density of 700 kg/m^3.

Source	Year	Fuel use Mt (Tg)
FAO (in Amous, 1999)	1990	317.1
BEST (in Amous, 1999)	1994	451.2
WEIS (in Amous, 1999)	1996	418.1
FAO (in Amous, 1999)	1999	371.4
IEA (2002)	1999	495.6
FAO (Broadhead *et al*. 2001)	2000	452.0
Bailis (2005) (household use only)[4]	2000	470.0
FAO (2010)	2005	429.5
FAO (Broadhead *et al*. 2001)	2010	493.0

Table 3 The quantity of biomass consumed by fire annually in sub-Saharan Africa (including Madagascar), nominally for the year 2000.

Source	Biomass consumed (Tg/y)			% Uncertainty[b]	% Interannual variation
	Best	lower	upper		
Wildfires	800[d]	716[d]	881[d]	10	5.4[b]
Wood as fuel	500	435	565	15	Growing at 1.5%/y
Land use change (deforestation – on-site burning only	46[a]	18	74	60 (area estimate uncertainty about 30% and biomass 30%)	Apparently stable in 1980s and 1990s
Agricultural residues (in-field burning)	50[c]	35	75	30	Small interannual variation, possibly growing
Total	1396	1204	1595	14	5, increasing trend

Notes

a. The total biomass involved is about ten times higher than this, but much is lost through decomposition rather than fire (we assume 50%), and of that which burns, we assume that 80% is already reflected in the 'wood as fuel' category.

b. Calculated as 0.5*(upper-lower) /best*100.

c. The Yevich and Logan estimate, with their estimate of what fraction is burned in-field, plus an additional 2 Tg/y for plantation residues, estimated by this paper.

d. Ellicott *et al*., 2009 estimate, based on observed Fire Radiative Power. Estimates based on modelled fuel loads are typically in the 2200 to 2700 Tg DM/y range, but are in poor agreement with observed fuel loads.

4. Summary and Perspectives

Table 3 combines, in our opinion, the best estimates of biomass combustion from each of the four pathways discussed in the preceding sections (wildfires, domestic and industrial biofuels, land-use-change fires and burning of agricultural residues) along with our evidence-guided judgement of the likely range and notes on the trend or interannual variability. The given range is our expert judgement of the 'likely feasible range,' in other words, excluding outlier or outdated studies. Although not strictly statistically-derived, it is conceptually closer to a 95% confidence interval than either an absolute range or a standard deviation.

Table 3 shows that wildfires dominate the carbon emissions from Africa, being nearly twice as large a consumer of biomass as the next largest category, which is biofuel use. The land use change and agricultural residue categories are both quite small *assuming that much of this material actually ends up as domestic fuels, and is* *therefore already accounted for under that category*.

The situation for individual trace gases may differ substantially from that for carbon as a whole, since the chemical profile of emissions resulting from wildfires (especially those in savannas and grasslands) is quite different from the profile resulting from charcoal manufacture or the burning of charcoal and wood in enclosed stoves. In general, the grass-dominated wildfires produce a higher fraction of highly-oxygenated products, such as CO_2, and less partially-oxidated products such as CO, CH_4 and non-methane hydrocarbons and aerosols than do fires consuming woody fuels, or those in confined spaces such as kilns, stoves or hearths. Thus the regional budgets for CO, tropospheric ozone and smoke particles is likely to be more evenly split between wildfires and domestic biofuels than the quantity of fuel consumed suggests.

The pathways of emission also differ with respect to whether they constitute net CO_2 emissions or not. In general, it is assumed that the emissions of CO_2 from wildfires and burning of agricultural residues in SSA do not represent a net emission, because the CO_2 is taken up again by the regrowth of the vegetation or crop within a year or two. Emissions from net land use change, on the other hand, are regarded as net CO_2 emissions. To the extent that the domestic and industrial biofuel used originates from biomass made available through land use transformations (and we suggest that at least half of it does), the biofuel emissions also represent net emissions.

A way to check the validity of bottom-up pyrogenic emission estimates is to compare them with regional budgets of atmospheric trace gases and aerosols generated by fires. Candidate pyrogenic proxies are carbon monoxide, smoke aerosols (particularly black carbon) and tropospheric ozone. Studies of this sort remain few and not yet convergent (Novellie *et al*., 1998; Arellano *et al*., 2004; Petron *et al*., 2004; Ito & Penner 2005; Ito *et al*., 2007). The inferred emission values for SSA are in the region of 239 ± 160 TgCO/y ($\pm$SD) (Petron *et al*., 2004).

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