State of the Art

Trace Gas Emission Estimation in Biomass Burning

Edited by

Alicia Palacios, Emilio Chuvieco and César Carmona

2002 EUR 20376 EN

Fuego II Report nº 7.0 January 2002

Contract nº JRC-IES 16881-00

EUROPEAN COMMISSION
JOINT RESEARCH CENTRE

Institute for Environment and Sustainability

Trace Gas Emission Estimation in Biomass Burning.

State of the Art.

Edited by

Alicia Palacios, Emilio Chuvieco and César CARMONA

Contract No:	JRC-IES 16881-00
Document No:	7.*0*
Issue No:	1.*0*
Date:	*01-02*

A great deal of additional information on the European Union is available on the Internet. It can of accessed through the Europa server (http://europa.eu.int)

Printed in Italy

Table of contents

1. Introduction: The role of fire in atmospheric chemistry

The anthropogenic modification of climate and the atmosphere is growingly considered a critical issue. Trace gas emissions and aerosols from biomass burning represent a significant part of the total gas emissions to the atmosphere. Andreae (1991) estimated the total amount of biomass consumed as 8680 Tg annually with a release of 3500 Tg of carbon in the form of CO_2. From that amount, it is roughly estimated that 42% comes from savanna fires, 23% from agricultural wastes, 17% from forests and another 18% from woodfuels.

Biomass burning is a source of aerosols composed by organic hygroscopic particle, graphitic carbon, and variable amounts of trace gases (Andreae, 1991; Ferek et al., 1998; Kaufman et al., 1992; Yamasoe et al., 2000). Among other consequences, smoke particles have a significant effect in the radiation budget due to changes in the radiant energy balance, such as in surface albedo, and atmospheric scattering and reflectance (Kaufman, 1990). Out of the gas species released in a fire most of the carbon is released in form of Carbon dioxide (CO_2), Carbon Monoxide (CO), and hydrocarbons (CH_4, C_2H_2…). Nitrogen and sulphur are also recovered as trace gases as Nitrous oxide (N_2O), nitric oxides (NO_2, NO), and ammonia (NH_3). On the other hand, most of the halogens are recovered in aerosol form. The increase of trace gas concentration is closely related to the greenhouse effect, the production of nitric acid, which is an important component of acid precipitation, and the photochemical production of ozone in the troposphere. Carbon dioxide, Methane, and Nitrous oxide are greenhouse gases, and carbon monoxide, methane, and nitrous oxide are precursors of the tropospheric ozone formation by complex chemical atmospheric reaction (Andreae et al., 1998; Sanhueza et al., 1999). NO also has a strong influence on the formation of acid precipitation.

Gas emission have as well long term effects, for instance in the case of the CO_2 and N_2O the long term effect can be more significant that the emission at the time of the fire (for instance the N_2O molecule has a lifetime of 150 years). These effects of biomass burning are stressed since vegetation acts as a sink for carbon dioxide, consequently, as burning occurs not only large amounts of carbon dioxide are released, but also the biosphere looses part of its potential to store CO_2.

The significance of the trace gases released depends mainly on the impact of the specific gas species on the natural cycle, and on the amount of gas emitted in relation to the normal concentration in the atmosphere and in relation to other sources. For instance, after carbon dioxide, the most significant greenhouse gas is methane, because although this species is about 200 times less abundant than carbon dioxide in the atmosphere, molecule for molecule methane is 20 times more effective at trapping heat.

The highest proportion of the biomass burning occurs in the tropical areas, (Andreae et al., 1988; Crutzen and Goldammer, 1993; Levine, 2000), hence these areas have a strong impact in trace gas increase and in its effects not only in the lower but also in the middle and upper troposphere due to the high surface fluxes observed in the tropics. These fluxes are likely to influence the global atmosphere due to strong vertical mixing (Andreae et al., 2001; Delmas et al., 1999; Yamasoe et al., 2000). Biomass burning in these regions is associated to agricultural activities and forest destruction. Several authors estimate that tropical savanna fires contribute to 25% of global emissions of carbonaceous particulate (Delmas et al., 1999). In some regions as the Venezuelan savanna, the Nitrogen cycling budget has been shown to be driven by biomass burning (Sanhueza et al., 1999). Although most of the fires occur in the tropics, in the last years, it has been identified that large fires also affect the boreal regions and that gas emissions have been underestimated for these regions (Conard and Ivanova, 1997; Hegg et al., 1990). Boreal forests represent a large pool of terrestrial organic carbon and once a fire occurs it takes a long time to grow back. As a consequence, post-fire biogenic emissions become highly significant as well. The impact on the carbon cycle and climate can be critical in these latitudes, due to the delicate equilibrium affecting the mid-latitude regions where small changes of temperature have a strong effect in climate (Phadnis and Carmichael, 2000). Evidences of the global impact of biomass burning have been found in remote areas (Andreae et al., 1988). Singh et al. (2000) observed that pollution plumes from burning area could be transported long distances throw the free troposphere.

The estimation of gas amounts and types released from fires is a significant issue not only as an environmental concern but also as a political issue in the context of the

Framework Convention of Climate change and the Kyoto protocol. The estimation of gas released by wild fires can have great importance at regional level for certain developing countries where fires are considered a routine activity for energy generation, forest clearing and pasture improvement. They represent the most significant source of greenhouse gases respect to the total emissions of these countries. For instance, in Africa, energy generated from biomass burning accounts for 80 to 90% of total energy in low-income population groups, 55-65% in middle-income and 30-40% in high income groups.

The estimation of the amount of gases released by biomass burning is difficult due to the great spatial variety of fires and to the high diversity of the type of fires and vegetation burnt. Traditionally, there have been methods to evaluate gas emissions based mainly on country statistics and traditional inventory methods of burnt areas.

Presently, the Global Change scientific community is concerned with the estimation of gas emission amounts and the political community needs methodologies for evaluating biomass burning gas emissions at different scales. The composition of the atmosphere embraces a global dimension, and therefore it needs to be evaluated in a global context. The difficulty of providing such global estimations implies the proposal of methodologies with scientific and objective basis that can be updated on a frequent temporal basis. One of the more urgent tasks in biomass burning emission characterization is to perform inventories of biomass burning at global scale, and to establish temporal and spatial time series analyses. Local measurements are necessary to understand the mechanism of emissions and regional and global modeling is necessary to understand the net effect of emissions in the atmosphere and in the global climate change.

In this review, the problems and previous undertakings for gas emissions estimations are presented. A summary of the factors affecting gas emissions in wild-land fires is analyzed, as well as the different methodologies to compute these emissions, including a discussion of the potentials and limitations of those methodologies.

2. Factors affecting the amount and proportions of gas species released in biomass burning

Ecosystems react to fire in different manners depending on the type of ecosystem and on fire characteristics. Hence, the amount and type of species released from a fire are conditioned by the chemical and physical features of the ecosystem, and by the environmental factors such as humidity, temperature and wind speed (Ward et al., 1992). In this section the influence of each of the factors in the behavior of fire and in the amount and type of emissions are summarized. Two general parameters have been defined: biomass consumption, and type of combustion. Both integrate several variables that are interrelated.

2.1. Biomass consumption: burning efficiency, land cover type, and biomass amount.

The amount of trace gas emissions is directly related to biomass and landcover through the amount and composition of the fuel burnt (Kasischke et al., 1995a; Scholes et al., 1996; Ward et al., 1996). The quantity of fuel consumed varies greatly depending on vegetation type and biomass amount, and on the burning efficiency of the process.

Although the amount of biomass is highly dependent on vegetation type, it is also variable depending on the environmental conditions. In a simplistic manner, it can be said that the higher the amount of biomass the higher the amount that can be burnt, and therefore the higher the total amount of carbon, nitrogen or other elements that can be released as trace gases. Nevertheless, as it will be explained, not all the biomass present in an ecosystem is available for burning and therefore, when evaluating the biomass consumption in a realistic manner is critical to properly characterize the type of fuel affected by the fire.

In this framework, the concept of Burning efficiency is important to accurately estimate biomass consumption. Burning efficiency is defined as the percentage of the total biomass that is actually consumed. Some authors like Ward et al. (1992) define this concept as combustion factor, which is is highly dependant on land cover type properties (e.g. flammability, phenology and composition, and structure of vegetation), actual vegetation state (e.g. water content, fine fuel moisture, amount of dead fuel), and environmental conditions (e.g. air humidity, temperature, and wind speed).

2.1.1 Fuel Flammability and resistance to fire

In some ecosystems, such in some Mediterranean vegetaion types or some coniferous forest, the fire is a natural factor, because it favours seed dispersal, ecosystem regeneration and species succession (Pausas and Vallejo, 1999). Many species from these ecosystems contains flammable oils that help fire ignition and propagation. In other ecosystems, fire is an external factor that alters completely the ecosystem and presents long term negative effects.

2.1.2 Phenology

The relation between the time of the year when the fire happens and the phenological cycle of the plant has a great impact on the biomass consumption rates. It has been shown that in low precipitation areas, biomass consumption is higher than in more humid climates (Ward et al., 1992). In regions with dry and high-temperature periods, biomass consumption is higher as well. Phenology also affects the proportions of dead and live material an the vegetation moisture content.

2.1.3 Fuel Composition and structure

Vegetation structure plays a significant role in fire burning efficiency, as well as in fire propagation, and smoke emissions characteristics. While in some ecosystems the total biomass amount is susceptible to be burnt, in others only some components of the total biomass have a high probability of being consumed by fire (eg. dead material, leaves, small branches), and total biomass will only be consumed when an extraordinary intense fire occurs. Ward et al. (1992) report that in grassland types, the fuel loads are equivalent to the total aboveground biomass, while in semi-deciduous trees, trunks and canopies are relative resistant to fire and litter is the main component that is burnt. The fire spreading rates also depend largely on biomass composition. For instance, ground litter and fine dead fuel are usually completely consumed and contribute heavily to the propagation of surface fires in forest. Phadnis and Carmichael (2000) report that biomass consumption per unit area in boreal forest is an order of magnitude higher than for tropical ecosystem, 25,000 kg per ha in the boreal versus 3,000 kg per ha in the tropics. A distinct characteristic of boreal fires is the type of emissions, since in these areas a high proportion of the biomass is stored in the soil, and the combustion products are different, being more frequent those incompletly burnt.

Fires in the same ecosystem can have different emission properties due to different material burnt. Conard and Ivanova (1997) report that in Russia surface fires result in lower carbon emissions than crown fires. This is caused by the lower fuel consumption because few needles and fine aerial fuels are burnt. On the other hand, a 75% of carbon stored in boreal forest is on the litter forest floor and soil layer and depending on the seasonality and intensity of the fire the average carbon emitted by this layer can be on average from 40 to 60% (Kasischke et al., 1995b). It has been estimated that crown fires burn 40% of the total aboveground biomass. This amount is lower in surfaces fires and depends highly on the severity of the fire (Conard and Ivanova, 1997).

Frequently, in the forest fire literature the composition and structure of vegetation serve to establish fuel types, in which these characteristics are parameterized from a fire propagation point of view (Anderson, 1982; Andrews, 1986; Burgan and Rothermel, 1984; Viegas and Viegas, 1993). The concept of fuel type is useful when working with fire emissions because it includes an estimation of biomass loads, as well as dead and live fuel proportions. Fuel type systems are defined at different resolutions depending on the working scale (Burgan et al., 1998; Burgan and Shasby, 1984; Riaño et al., 2001; Yool et al., 1985). When working at regional or global level fuel types can be defined based on the land cover classes.

Plant ecological characteristics are also important when studying the long term effects of fire emissions. For instance savanna biomes grow immediately after fires while in other land cover types fire produces a lengthy change which need to be taken into account in the following years. Consequences of post-fire mortality and decomposition are the increase of biogenic emissions and other changes in carbon flux (Conard and Ivanova, 1997; Levine et al., 1996). Fire return interval plays a significant role in the amount of biomass available for fire propagation. This interval is different among vegetation types and also depends on the climatic conditions. Fire frequency is about twice a year in the Venezuelan savanna (Sanhueza et al., 1999) while in the Cerrado ecosystem fires occur every 1-3 years (Ward et al., 1992). Olson (1978) relates the continuum of fire frequency and intensities to mean annual carbon burning in major ecosystems of the world. He formulates a hypothesis of inverse relation between biomass amounts and fire frequency and establishes several fire return interval categories for different land covers, the relation of these categories are related to trace gas emissions patterns. In this way, pre and post-fire data could be related to fire frequencies in order to estimate fuel availability and carbon burnt. Conard et al. (1997) established a theoretical relationship between area burnt and fire return interval in Russian boreal forest. This relationship was variable and for land cover types and for different latitudes.

Cofer et al. (1990) showed the importance of characterizing biomass burning emissions for the major global vegetation/ecosystems in order to couple combustion emissions to their vegetation ecosystem due to the different emission ratios in ecosystems. In this case emission ratios which were much higher for boreal forest fires than for wetland fires in central Florida.

2.1.4 Weather conditions

Low humidity and high temperature can increase burning efficiency dramatically. Kasischke et al. (2000) show a linear relationship between annual area burnt and fraction of biomass consumed, this means that in warmer years, when a higher number of fires occur the burning efficiency is higher as well. A similar effect was found in in the Zambian savanna, where the amount of burnt fuel followed seasonal trends and a high correlation between fires and vegetation moisture content was found (Hoffa et al., 1999).

2.1.5 Fuel moisture status

The moisture content of live and dead fuels is determinant for fire ignition and propagation, as well as for biomass consumption. In warm periods, fine dead material is dried faster than heavier fuels, and reaches low moisture levels. Live vegetation is able to maintain higher moisture contents, since plants present several mechanisms to reduce water consumption in situations of potential water stress (stomatal closure, increase root absorption efficiency, etc.). Consequently, the fine dead material is more likely to ignite and be affected by the fire that other components of the fuel complexes. Kasischke et al. (2000) showed that in boreal forest, as much as 90% of the carbon released by severe fires may be originated from the ground-layer biomass.

2.1.6 Carbon and Nitrogen contents

The amount of carbon and nitrogen stored in vegetation are factors directly involved in the amount of gases released, since the higher the proportion of the element, the higher the amount of trace gas that can be emitted. However, as it will be explained in the next section, these amounts are also highly dependent on the type of combustion. Carbon content in vegetation varies on a limited range (37 %- 55%) (Andreae, 1991; Andreae et al., 1998; Andreae and Merlet, 2001; Ward et al., 1992; Yokelson et al., 1996) and therefore the emission amounts for different compounds depend mainly on the type of combustion process. Usually when modeling emissions this value is kept constant. On the contrary, nitrogen content is more variable due to the higher proportion of this element in litter, also, this proportion is highly dependent on variable factors such as annual rainfall and grazing pressure (Yokelson et al., 1996). Since litter is preferentially burnt, nitrogen will be highly variable even inside the same fuel complex.

2.2. Fire intensity and duration.

Combustion efficiency is defined as the proportion of CO_2 with respect to the total amount of carbonaceous species released (Andreae and Merlet, 2001; Ward et al., 1992). It characterizes the completeness of the combustion and usually a modified combustion efficiency value is used, that is calculated as the molar ratio of emitted CO_2 to the sum of CO and CO_2 above ambient levels.

Main factors affecting combustion efficiency are fire intensity and vegetation structure and composition. Regarding the former, it is generally accepted that high combustion efficiency is associated to availability of oxygen and strong and high-temperature fires, where the emissions can reach high altitudes into the troposphere due to the intense heat release. Vegetation moisture has been shown to be as well a main factor affecting combustion efficiency. Hoffa et al (1999) found that incomplete combustion emissions were much lower during the late dry season when there was lower moisture content, this fact had a positive effect in the combustion efficiency. This parameter also expresses the ratio between flaming and smoldering phases in a fire. The proportion of gas species released depends of the relative weights of each of the phases. During smoldering phases fires combustion efficiency and temperature are lower and the dominant gas species released are the incomplete combustion gases, mainly, CO, NH_3, H2 and hydrocarbons. Fires with temperatures below 850°K are predominantly in the smoldering phase. Flaming phases are characteristics of high intensity fires where the highest proportion of gases released are the oxidized species: CO_2, NO, NO_2, N_2O, and N_2 are released predominantly during flaming combustion. Combustion efficiency has been used as a predictor of the smoke gas composition (Ward et al., 1996) although both types of combustion are present in most of the fires. The duration and time of the fire are important in terms of emission species because usually flaming combustion is dominant on the first stages of the fires and smoldering phases on later stages (Andreae and Merlet, 2001). Also, emission rates are lower in fires happening at night (Ferguson et al., 2000).

Vegetation composition and structure have also an important influence of combustion efficiency. In savanna and grassland ecosystems the majority of the biomass are fine fuels that can support fires of high intensity and dominant flaming combustion. Results from savanna fires show that the flaming phase has a combustion efficiency of 0.94 and the amount of biomass burnt is 90%, while the smoldering phase has a combustion efficiency of 0.9 and burns only 10% of the biomass (Ward et al., 1992). On the contrary, in forest ecosystems for higher combustion efficiency rates (0.90) the biomass consumption may be low (20%), while in the smoldering phase, a high amount of biomass (aroung 80%) is burnt.

3. Summary of experiments to estimate gas emissions

Several experiments have been carried out at global and regional level in the context of biomass burning emissions estimation. The general objectives of these experiments range from detecting burnt surfaces to analyzing composition and amount of gas emissions. Specific objectives related to gas emissions were the quantification of gas emissions, the distribution of gas species emitted, the dynamism of the trace gases, and their atmospheric consequences. These experiments have been carried out at representative sites around the globe in order to obtain enough information about emissions that can be extrapolated to areas were no emission measurements can be carried out. The final purpose is to make realistic inferences on emission rates for different vegetation complexes, in order to obtain accurate global estimations. Field experiments try to establish robust relationships between vegetation types and emission characteristics. Some of these experiments have been carried out in the framework of the International Global Atmospheric Chemistry (IGAC), which is one of the core projects of the International Geosphere-Biosphere program (IGBP).

During the Amazon boundary layer experiment (ABLE2A) (http://www-gte.larc.nasa.gov/gte_fld.htm: Andreae et al., 1988) the characteristics of the haze layers were investigated and optical measurements by airborne Lidar of CO_2, CO, NO, and O_3 were carried out using an airborne Lidar sensor. It was observed that the frequency of occurrence and density of the haze layers was higher when an increase of biomass burning at the southern periphery of the Amazon basin happened. Aerosol atmospheric measurements were also carried out, as well as chemical analyses from air samples.

The Biomass Burning Experiment: Impact on the Atmosphere and Biosphere (BIBEX, http://dionysos.mpch-mainz.mpg.de/~bibex/) is part of Activity 2.3 of IGAC Focus 2 which is Natural Variability and Anthropogenic Perturbations of Tropical Atmospheric Chemistry. In the context of BIBEX several campaigns have been carried out in different locations. Among these project some of them have been specially focused on the gas emissions evaluations. The STARE (http://dionysos.mpch-mainz.mpg.de/~bibex/Welcome.html#STARE) project was an aircraft- and ground-based measurement program initiated in May, 1990. The goal of this initiative was the analysis of sources of trace gases, their atmospheric transport, and the chemical processes in the atmosphere that leaded to elevated levels of O_3, CO, and other trace gases over the southern tropical Atlantic Ocean. In this context three field campaigns were carried out: STARE/TRACE-A/SAFARI. TRACE-A covered the western portion of the STARE region and involved chemical and meteorological measurements in Brazil (ground and aircraft component, and ozone-sonde launches in the Congo Republic and on Ascension Island). Its main objective was to investigate the chemical composition, transport, and chemistry of the atmosphere over the southern tropical Atlantic Ocean and the adjacent South American continent. The SAFARI experiment (*Southern African Fire-Atmospheric Research Initiative*: Lindesay et al., 1996) covered primarily the African portion of the STARE region and also emphasized the role of the African savannas in the gas emission. The Southern African Atmosphere Research Initiative (SAARI-94) was planned as the continuation of SAFARI92. Seasonal tropospheric distributions of ozone, carbon monoxide, and aerosols and their relationship to sources over southern Africa were compared in the two airborne sampling campaigns.

The *Experiment for Regional Sources and Sinks of Oxidants* (EXPRESSO) was a campaign designed to investigate tropical biogeochemistry and took place in the Central African Republic (CAR) and the Republic of Congo in the savanna and in the tropical forest to. The field campaigns included ground based field and aircraft studies in order to determine the fluxes of important carbon and nitrogen containing trace gases and compare with the climatology of the area. Also, remote sensing studies were used to define the location and extent of biomass burning and to aid in vegetation characterization.

The *African Fire-Atmosphere Research Initiative* (AFARI) is a regional expansion and continuation of the SAFARI. This experiment took place over the Kenyan savannas and was focused on the relationship between aerosol production and associated CO and CO_2 formation during prescribed experimental burns and wildfires of opportunity.

The *Zambian International Biomass Burning Emissions Experiment* (ZIBBEE) experiment was organized in order to quantify the aerosol and trace gas fluxes from the Miombo woodlands of southern Africa. To quantify the consumption of biomass (carbon) in biomass burning, validation of aerosol retrievals from various satellite sensors, and direct radiative forcing by biomass burning aerosols were some of the issues of the project.

The *Fire Research Campaign Asia-North* (FIRESCAN) began in 1992 and addressed the role of fire in boreal ecosystems and the consequences for the global atmosphere and climate

In the context of *the Large Scale Biosphere-Atmosphere Experiment in Amazonia* (LBA) project (http://lba.cptec.inpe.br/lba/) several experiments oriented to monitor biomass burning emissions in the Amazonian were carried out. The *Biomass burning, Airborne and Spaceborne Experiment-Amazonas* (BASE A) was focused on establishing a link between the optical characteristics of the trace gases and smoke particles and the properties of the upward radiation detected by satellites as well as the relationship between levels of ozone and spatial distribution of fires (Kaufman et al., 1992).

The goal of the *Smoke, Clouds, And Radiation* (SCAR) series of experiments were to obtain simultaneous in situ and remote measurements of the physical and chemical properties of the smoke produced by biomass burning, and the effects of the smoke on the Earth's radiation balance and climate. Remote sensing data were acquired by the MODIS Airborne Simulator in order to develop methodologies for the future MODIS data. The SCAR-C measured the properties and radiative effects of smoke aerosol and trace gases emitted from wild and prescribed fires in the Pacific Northwest of the US. One of the specific objectives of the SCAR-C experiment was to measure the emission factors for aerosols and a suite of trace gases which includes CO_2, CO, CH_4, NOx, N_2O, SO_2, and CH_3Cl., using the carbon-balance technique. The SCAR-B project (http://www-eosdis.ornl.gov/lba_cptec/prelba/scarb.html) was an experiment conducted in Central Brazil and southern Amazon Basin in order to obtain measurements of the physical chemical and radiative properties of the smoke produced during the burning season. It emphasized measurements of surface biomass, fires, smoke aerosol and trace gases, clouds, and radiation.

4. Approaches to gas emission estimation

Experimental efforts to estimate smoke emissions have been conducted in several directions. The most significant procedures are by smoke sample collection, by remote sensing measurements, or by modeling. The first method is based on measuring optical properties of the smoke, to derive emission rates. Sample collection measurements can be based on field sensors located at specific experimental sites or in the laboratory. Remote sensing methods are also direct measurements, based on aerial and satellite images, most commonly over experimental fires. Finally, the modeling approach relies on indirect estimations, based on the analysis of the different factors affecting emission rates, with special emphasis on the spatial distribution of those factors.

4.1. In situ gas measurements

Most of the emission characterization experiments are based on direct measurements of the excess of gas species present in the fresh smoke respect to the standard amounts in the atmosphere from prescribed or natural fires (Andreae et al., 1998; Ferek et al., 1998). In some cases it has been possible to derive emission parameters from plume layers embedded in the regional background as well (Levine, 2000; Singh et al., 2000). Usually, emission field and laboratory measurements have been accomplished with research purposes in order to derive emission parameters that could later be used to estimate gas emissions where no measurements were available (Ferek et al., 1998). Measurements have been conducted either outside in natural or prescribed fires or in the laboratory experiments in combustion chambers or open fires (Jenkins et al., 1996).

When measuring fire emissions in natural conditions the two protocols that need to be planned are the sampling and the analytical procedures. Gaseous phase, aerosols and particles can be collected by sampling techniques carried out in the field or by aircraft sampling, either airplane or helicopter. In both cases sample collection can be done in a continuous manner or by gathering discrete samples. Analyses can be done as well in situ or taken the samples into the laboratory.

Emission factors can be calculated by dividing the concentration of the emission gases above background (grams per cubic meter) by the total carbon concentration multiplied by the ratio of fuel mass to carbon mass. Rate of fuel consumption is calculated by multiplying the carbon concentration above atmospheric background with real time sensors divided by the vertical velocity and by the ratio of fuel to carbon (Ward et al., 1992).

When intermittent sampling is accomplished either in the field or from aircraft, a volume of air is stored in sampling bags or in stainless steel canisters to be analyzed afterward in the laboratory. Ground sampling system are described in various works, Hegg et al. (1990 collected smoke samples from towers. Several aircraft, helicopters and airplanes with several systems have been used to undertake discrete sampling. The aircraft can count with a forward mounted nose probes through which smoke samples are drawn using different systems (Blake et al., 1996; Cofer et al., 1996a; Cofer et al., 1990; Cofer et al., 1993; Cofer et al., 1998; Cofer et al., 1996b). Hurst et al. (1994) used an inlet hose hold 15 cm outside the plane in front of the wing mounted engines. During the FOS DECAFE experiment (Lacaux et al., 1995) the sample collecting system was located on the upper left side of the airplane 20 cm apart from a reinforced window. One of the problems when measurements are done from the aircraft is that the required sampling time is longer that the time that the aircraft is inside the plume. In order to overcome this problem Ferek et al. (1998) used a grab-bag technique in which a 2.5 m^3 plastic bag took 12 seconds to be filled with smoke. When steel canisters were used (which took 45 seconds) two penetrations of the plume were required to fill the canisters. Cofer et al. (1990) conducted also two passes with a helicopter through the selected plume. In this case, flaming, smoldering and mixed phase plumes were differentiated.

Analytical determination of gas species in discrete samples is frequently carried out in laboratory. Techniques for measuring gas concentration in sample bags include thermal conductivity, gas chromatography, non-dispersive infrared gas analyzer, mass spectrometry, laser absorption spectrometry, and flame ionization gas chromatography (Andreae et al., 1998; Cofer et al., 1993; Ferek et al., 1998; Hao and Ward, 1993; Levine, 2000; Rudolph et al., 1995; Ward et al., 1992). NH_3, NO and NO_2 species are analyzed by chemiluminescence as well. It is important to take into account the concentration or dilution of the sample, the period of time between the sampling and the analyses because of the possible change of species such as the production of NO_2 from nitrous species (Cofer et al., 1993). Another technique used is the high-resolution Fourier transform infrared (FTIR) spectrometer, for CO_2 CO and CH_4 (Cofer et al., 1993). This is an optical technique where gas spectral measurements are taken

Continuous determination of gas emissions is performed with real-time instruments installed in the field or carried aboard an aircraft. In these cases, the smoke and the fresh air can be drawn with pumps and the airflow regulated by air flow controllers (Delmas et al., 1995; Hurst et al., 1994; Ward et al., 1992) that can be connected to a dilution system to avoid saturation of the instruments. One of the systems widely used has been the *Fire Atmosphere Sampling Systems* (FASS) (Andreae et al., 1996; Radke et al., 1988; Ward et al., 1992). Hao and Ward (1993) used this system from towers while other authors (Hao et al., 1996; Ward et al., 1996) used the same system but buried below ground to minimize the effect of high heat. A factor to be taken into account is the transit time of air through the sampling tube.

Some of the analytical *in situ* measurement techniques are non-dispersive infrared absorption, laser absorption spectrometry for CO, CH_4, NO_2, HCHO, and N_2O. NO and NO, NOx, and NH_3 are determined as well by chemiluminiscence and SO_2 is measured through pulsed-fluorescence analysis (Andreae et al., 1988; Ferek et al., 1998; Hurst et al., 1994; Levine, 2000). When on board sensors are used calibration of can be calibrated during each flight using standard mixture (Ferek et al., 1998).

Optical measurements have also been accomplished using airborne lidar during the ABLE2A flights over the Amazonia (Andreae et al., 1988). In this case the data collection was on the haze layers by discrete grab samples and lab measurements of CO, CO_2, NO and O_3 were done. Another optical system used from aircraft is the Airborne Fourier Transformed Infrared reflectance (AFTIR: Goode, 2000 #106]) which is a FTIR coupled with a flow-through multipass cell. This system takes FTIR spectra of air samples in a cell inside the aircraft.

Laboratory experiments contribute in a great manner to the understanding of emission from biomass burning and to obtain laboratory measurements of emission factors and ratios. These experiments can be carried out either in open fields (Goode et al., 1999; Hao et al., 1991; Yokelson et al., 1999) or in combustion chambers (Jenkins et al., 1996). These systems provide better control over the experiment than field testing. Analytical techniques used are the same that those described in previous sections.

One advantage of the airplane over field measurements is their capacity to characterize the vertical and regional chemical composition of air masses. In order to use aircraft data for different types of models or at different scales the sampling can be done directly over the fresh smoke plume or on the haze layers developed due to the fire. This type of measurements were used in the EXPRESSO project to provide information on interaction mechanisms between savanna and forest ecosystems (Delmas et al., 1999). In SCAR-C it was done by crisscrossing a vertical section of a smoke plume, deduce the total fluxes from a fire of all the various species measurable aboard the aircraft (Hurst et al., 1994). Also, aircraft collected samples represent better the integrated emissions of flaming and smoldering combustion that field sampling. Ground measurements are bias toward smoldering combustion because of the difficulty of measuring smoke from hot flaming combustion. Andreae et al. (1996 also remark the airplane preference for measuring the flaming-derived gases and the ground measurements bias towards the smoldering derived gases, because these species tend to remain closer to the ground, while the former ones tend to rise to higher altitudes.

In all cases background samples need to be obtained in order to be subtracted from the concentrations measured in the smoke plume, these samples can be gathered upwind of the fires or by sampling before and after the fire (Andreae et al., 1998; Cofer et al., 1990; Ferek et al., 1998).

Evaluation of the emissions in experimental fires can be accomplished as well through mass balance analysis (Hurst et al., 1994). In these types of measurements aboveground fuel is collected before the fire and residual fuel and ash fraction are collected after the fire. By oven drying and weighting before and after, carbon and nitrogen contents are computed and it is estimated how much of the carbon burnt is transferred to the atmosphere and how much is deposited in the ash and remaining fuel. Ward et al. (1992) estimated fuel consumption by establishing plots along transects and measuring biomass prior and after the fire. Ash samples were collected and measured as well.

4.2. Remote sensing experiments for gas emission estimation

The most general use of remote sensing in gas emission assessment is focused on estimation of the variables involved in the emissions models (e.g. burnt surface mapping, biomass estimation, or moisture content among other), as it will be explained in the next section. In this one, direct estimations from biomass burnings will be reviewed.

An extended list of references may be commented on the use of satellite images for fire detection and burned land mapping (see, among many, Ahern et al., 2001; Martín et al., 1999). Spectral analysis from emitted aerosols makes it possible to monitor smoke plumes and perform some estimations of fire atmospheric emissions (Kaufman et al., 1992). Particle concentration can be estimated through calculation of the optical thickness and single scattering albedo of the smoke plume, which is the ratio of light scattering to light extinction. This value can be determined using the AVHRR red and near infrared (Kaufman, 1990) or by using the new multi-angular sensors on board the Terra (MISR) and Polder experiments (King et al., 1999). This ratio is related to the graphitic carbon of the smoke and has different values for smoldering and flaming conditions. Several experiments have made it possible to convert the remotely detected mass of emitted particles into a mass of emitted trace gases through relationships found in the literature between emitted particles and trace gases. For instance, as a result of the BASE A experiment Kaufman et al. (1992) found that the ratio between smoke particles and trace gases such as CO and CH_4 varied much less than the ratio between these gases and CO2. Therefore, they concluded that remote sensing of smoke particles is a direct measure of the emission of trace gases, and also of the combustion efficiency. Liousse et al. (1997) suggest that the optical impact of smoke depends primarily on the combustion nature and intensity. They use AVHRR data to identify and quantify smoke plumes by measuring plume and background albedo.

In the last year several techniques and sensors are being developed in order to obtain the amout of gas released in a plume fire. MOPITT on board the Terra satellite, is intended for these objectives, and MODIS data ,on board of same satellite can be used also for the same purposes.

4.3. Modeling approaches for gas emissions estimation

4.3.1 Types of models

As a results of the field and laboratory experiments conducted a set of models have been developed with the purpose of computing trace and particulate emissions from fires at different spatial scales and levels of detail. Since biomass burning is a complex issue that occurs as a result of both, natural and anthropogenic processes the factors that determine fire occurrence and nature can be considered from an environmental perspective at several temporal and spatial scales, and may consider not only physical but also human factors. Consequently, fire emissions estimation can be approached by modeling fire behavior at several scales, or by sociological analysis of the typical fire occurrence and intensity in a specific area.

When working at global scales it is observed that the fire distribution follows similar spatial trend every year. Moreno-Ruiz (1999) mapped fire occurrence each month from 1982 to 1992 at global level using AVHRR GAC data. They observed that the maximum fire density happens in the tropics and that fire distribution follows every year similar patterns. Only in cases when big events such as the Pinatubo eruption or the Niño event occurred, anomalous fire distribution was observed (Matsueda et al., 1999). Modeling emissions at this level is essential when working with atmospheric models. Although fires happen at local scale, on the medium and long term they have a net effect in the global atmosphere. The regional climate characteristics and the distinct properties of the fires of that region condition this effect. At this level fire emissions are computed in order to be coupled with global circulation models. These models work at low spatial resolution (half a degree or less in many cases), cover extent areas or the whole globe and highly dynamic, mainly in the temporal dimension. The emission estimates necessary at this scale,are based on static emission models that assume constant environmental variables and fix fire properties, not considering significant parameters such as seasonality or diurnal timing. At this level of detail, Granier et al. (2000) used a three-dimension chemical transport model of the troposphere (IMAGES) in order to assess the significance of biomass burning in the global ozone budget. They estimated the trace gas emissions parameters using only five broad categories, and assume fix variables for each of them. Hauglustaine et al. (2000) used a global chemical transport model (MOZART) to evaluate the global impact of the 1997 Indonesian fires, in this case they assume a general scenario with total emission amounts for forest fires and for peat soils which correspond just to four 300 km^2 area grid cells. Galanter et al. (2000) utilized a three-dimensional global chemical transport model to quantify the impact of biomass burning on tropospheric concentration of several gases. They divided the globe into twenty regions based on broad similarities in vegetation type, cultural patterns, and climate to construct an emission sources global inventory.

The other extreme is when working with prescribed burning either with management purposes or designed with experimental objectives. In these cases higher number of variables can be modeled in a much more accurate manner. In this models fires are ignited in relatively small and controlled areas where each of the parameters can be measured. Fuel types are defined in a narrower manner and environmental conditions are modeled as well. Emission factors are not defined for land cover types but for the specific components of the fuel. Another variable that is modeled is the ratio of flaming to smoldering phases and its variability with time. The First Order Forest Fire Effects Model (FOFEM: Reinhardt et al., 1997) has been developed to meet the needs of resource managers, planners and analysts to predict and plan the fire effects. This model is design for each of the US general geographic regions, and fuel types and the algorithms are part of the decision key and the user can choose different equations for environmental conditions and fuel types and components such as crown density or fire intensity. This model has been integrated into a Geographic Information System in order to compute emissions inventory for wildfires and prescribed burning in the state of California (Scarborough et al., 2001). The *Emission Production Model* (EPM) developed by Ferguson et al. (2000) provides a time sequence of heat release rate, biomass consumption, and emission production in fires and the inputs are the description of fuel bed, rate of fire ignition and biomass consumed. It is designed to be linked to a biomass consumption model such as CONSUME (Ottmar et al., 1993) and to a fire spread model such as FARSITE (Finney, 1998). The advantage of these types of models is that they can capture much of the transient and spatial variability that is lacking in global models.

On the other hand, much information is needed and they are difficult to use in most of the wildland fires and are not suited for global or regional scale evaluations.

Evaluating emissions at intermediate scales can be approached in several manners. One way is to model and predict fires by integrating environmental variables (e.g. vegetation type and density, greenness, or previous burning state among others) to emissions. Ward et al. (1996) built a nomogram to calculate emission released per unit area. Variables needed for this model were the amount of biomass before the fire, the percentage of biomass burnt, and the ratio of grass to the sum of grass and litter. The nomogram is based first on the correlation found between the combustion factor and the amount of litter and grass, and second and on the correlation among the amount released of several gas species. It first calculates the carbon released and then estimates emission factors and total emissions for several gases. Olson (1978) set up a fire model according to the fire historical occurrence. This is a probabilistic model based on the biomass load available to be burnt. Related to the time period when no fires have occurred.

General bioclimatic conditions such as mean annual temperature, length of dry period and mean annual precipitation can be used as well to predict emissions in general terms. Dwyer et al. (2000) discriminated five types of fire activities in Africa based on their spatial and temporal characteristics. They developed warmth and moisture indices and combined with vegetation types. These variables were bio-temperature, total annual precipitation, effective precipitation (i.e. difference between total annual precipitation and evapotranspiration) and dry period, (number of months with P-ETP < 0). They used also three parameters for the classification: fire number, fire agglomeration size and fire season duration.

The most generalized model to compute gas emissions released at a regional or local scale follows the general equation from Seiler and Crutzen (Seiler and Crutzen, 1980). In this model, the type and amount of emission are linked to the fuel consumed through the emission factors or ratios. The general equation is:

$$M(X) = M * B * E$$

Where *M(X)* is the amount of gas released, *M* is the biomass loading per surface unit, *P* is the percentage of biomass consumed and *E* is the emission factor, which is the amount of gas species released per unit of dry matter. The variable *E* can be given directly as an emission factors or can be calculated from the emission ratios and the combustion efficiency. The emission ratios represent the amount of a specific gas species released relative to the amount released by a reference gas, usually CO_2. These ratios are estimated in experiments and can be used to calculate the emission factors in the following way:

$$E = ERk*CE*AC*CCO$$

where *CE* is the combustion efficiency, *AC* is the percentage of carbon in vegetation, *CCO* is the ratio of the molecular weight of the reference gas to the atomic weight of carbon (3.67 for CO_2) and *ERk* is the emission ratio that is the percentage of the amount gas species k to the amount of reference gas.

As explained previously, this equation integrates several biophysical variables that can be estimated and applied at different scales. Also several levels of generalization can be assumed in order to simplify the model. In the following paragraphs methodologies to evaluate each of the variables will be explained.

4.3.2 Emission ratios and emission factors

The emission potential of a certain ecosystem in specific conditions can be expressed as a set of parameters called emission factors and emission ratios (Andreae and Merlet, 2001). These parameters are useful to be used in the models in order to calculate the amount of emissions.

Emission ratios express the relationship between the concentration of a specific trace gas released and the concentration of a reference gas. This parameter is expressed as mole ratios of trace gas relative to the reference gas species, which is usually CO or CO_2 (Andreae et al., 1996). They are based on the correlation found between the concentration of a certain gas species and the concentration of CO or CO_2 emitted. The ratios for carbonaceous species depend just on the type of combustion, while the ratios for other species such as nitrous or halogen species depend as well on fuel composition. Because smoke trace gases composition change with the type of combustion, emission ratios change as well, which means that ratios are different for flaming phases and for smoldering phases. Since correlation found between smoldering-derived species and CO is high and flaming-derived species emissions are better correlated with the amount of CO_2 released, the reference gas should be chosen according to the specific species, and different values should be used in different phases of the fire. However, this is almost impossible because usually both phases mix in the same fire and in addition, since most of the biomass carbon is released as CO_2 the emission ratios relative to this compound are the most suitable for regional or global estimations (Andreae and Merlet, 2001).

Emission factors relate the emission of a gas species of interest to the amount of fuel burnt thus, they are defined as the amount of a trace gas compound released per amount of fuel consumed expressed in grams of gas compound per kilogram of dry matter. This parameter depends on the amount of element in the fuel as well as on the type of combustion. Flaming phases present higher emission factors for oxidized gas species, while in smoldering phases incomplete combustion products present higher emission factors. The use of emission factors provides a more direct way to compute fire emissions than using emission ratios, however they are more difficult to compute, because it is necessary to know the amount of compound released, the amount of fuel burnt, and the concentration of the element in the fuel. When these variables are unknown the computation can be accomplished using the smoke concentration of the compound released and the carbon budget of the fire. As a consequence it is more common to use just the emission factors for a reference gas (commonly CO_2) and use the emission ratios for the rest of the gas species.

Emission ratios and factors are calculated through experiments for different vegetation types and environmental conditions where the rest of the variables are known. As explained before, previously experiments can be accomplished in controlled situations either in the laboratory or in the field, and in natural conditions either with prescribed or with natural fires (Bonsang et al., 1995). Computation of ratios and factors is easily done in controlled situations when the total amount of gas can be measured and also the amount and composition of fuel burnt is known. It becomes more difficult when translated to the field where only atmospheric measurements can be conducted. In these cases the excess of the mixing ratios of gases over their background levels are used to derive emission ratios relative to CO or CO_2. The following equation is used to calculate the emission ratios with the results expressed in terms of "molar ratios".

$$ERXi = \Delta Xi/\Delta CO2 = (Xismoke - Xiambient) /(CO2\ smoke - CO2\ ambient)$$

where ΔXi and ΔCO_2 are the enhancement of trace gas and CO_2 respectively above background levels.

The emission factor for the compound *X* is expressed by Andreae and Merlet (2001) in the following way:

$$EFx = Mx/M_{biomass} = (Mx/Mc) * [C]_{biomass}$$

where *EFx* is the emission factor for the compound *X*, *Mx* is the amount of compound *X* released, *Mc* is the mass of carbon emitted and $[C]_{biomass}$ is the concentration of carbon in the fuel burnt. When the total amount can not be measured the following equation can be used instead:

EFx is equivalent to $[X/([Cco2] + [Cco] + [Cch4]+[Cvoc])] * [C]biomass$

where the concentration of the total carbon emitted is represented by the sum of the concentration of the various carbon species in the smoke. For these calculations a fuel carbon content of 45% is usually assumed.

Both parameters are useful to evaluate the amount of emissions of a specific gas species in fires where direct estimation can not be accomplished. Emission ratios have the advantage that they do not require knowledge of the fuel composition and amount of fuel burnt and therefore are suitable for field studies (Andreae and Merlet, 2001). Emission factors represent a more direct way of calculated the compound amount released but it is necessary to know the amount of fuel burnt.

Each type of vegetation and environmental conditions has specific burning properties characterized by distinctive ratios and factors. In most of the cases CO_2 is used as a reference gas, and in cases where the smoldering phase is highly dominant this ratio can be calculated first respect to CO and then multiplying it with the average CO/CO_2 emission ratio of the fire. When only the amount of fuel burnt is known it is better to use the amount of CO_2 as a reference gas and then, the mass of any other gas released can be calculated as a function of the amount of CO2 emitted as it was explained in the equation from Seiler and Crutzen.

The emission factors of trace gases and aerosols from savanna fires are now quite well known as a result of STARE (http://dionysos.mpch-mainz.mpg.de/~bibex/Welcome.html#STARE) and some other campaigns. However, large uncertainties persist with regard to the amounts of biomass burnt as a function of locality and time. During the SAFARI 92 campaign a mean value of the CO2 emission ratio was estimated and after knowing the carbon content of the biomass was used to estimate the emission factor of other gas species.

4.3.3 Land Cover and Biomass estimations

One of the main inputs when applying spatial modeling to emission estimations is the type of land cover and the spatial information of carbon storage that is available to be burnt. One of the main parameters that need to be evaluated when applying physical models is the amount of Biomass that can be burnt. Estimation of biomass loads is a difficult task due to the high heterogeneity of most of the ecosystems and to the dynamic character of land cover, which makes difficult to obtain updated estimations, specially because the amount of live and dead biomass are important parameters. The biomass evaluation can be accomplished from continuos or a discrete approach. When working with land cover classes standard biomass amounts can be assigned to each land cover (Stroppiana et al., 2000). When a reliable spatially continuous data are available, biomass continuous estimations can be derived. Those data can be obtained from remote sensing sources (Anderson et al., 1993; Box et al., 1989; Harrell et al., 1995), or may be derived from spatial interpolation methods (Mitas and Mitasova, 1999).

When the inputs to the emission models are the land cover classes, the variability inside these classes with respect to fire need to be small. Land cover types should be grouped in a way that have a similar behavior to fire and share similar values of the parameters that determine emission potential. Similar proportions of carbon and nitrogen contents in land cover classes are convenient as well to be able to use the same emissions factors or emission ratios.

The type of fuel is also important in influencing the type of combustion dominant in a fire, when a great amount of small size fuels are available fire starts and flame easily. Since those fuels have a high surface to volume area with good heat transfer and combustion properties (Cofer et al., 1998), the flaming phase will be dominant. On the other hand, large size fuels burnt at lower temperatures having a dominant smoldering phase.

The land cover map used in the model depends at a great extend on the working scale. When working at a detailed scale or with prescribed fires, the type of fuel can be modeled using the definition of fuel types. The vegetation fuel types are characterized by the amount, type, and state of vegetation. They are useful when determining the type of fire and the type and amount of gases emitted in a fire. Also fuel models are commonly used to predict fire risk but could be used to evaluate the amount of biomass burnt as well. Approximated detailed estimation of biomass can also be accomplished by spatially sampling distributed points in a detailed manner and interpolating vegetation values or correlating with environmental data. Delmas et al. (1982) carried on specific measurements on vegetation amounts and compositions of carbon, nitrogen, and sulfur to estimate gas emissions.

When working at global or regional scales land cover types need to be more general. At these scales there are several land cover data set that could be used to model emissions. For assigning biomass amounts at this level of detail, a common practice is the assignment of average biomass values to each cover type. Commonly these values are generalizations of field measurements at specific sites. For instance, Stroppiana et al. ([, 2000 #251) used a functional vegetation cover map derived by Janodet et al. (1995) and used a constant amount of 2 ton/ha for desert and semi-desert ecosystems and the Sudanian-sahelian savanna. They used 4 ton/ha for the Somalian bush thickets.. Other experts have provided estimations of biomass loads for savannas (the Oak Ridge National laboratory, Menaut et al., 1991 and Shea et al., 1996 among others). Other authors have proposed biomass estimations in the context of land cover/land use change (DeFries et al., 1999). They assume that land cover changes lead to land cover types with lower biomass. This can also be assumed in the case of fire and therefore this type of modeling can be linked to a gas emissions model in order to introduce the effect of fire in the fuel load variable and in the land cover types. Satellite observations are an essential part for accomplishing these tasks. Several authors have used RS for evaluating biomass for emission estimations, Barbosa et al (1999) calculated the emissions based on biomass amounts sintetized from a historical AVHRR NDVI composite data set. These analyses have been carried out in data sets taken over a period of years. Inventory biomass data has been used as well, but one problem when using this type of information is the bias of ecologist to place plots on mature forest, the effect is to overestimate biomass density Brown and Gaston, 1996.

4.3.4 Burning Efficiency

As said before, burning efficiency is related to several factors such as vegetation water content and fine fuel moisture content. Levine et al. (2000) empirically derived the burning efficiency for three types of biomes. Other authors estimated global biomass emissions by using a fire model that computes burning efficiencies for several vegetation groups (Mack et al., 1996). In this model the burning efficiency was derived based on the dead fine fuel moisture content. Fuel moisture content can be calculated following several methods for different biomes, but they are commonly based on meteorological indices, that take into account air temperature, humidity, rainfall and wind patterns.

Estimation of grass moisture content requires specific methods that can not be easily applied to heavier fuels. The degree of curing in grasses can be estimated from meteorological indices based on rainfall temporal trends. Some authors have proposed the use of satellite greenness indices as well (Burgan et al., 1998). The estimation of degree of dryness for heavy fuels depends substantially on the previous weather conditions what will change the moisture of the wood, and the conditions when the burns occurs.

Barbosa et al. (1999) calculated the burning efficiency as a direct function of the greenness (RGI) index. In this caswe, Burning efficiency was defined as 100 – RGI. It can be done for each pixel or for each veg type.

5. Conclusions

The estimation of the amount of gas released in wildland fires is a complex issue due to the large number of variables that are involved the emission process. Authors have approached this type of analysis in several ways, depending the factors such as the size of the region under study, the working scale and the requirement of accuracy, among others.

Direct gas estimations are mainly conducted by air samples chemical analyses in experimental fires and in the laboratory and are mainly focused on the calculation of the emission ratios and factors to be applied in wildland fires. Remote sensing techniques are based on indirect measurements of the trace gases, these methodologies are still under development.

Presently, modeling techniques seem the most feasible way to accomplish wildfire trace gas emissions. The type of modeling conducted depends on factors such as the working scale, and the amount of information available. The variables involved in most of the models are the burnt area, the amount of fuel available, the burning efficiency and the emission factors. Among these parameters burnt surface is the most easily achievable parameter from remote sensing data, while the others have a much higher level of uncertainty. This uncertainty comes mainly from the lack of data at global scale and the difficulty to spatially extrapolate local-site estimations. Biomass is a parameters that varies not only spatially but also in a temporal scale; remote sensing may provide a good insight into this temporal and spatial evolution, but further developments are required to consistently relate spectral data and vegetation amount (lidar techniques may be very promising in this aspect).

The burning efficiency depends on the vegetation type and the intensity of fire but also on the environmental conditions which makes it even more complex to be evaluated. About the emission factors there is data available only for specific sites in the globe or for laboratory experiments. The use of common emission factors for very diverse conditions can enter a high level of error into the calculations.

Since reliable emissions data are necessary, the efforts need to be oriented in developing good methodologies to obtain enough accurate input data for these models.

6. References

Ahern, F.J., Goldammer, J.G. and Justice, C.O. (Eds.) (2001). Global and Regional Vegetation Fire Monitoring from Space: Planning a coordinated international effort. SPB Academic Publishing, The Haghe, The Netherlands.

Anderson, G.L., Hanson, J.D. and Haas, R.J. (1993), Evaluating Landsat Thematic Mapper derived vegetation indices for estimating above-ground biomass on semiarid rangelands, Remote Sensing of Environment. 45(2): 165-175.

Anderson, H.E. (1982). Aids to determining fuel models for estimating fire behavior. General Technical Report INT-122, USDA, Forest Service, Ogden, UT.

Andreae, M.O. (1991), Biomass burning: its history, use and distribution and its impacts on environmental quality and global climate. In: Global biomass burning : atmospheric, climatic, and biospheric implications MIT Press, Cambridge, Mass., pp. 3-21.

Andreae, M.O. et al. (1998), Airborne studies of aerosol emissions from savanna fires in southern Africa: 2. Aerosol chemical composition, Journal of Geophysical Research-Atmospheres. 103(D24): 32119-32128.

Andreae, M.O. et al. (2001), Transport of biomass burning smoke to the upper troposphere by deep convection in the equatorial region, Geophysical Research Letters. 28(6): 951-954.

Andreae, M.O. et al. (1996), Trace gas and aerosol emissions from savanna fires. In: Biomass burning and global change (J.S. Levine, Ed.) Eds.), MIT Press, Cambridge, MA, pp. 278-295.

Andreae, M.O. et al. (1988), Biomass-burning emissions and associated haze layers over Amazonia, Journal Of Geophysical Research-Atmospheres. 93(D2): 1509-1527.

Andreae, M.O. and Merlet, P. (2001), Emission of trace gases and aerosols from biomass burning, Global Biogeochemical Cycles. 15(4): 955-966.

Andrews, P.L. (1986). BEHAVE: Fire behavior prediction and fuel modeling system. Burn subsystem. Part 1. GTR INT-194, USDA Forest Service, Ogden, UT.

Barbosa, P.M., Stroppiana, D., Gregoire, J.M. and Pereira, J.M.C. (1999), An assessment of vegetation fire in Africa (1981-1991): Burned areas, burned biomass, and atmospheric emissions, Global Biogeochemical Cycles. 13(4): 933-950.

Blake, N.J. et al. (1996), Biomass Burning Emissions and Vertical Distribution Of Atmospheric Methyl Halides and Other Reduced Carbon Gases In the South Atlantic Region, Journal Of Geophysical Research-Atmospheres. 101(D19): 24151-24164.

Bonsang, B., Boissard, C., Le Cloarec, M.F., Rudolph, J. and Lacaux, J.P. (1995), Methane, Carbon Monoxide and Light Non-Methane Hydrocarbon Emissions from African Savanna Burnings During the FOS/DECAFE Experiment, Journal of Atmospheric Chemistry. 22(1-2): 149-162.

Box, E.O., Holben, B.N. and Kalb, V. (1989), Accuracy of the AVHRR vegetation index as a predictor of biomass, primary productivity and net CO_2 flux, Vegetatio. 80: 71-89.

Brown, S. and Gaston, G. (1996), Estimates of biomass density for tropical forest. In: Biomass burning and global change (J.S. Levine, Ed.) Eds.), MIT Press, Cambridge, MA.

Burgan, R.E., Klaver, R.W. and Klaver, J.M. (1998), Fuel models and fire potential from satellite and surface observations, International Journal of Wildland Fire. 8(3): 159-170.

Burgan, R.E. and Rothermel, R.C. (1984). BEHAVE: Fire Behavior Prediction and Fuel Modeling System. Fuel Subsystem. GTR INT-167, USDA Forest Service, Ogden, Utah.

Burgan, R.E. and Shasby, M.B. (1984), Mapping broad-area fire potential from digital fuel, terrain, and weather data, Journal of Forestry. 82: 228-231.

Cofer, W.R., Levine, J.S., Winstead, E.L., Cahoon, D.R., Sebacher, D.I., Pinto, J.P. and Stocks, B.J. (1996a), Source Compositions Of Trace Gases Released During African Savanna Fires, Journal Of Geophysical Research-Atmospheres. 101(D19): 23597-23602.

Cofer, W.R., Levine, J.S., Winstead, E.L. and Stocks, B.J. (1990), Gaseous Emissions From Canadian Boreal Forest Fires, Atmospheric Environment Part a-General Topics. 24(7): 1653-1659.

Cofer, W.R., Levine, J.S., Winstead, E.L., Stocks, B.J., Cahoon, D.R. and Pinto, J.P. (1993), Trace Gas Emissions From Tropical Biomass Fires: Yucatan Peninsula, Mexico, Atmospheric Environment Part a-General Topics. 27(12): 1903-1907.

Cofer, W.R., Winstead, E.L., Stocks, B.J., Goldammer, J.G. and Cahoon, D.R. (1998), Crown fire emissions of CO2, CO, H2, CH4, and TNMHC from a dense jack pine boreal forest fire, Geophysical Research Letters. 25(21): 3919-3922.

Cofer, W.R.I., L., W.E., Stock, B.J., Overbay, L.W., Goldammer, J.G., Cahoon, D.R. and Levine, J.S. (1996b), Emissions from boreal forest fires: Are the atmospheric impacts underestimated? In: Biomass burning and global change (J.S. Levine, Ed.) Eds.), MIT Press, Cambridge, MA.

Conard, S.G. and Ivanova, G.A. (1997), Wildfire in Russian boreal forests - Potential impacts of fire regime characteristics on emissions and global carbon balance estimates, Environmental Pollution. 98(3): 305-313.

Crutzen, P.J. and Goldammer, J.G. (1993). Fire in the environment : the ecological, atmospheric, and climatic importance of vegetation fires : report of the Dahlem Workshop, held in Berlin, 15-20 March 1992, Wiley, Chichester, England, New York.

DeFries, R.S., Field, C.B., Fung, I., Collatz, G.J. and Bounoua, L. (1999), Combining satellite data and biogeochemical models to estimate global effects of human-induced land cover change on carbon emissions and primary productivity, Global Biogeochemical Cycles. 13(3): 803-815.

Delmas, R. (1982), On the emission of carbon, nitrogen, and sulfur in the atmosphere during bushfires in the intertropical savanna zones, Geophysical Research Letters. 9(7): 761-764.

Delmas, R., Lacaux, J.P., Menaut, J.C., Abbadie, L., Leroux, X., Helas, G. and Lobert, J. (1995), Nitrogen Compound Emission From Biomass Burning In Tropical African Savanna FOS/DECAFE 1991 Experiment (Lamto, Ivory Coast), Journal Of Atmospheric Chemistry. 22(1-2): 175-193.

Delmas, R.A. et al. (1999), Experiment for Regional Sources and Sinks of Oxidants (EXPRESSO): An overview, Journal Of Geophysical Research-Atmospheres. 104(D23): 30609-30624.

Dwyer, E., Grégorie, J.-M. and Pereira, J.M.C. (2000), Climate and vegetation as driving factors in global fire activity. In: Biomass burning and its inter-relationships with the climate system (J.L. Innes, M. Beniston and M.M. Verstraete, Eds.), Kluwer Academic Publishers, Dordrecht, Boston, London, pp. 171-191.

Ferek, R.J., Reid, J.S., Hobbs, P.V., Blake, D.R. and Liousse, C. (1998), Emission factors of hydrocarbons, halocarbons, trace gases and particles from biomass burning in Brazil, Journal Of Geophysical Research-Atmosphere. 103(D24): 32107-32118.

Ferguson, S.A., Sandberg, D.V. and Ottmar, R. (2000), Modelling the Effect of Landuse Changes on Global Biomass Emissions. In: Biomass burning and its inter-relationships with the climate system (J.L. Innes, M. Beniston and M.M. Verstraete, Eds.), Kluwer Academic Publishers, Dordrecht, Boston, London, pp. 33-50.

Finney, M.A. (1998). FARSITE Fire Area Simulator Version 1.0: Users Guide and Technical Documentation, Systems for Environmental Management, Missoula, MT.

Galanter, M., Levy, H. and Carmichael, G.R. (2000), Impacts of biomass burning on tropospheric CO, NOx, and O-3, Journal Of Geophysical Research-Atmospheres. 105(D5): 6633-6653.

Goode, J.G., Yokelson, R.J., Susott, R.A. and Ward, D.E. (1999), Trace gas emissions from laboratory biomass fires measured by open-path Fourier transform infrared spectroscopy: Fires in grass and surface fuels, Journal of Geophysical Research-Atmosphere. 104(D17): 21237-21245.

Granier, C., Müller, J.-F. and Brasseur, G. (2000), The impact of biomass burning on the global budget of ozone and ozone precursors. In: Biomass burning and its inter-relationships with the climate system (J.L. Innes, M. Beniston and M.M. Verstraete, Eds.), Kluwer Academic Publishers, Dordrecht, Boston, London, pp. 69-85.

Hao, W.M., Scharffe, D., Lobert, J.M. and Crutzen, P.J. (1991), Emissions of N2O from the Burning of Biomass in an Experimental System, Geophysical Research Letters. 18(6): 999-1002.

Hao, W.M. and Ward, D.E. (1993), Methane Production From Global Biomass Burning, Journal of Geophysical Research-Atmosphere. 98(D11): 20657-20661.

Hao, W.M., Ward, D.E., Olbu, G. and Baker, S.P. (1996), Emissions Of Co2, Co, and Hydrocarbons From Fires In Diverse African Savanna Ecosystems, Journal Of Geophysical Research-Atmospheres. 101(D19): 23577-23584.

Harrell, P.A., Bourgeauchavez, L.L., Kasischke, E.S., French, N.H.F. and Christensen, N.L. (1995), Sensitivity of ERS-1 and JERS-1 Radar Data to Biomass and Stand Structure in Alaskan Boreal Forest, Remote Sensing of Environment. 54(3): 247-260.

Hauglustaine, D.A., Brasseur, G.P. and Levine, J.S. (2000), Impact of the 1997 Indonesian fires on tropospheric ozone and its precursors. In: Biomass burning and its inter-relationships with the climate system (J.L. Innes, M. Beniston and M.M. Verstraete, Eds.), Kluwer Academic Publishers, Dordrecht, Boston, London, pp. 87-99.

Hegg, D.A., Radke, L.F., Hobbs, P.V., Rasmussen, R.A. and Riggan, P.J. (1990), Emissions of some trace gases from biomass fires, Journal of Geophysical Research. 95(D5): 5669-5675.

Hoffa, E.A., Ward, D.E., Hao, W.M., Susott, R.A. and Wakimoto, R.H. (1999), Seasonality of carbon emissions from biomass burning in a Zambian savanna, Journal of Geophysical Research-Atmosphere. 104(D11): 13841-13853.

Hurst, D.F., Griffith, D.W.T. and Cook, G.D. (1994), Trace gas emissions from biomass burning in tropical Australian savannas, Journal of Geophysical Research. 99(D8): 16441-16456.

Janodet, E. (1995). Stratification saisonnière de l'Afrique continentale et Cartographie fonctionnelle des écosystems forestiers africains, MTV-IRSA-JRC, Ispra, Italy.

Jenkins, B.M., Jones, A.D., Turn, S.Q. and Williams, R.B. (1996), Emission Factors For Polycyclic Aromatic Hydrocarbons From Biomass Burning, Environmental Science & Technology. 30(8): 2462-2469.

Kasischke, E.S., Christensen, N.L. and Stocks, B.J. (1995a), Fire, Global Warming, and the Carbon Balance of Boreal Forests, Ecological Applications. 5(2): 437-451.

Kasischke, E.S., French, N.H.F., Bourgeauchavez, L.L. and Christensen, N.L. (1995b), Estimating Release of Carbon From 1990 and 1991 Forest Fires in Alaska, Journal of Geophysical Research-Atmospheres. 100(D2): 2941-2951.

Kasischke, E.S., Stocks, B.J., O´Neill, K., French, N.H.F. and Bourgeau-Chavez, L.L. (2000), Direct Effect of fire on the boreal forest carbon budget. In: Biomass burning and its inter-relationships with the climate system (J.L. Innes, M. Beniston and M.M. Verstraete, Eds.), Kluwer Academic Publishers, Dordrecht. Boston. London, pp. 61-71.

Kaufman, Y.J. (1990), Remote Sensing of Biomass Burning in the Tropics, Journal of Geophysical Research. 95(D7): 9927-9939.

Kaufman, Y.J. et al. (1992), Biomass burning airborne and spaceborne experiment in the Amazonas (Base-A), Journal of Geophysical Research. 97(D13): 14581-14599.

King, M.D., Kaufman, Y.J., Tanré, D. and Nakajima, T. (1999), Remote Sensing of Troposheric Aerosols from Space: Past, Present and Future, Bulletin of the American Meteorological Society. 80(11): 2229-2259.

Lacaux, J.P. et al. (1995), Biomass Burning in the Tropical Savannas of Ivory Coast: An Overview of the Field Experiment Fire of Savannas (FOS/DECAFE 91), Journal of Atmospheric Chemistry. 22(1-2): 195-216.

Levine, J.S. (2000), Global Biomass Burning: A Case Study of the Gaseous and Particulate Emissions Released to the Atmosphere During the 1997 Fires in Kalimantan and Sumatra, Indonesia. In: Biomass burning and its inter-relationships with the climate system (J.L. Innes, M. Beniston and M.M. Verstraete, Eds.), Kluwer Academic Publishers, Dordrecht, Boston, London, pp. 15-31.

Levine, J.S. et al. (1996), Biogenic Soil Emissions Of Nitric Oxide (No) and Nitrous Oxide (N2o) From Savannas In South Africa - the Impact Of Wetting and Burning, Journal Of Geophysical Research-Atmospheres. 101(D19): 23689-23697.

Lindesay, J.A. et al. (1996), International Geosphere-Biosphere Programme International Global Atmospheric Chemistry Safari-92 Field Experiment - Background and Overview, Journal Of Geophysical Research-Atmospheres. 101(D19): 23521-23530.

Liousse, C., Dulac, F., Cachier, H. and Tanre, D. (1997), Remote sensing of carbonaceous aerosol production by African savanna biomass burning, Journal Of Geophysical Research-Atmospheres. 102(D5): 5895-5911.

Mack, F., Hoffstadt, J., Esser, G. and Goldammer, J.G. (1996), Modeling the influence of vegetation fires on the global carbon cycle. In: Biomass burning and global change (J.S. Levine, Ed.) Eds.), MIT Press, Cambridge, MA.

Martín, M.P., Ceccato, P., Flasse, S. and Downey, I. (1999), Fire detection and fire growth monitoring using satellite data. In: Remote Sensing of Large Wildfires in the European Mediterranean Basin (E. Chuvieco, Ed.) Eds.), Springer-Verlag, Berlin, pp. 101-122.

Matsueda, H., Inoue, H.Y., Ishii, M. and Tsutsumi, Y. (1999), Large injection of carbon monoxide into the upper troposphere due to intense biomass burning in 1997, Journal Of Geophysical Research-Atmospheres. 104(D21): 26867-26879.

Menaut, J.D., Abbadie, L., Lavenu, F., Loudjani, P. and Podaire, A. (1991), Biomass burning in West African savannas. In: Global biomass burning : atmospheric, climatic, and biospheric implications (J.S. Levine, Ed.) Eds.), MIT, Press, Cambridge, MA.

Mitas, L. and Mitasova, H. (1999), Spatial Interpolation. In: Geographical Information Systems (P.A. Longley, M.F. Goodchild and y.D.W. Rhind, Eds.), John Wiley & Sons, inc., New York.

Moreno-Ruiz, J.A., Barbosa, P.M., Carmona-Moreno, C., Gregoire, J.M. and Belward, A.S. (1999). Glints-BS- Global Burn Scar Detection System, Functional Description and User Manual Document. I.99.167, Europen Comission. Joint Research Center.

Olson, J.S., (1978). Carbon balance in relation to fire regimes, Fire Regimes and Ecosystem Properties, Honolulu, Hawaii.

Ottmar, R.D., Burns, M.F., Hanson, A.D. and Hall, J.N. (1993). Consume Users Guide, U.S. Department of Agriculture, Forest service, Pacific Northwest Research Station, Portland, OR.

Pausas, J.G. and Vallejo, V.R. (1999), The role of fire in European Mediterranean ecosystem. In: Remote Sensing of Large Wildfires in the European Mediterranean Basin (E. Chuvieco, Ed.) Eds.), Springer-Verlag, Berlin, pp. 3-16.

Phadnis, M.J. and Carmichael, G.R. (2000), Forest fire in the Boreal Region of China and its impact on the photochemical oxidant cycle of East Asia, Atmospheric Environment. 34(3): 483-498.

Radke, L.F., Hegg, D.A., Lyons, J.H., Brock, C.A., Hobbs, P.V., Weiss, R. and Rasmunssen, R. (1988), Airborne measurements of smokes from biomass burning. In: Aerosols and climate (P.V. Hobbs and M.P. McCormick, Eds.), aA Deepak.

Reinhardt, E.D., Keane, R.E. and Brown, J.K. (1997). First Order Fire Effects Model: FOFEM 4.0, User's Guide, USDA Forest Service General Technical Report INT-GTR-344.

Riaño, D., Salas, J. and Chuvieco, E. (2001), Cartografía de modelos de combustible con teledetección: aportaciones a un desarrollo ambiental sostenible, Estudios Geográficos. 62(243): 309-333.

Rudolph, J., Khedim, A. and Koppmann, R. (1995), Field study of the Emissions of Methyl Chloride and Other Halocarbons from Biomass Burning in Western Africa, Journal of Atmopheric Chemistry. 22(1-2): 67-80.

Sanhueza, E., Crutzen, P.J. and Fernandez, E. (1999), Production of boundary layer ozone from tropical American Savannah biomass burning emissions, Atmospheric Environment. 33(30): 4969-4975.

Scarborough, J., Clinton, N., Pu, P. and Gong, P. (2001). Creating a Statewide Spatially and Temporally Allocated Wildfire and Prescribed Burn Emission Inventory Using Consistent Emission Factors, University of California, Berkeley, CA.

Scholes, R.J., Kendall, J. and Justice, C.O. (1996), The Quantity Of Biomass Burned In Southern Africa, Journal Of Geophysical Research-Atmospheres. 101(D19): 23667-23676.

Seiler, W. and Crutzen, P.J. (1980), Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning, Climate change. 2: 207-248.

Shea, R.W., Shea, B.W., Kauffman, J.B., Ward, D.E., Haskins, C.I. and Scholes, M.C. (1996), Fuel Biomass and Combustion Factors Associated With Fires In Savanna Ecosystems Of South Africa and Zambia, Journal Of Geophysical Research-Atmospheres. 101(D19): 23551-23568.

Singh, H.B. et al. (2000), Biomass burning influences on the composition of the remote South Pacific troposphere: analysis based on observations from PEM-Tropics-A, Atmospheric Environment. 34(4): 635-644.

Stroppiana, D., Brivio, P.A. and Grégorie, J.-M. (2000), Modelling the impact of vegetation fires, dectected from NOAA-AVHRR data, on tropospheric chemistry in Tropical Africa. In: Biomass burning and its inter-relationships with the climate system (J.L. Innes, M. Beniston and M.M. Verstraete, Eds.), Kluwer Academic Publishers, Dordrecht, Boston, London, pp. 193-213.

Viegas, D.X. and Viegas, M.T. (1993). Development of a Fire Danger Map Based on Fuel Properties for Poiares Council, University of Coimbra, Madrid.

Ward, D.E., Hao, W.M., Susott, R.A., Babbitt, R.E., Shea, R.W., Kauffman, J.B. and Justice, C.O. (1996), Effect Of Fuel Composition On Combustion Efficiency and Emission Factors For African Savanna Ecosystems, Journal Of Geophysical Research-Atmospheres. 101(D19): 23569-23576.

Ward, D.E. et al. (1992), Smoke and Fire Characteristics for Cerrado and Deforestation Burns in Brazil: BASE-B Experiment, Journal of Geophysical Research. 97(D13): 14601-14619.

Yamasoe, M.A., Artaxo, P., Miguel, A.H. and Allen, A.G. (2000), Chemical composition of aerosol particles from direct emissions of vegetation fires in the Amazon Basin: water-soluble species and trace elements, Atmospheric Environment. 34(10): 1641-1653.

Yokelson, R.J. et al. (1999), Emissions of formaldehyde, acetic acid, methanol, and other trace gases from biomass fires in North Carolina measured by airborne Fourier transform infrared spectroscopy, Journal of Geophysical Research-Atmospheres. 104(D23): 30109-30125.

Yokelson, R.J., Griffith, D.W.T. and Ward, D.E. (1996), Open-Path Fourier Transform Infrared Studies of Large-Scale Laboratory Biomass Fires, Journal of Geophysical Research-Atmospheres. 101(D15): 21067-21080.

Yool, S.R., Eckhardt, D.W., Estes, J.E. and Cosentino, M.J. (1985), Describing the brushfire hazard in southern California, Annals of the Association of American Geographers. 75(3): 417-430.