Trace Gas Emission Estimation from Biomass Burning. The Main Variables*

*(Alicia Palacios et al., 2004) – A. Palacios, A. Parra, E. Chuvieco and C. Carmona-Moreno. "Remote sensing and geographic information systems methods for global spatiotemporal modelling of biomass burning emissions: Assessment in the African Continent". Journal of Geophysical Research, Vol. 109, D14S09, doi: 10.1029/2004JD00434, 2004.

Factors Affecting Gas Species Released in BB

- The Amount and Type of gas species released from fire are conditioned by:
  - Chemical and Physical features of the Ecosystem
  - Environmental factors: Humidity, Temperature and Wind Speed.

Factors Affecting Gas Species Released in BB

- Two general parameters are defined:
  - Biomass Consumption:
    - The amount of trace gas emissions is directly related to **Biomass** and **Landcover** type through the amount and composition of the fuel burnt.
  - Type of Combustion:
    - Combustion Factor is highly dependent on:
      - Land cover type properties:
        - » Flammability, Phenology and composition, and structure of vegetations
      - Actual vegetation state:
        - » Water content, fine fuel moisture, amount of dead fuel
      - Environmental conditions
        - » Air humidity, temperature and wind speed.
    - **Combustion efficiency** is defined as the proportion of CO_2 with respect to the total amount of carbonaceous species released.
    - High **combustion efficiency** is associated to availability of oxygen and strong and high temperature fires
    - This parameter also expresses the ratio between the flaming and smoldering phases in a fire
    - **Flaming Phases** are characteristics of high intensity fires -> CO_2, NO, NO_2, N_2O, N_2:
      - Savanna fires show a high combustion efficiency (0.94) and the amount of biomass burnt is 90%
      - Forest fires with high combustion efficiency (0.90) the biomass amount may be ~20%
    - In **Smoldering Phases**, the combustion efficiency and temperature are lower and the predominant gases are incomplete combustion gases: CO, NH_3, H_2 and hydrocarbons
      - Savanna fires show a lower combustion efficiency (0.90) and the amount of biomass burnt is 10%
      - In Forest fires, the total amount of biomass burnt could be around 80%.

Factors Affecting Gas Species Released in BB

- The quantity of fuel consumed varies greatly depending on :
  - Vegetation type (fuel type):
    - Vegetation structure plays a significant role in fire burning efficiency, fire propagation, and smoke emissions characteristics.
    - It includes an estimation of biomass loads, and dead and live proportions
    - At Global/Regional scales, fuel types can be defined based on the land cover classes (grass, shrubs, type of forests, …)
  - Biomass Load (quantity of fuel):
    - Highly dependant on vegetation type, phenology and structure
  - Burning efficiency:
    - It's defined as the percentage of the total biomass that is actually consumed by fire

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Factors Affecting Gas Species Released in BB

- **Fuel Flammability and Resistance to Fire**
  - It's related to the capacity of the vegetation type to burn
  - Vary from ecosystem to ecosystem, and it's inherent to the vegetation cycle in some vegetation species
- **Phenology**
  - Phenological cycle of the plant has a great impact on the biomass consumption rates.
  - Phenology affects the proportions of dead and live material, and vegetation moisture content
- **Fuel Composition and Structure**
  - Important role in fire efficiency, propagation and smoke emissions characteristics.
  - Some examples:
    - grasslands : fuel loads are equivalent to the total aboveground biomass
    - Semi-deciduous trees:
      - trunks and canopies -> resistant to fire
      - Litter is the main component that burn
    - Ground litter and fine dead fuel are usually completely consumed and contribute heavily to the propagation of surface fires in forest
- **Weather Conditions**
  - Low humidity and High temperature increase burning efficiency
- **Fuel Moisture Status**
  - Moisture content of live and dead fuels is determinant for fire ignition and propagation, but also for biomass consumption.
    - In warm periods, fine dead material is dried than heavier fuels and reaches low moisture levels.
    - Kasischke et al. 2000 showed that in boreal forest, as much as 90% of carbon released by severe fires may be originated from ground-layer biomass

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Approaches to Gas Emission Estimation

- **Experiments**:
  - efforts are oriented to estimate smoke emissions in several directions:
    - Sample collection
      - Measuring optical properties of the smoke to derive emission rate
      - Sample collection measurements can be based on field sensors located at specific experimental sites or in the laboratory
    - Remote Sensing Measurements
      - Real time measurements based on aerial and satellite images
    - Modeling
      - Indirect estimations based on the analysis of the different factors affecting emission rates, with special emphasis on the spatial distribution of those factors.

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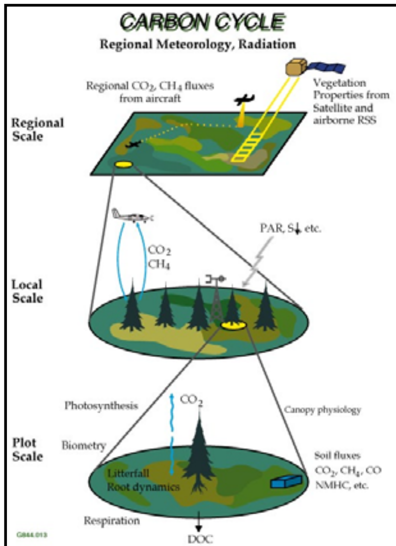

Tower

Field Measure

Earth Observation Satellite

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Approaches to Gas Emission Estimation

- **Experiments**:
  - At global and regional level:
    - Ranged from detecting burnt surfaces to analyze the composition and amount of gas emissions.
    - Carried out in representative sites around the globe
    - Final Purpose: To make realistic inferences on emission rates for different vegetation complexes for accurate global estimations
  - Examples:
    - **ABLE2A**: Amazon. Characterize the haze layers from optical measurements by airborne
    - **STARE**: Analysis of sources of trace gases, atmospheric transport and chemical processes
    - **EXPRESSO**: Central African Republic. Investigate the tropical biogeochemistry. Fluxes of carbon and nitrogen
    - **AFARI**: A regional expansion of SAFARI. Kenyan savannas. Relationship between the aerosol production and associated CO and CO2 formation
    - **ZIBBEE**. Quantify the aerosol and trace gas fluxes from Miombo woodlands of SA
    - **FIRESCAN**. Analyze the role of fire in boreal ecosystems and the consequences for global atmosphere and climate.
    - **LBA**. Oriented to monitor biomass burning emissions in the Amazonian.
    - **SCAR**. To obtain 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.

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Approaches to Gas Emission Estimation

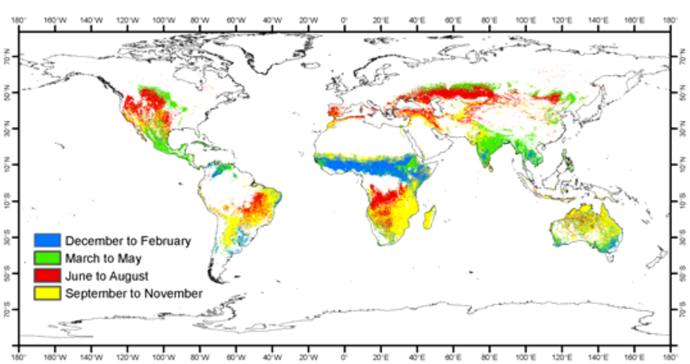
- **Model to compute Gas Emissions from Biomass Burning (*Seiler and Crutzen, 1980*):**
  - The type and amount of emission are linked to the fuel consumed through the emission factors or ratios:
    - **M(*x,i,m*)** = BL*i* x BS*i* x BE*im* x E*x*
      - Where **M(*x, i*)** = amount of gas released ***x*** from land-cover type ***I*** for the period of the year ***m***
      - **BL*i*** = biomass loading per surface unit of the land-cover type ***I***
        - » ***STRONG HYPOTHESIS = The area has a homogenous cover of fuel/vegetation type i***
      - **BS*i*** = Burned surface of land-cover type ***i***
      - **BE*im*** = Burned efficiency of fuel/vegetation type ***i*** and period ***m*** = percentage of biomass consumed of fuel/vegetation type ***i*** during the period ***m***
      - **E*x*** = emission factor = the amount of gas species released ***x*** per unit of dry matter

Approaches to Gas Emission Estimation

- **Biomass Loads (BLi)**
  - The amount of material available to be consumed has been considered as total biomass load (BL).
  - It's a complex issue since it involves wide spatial and temporal variability, even within species.
  - Consequently, at a global scale, simplification need to be adopted.
  - The global approach passes by a "biomass load" table per vegetation class pondered by a yearly accumulated normalized difference vegetation index (ANDVI).
    - $BL_i = BLmin_i + (ANDVI_i – ANDVImin_i)/(ANDVImax_i - ANDVImin_i) * (BLmax_i-BLmin_i)$
    - $ANDVI_i = \sum NDVI_{it}$

Approaches to Gas Emission Estimation

- **Burned Surfaces (BSi)**
  - Computed from the reflectance of burned surfaces by Remote Sensing data



Approaches to Gas Emission Estimation

- **Burning Efficiency (BEim)**
  - It's defined as the percentage of the total carbon released from initial stock of carbon contained in the pre-burn aboveground biomass
  - The consumption rate depends on:
    - Vegetation type : correlated with morphology and chemical composition of the vegetation
    - Fire characteristics (wind, topography and moisture conditions):
      - Spread
      - Intensity : correlated with the period of the year.
  - Moisture estimations has been traditionally based on meteorological danger indices
    - The use of these indices to approximate BE seems a logical approximation => BE requires meteorological measurements with continuous spatial coverage -> Unavailable at a global scale.
  - Good correlation between NDVI and related indices (greenness) with moisture content for grasslands
    - Detected problems in extending such relationships to other VGT types
    - NDVI doesn't include short wave infrared information -> more sensitive to water content.
    - NDVI has been however used as a surrogate of BE

Approaches to Gas Emission Estimation

- **Burning Efficiency (BE_{im}) – cont.**
  - $BE_{im} = \{[1 – (NDVI_{im} – NDVI_{i,min})/(NDVI_{i,max} – NDVI_{i,min})] \times BLF_i + DF_i\} \times BES_i$
    - Where BEim is the burning efficiency for the vegetation ***i*** and ***m*** period of the year.
    - NDVIim is the NDVI of the vegetation ***i*** for the period ***m*** of the year
    - NDVIi,min is the minimum value of the NDVI of the vegetation ***i*** in the year
    - NDVIi,max is the maximum value of the NDVI of the vegetation ***i*** in the year.
    - BLFi and DFi are the proportions of life and dead fuels of vegetation ***i***.
    - BESi is the standard burning efficiency values of the vegetation ***i***.

Approaches to Gas Emission Estimation

- **EMISSION FACTOR (Ex)**
  - **E** can be given directly as an **emission factor** or can be calculated from the emission ratios and the combustion efficiency.
    - Emission ratios = the amount of a specific gas species released relative to the amount released by a reference gas (usually CO2)
  - E = Erk x CE x AC x CCO
    - Where: CE = combustion efficiency
    - AC = Percentage of Carbon Vegetation
    - CCO = ratio of the molecular weight of the reference gas to the atomic weight of Carbon (3.67 for CO2); and,
    - ERk = the emission ratio that is the percentage of the amount of gas species k to the amount of reference gas.

Gas Emission Estimation: Example

- **The Global Fire Analysis (GFA)**
  - **It's a GIS tool for spatial-temporal estimations and analysis of biomass burning emissions at regional and global scales.**
  - **Implementation of Seiler and Crutzen, 1980**
  - **A. Palacios-Orueta et al., 2004. Remote Sensing and Geographic information systems methods for global spatiotemporal modeling of biomass burning emissions: Assessment in the African continent. Journal of Geophysical Research, Vol. 109, 2004.**
  - **Based on Olson Ecosystem Classes is the only one that provides global consistent carbon content values.**
  - **Olson classes were defined on the basis of their potential to burn, and their carbon contents were revised according to a study of the state of the art in the domain (read paper for further information).**

Gas Emission Estimation: Example

Table 1. Area and Reference Parameters Used in the GFA-II Model for Each Olson Ecosystem Classes (OCE) in the Study Site[a]

OCE	Area, km^2	BL	OC_{min}	OC_{max}	BLF	BES	CE	ERCO
Barren deserts volcanos	1,931,732	444	44	444	0.05	0.7	0.95	0.045845
Closed shrubland (scrub)	583,260	10,000	4444	10,000	0.73	0.5	0.91	0.069561
Cropland herbaceous and villages	2,287,324	2196	1556	5556	0.05	0.7	0.96	0.039916
Cropland/grass-woods(field-woods)	1,152,962	3843	6667	6667	0.70	0.4	0.9	0.07549
Evergreen broadleaf forest	2,441,617	21,959	11,111	35,556	0.70	0.2	0.9	0.081419
Forest-field mix (40–60% woods)	209,803	9881	11,111	11,111	0.70	0.45	0.9	0.07549
Grassland	1,825,062	1647	667	1778	0.05	0.96	0.96	0.039916
Open shrubland (semidesert)	2,004,000	2745	1200	2000	0.69	0.5	0.93	0.057703
Permanent wetlands	65,216	3294	4444	15,556	0.20	0.96	0.85	0.105135
Savanna trees (10–30%)	4,206,584	5490	3333	3333	0.70	0.6	0.94	0.051774
Urban/suburban built-up	6110	0	0	3333	0.00	0.1	0	
Woodlands trees (40–60% > 5 m)	1,131,400	19,214	8889	13,333	0.80	0.35	0.916	0.066004
Woody savanna (30–60% > 2 m)	3,396,238	9881	10,000	10,000	0.80	0.45	0.93	0.057703

[a]Here OEC_{min} and OEC_{max} are minimum and maximum biomass loads for each OEC in g m^{-2}; BLF is biomass live fraction; BES is standard burning efficiency; CE is combustion efficiency; and ERCO is emission ratio of CO, as referenced to CO_2. Sources are as follows: OEC, J. S. Olson (personal communication, 2002); BLF, R. D. Ottmar (personal communication, 2002, based on the work of *Ottmar and Vihnanek* [1998, 1999, 2000] and *Ottmar et al.*, 2001, 2000a, 1998, 2000b]); BES values, *Akerelodu and Isichei* [1991], *Bilbao and Medina* [1996], *Dignon and Penner* [1996], *Hoffa et al.* [1999], *Hurst et al.* [1994], *Kasischke et al.* [2000], and *Levine* [2000]; CE and ERCO values, *Hao and Ward* [1993], *Delmas et al.* [1995], *Granier et al.* [2000], *Lacaux et al.* [1996], and *Cofer et al.* [1990].

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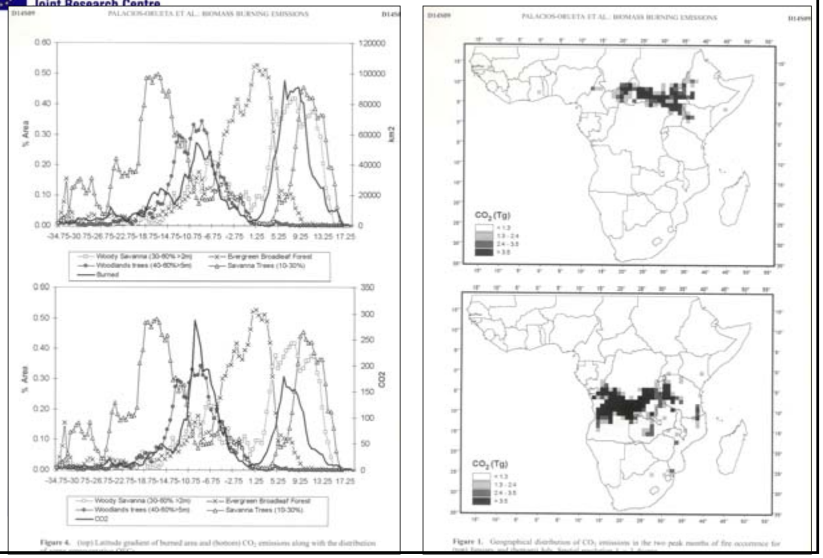
Gas Emission Estimation



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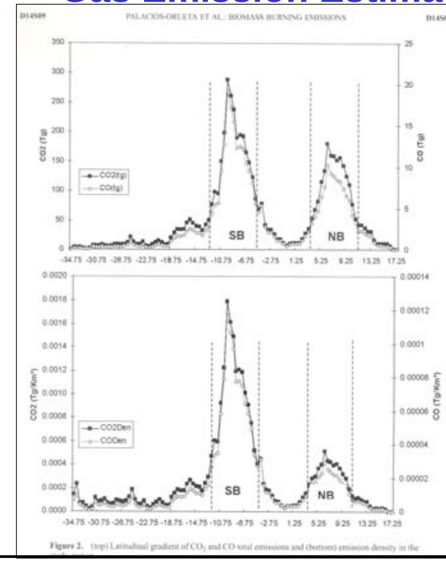

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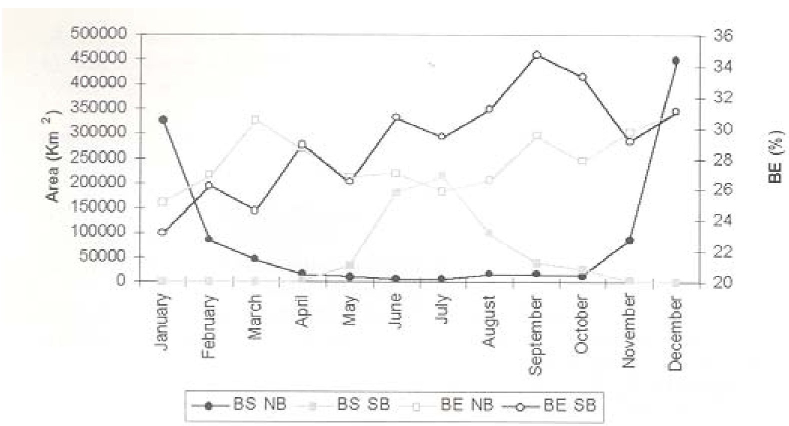

Figure 5. Temporal evolution of burned areas and BE for the two bands most affected by fires.

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CONCLUSIONS

- This is only a first flavour of Trace Emission Gas Species from Biomass Burning
- Trace Gas Emissions from BB are very complex to estimate at regional and global scales:
  - Estimations are conditioned by:
    - The structure and conditions of vegetation affected by fire: Chemical and Physical features
    - Fire itself: dependant on environmental factors – humidity, temperature and wind speed.
- We have defined several variables involved in the estimation:
  - Biomass Load, Burning Efficiency, Burned Areas, Biomass Load
- Experiments oriented to estimate the different variables and ratios
  - Field experiments
  - Remote Sensing
  - Laboratory experiments
- Remote Sensing also provides the possibility of spatial distributing the estimations.
  - Providing a close to actual global map of vegetation
  - Providing a close to actual global map of burned surfaces
  - Providing a close to actual state of the vegetation
- A JRC GIS tool: GFA for gas emissions estimations from BB
  - Put in evidence the complexity of estimations
  - Parameters have to be improved: Burn Efficiency and Combustion Efficiency

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