Africa as a regional and global source of atmospheric gases and particulates

Lawrence Mtetwa
College of William and Mary

Follow this and additional works at: https://scholarworks.wm.edu/etd
Part of the Atmospheric Sciences Commons, Environmental Sciences Commons, and the Geography Commons

Recommended Citation
https://dx.doi.org/doi:10.21220/m2-hp8p-1747

This Dissertation is brought to you for free and open access by the Theses, Dissertations, & Master Projects at W&M ScholarWorks. It has been accepted for inclusion in Dissertations, Theses, and Masters Projects by an authorized administrator of W&M ScholarWorks. For more information, please contact scholarworks@wm.edu.
INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6” x 9” black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.
AFRICA AS A REGIONAL AND GLOBAL SOURCE OF ATMOSPHERIC GASES AND PARTICULATES

A Dissertation
Presented to
The Faculty of the Department of Applied Science
The College of William and Mary in Virginia

In Partial Fulfillment
Of the requirements for the degree
of Doctor of Philosophy

by

Lawrence Mtetwa
May 1998
APPROVAL SHEET

This dissertation is submitted in partial fulfillment of
the requirements for the degree of

Doctor of Philosophy

_____________
Lawrence Mtetwa

Approved, May 1998

_____________
Joel S. Levine
(Chairperson of Dissertation committee)

_____________
Gregory M. Capelli

_____________
Richard S. Eckman

_____________
Mark K. Hinders

_____________
Gerald H. Johnson
Table Of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>TABLE OF CONTENTS</td>
<td>iii</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>ix</td>
</tr>
<tr>
<td>UNITS AND CONVERSIONS</td>
<td>xiii</td>
</tr>
<tr>
<td>LIST OF SYMBOLS AND ABBREVIATIONS</td>
<td>xiv</td>
</tr>
<tr>
<td>LIST OF AFRICAN COUNTRIES</td>
<td>xix</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>xx</td>
</tr>
<tr>
<td>CHAPTER</td>
<td></td>
</tr>
<tr>
<td>I. INTRODUCTION</td>
<td>2</td>
</tr>
<tr>
<td>Backgroud</td>
<td>4</td>
</tr>
<tr>
<td>Global population trends</td>
<td>6</td>
</tr>
<tr>
<td>Major issues relating to the importance of Africa in trace gas</td>
<td>7</td>
</tr>
<tr>
<td>emissions</td>
<td></td>
</tr>
<tr>
<td>II. EMISSIONS FROM FOSSIL FUEL USES IN AFRICA</td>
<td>12</td>
</tr>
<tr>
<td>2.1 INTRODUCTION</td>
<td>12</td>
</tr>
<tr>
<td>2.2 Data Sources and Scope</td>
<td>17</td>
</tr>
<tr>
<td>2.3 Methodology</td>
<td>19</td>
</tr>
<tr>
<td>2.3.1 Calculating CO2 Emissions</td>
<td>19</td>
</tr>
<tr>
<td>2.3.2 Estimating CH4 Emissions</td>
<td>23</td>
</tr>
<tr>
<td>2.3.3 Estimating NOx and CO2 from Fossil Fuel Generation of Electricity</td>
<td>28</td>
</tr>
<tr>
<td>2.3.4 Estimation of Future Emissions</td>
<td>29</td>
</tr>
</tbody>
</table>
Acknowledgments

Sincere thanks go to my advisor, Dr. Joel S. Levine for his encouragement and assistance, and under whose guidance this work was completed. I would also like to thank the rest of my committee members, Professors Gregory M. Capelli, and Mark K. Hinders and Gerald H. Johnson and Dr. Richard S. Eckman. Many thanks also go to Dr. Geoffrey Considine for reading this dissertation and making many kind and helpful suggestions concerning the material in its early stages.

I thank Dr. Hiram Levy, and Jim Yienger of the NOAA Geophysical Fluid Dynamics Laboratory (GFDL), Princeton, N.J. for the use of their empirical model, and for their assistance in learning the GFDL Biogenic Soil NO$_x$ Model. I appreciate the assistance I received from Jim Yienger and his patient explanations of the model.

I am grateful to the Applied Science Department of the College of William and Mary and its chair, Professor Dennis M. Manos, and to the Theoretical Studies Branch, Atmospheric Sciences Division at NASA Langley for providing research facilities and support. This research was supported by funding from the NASA Earth Science Program (formerly the Mission to Planet Earth Program) and the Global Change Program of the U.S. Environmental Protection Agency under Interagency Agreement DW-80936540-01-1.

This acknowledgment would not be complete without mentioning the following people whose love and support I will always cherish --- my friends at the East Hampton United Methodist Church, Doris King, Dr. Arlene Levine, Jeanette Reavis, Tony Spain, Jeterfonee Jones-Giles and Kenneth Giles.

I am eternally indebted to my parents, my mother, Esther Mtetwa and my late father, Johnson Mubizani Mtetwa, for their unlimited energy, inspiration and guidance. Finally I thank God for his many blessings and for making things possible.
LIST OF TABLES

2.1 Fossil Fuel Types by Phase Category .................................................. 15
2.2 Fossil Fuel Carbon Emission Factors .................................................. 22
2.3 Fraction of Carbon Stored (FCS) and Fraction of Carbon Oxidize (FCO) For Fuel Types .................................................. 22
2.4 Revised Emission Factors for Methane from Oil And Gas Activities Systems (Kg/ PJ) for the Rest of The World Category, under which Africa is Classified .................................................. 26
2.5 CO2 National Totals from Fossil Fuel Combustion and Emissions per 10^6 Inhabitants and Socioeconomic Factors .................................................. 43
2.6 CH4 National Totals from Fossil Fuel Combustion and Emissions per 10^6 Inhabitants and Socioeconomic Factors .................................................. 45
2.7 National Totals for NOx Emissions from Electricity Generation and Emissions per 10^6 Inhabitants and Socioeconomic Factors .................................................. 47
2.8 Demographic Data for Africa .................................................. 48
2.9 Uncertainties Due to Emission Factors and Activity Data for Fossil Fuel Estimates .................................................. 39
3.1 Mean Mission Factors .................................................. 88
3.2 Mean Emission Ratios .................................................. 90
3.3 Estimated Biomass Burning Emissions of Trace Gases and Particulates from African Countries .................................................. 111
3.4 Estimates for Total Regional (Africa) Biomass Burning Emissions, Savanna Africa, all Biomass Burning(Global), and Percentage
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Total Carbon Dioxide Emissions from the Use of Fossil Fuel in Africa: 1994</td>
<td>53</td>
</tr>
<tr>
<td>2.2</td>
<td>Carbon Dioxide Emissions from Gas Flaring in Africa: 1994</td>
<td>54</td>
</tr>
<tr>
<td>2.3</td>
<td>Relative Distribution of Fossil Fuel Types Contributing to Carbon Dioxide Emissions in African Countries: 1994</td>
<td>55</td>
</tr>
<tr>
<td>2.4</td>
<td>Carbon Dioxide Emissions from the Use of Liquid Fossil Fuel in Africa: 1994</td>
<td>56</td>
</tr>
<tr>
<td>2.5</td>
<td>Carbon Dioxide Emissions from the Use of Gaseous Fossil Fuel in Africa: 1994</td>
<td>57</td>
</tr>
<tr>
<td>2.6</td>
<td>Carbon Dioxide Emissions from the Use of Solid Fossil Fuel in Africa: 1994</td>
<td>58</td>
</tr>
<tr>
<td>2.7</td>
<td>Total Regional Emissions of Methane from the Use of Fossil Fuels in Africa:</td>
<td>59</td>
</tr>
<tr>
<td>2.8</td>
<td>Emissions of Methane from the Use of Liquid Fossil Fuels in Africa: 1994</td>
<td>60</td>
</tr>
<tr>
<td>2.9</td>
<td>Emissions of Methane from the Use of Gas Fossil Fuels in Africa: 1994</td>
<td>61</td>
</tr>
<tr>
<td>2.10</td>
<td>Emissions of Methane from the Use of Solid Fossil Fuels in Africa: 1994</td>
<td>62</td>
</tr>
<tr>
<td>2.11</td>
<td>Relative Distribution of Fossil Fuel Types Contributing to Methane Emissions in African Countries: 1994</td>
<td>63</td>
</tr>
<tr>
<td>2.12</td>
<td>Emissions of NOx from Fossil Fuel Generation of Electricity in Africa: 1994</td>
<td>64</td>
</tr>
</tbody>
</table>
2.13 Natural Gas Consumption and Corresponding CO₂ Emissions from Africa 1970-1995

2.14 Solid Fuel Consumption and Corresponding CO₂ Emissions

2.15 Liquid Fuel Consumption and Corresponding CO₂ Emissions from Africa 1970-1995

2.16 Trends of Total Fossil Fuel CO₂ Emissions for Africa


2.18 Projected CO₂ Emissions from Fossil Fuel Combustion in Africa Under a No-Further-Control Scenario

2.19 Fossil Fuel CO₂ Emissions Normalized by Population

2.20 Fossil Fuel CO₂ Emissions Normalized by GNP per Capita

2.21 Fossil Fuel CO₂ Emissions Normalized by None

3.1 Biomass Burning Emissions Estimation Scheme

3.2 Night-time Low-Light DMSP Imagery Annual Composite of Fires in Africa (1986-1987)

3.3 DMSP Annual Composite Highlighting Fire Distribution and Pixels (1986-1987) 1°x1° Grid

3.4 Matthews Global Vegetation Index - 32 Type

3.5 Reclassified 1°x1° Grid with 11 Broad Vegetation Types

3.6 1°x1° Grid Showing Distribution of Total Monthly Biomass Burning (1000 tons/ Month) - January

3.7 1°x1° Grid Showing Distribution of Total Monthly Biomass Burning (1000 tons/ Month) - February

3.8 1°x1° Grid Showing Distribution of Total Monthly Biomass Burning (1000 tons/ Month) - March

x

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
4.4 Past case Pre-industrial January Soil - NOX Emissions 163
4.5 Present-day case (1995) January Soil - NOX Emissions 164
4.6 Future-case (2020) January Soil - NOX Emissions 165
4.7 Past-case Pre-industrial July Soil - NOX Emissions 166
4.8 Present-day case (1995) July Soil - NOX Emissions 167
4.10 % Total Annual Biogenic Soil- NOX Emissions- Past Case Pre-Industrial 169
4.11 % Total Annual Biogenic Soil- NOX Emissions- Present Case 1995 170
4.12 % Total Annual Biogenic Soil- NOX Emissions- Future Case 2020 171
4.13 Total Annual Biogenic Soil- NOX Emissions- Fertilizer Induced Present Case 1995 172
4.14 Total Annual Biogenic Soil Emissions- Fertilizer Induced Future Case 2020 173
4.15 Sources of Biogenic Soil NOX Emissions- Ecosystem-Biome Sources - Strongest Biome Type Emitters Present Day Case 174
4.16 Sources of Biogenic Soil NOX Emissions- Ecosystem-Biome Sources - Strongest Biome Type Emitters Present Day Case 175
4.17 Sources of Biogenic Soil NOX Emissions- Ecosystem-Biome Sources - Strongest Biome Type Emitters Future Case 2020 176
Units and Conversions

Standard Equivalents for Mass

<table>
<thead>
<tr>
<th>Unit</th>
<th>Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ton of oil equivalent (toe)</td>
<td>$1 \times 10^{10}$ calories</td>
</tr>
<tr>
<td>$10^3$ toe</td>
<td>41.868 TJ</td>
</tr>
<tr>
<td>1 short ton</td>
<td>0.9072 ton</td>
</tr>
<tr>
<td>1 ton</td>
<td>1.1023 short tons</td>
</tr>
<tr>
<td>1 kiloton</td>
<td>1 gigagram</td>
</tr>
<tr>
<td>1 megaton</td>
<td>1 teragram</td>
</tr>
<tr>
<td>1 kilogram</td>
<td>2.2046 lbs</td>
</tr>
<tr>
<td>1 calorie</td>
<td>$4.1868 \text{ Joules}$</td>
</tr>
<tr>
<td>1 atmosphere</td>
<td>101.325 kpa</td>
</tr>
<tr>
<td>PJ</td>
<td>Petajoule ($10^{15}$\text{Joules})</td>
</tr>
</tbody>
</table>

General Conversion Factors for Energy

<table>
<thead>
<tr>
<th>To</th>
<th>TJ</th>
<th>Gcal</th>
<th>Mtoe</th>
<th>MBtu</th>
<th>GWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>From</td>
<td>multiply by</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TJ</td>
<td>$1$</td>
<td>$238.8$</td>
<td>$2.388 \times 10^{-5}$</td>
<td>$947.8$</td>
<td>$0.2778$</td>
</tr>
<tr>
<td>Gcal</td>
<td>$4.1868 \times 10^{-3}$</td>
<td>$1$</td>
<td>$10^{-7}$</td>
<td>$3.968$</td>
<td>$4.1868 \times 10^{3}$</td>
</tr>
<tr>
<td>Mtoe</td>
<td>$4.1868 \times 10^{4}$</td>
<td>$10^{7}$</td>
<td>$1$</td>
<td>$3.968 \times 10^{7}$</td>
<td>$11630$</td>
</tr>
<tr>
<td>MBtu</td>
<td>$1.0551 \times 10^{-3}$</td>
<td>$0.252$</td>
<td>$2.52 \times 10^{-8}$</td>
<td>$1$</td>
<td>$2.931 \times 10^{-4}$</td>
</tr>
<tr>
<td>GWh</td>
<td>$3.6$</td>
<td>$860$</td>
<td>$8.6 \times 10^{-5}$</td>
<td>$3412$</td>
<td>$1$</td>
</tr>
</tbody>
</table>
### List of Symbols and Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVHRR</td>
<td>Advanced Very High Resolution Radiometer</td>
</tr>
<tr>
<td>cal</td>
<td>Calorie</td>
</tr>
<tr>
<td>CFC's</td>
<td>Carbon fluoro compounds</td>
</tr>
<tr>
<td>CH$_3$Br</td>
<td>Methyl bromide</td>
</tr>
<tr>
<td>CH$_3$Cl</td>
<td>Methyl chloride</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>Methane</td>
</tr>
<tr>
<td>cm</td>
<td>Centimeter</td>
</tr>
<tr>
<td>CO</td>
<td>Carbon monoxide</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>DACAFE</td>
<td>Dynamique et Chimie Atmospheric en Foret Equatoriale</td>
</tr>
<tr>
<td>dm</td>
<td>Dry matter</td>
</tr>
<tr>
<td>DMSP</td>
<td>Defense Meteorological Satellite Program</td>
</tr>
<tr>
<td>E</td>
<td>East</td>
</tr>
<tr>
<td>EF</td>
<td>Emission factor</td>
</tr>
<tr>
<td>EOS</td>
<td>Earth Observing System</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>EPRI</td>
<td>Electric Power Research Institute</td>
</tr>
<tr>
<td>ER</td>
<td>Emission ratio</td>
</tr>
<tr>
<td>FAO</td>
<td>Food and Agricultural Organization of the UN</td>
</tr>
<tr>
<td>FOS/DECAFE-91</td>
<td>Fire of savannas/ Dynamique et Chimie Atmospheric en Foret Equatoriale</td>
</tr>
<tr>
<td>g</td>
<td>Gram</td>
</tr>
<tr>
<td>GCM</td>
<td>General Circulation Model</td>
</tr>
<tr>
<td>GCTM</td>
<td>Global Chemical Transport model</td>
</tr>
<tr>
<td>Acronym</td>
<td>Full Form</td>
</tr>
<tr>
<td>---------</td>
<td>-----------</td>
</tr>
<tr>
<td>GFDL</td>
<td>Geophysical Fluid Dynamics Laboratory (Princeton, USA)</td>
</tr>
<tr>
<td>Gg</td>
<td>Giga grams</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographical Information System</td>
</tr>
<tr>
<td>GISS</td>
<td>Goddard Institute for Space studies (NASA, USA)</td>
</tr>
<tr>
<td>GM</td>
<td>Greenwich meridian</td>
</tr>
<tr>
<td>GNP</td>
<td>Gross National Product (an estimate of the total value of goods and services produced in any specified country in a year and can be reported for a country as a total amount or as an amount per capita)</td>
</tr>
<tr>
<td>GSFC</td>
<td>Goddard Space Flight Center</td>
</tr>
<tr>
<td>GWP</td>
<td>Global warming Potential</td>
</tr>
<tr>
<td>H</td>
<td>Northern hemisphere</td>
</tr>
<tr>
<td>H₂O</td>
<td>Water vapor</td>
</tr>
<tr>
<td>ha</td>
<td>Hectare (=10⁴ meters²)</td>
</tr>
<tr>
<td>HCFCs</td>
<td>Hydrocarbon fluoro compounds</td>
</tr>
<tr>
<td>HNO₃</td>
<td>Nitric acid</td>
</tr>
<tr>
<td>HNO₄</td>
<td>Nitrous acid</td>
</tr>
<tr>
<td>HO₂</td>
<td>Hydrogen dioxide</td>
</tr>
<tr>
<td>hr</td>
<td>Hour</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel On Climate Change</td>
</tr>
<tr>
<td>ITCZ</td>
<td>Inter Tropical Convergence Zone</td>
</tr>
<tr>
<td>J</td>
<td>Joule</td>
</tr>
<tr>
<td>K</td>
<td>Kelvin (unit of Temperature)</td>
</tr>
<tr>
<td>km</td>
<td>Kilometer</td>
</tr>
</tbody>
</table>
LIC Less Industrialized Countries
m Meter
m$^3$ Cubic meter
mb Millibar (= $10^{-3}$bars)
MIC More Industrialized Countries
mm Millimeter (= $10^{-3}$ meters)
MT Metric tonne
N North
N$_2$O Nitrous oxide
NASA National Aeronautics and Space Administration, USA
NE North East
NFC No-Further-Control
NH$_3$ Ammonia
nm Nanometer
NO Nitrogen monoxide
NO$_2$ Nitrogen dioxide
NOAA National Oceanic and Atmospheric Administration, USA
NO$_x$ Odd nitrogen (= NO + NO$_2$)
NW North west
O($^1$D) excited state (metastable) atomic oxygen
O$_3$ Ozone
$^\circ$C Degrees Celsius
OECD Organization for Economic Cooperation and Development
OH Hydroxyl radical
PAN Peroxyacetyl Nitrate
$P'$ Surface Pressure

ppbv Parts per billion by volume

pptv Parts per trillion by volume

R Mixing ratio

RCW Rapidly Changing World

S South

s Second

SADC Southern African Development Cooperation Community

SAFARI-92 Southern African Fire-atmosphere research Initiative

SAGE Stratospheric Aerosol Gas experiment

SE South East

SH Southern Hemisphere

SO2 Sulfur dioxide

SW South west

T Temperature

t Ton (=1000 kilograms)

$T_g$ Teragram (=10^{12} grams)

$T_J$ Terajoules (=10^{12} Joules)

TOMS Total Ozone Mapping Spectrometer

TRACE-A Transport and Atmospheric Chemistry near the Equator - Atlantic

UN United Nations

USA United states of America

w West

wavelength
WEC  World Energy Council
WMO  World Meteorological Organization
yr   Year
yr-1  Per year
μm   Micrometers
### African Countries

<table>
<thead>
<tr>
<th>Country</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algeria</td>
<td>Madagascar</td>
</tr>
<tr>
<td>Angola</td>
<td>Malawi</td>
</tr>
<tr>
<td>Benin</td>
<td>Mali</td>
</tr>
<tr>
<td>Botswana</td>
<td>Mauritania</td>
</tr>
<tr>
<td>Burkina Faso</td>
<td>Mauritius</td>
</tr>
<tr>
<td>Burundi</td>
<td>Morocco</td>
</tr>
<tr>
<td>Cameroon</td>
<td>Mozambique</td>
</tr>
<tr>
<td>Cape Verde</td>
<td>Namibia</td>
</tr>
<tr>
<td>Central African Republic</td>
<td>Niger</td>
</tr>
<tr>
<td>Chad</td>
<td>Nigeria</td>
</tr>
<tr>
<td>Comoros</td>
<td>Reunion</td>
</tr>
<tr>
<td>Congo</td>
<td>Rwanda</td>
</tr>
<tr>
<td>Cote d'Ivoire</td>
<td>Senegal</td>
</tr>
<tr>
<td>Djibouti</td>
<td>Seychelles</td>
</tr>
<tr>
<td>Egypt</td>
<td>Sierra Leone</td>
</tr>
<tr>
<td>Equatorial Guinea</td>
<td>Somalia</td>
</tr>
<tr>
<td>Eritrea</td>
<td>South Africa</td>
</tr>
<tr>
<td>Ethiopia</td>
<td>Sudan</td>
</tr>
<tr>
<td>Gabon</td>
<td>Swaziland</td>
</tr>
<tr>
<td>Gambia The</td>
<td>Tanzania</td>
</tr>
<tr>
<td>Ghana</td>
<td>Togo</td>
</tr>
<tr>
<td>Guinea</td>
<td>Tunisia</td>
</tr>
<tr>
<td>Guinea-Bissau</td>
<td>Uganda</td>
</tr>
<tr>
<td>Kenya</td>
<td>Western Sahara</td>
</tr>
<tr>
<td>Lesotho</td>
<td>Zaire (Now Democratic Peoples Republic of Congo)</td>
</tr>
<tr>
<td>Liberia</td>
<td>Zambia</td>
</tr>
<tr>
<td>Libya</td>
<td>Zimbabwe</td>
</tr>
</tbody>
</table>

Total Population (1998): 760 million people  
Projected Population (2020): 1.2 billion people  
Area: $11.55 \times 10^6$ square miles
ABSTRACT

The role of the continent of Africa as a source of gaseous and particulate emissions to the atmosphere is investigated in this study. Sources of gases and particulates from Africa include fossil fuel combustion, biomass burning, and biogenic soil emissions of nitric oxide. This study represents the first comprehensive database of gaseous and particulate emissions developed for the continent of Africa on a country by country basis and establishes the framework for country-by-country assessment of greenhouse gases emissions as required by the Kyoto Conference on Global Warming, which was attended by representatives from more than 100 countries.

Calculations of gases and particulates resulting from fossil fuel combustion were based on the Intergovernmental Panel on Climate Change (IPCC) guidelines. Calculations of gases and particulates resulting from biomass burning were based on fire counts obtained from the Defense Meteorological Satellite Program (DMSP) Block 5 satellites and emission ratios for various gaseous and particulate fire products obtained during the recent Southern African Fire-Atmosphere Research Initiative (SAFARI), an activity of the international Global Atmospheric Chemistry (IGAC) Project, part of the international Geosphere-Biosphere Program (IGBP). The calculations of biogenic soil emissions of nitric oxide were obtained with the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) Biogenic Soil NOX Model.

Africa was found to be a significant global source of the following gases: carbon dioxide (CO₂), carbon monoxide (CO), methyl chloride (CH₃Cl), oxides of nitrogen (NOₓ), and carbon particulates. The results indicate that Africa is the world's single largest continental source of emissions due to biomass burning and that these emissions are likely to increase with time. The study established that on a global
scale. Africa was the largest source of soil biogenic NOX. The importance of Africa as a key global source of trace gases and aerosols has been underestimated in the past. This research offers a new picture of gaseous and particulate emissions from Africa. Africa's global significance as a source of atmospheric gases is very important, i.e., more than 11% of the world's total anthropogenic CO2 production results from biomass burning in Africa. Africa contributes nearly a third of the global anthropogenic CH3Cl, a third of the global anthropogenic NOX, and almost 20% to the world's global carbon particles anthropogenic budget.
AFRICA AS A REGIONAL AND GLOBAL SOURCE OF ATMOSPHERIC GASES AND PARTICULATES
CHAPTER I

1.0 Introduction

Recent studies have suggested that Africa may be a significant regional and global source of atmospheric gases and particulates (Levine et al., 1995; Scholes 1995; and Andreae et al., 1996). The major producers of atmospheric gases and particulates in Africa are biomass burning (Levine et al., 1995; Hao and Liu 1994), biogenic sources (Yienger and Levy 1995; Scholes et al., 1996), and fossil fuel combustion. Emissions from the consumption of fossil fuels in Africa appears to be increasing (Marland and Rotty, 1984; Kasibhatla et al., 1993; De Castro and Rahman, 1996) as population growth and industrialization places greater need for fossil fuels. The energy sources at present in many African countries are primarily non-commercial biomass use is mainly for cooking and other domestic purposes (Lashof and Tirpak, 1990). Studies of emissions from African countries are lacking relative to the industrialized world.

The goal of this research is to develop an inventory of the sources of gases and particulates from Africa. Specifically, this study will assess and estimate emissions from the chief primary sources: biomass burning gases and particulates, fossil fuel combustion, and biogenic emissions. Gases and particulates of interest include carbon dioxide (CO2), carbon monoxide (CO), methane (CH4), methyl chloride (CH3Cl), methyl bromide (CH3Br), oxides of nitrogen (NOx), non-methane hydrocarbons (NMHC'S), sulfur dioxide (SO2), and ammonia (NH3), as well as total particulate matter (TPM), particles< 2.5 μm, and carbon particles black (soot). This study provides estimates on a country by country basis, and also gives 1° x 1° spatial...
resolution for biomass burning activities. Specific Objectives are discussed in more
detail in the individual chapters addressing the different aspects of this research.

Presently, there no information exits on methane emissions from the use of
fossil fuels in Africa. While a study on efficient electrical end use technologies for
mitigating greenhouse gas emissions in Africa has been performed (De Castro and
Rahman, 1996), on seven countries based on electrical use by sector, a wide range of
uncertainty in emissions of NO\(_X\) by fossil fuel electricity generation remains. The De
Castro and Rahman study used a simple approximation for emissions per KWh to
convert electricity statistics into emissions. However, this inventory needs to be
expanded to include most of Africa and establish an inventory based on more recent
methodologies. An inventory of carbon dioxide emissions in Africa based on the
procedure of Marland (1984) and production data only has been attempted before
(Marland and Rotty, 1994). There are a number of problems with this approach,
because much representative information from consumption and trade is left out.
There is a need to establish a new carbon dioxide fossil fuel inventory based on recent
statistics provided by the IEA -OECD data on production and consumption together
with process emission factors. In the future, Africa will become a major source of
emissions from the use of fossil fuels. An attempt must be made to establish this
inventory on a country-by-country basis as very little information exists with this
regard. It is also crucial for the future of global emissions that research establishes the
time history of these gases, whether they increasing or decreasing with time and make
projections for the future levels of these emissions. The correlation of emissions with
GNP (impact of economic growth on emissions), and correlation of emissions with
population (impact of population on emissions) in Africa has not been established.
A number of studies have been carried out on emissions of gases and particulates from biomass burning in Africa (see Chapter 3 introduction). However, no complete continental inventory of these emissions has been provided. Studies in the past have suffered limitations in estimating emissions due to lack of emission factors and emission ratio data and this has been discussed in detail in Chapter 3. Some studies have tried to model emissions in Southern Africa, with a high degree of uncertainty. There remains a wide gap in national inventories of biomass burning emissions in Africa. In order to better understand the spatial distribution of biomass burning in Africa, a inventory on 1x1 degree spatial resolution must be established. While it is generally agreed that Africa may be the largest continental source of gases and particulates from biomass burning, a more qualitative and quantitative approach giving percentage contributions needs to be carried out.

In the last decade, research has been conducted to understand biogenic soil NO\textsubscript{x} emissions in Africa and its contribution to the global budget (Yienger and Levy, 1995). However, within the constraints of the existing data when the study was done, the results can only be looked at as a best guess estimate and were centered primarily on emissions by biome type. Africa's importance and continental contributions have not been established. There is a need to make new estimates the emissions based on new available data.

**Background**

The Industrial Revolution caused significant changes in the global budgets of many atmospheric gases and particulates (World Meteorological Organization, 1994; Intergovernmental Panel on Climate Change, 1992, 1995). Throughout the 4.5-billion year history of the Earth, the composition and chemistry of the atmosphere, as
well as the climate of our planet, have been shaped by the production of atmospheric
gases within the biosphere (Levine, 1995). There is scientific consensus that
anthropogenic contributions of atmospheric gases and particulates have begun to tip a
delicate balance, significantly increasing the amounts of certain trace species and
particulates emissions in the atmosphere and with possible harmful effects on our
climate (IPCC, 1992, Levine et al., 1995).

Industrialization, accompanied by an increase in fossil fuel combustion and
associated emissions, is increasingly important as a global source of atmospheric
pollution. Worldwide, combustion of coal, oil, and natural gas releases about 6 billion
tons of carbon into the atmosphere annually (IPCC, 1995). These emissions are fairly
well documented. By contrast biomass burning, however, is not so well documented
because a much larger fraction of biomass burning is not well documented because
people do not keep statistics on biomass burning activities.

Biomass burning is an enormous and rapidly increasing source of trace gases
and particulates (Levine, 1995). The burning of forests alone contributes 1-2 billion
tons of carbon dioxide annually to the atmosphere (Hao, 1990). Natural and human
biomass burning contributes almost a third of the total global carbon dioxide emitted
annually (Levine, 1995).

Some agricultural and pastoral practices complement other sources of
pollution. Natural processes such as emissions from the oceans, biogenic emissions
and windblown particulates are also major sources of atmospheric gases and
particulates. Of these sources, only biogenic emissions are relevant to the African
continent because of Africa's vast savanna and tropical biomes, wet and dry seasons,
and biomass burning activities. In light of these rapid changes, the study of emissions
on both regional and global atmospheric chemistry is becoming increasingly important.

The developed world is currently responsible for the greatest fraction of gaseous emissions per capita. In 1995, 73% of the global CO₂ emissions came from anthropogenic activities in the developed countries (Marland et al., 1995). The United States of America, being the single most important source, accounted for 22% of the total, with carbon emissions per person now exceeding 5 tons per annum (Marland et al., 1995).

**Global Population Trends**

Perhaps the major factor affecting gas and particulate emissions is the increase in human population. As population levels rise, increasing pressures is placed on the environment by increased demands for food and improved standards of living. Higher population levels lead to increased emissions of gases.

Population levels and growth rates have increased tremendously over the last 200 years, and these changes have been most acute in the developing regions, particularly Africa and Asia where annual growth rates exceed 2%. (Lashof and Tirpak, 1990). World population in the year 1 A.D was approximately 0.25 billion. it doubled by 1650 and doubled again by 1850 to roughly 1.1 billion. In 1930, world population was 2 billion and doubled by 1975. Rapid population growth is highest in developing nations, particularly on the African continent where many African countries continue to experience annual growth rates between 2 and 3% (Lashof and Tirpak 1990). Forty-one African By the year 2020, world population is predicted to reach the 8 billion mark (US Bureau of Census, 1998; Lashof and Tirpak, 1990). Over the years, the time period in which global population has doubled has declined.
countries have a growth rate of 2% or greater. Declining death rates and high birth rates are main factors contributing to higher growth rates in the twentieth century.

Projections indicate that 90% of the world's population growth will take place in the developing countries over the next few decades. Per capita energy use in the developing countries which is currently 1/10 to 1/20 of U.S level, is anticipated to drastically increase (Marland et al., 1995). If current trends continue, emissions from developing countries will exceed those of the developed world before the middle of the next century (De Castro and Rahman, 1996).

Scenarios for future fossil fuel emissions are unclear. Population and economic growth, structural changes in economies, energy prices, technological advance, fossil fuel supplies, nuclear and renewable energy availability and rapid changes in the third world countries are among the factors which could strongly influence future levels of fossil fuel related emissions. Rapid changes, such as those in developing countries, now incorporated into all the scenarios, have important implications for future fossil fuel carbon emissions.

**Major Issues Relating to the Importance of Africa in Trace Gas Emissions**

Africa has a large impact on global atmospheric chemistry, climate and atmospheric composition. Africa's role in determining global budgets of trace gas species is likely to increase because Africa is currently characterized by rich natural resources, rapidly increasing population, emerging industries, land use change accompanying population increases, a growing agricultural infrastructure, extensive biomass burning, rapid deforestation, and severe desertification and droughts. Africa is characterized by vast biogenic activity in both tropical and savanna biomes with a
correspondingly large potential for biogenic emissions. Below is a brief discussion of some of the important factors affecting gaseous atmospheric emissions from Africa.

(1) Rapidly Increasing Population

Africa is experiencing rapid population growth. It is estimated that by the year 2020 over 1.2 billion people will be living in Africa an increase of 50% on the current 0.8 billion population (US Bureau of Census, 1998). Most of the growth will be in sub-Saharan Africa. Statistics show that the human population growth for Africa has increased from 2.3%/yr in 1955 to 3%/yr in 1997, and Africa has the highest fertility rates and population growth rates in the world today (Lashof and Tirpak, 1990). It is extremely important to assess and understand the spatial distribution and density of the population of Africa in order to establish the basic component of the anthropogenic aspect of human-induced gaseous emissions and particulates.

(2) Emerging Industries and Increased Energy Demands

Africa is may undergo a tremendous economic boom which will inevitably be accompanied by rapid industrialization and increased energy demand (IPCC 1995, UNEP, 1991). For example, presently less than 30% of urban households and 5% of rural households have access to electricity in central Africa. With existing electrification programs, however, it is expected that 90% of urban households and 35% of rural households will be connected to the electrical grid by the year 2025 (De Castro and Rahman, 1996). Higher energy demand will result in a large increases in nitrogen oxides (NOx) emissions in Africa. This will increase ambient concentrations of NOx and regional levels of acid deposition and tropospheric ozone.
(3) A Growing Agricultural Infrastructure

African agricultural and pastoral practices typically include annual or biennial burning of the savanna vegetation. As the population of Africa increases, the continent is expected to undergo a tremendous boom in agricultural production to sustain the growing population. Higher fertilizer usage which will influence biogenic emissions and increased domestic animal population and recent environmental conservation laws will result in growing populations of African wildlife.

(4) Prevalent Biomass Burning

Most of Africa has a strongly seasonal climate, with hot, wet summers and warm dry winters. This climate promotes the growth of savanna type vegetation. Over two thirds of the world's savannas are located in Africa. African fires are suspected to account for nearly one third of the biomass burned in the tropics worldwide (Hao and Liu 1994). Even in the absence of humans, natural savanna fires are common due to lightning and abundant dry vegetation in savannas. African people contribute to biomass burning for several seasons: to clear vegetation to provide land for agricultural and grazing purposes, to control weeds, and to eliminate agricultural waste after harvest and for domestic purposes such as heating and cooking.

(5) Enhanced Biogenic Emissions

Soil biogenic emissions from the African continent are expected to double within the next 30 years due to increased fertilizer utilization and burning (Yienger and Levy, 1995). Presently global soil biogenic emissions are on the order of 4-20 Tg N/yr. (Levy et al., 1991). Most of the soil biogenic emissions come from tropical and
savanna biomes and are stimulated by burning and strongly seasonal wet and dry conditions, all of which are important in Africa.

(6) Deforestation in Africa

The world's forest and woodlands have been reduced about 15% since 1850, primarily to accommodate the expansion of cultivated lands (World Resources Institute and International Institute for Environment and Development, 1987). The largest changes in forest cover during this period have occurred in Africa, Asia and Latin America. Use of wood as fuel also contributed to deforestation, particularly in Africa where wood is a major source of residential energy (Policy Options for Stabilizing Global Climate, 1990)

Significant tropical deforestation began at the end of the last century and has dramatically increased in the last 30 years as a result of population increases. In western Africa for example, 70% of the forested area that existed at the beginning of the century has already been cleared. (Delmas et al., 1995)

(7) Desertification in Africa

Desertification has become one of the most serious environmental and socio-economic problems of Africa. The global assessment carried out by UNEP in 1990-1991 shows that desertification continues to spread and intensify. Desertification affects almost all of the African countries, with about 55% of the total area of the continent affected (Grushevskii, 1989). More than 650 km² of productive land in 16 countries of the Sudan-Sahel zone have been converted into desert over the last 50 years (Mendez, 1981). Africa experiences frequent drought periods and has experienced some of the worst drought seasons in last few decades.
This study examines the importance of Africa as a source of regional and global atmospheric gases and particulates. Chapter 2 provides estimates of emissions of CO₂, CH₄, NOₓ and from the fossil fuel consumption in Africa. The results are presented on a country by country basis and comparison with world emissions is made. Chapter 3 presents the first regional and national inventory of estimates of gaseous and particulate emissions from biomass burning in Africa. Chapter 4 presents results of biogenic soil NOₓ emissions for Africa compared to the whole world. Results are presented on a country-by-country basis and 1°x1° grids are provided for distribution of biomass burning activities in Africa. Chapter 5 covers the relative importance of the sources of gases and particulates in this study, in the form of relative contributions to the regional budget and an overall assessment of the importance of Africa as a regional and global source of atmospheric gases and particulates.
CHAPTER 2
Fossil Fuel Related Emissions

2.1. Introduction

African countries are experiencing rapid population growth which is expected to inevitably stimulate economic expansion. Additionally, these countries are experiencing a transition from an energy sector largely dominated by traditional biomass fuels to increased use of fossil fuels caused by increasing energy demands (De Castro and Rahman 1996). The role of emissions from fossil fuels and the industrial sector in affecting (i) global warming (ii) determining the global oxidizing power of the troposphere and (iii) influencing the chemical and radiative properties/interactions of the atmosphere is well recognized (Lashof and Tirpak, 1990). The majority of fossil fuel emissions come largely from the developed countries (in 1995, 73% of the total CO$_2$ emissions from anthropogenic activities came from the developed countries, with the United States of America constituting the single largest national source at 22%). Per capita energy use which is currently 1/10 to 1/20 of the USA level, will also increase (Marland et al., 1995). There are indications however, that emissions from developing countries will exceed those from developed countries before the year 2035 (De Castro and Rahman, 1996). An understanding of the spatial and temporal distribution of these emissions in developing regions is therefore important in establishing the role and contribution to global emissions budgets of the developing world. The purpose of this Chapter is to present a detailed study of fossil fuel emissions in Africa.

In this Chapter, CO$_2$, CH$_4$ emissions for Africa arising from fossil fuel combustion, natural gas flaring, and NO$_x$ emissions from electricity generation from fossil fuels for the base year 1994 are estimated and discussed. This is the first
inventory of fossil fuel related emissions for methane and a new improved and expanded inventory of fossil fuel carbon dioxide NO\textsubscript{x} emissions. 1994 was selected as the base year because it is the most recent year with the most complete inventory of statistics need to carry out the estimation procedures. The first inventory on methane emissions from the use of fossil fuels in Africa for both national and regional emissions is presented. This chapter also presents the first expanded estimates to include most of Africa and establish an inventory based on more recent methodologies for the determination of NO\textsubscript{x} emissions from fossil fuel generation of electricity. An inventory of carbon dioxide emissions in Africa has been attempted based on recent statistics provided by the Organization for Economic Cooperation and Development (OECD) and the International Energy Agency (IEA), statistics on production and consumption data together with process emission factors. An analysis has been performed to establish whether Africa is an emerging source of emissions from the use of fossil fuels. Trends on fuel consumption and the emissions of gases have been established based on projections for the future levels of these emissions given. The correlation of emissions with GNP (impact of economic growth on emissions), and correlation of emissions with population (impact of population on emissions in Africa) has been investigated.

Results for national, regional and global estimates are presented. These estimates are based on consumption and process emission factors. CO\textsubscript{2} emissions are compared to those published by Marland (1995) which were calculated based on production data. The CH\textsubscript{4} and NO\textsubscript{x} emissions will are a new inventory.

Emissions for are also projected to the year 2020 under a "no further control" scenario. Over the long term, carbon dioxide emissions are related to trends in economic activities, energy consumption, and particulars of choice of fuel (EPA,
Most end use carbon dioxide emissions come from industries (manufacturing, mining, agriculture, fisheries, and forestry), transportation, residential, commercial, and electric utilities.

In recent years, considerable advances have been made in formulating methods for estimating the emissions of the major gases from fossil fuel production and consumption (Marland and Rotty, 1984; Rotty, 1987). In addition, three dimensional global chemical transport models (CTM's) have steadily evolved to provide a tool with which to synthesize the information gathered from fossil fuel emissions studies. Nevertheless, significant gaps exist in our knowledge of the actual contributions from Africa as a whole and from the individual countries. At present it is generally accepted that emissions from Africa are minimal at , ~<4% of the global totals (Marland et al., 1995), but the concern is to understand future trends as African populations expand and industrialization increases.

The goal of this chapter is to quantify the magnitude of the emissions of carbon dioxide (CO$_2$), methane (CH$_4$), and nitric oxides (NO$_X$) from individual countries in Africa due to industrial sources. We categorize fossil fuels by phase: solid, liquid and natural gas fossil fuels. Fuel types are defined so that each fuel unit is only counted once. Table 2.1 lists the different types of fossil fuels examined and categories.
Table 2.1: Fossil Fuel Types by Phase Category.

<table>
<thead>
<tr>
<th>Gases</th>
<th>Liquids</th>
<th>Solids</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas (dry)</td>
<td>crude oil</td>
<td>anthracite</td>
</tr>
<tr>
<td></td>
<td>natural gas liquids</td>
<td>coking coal</td>
</tr>
<tr>
<td></td>
<td>gasoline</td>
<td>other bitumen coal</td>
</tr>
<tr>
<td></td>
<td>jet kerosene</td>
<td>sub bitumen coal</td>
</tr>
<tr>
<td></td>
<td>other kerosene</td>
<td>lignite</td>
</tr>
<tr>
<td></td>
<td>gas/diesel oil</td>
<td>peat</td>
</tr>
<tr>
<td></td>
<td>residual fuel oil</td>
<td>bkb and patent fuel</td>
</tr>
<tr>
<td></td>
<td>LPG</td>
<td>coke</td>
</tr>
<tr>
<td></td>
<td>ethane</td>
<td></td>
</tr>
<tr>
<td></td>
<td>naphtha</td>
<td></td>
</tr>
<tr>
<td></td>
<td>bitumen</td>
<td></td>
</tr>
<tr>
<td></td>
<td>lubricants</td>
<td></td>
</tr>
<tr>
<td></td>
<td>petroleum coke</td>
<td></td>
</tr>
<tr>
<td></td>
<td>refinery feed stocks</td>
<td></td>
</tr>
<tr>
<td></td>
<td>other oil</td>
<td></td>
</tr>
</tbody>
</table>
Carbon dioxide (CO\textsubscript{2}) is the most abundant gas from fossil fuel use and is an important greenhouse gas in the atmosphere. Global CO\textsubscript{2} emissions from fossil fuels are estimated to be 6.0 Gt C in 1990 compared to 5.7 Gt C in 1987 (IPCC, 1990). Historical trends show evidence of continued increases in fossil fuel related atmospheric emissions (IPCC, 1995).

Another important gas from fossil fuel combustion is methane (CH\textsubscript{4}) which accounts for ~90\% of natural gas production and consumption. CH\textsubscript{4} is introduced into the atmosphere due to leakage's from pipelines and venting of natural gas from oil and gas wells representing 25 - 30 Tg CH\textsubscript{4} / yr. However, the nature of this source makes it difficult to estimate how much this source contributes to the atmospheric abundance of methane. Large amounts of methane are trapped in coal reserves. The percentage of the CH\textsubscript{4} component increases with age and depth of the coal and is released to the atmosphere during mining and processing/crushing of coal. Globally the amount of methane in coal is ~0.5\% of the mass of coal extracted (Lashof and Tirpak, 1990). This source is estimated to be 15-45 Tg CH\textsubscript{4}/yr (Policy Options for Stabilizing Global Climate, 1990). Methane is the most abundant trace gas in the atmosphere that is active both radiatively and chemically (Lashof and Tirpak, 1990).

Nitrogen oxides NO\textsubscript{x} (NO\textsubscript{x} = NO + NO\textsubscript{2}) are also produced in fossil fuel combustion. These oxides play a major role in determining the global oxidizing power of the troposphere (Levine, 1995, Yienger and Levy, 1995).
2.2 Data Sources and Scope

The data described here includes global, regional and national annual fossil fuel usage and corresponding gaseous emissions. Annual estimates of CO₂, CH₄, and NOₓ for 1994 for the individual African countries and total for the region are provided. In addition, world estimates have also been included to form a basis for comparison with African countries.

The primary database used to estimate the amount of CO₂, CH₄, and NOₓ emitted to the atmosphere from fossil fuel burning and gas flaring in Africa is the IEA statistics: Energy Statistics and balances of non-OECD countries, 1993-1994. (Organization for Economic Cooperation and Development). These statistics are published under the auspices of the International Energy Agency (IEA), an autonomous body established in November 1974 within the framework of the Organization for Economic Cooperation and Development(OECD) to implement international energy program.

It is imperative for energy analysis purposes that a comprehensive presentation of basic statistics in original units such as tons of coal and kilowatt-hours of electricity be given. The usefulness of such basic data is considerably improved by expressing them in a common energy unit suitable for uses such as estimation of total energy supply, forecasting, and the study of substitution and conservation. The energy balance is a presentation of the basic supply and demand data for all fuels in a manner which shows the main fuels together but separately distinguished and expressed in a common energy unit. Both of these characteristics will allow easy comparison of the contribution each fuel makes and the interrelationships through the conversion of one fuel into another.
The IEA/OECD publication provides basic energy statistics and balances for more than 100 non-OECD countries, including developing countries (all African countries), central and eastern European countries and the former USSR. The database also gives historical series for the years 1971 to 1994 and has a high level of accuracy, reliability, and is complete for all parts of the world. The units are homogenous and consistent from country to country. Production, imports, exports, and consumption of coal, oil, gas, and electricity are set out in original units for individual countries as well as for selected world regions.

As a result, the data from the Energy Statistics and Balances of Non-OECD countries and the Yearbooks of World Energy Statistics, published by the United Nations, was accepted as the best available datasets and meeting the best needs.

The Intergovernmental Panel on Climate Change (IPCC) guidelines for National Greenhouse Gas Inventories was approved by the Scientific Assessment Working Group of the IPCC in September, 1994 and subsequently adopted by the entire IPCC in November, 1994. The guidelines represent a first, substantial step towards the assembly and dissemination of the methodologies needed for inventory construction. These guidelines have also been adopted by the United Nations Environment Program (UNEP), the Organization for Economic Co-operation and Development (OECD), and the International Energy Agency (IEA). The guidelines are summarized in a three volume series, (1) The Greenhouse Gas Inventory Reporting Instructions, (2) The Greenhouse Gas Inventory Workbook, and (3) The Greenhouse Gas Inventory Reference Manual.

These books together provide the range of information needed to plan, carry out and report results of a national inventory using the IPCC system. The Reporting Instructions (Volume 1) provides step-by-step directions for assembling.
documenting, and transmitting completed national inventory data consistently, regardless of the method used to produce the estimates. The Workbook (Volume 2) contains suggestions about planning and getting started on a national inventory where no such inventory is available. It also contains step-by-step instructions for calculating emissions of carbon dioxide (CO\textsubscript{2}) and methane (CH\textsubscript{4}), as well as some other trace gases (N\textsubscript{2}O, NO\textsubscript{X}, CO, and others) from six major source categories. The Reference Manual (Volume 3) provides a compendium of information on methods for estimation of emissions for a broader range of greenhouse gases and a complete list of source types for each. It summarizes a range of possible methods for many source types and provides summaries of the scientific basis for the inventory methods recommended, and gives extensive references to the technical literature.

2.3 METHODOLOGY

The methods used to estimate energy related emissions in Africa are based on the Procedures outlined by the IPCC. The Procedures are outlined in precise detail in the IPCC Greenhouse Gas Inventory, workbook, Volume 2 (1995).

2.3.1 CO\textsubscript{2} from Energy in Africa

National, regional and total world emission estimates were made based on amounts of fuels used and the carbon content of fuels. The procedure used to compute carbon dioxide emissions follows six steps:
The empirical relationships used to compute emissions are of the form:

\[
\text{CO}_2 \text{ emissions} = AC \times CF \times CEF(i) \times FCS(i) \times FCO(i) \times 44/12
\]  
(2-1)

where:
- \(AC\) = Apparent consumption (\(10^6\) tonnes of fuel for liquids and solids; toe for gas)
- \(CF\) = Conversion factor (see table of factors to convert appropriately to TJ)
- \(CEF(i)\) = Carbon emission factor for fuel \(i\) (t C/TJ)
- \(FCS(i)\) = Fraction of carbon stored in fuel \(i\)
- \(FCO(i)\) = Fraction of carbon oxidized
- \(44/12\) = Mass ratio of \(\text{CO}_2/C\) (converts to actual carbon dioxide emissions in expressed in Tg/\(\text{CO}_2\))

Note: Apparent consumption, this concept deals with apparent rather than actual consumption because it tracks the consumption of fuels to an economy with adjustments for net imports and stock exchanges in fuels. Whereas this procedure ensures that all of the carbon in fuels is accounted for, it does not produce actual consumption by specific fuel or fuel product. In cases where exports exceed imports, it will produce negative numbers.
Step 1: Estimation of Apparent Fuel consumption

Apparent Consumption (AC) = P + I - E - IB - SC  \hspace{1cm} (2-2)

where:

P = Production
I = Imports
E = Exports
IB = International bunkers
SC = Stock change

Step 2: Conversion to a Common Energy Unit

The computed apparent consumption is converted from the original units (either J, MJ, GJ, toe, tonnes) to TJ (Terajoules), by multiplying by the relevant conversion factor (CF).

Step 3: Multiplying by Emission Factors to compute the carbon content

The apparent consumption is converted into carbon content by multiplying by a carbon emission factor (CEF) for the fuel type. Table 2.2 lists carbon emission factors for various fuel types.
Table 2.2: Carbon Emission Factors (CEF) in tC/TJ.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Carbon Emission Factor (t C/TJ)¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid fossil</td>
<td>16.8 - 20.0</td>
</tr>
<tr>
<td>Natural gas</td>
<td>17.2</td>
</tr>
<tr>
<td>Solid fossil</td>
<td>26.8 - 28.9</td>
</tr>
</tbody>
</table>

1. Source: IPCC Workbook, 1995

**Step 4: Computing Amount of Carbon Stored**

The carbon content is multiplied by the fraction of carbon stored (FCS) for the fuel type to give the total carbon stored. This calculation yields net carbon emissions. The values for FCS are listed in table 2.3.

Table 2.3: Fraction of carbon Stored (FCS) and Fraction of Carbon Oxidized (FCO) for Fuel Types

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Carbon content</th>
<th>Effective fraction of C oxidized in yr of production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid fossil</td>
<td>0.746±2%</td>
<td>0.982 ± 2%</td>
</tr>
<tr>
<td>Liquid fossil</td>
<td>0.85±1%</td>
<td>0.918 ± 3%</td>
</tr>
<tr>
<td>Natural gas</td>
<td>0.0137±2%</td>
<td>0.98 ± 1%</td>
</tr>
<tr>
<td>Natural gas flaring</td>
<td>0.525±3%</td>
<td>1.0 ± 1%</td>
</tr>
</tbody>
</table>

a Carbon content in tonnes of carbon per ton fuel equivalent

b Carbon content in 10^6 tonnes per thousand 10^12 J

c Carbon content in tonnes per 10^3 m^3 fuel equivalent

Source: IPCC Workbook, 1995; and Trabalka, 1986

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Step 5: Correcting for Incomplete Combustion

The net carbon emissions are multiplied by the fraction of carbon oxidized (Table 2.3) to yield actual carbon emissions.

Step 6: Conversion of the Oxidized Carbon to CO2 Emissions

The actual carbon emissions are multiplied by 44/12 to find the total carbon dioxide (CO2) emitted from fossil fuel combustion. Final figures were expressed in million tonnes or Tg (CO2).

2.3.2 Estimating Methane Emissions.

Fossil fuel methane emissions originate from two sources, (1) coal mining and handling activities and (2) oil and natural gas activities. These energy sources are usually referred to as fugitive sources to distinguish them from combustion sources.

Coal Mining and Handling Activities

The procedure used to compute emissions from source 1, coal mining and handling activities is outlined below. This method is described in precise detail in the IPCC Workbook for Greenhouse Gas Inventory, 1995):

The equation for calculating CH4 emissions from this source is:

$$\text{CH}_4 \text{ Emissions (Gg)} = \text{CP} \times \text{EF} \times \text{CF}$$

(2-3)

where:

- \(\text{CP} = \text{Coal Production (10}^6\text{t)}\)
- \(\text{EF} = \text{Emission Factor (m}^3\text{ CH}_4/\text{ton of coal)}\)
- \(\text{CF} = \text{Conversion Factor (Gg CH}_4/10^6\text{ m}^3\text{ CH}_4)\)
Step 1: Estimating Methane Emissions from Coal Mining and Handling Activities

The amount of coal produced or consumed by each country is expressed in million tonnes and is consistent with the data used in the carbon dioxide module. An appropriate emission factor is assigned for each mining activity in the each countries inventory. An average value is assigned when the needed information is not available for any country. Default values provided by the IPCC were also incorporated when necessary.

Step 2: Converting Methane Emissions in m$^3$ to Methane emissions in Gg

A conversion factor is used to convert methane emissions in m$^3$ to methane emissions in Gg. The factor converts emissions in volume of methane to a weight measure (Gg) using the density of methane at 20 °C and at a pressure of 1 atmosphere. The conversion factor is 0.67 Gg / 10$^6$ m$^3$. The methane emissions in millions of cubic m were multiplied by the conversion factor to give methane emissions in Gg.

Oil and Natural Gas Activities

This category includes all emissions from production, processing, transport, and use of oil and natural gas and from non-productive combustion. It excludes use of oil and gas or derived fuel products to provide energy. The latter are considered fuel combustion and are treated in the combustion section. This section does not include the emissions resulting from natural gas flaring as this source. That is treated separately.
The IPCC suggests three methods for estimating emissions from this source: (1) production-based average emission factors approach, (2) mass balance approach, and (3) rigorous source-specific approach. Method 1 is used here because source of African energy statistics are not detailed enough to allow computations from either method 2 or 3. The first method requires assembling activity data (production, etc.) for the country, selecting emission factors based on information in the tables of typical regional values (IPCC, 1995), and multiplying through to produce estimates by major sub category. Explanations of regions are provided in detail in the (IPCC Guidelines for Greenhouse Gas Inventory Workbook, 1995).

The equation for calculating CH₄ emissions from this source is:

\[
\text{CH}_4 \text{ Emissions (Gg) } = \left( \frac{PA \times EF}{10^6} \right)
\]

where:
- \( PA \) = data for oil or gas Production (10⁶t)
- \( EF \) = Emission Factor (Kg/ PJ)
- \( 10^6 \) = Conversion Factor to convert emissions from Kg to Gg

Emission Factors for methane from Oil and Gas Activities Systems (Kg/ PJ) used to estimate emissions are presented in Table 2.4.
Table 2.4: Revised Emission Factors for Methane from Oil and Gas Activities Systems (Kg/ PJ) for the Rest of the World Category, Under Which Africa is Classified.

<table>
<thead>
<tr>
<th>Source Type</th>
<th>Basis</th>
<th>Emission Factor (Kg/ PJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil and gas production</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fugitive and other routine</td>
<td>300- 5,000</td>
</tr>
<tr>
<td></td>
<td>maintenance emissions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>from oil production</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fugitive and other Routine</td>
<td>44,000 - 96,000</td>
</tr>
<tr>
<td></td>
<td>maintenance emissions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>from gas production</td>
<td></td>
</tr>
<tr>
<td></td>
<td>venting and flaring from oil</td>
<td>no data (default- 3000,</td>
</tr>
<tr>
<td></td>
<td>and gas production</td>
<td>-14,000 as for US and</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Canada</td>
</tr>
<tr>
<td></td>
<td>oil produced</td>
<td>no data (default - 1,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-3000 as for Western</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Europe)</td>
</tr>
<tr>
<td></td>
<td>gas produced</td>
<td>175,000 - 209,000</td>
</tr>
</tbody>
</table>

Source: IPCC Workbook, 1995
<table>
<thead>
<tr>
<th>Source Type, Basis</th>
<th>Emission Factor (Kg/PJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude oil transportation, storage and refining</td>
<td></td>
</tr>
<tr>
<td>Transportation oil tankered</td>
<td>745</td>
</tr>
<tr>
<td>Refining oil refined</td>
<td>90 - 1,400</td>
</tr>
<tr>
<td>Storage tanks oil refined</td>
<td>20 - 250</td>
</tr>
<tr>
<td>Natural gas processing, transport and distribution</td>
<td></td>
</tr>
<tr>
<td>Emissions from gas produced</td>
<td>288,000</td>
</tr>
<tr>
<td>processing, transmission and distribution</td>
<td></td>
</tr>
<tr>
<td>gas consumed</td>
<td>118,000</td>
</tr>
<tr>
<td>Leakage at Industrial power non residential gas consumed</td>
<td>0 - 175,000</td>
</tr>
<tr>
<td>Leakage in the residential and commercial sectors</td>
<td>0 - 87,000</td>
</tr>
</tbody>
</table>

source IPCC Workbook, 1995

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
2.3.3 Estimation of NOx and CO\textsubscript{2} Emissions from Fossil Fuel Generation of Electricity

(CO\textsubscript{2} emissions from this source will not be counted separately as they were already included in module I for combustion.)

There are no well documented methods for estimating fossil fuel NOx related emissions. The method that is used here is a modification to suggestions from EPA [personal communication with Saifur Rahman (1997)] and the works of De Castro and Rahman, 1996. Data on electricity production is available for the major electricity producing countries in Africa (22 countries). The general formula used to compute national and regional estimates outline below:

\[ \text{NOx or CO}_2 \text{ Emissions} = EP \times CF1 \times CF2 \times EF(\text{g}) \]  

where:

- \( EP \) = Electricity Production (GWh)
- \( CF1 \) = Conversion Factor (converts to TJ of electricity produced)
- \( CF2 \) = Conversion Factor (converts to MBtu)
- \( EF \) = Emission factor for NOx and CO\textsubscript{2} em\( \text{NOx and CO}_2 \) emissions per KWh used to multiply coal, oil, and gas-fired generation in each country were based on US experience (Electric Power Research Institute (EPRI, 1989))

1. Express national electricity production in GWh
2. Convert to TJ by multiplying by a conversion factor of 3.6
3. Convert data to MBtu by multiplying by a conversion factor (947.8)

4. Estimate NOx and CO2 emissions by applying an emission factor

5. Convert Gg to Tg of emissions.

2.3.4 Estimation of Future Emissions

For calculation of future emissions (years 2000, 2010, and 2020), a consumption scenario based on a no-further-control (NFC) assumption was used. This means that no emissions controls were installed beyond those required under existing law and that no fuel substitution measures were installed to minimize atmospheric emissions. The consumption growth is based on assumptions of growth in GNP, and population (van Aardenne et al., 1997; Foel et al., 1995). This situation is referred to as a "Rapidly Changing World" (RCW) and it assumes that rapid economic growth and structural change occurs while little attention is given to the global environment. The method used here follows an empirical relationship as follows: Present Emissions per $10^6$ inhabitants and GNP per capita were computed and then future emissions calculated based on population and GNP changes.

2.4 RESULTS

Results for CO2 national totals from fossil fuel combustion and emissions per $10^6$ inhabitants, CH4 national totals from fossil fuel combustion and emissions per $10^6$ inhabitants, and national totals for NOx emissions from electricity generation and emissions per $10^6$ inhabitants, are presented in Tables 2.5, 2.6 and 2.7 respectively. Figures 2.1-2.17 show graphics of these data results from this section.
DISCUSSION

CO₂ Emissions from Fossil Fuel Combustion in Africa

Total CO₂ Emissions (Figure 2.1)

In 1994, the total CO₂ emissions from fossil fuel combustion in Africa was 1617.1 Tg CO₂ (6±0.4% global contribution). Of this total, 57±5% came from liquid fuels, 34±4% from solid fuels and 9±1% from gas fuels. It is interesting to note that the majority, over 90% of fossil fuel combustion CO₂ in Africa came from the combustion of liquid and solid fuels.

Figure 2.1 shows the greatest national contributors as South Africa (433±26 Tg), Egypt (83±5 Tg), Nigeria (57±3 Tg), and Algeria (55±3 Tg). These countries are more industrialized than the other African countries and all have more developed transport sectors and industries.

Gas Flaring CO₂ (Figure 2.2)

The results of CO₂ emissions from gas flaring (Figure 2.2) are highly speculative and this is explained under uncertainties and errors. However, this source may have yielded an additional 23±5 Tg CO₂ for the year 1994, with nearly all gas flaring emissions coming from Algeria (56±13%), Libya (18±4%), Gabon (14±3%), Angola (11±3%), and Congo (1±0.2%). These are the countries in Africa that are involved in natural gas production. The rest of the African countries rely on imported natural gas to meet their energy requirements from this fuel type. Emissions by fuel type are presented below: Figure 2.3 shows relative distributions of carbon dioxide emissions by fuel type in the major contributing countries.

Liquid Fuel CO₂ (Figure 2.4)
According to these estimates the biggest national contributors of liquid fuel CO₂ emissions were Egypt (20±2%), South Africa (18±2%), Nigeria (16±1%), Morocco (7±0.6%), Algeria (7±0.6%), and Libya (6±0.5%). These countries together account for more than 75% of CO₂ emissions from the use of liquid fuels.

**Gas Fuel CO₂** (Figure 2.5)

For gas fuels, the greatest contributors were Algeria (42±6%), Egypt (27±4%), Nigeria (12±2%), Libya (11±2%), and Tunisia (5±0.7%). These results are consistent with the fact that these countries are the largest and almost the only producers of gas fuels in Africa.

**Solid Fuel CO₂** (Figure 2.6)

For solid fuels, South Africa (92±11%), Morocco (1±0.1%), Egypt (1±0.1%), and Algeria (0.5±0.06%). South Africa is Africa's largest producer and consumer of coal, and as a result it accounts for over 92% of CO₂ emissions from solid fuel use. In Africa, only South Africa and Zimbabwe engage in extensive coal mining activities. The majority of the Southern African Development Cooperation Community (SADCC) countries depend on these two countries for their solid fuel needs. The estimates of carbon dioxide for 1994 are in agreement with those published by Marland (1995).

**CH₄ Emissions from Fossil Fuel Combustion in Africa**

**Total CH₄** (Figure 2.7)

In 1994, the total CH₄ emissions from fossil fuel combustion in Africa was 5±2 Tg CH₄ (4±1% Global contribution). Of this total, 57±19% came from liquid fuels.
fuels, 37±2% from solid fuels and 6±2% from gas fuels. More than 99% of fossil fuel combustion CH4 in Africa came from the combustion of gas and solid fuels. According to these estimates the biggest national contributors of liquid fuel CO2 emissions (Figure 2.8- 2.10) were. Egypt, Algeria, South Africa, Nigeria, Libya and Zimbabwe. The geographical distribution of these emissions is mainly northern Africa, all the countries stretching from Morocco to Egypt (Figure 2.7) and the western African countries of Nigeria and Gabon. The southern African belt comprising South Africa, Zimbabwe, Zambia, Mozambique and Angola also make strong contributions. The contribution by Central and Eastern African nations is almost insignificant.

**CH4 Emissions by Fuel Type**

Figures 2.8, 2.9 and 2.10 show emissions from liquid, gas and solid fuels for methane emissions for 1994. Figure 2.11 shows relative distributions of methane emissions by fuel type in the major contributing countries.

Liquid fuel emissions are more concentrated in the northern African countries of Algeria, Libya and Egypt; the western African countries of Nigeria, Cameroon and Gabon and Congo; and South Africa. The spatial distribution of these emissions follows an interesting pattern as shown in Figure 2.8. The spatial distribution of natural gas emissions (Figure 2.9) falls in the same region as for liquid fuel emissions except for the inclusion of Angola and Mozambique. Figure 2.10 shows the spatial distribution of solid fuel methane emissions. The major contributors north of the equator are Morocco and Nigeria. Southern Africa dominates emissions from this fuel type with emissions concentrated in South Africa with relatively strong contributions from Zimbabwe, Zambia, and Zaire.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
NO\textsubscript{X} Emissions from Fossil Fuel Generation of Electricity in Africa (Figure 2.12)

In 1994, the total NO\textsubscript{X} emissions from fossil fuel generation of electricity in Africa was 813±70 Gg NO\textsubscript{X} (4±0.3\% of the global contribution). According to these estimates the biggest national contributors in Africa (Figure 2.17) were. South Africa (60±5\%), Egypt (14±1\%), Algeria (7±0.6\%) and Libya (6±0.5\%). South Africa is Africa's most developed nation and produces and consumes the largest quantities of electricity.


Trends in fossil fuel uses and resulting emissions are highlighted in Figures 2.13 through 2.16 for gas, solid, liquid, and totals.

Gas

With the exception of a decline between 1980 and 1982, gas fuel consumption in Africa (Figure 2.13) showed an increase since 1971. CO\textsubscript{2} emissions decreased through the period 1980-1982 and Rotty and Marland, 1984, attributed this decline to economic factors. Emissions and consumption have continued to increase since 1980. Gas fuel consumption in Africa increased by a factor of almost 18 during the period from 1971-1994.

Solid

Solid fuels showed an increasing trend (Figure 2.14). Between 1971 and 1988, solid fuel consumption increased by a factor of three and decreased slightly between 1989 and 1990. Consumption peaked again in 1991 and dropped in 1992 and it has increased since then. While this period shows an interesting pattern, it must be
pointed that emissions during this period ranged only between 489 and 506 Tg CO₂ per year. Because of such a narrow range in emissions during the period 1988 to 1992, African countries consumed solid fuels at an almost constant yearly rate usage, this might be as a result of no expansion in production by the chief coal producing countries, South Africa and Zimbabwe. Solid fuels have increased by a factor of 3 between 1971 and 1994, showing little change between 1988 and 1994.

Liquid

Liquid fuel consumption fluctuates up and down following no logical explanation (Figure 2.15). Consumption and the corresponding emissions increased from 1971-1973. The pattern shows a decrease in 1974, followed by a larger increase in 1977. There is a small drop in 1978, followed by another increase in 1979 and emissions then continue to decrease slowly up until about 1982. Emissions show a general increase pattern between 1982 and 1994 with deviations around 1986 and again another deviation in 1992. The 1990-1992 deviation trend coincides with the Gulf War when liquid fuel markets were remarkably affected as a result of Iraq/Kuwait conflict.

Totals Trend (Figure 2.16)

Because liquid fuels currently dominate emissions of CO₂ from fossil fuel use in Africa, they dictate the pattern of trends in total emissions.
Future emissions:

The figure 2.17 show population trends in Africa (1995 - 2020). The statistics were supplied by the US Department of Commerce, Bureau of Census.

Statistical estimates for the years 200, 2010, and 2020 were calculated and plotted in Figure 2.18. Solid fuel consumption is expected to rise and natural gas emissions will show a marked increase as well. Total CO\textsubscript{2} emissions will reach 9301.1 Tg CO\textsubscript{2} by the year 2020. Liquid fuels will continue to dominate emissions whereas the smallest increase will be in natural gas consumption. During the period 1995 to 2020, Africa's population will experience a decrease in average growth rate due to decreasing fertility rates. The increase in population and GNP will cause emissions to increase almost six fold during the same period. During the period from 1994-2020 the NO\textsubscript{X} emissions were predicted to increase nearly six fold to 4670 Gg NO\textsubscript{X}, and CH\textsubscript{4} emissions were predicted to increase to about 28840 Gg CH\textsubscript{4}.

Rising demands for energy production in the Southern African Development Cooperation Community (SADC) are currently forcing southern African countries such as South Africa and Zimbabwe to enlarge their coal mining sector. The transportation sector of most southern African countries is expanding rapidly and the demand for liquid fuels in the region is growing [Personal Communication with the Ministry of Energy and Transport, Zimbabwe, (1997)].

The above results illustrate that energy-related emissions in Africa unless severe economic conditions occur, are increasing will continue to grow over the decades to come. Because the region is undergoing dynamic changes, the future emissions are subject to a high degree of uncertainty and should be viewed simply as possible endpoints of present-day practices. The actual emissions trajectory will change, and be lower if the region resorts to the use of more efficient cleaner fuels.
implement further control policies and introduce energy saving programs. However, it is very informative to look more closely at these projections since they provide insight for future emissions in the region.

**Emissions and Socio-Economic Factors**

Tables 2.5, 2.6, and 2.7 include data on emissions and Gross National Product per Capita (GNP) and emissions per million inhabitants for each country. In general, there is a close association between emissions and GNP, with countries with high GNP per capita also having large emissions, except for Mauritania and Zimbabwe, which have low GNP per capita and high emissions per million inhabitants.

Emissions normalized by population presents a useful framework for discussion. The Africa wide-average for CO$_2$ emissions is 2 Tg/ million inhabitants (Table 2.5). South Africa and Libya show the highest values, 12 and 6 times higher than the Africa average, respectively (Figure 2.19). Only 11 countries in Africa have values at or above the average. In contrast, the remaining 43 countries have emission values below the average.

The average for CH$_4$ emissions is 7 Gg/ million inhabitants (Table 2.6). On this basis, Algeria, Libya, Egypt, Zimbabwe and Gabon have the highest values at 87, 59, 53, 9, 5 and 3, respectively (Figure 2.23). Even though Nigeria has high emissions, its value for emissions normalized by population is only 2 because of the highest population, almost 114 million people. The rest of the countries all have values less than the average.

The average for NOx emissions from fossil fuel generation of electricity is 1 Gg / million inhabitants (Table 2.7). South Africa, Libya, Tunisia, Egypt, Algeria, Zimbabwe, Gabon and Morocco have the highest values at 14, 11, 2, 2, 1, 1, and 1
respectively (Figure 2.26). The remaining countries all have lower per capita NO\textsubscript{x} emissions. NO\textsubscript{x} emissions resulting from fossil fuel electricity generation per million people is highlighted in figure 2.26.

These results also illustrate that growth in GNP outpaces the growth in population in influencing emissions (Figures 2.19, 2.20, and 2.21).

2.5 Uncertainties and Errors

The nature of the computations used here to estimate emissions and the data sources warrants a careful analysis of the results. A large number of assumptions and approximations are embodied in these computations but in nearly all cases the values are rather well constrained.

The global fossil fuel statistics presented by the IEA are consistent with numbers published elsewhere (e.g. the UN) and represent the best efforts to bring together reliable data.

The most speculative numbers in the computation are those that relate to how fuels are used and the rate at which they are oxidized. Over 90\% of fuels are used for fuels that burn within a short time of production and errors of only a few percent of total emissions are possible as a result of accounting inadequacies within the fraction remaining unoxidized. The fraction not oxidized results from both non-fuel use and combustion inefficiencies. The assumption of 98.5 with error 1 \% oxidation efficiency takes into account the fact that CO and most unburned or partially oxidized hydrocarbons will soon be rapidly oxidized in the environment whereas soot will remain unoxidized for long periods of time.
Data are not available to try to discern quantitatively the effect of changing nonfuel uses and increasing combustion efficiencies in the growth of emissions. Temporal variability and political changes also affect data.

There is sufficient data on the composition of fuels that the mean carbon content of fuels can be established with confidence. Errors in the procedures and computations stemming from carbon content or from the fraction oxidized are much smaller than those from fuel data.

With the present global fuel data, error limits cannot be assigned with scientific precision, but rather the ± values indicated represent the best subjective judgment for an approximate 90% confidence interval over distributions.

The estimated overall uncertainty associated with CO₂, CH₄, and NOₓ, emissions by the analysis below is depicted in Table 2.8. This analysis suggests that the estimates on the global total emissions of CO₂ from fossil fuels presented in Table 2.8 have an uncertainty of between 6 and 10%, excluding gas flared in the final computation depending on how one chooses to aggregate the uncertainties.

Uncertainties were calculated using the method of combining uncertainties shown below.

The overall uncertainty is calculated using the equation below:

\[ U_T = \pm \sqrt{\sum (U_i)^2} \]

where: \( U_T \) = overall percentage uncertainty

\( U_i \) is the uncertainty in the activity factors and emission factors involved in the computation of estimates.
Table 2.9: Uncertainties due to Emission Factors and Activity Data

<table>
<thead>
<tr>
<th>Species</th>
<th>Source Category</th>
<th>Activity Apparent Consumption</th>
<th>Carbon Emission Factor</th>
<th>Fraction of Carbon Stored in Fuel</th>
<th>Fraction of Carbon Oxidized</th>
<th>Total Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>Fossil Fuel Gas</td>
<td>10</td>
<td>11</td>
<td>2</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Fossil Fuel Liquid</td>
<td>8</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Fossil Fuel Solids</td>
<td>11.2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Gas Flaring</td>
<td>20</td>
<td>10</td>
<td>3</td>
<td>1</td>
<td>23</td>
</tr>
<tr>
<td>CH₄</td>
<td>Fossil Fuel Gas</td>
<td>10</td>
<td>37</td>
<td></td>
<td>38</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>Fossil Fuel Liquid</td>
<td>8</td>
<td>33</td>
<td></td>
<td></td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>Fossil Fuel Solid</td>
<td>11.2</td>
<td>55</td>
<td></td>
<td></td>
<td>56</td>
</tr>
<tr>
<td>NOₓ</td>
<td>Fossil Fuel</td>
<td>3</td>
<td>7</td>
<td>7.6</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

2. IPCC, 1995
Table 2.9 continued.

<table>
<thead>
<tr>
<th>Species</th>
<th>Gas fuel $U_g$</th>
<th>Liquid fuel $U_l$</th>
<th>Solid fuel $U_S$</th>
<th>Total Uncertainty $U_T^*$</th>
<th>Total Uncertainty $U_T^{**}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>15</td>
<td>9</td>
<td>12</td>
<td>6.6</td>
<td>10.4</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>38</td>
<td>34</td>
<td>56</td>
<td>31</td>
<td>44</td>
</tr>
</tbody>
</table>

Total uncertainty:

* If uncertainties for the individual fuels are mutually independent

$$UT^* = \pm \left[ \sum f_i \sqrt{\sum (U_i)^2} \right]^{1/2}$$

** If uncertainties for the individual fuels are not independent

$$UT^{**} = \pm \sum f_i \sqrt{\sum (U_i)^2}$$

$f_i$ is emissions from the $i$th fuel type divided by total 1994 emissions.

$(f_i \text{ gas } = 0.15; f_i \text{ liquid } = 0.6; f_i \text{ solid } = 0.12)$

The uncertainty in the value used for fuel produced is independent of the uncertainty in the estimate for fraction oxidized and the estimated carbon content. The uncertainty in the product of the individual terms is estimated by the square root of the sum of the squares of the uncertainty in each individual component. However, in summing the uncertainties for CO$_2$ emissions from each fuel type to obtain an overall uncertainty for global CO$_2$ emissions independence is not assured. If the data for each fuel type were totally independent, the square root of the sum of the squares would be the appropriate procedure and the estimated uncertainty would be 6.6%. The estimated uncertainty in the final emission numbers of between 6 and 10% is based on a 90% confidence interval.
The uncertainty of 6 to 10% is applicable to CO₂ emissions for a given year, but the uncertainty in the relative change from year to year is a different problem. The uncertainties for CH₄ are much higher because of higher uncertainty in the emission factors.

To reduce the uncertainty in the final result would require that the reliability (or confidence in) the fuel production data be substantially improved. It is shown clearly in Table 2.9 that most of the uncertainty in calculating emissions from fossil fuels comes directly from this source. Developing improved confidence in the OECD fuel statistics for even that small group of countries that produce most of the world's fuel, would require a major effort. Although the estimated uncertainty in the emissions is high, the trend of increasing emissions from fossil fuels is firmly established.

SUMMARY

Estimates of CO₂, CH₄, NOₓ emissions for Africa arising from fossil fuel combustion, natural gas flaring, and from fossil fuel generation of electricity for the base year 1994 are estimated and discussed. Historical trends in fossil fuel consumption and related emissions for the years 1971-1994, and future emissions are projected to the year 2020 under a no further control scenario. The results for national, and regional estimates are presented and discussed and the global contribution is assessed. These estimates are based on consumption and process emission factors. The new CO₂ estimates of are comparable to those published by Marland (1995). Table 2. 10 presents an assessment of Africa's contribution from fossil fuel source.

In 1994, the total CO₂ emissions from fossil fuel combustion in Africa was 1617.1 Tg CO₂ (6±0.4% global contribution). Of this total, 57±5% came from liquid...
fuels. 34±4% from solid fuels and 9±1% from gas fuels. Gas flaring added an additional 235 Tg CO₂. Emissions are dominated by liquid and solid fuels. Emissions are expected to increase nearly six fold by to ~9301 Tg CO₂; ~28840 Gg CH₄; and ~4670 Gg NOₓ by the year 2020 (with very high uncertainties). Africa's contribution to the global budget is expected to increase from 6±0.4 to nearly 9% by the year 2020 for CO₂ emissions. CH₄ emissions were 5±2 Tg CH₄ (4±1% global contribution) in Africa in 1994. NOₓ emissions from fossil fuel electricity generation in 1994 for Africa were 813±70 Gg NOₓ (4±0.3% global contribution). The following countries contributed for the majority of African emissions, Algeria Libya, Angola, South Africa, Morocco, and Egypt. As expected, high national emissions were directly linked to high GNP and higher population.
Table 2.5: National CO₂ production Totals From Fossil Fuel Combustion and Emissions Per 10⁶ Inhabitants and Socio-economic Factors.

<table>
<thead>
<tr>
<th>Country</th>
<th>Gas</th>
<th>Liquid</th>
<th>solid</th>
<th>Total Tg CO₂</th>
<th>Tg/10⁶ U</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Africa</td>
<td>3.2</td>
<td>53</td>
<td>377</td>
<td>433</td>
<td>12</td>
</tr>
<tr>
<td>Egypt</td>
<td>22</td>
<td>58</td>
<td>4</td>
<td>84</td>
<td>2</td>
</tr>
<tr>
<td>Nigeria</td>
<td>9</td>
<td>47</td>
<td>0.3</td>
<td>57</td>
<td>5</td>
</tr>
<tr>
<td>Algeria</td>
<td>33</td>
<td>20</td>
<td>2.0</td>
<td>55</td>
<td>2</td>
</tr>
<tr>
<td>Libya</td>
<td>8</td>
<td>18</td>
<td>0.0</td>
<td>27</td>
<td>6</td>
</tr>
<tr>
<td>Morocco</td>
<td>0.04</td>
<td>20</td>
<td>6</td>
<td>26</td>
<td>1</td>
</tr>
<tr>
<td>Tunisia</td>
<td>4.0</td>
<td>10</td>
<td>0.0</td>
<td>14</td>
<td>2</td>
</tr>
<tr>
<td>Kenya</td>
<td>0.0</td>
<td>6</td>
<td>0.3</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Sudan</td>
<td>0.0</td>
<td>5</td>
<td>0.0</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Zaire</td>
<td>0.0</td>
<td>4</td>
<td>0.4</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Ivory Coast</td>
<td>0.0</td>
<td>4</td>
<td>0.0</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Mauritania</td>
<td>0.2</td>
<td>2.7</td>
<td>0.1</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Ethiopia</td>
<td>0.0</td>
<td>2.9</td>
<td>0.0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Senegal</td>
<td>0.0</td>
<td>2.8</td>
<td>0.0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Angola</td>
<td>0.3</td>
<td>2.4</td>
<td>0.0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Ghana</td>
<td>0.0</td>
<td>2.7</td>
<td>0.01</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Gabon</td>
<td>0.1</td>
<td>2.6</td>
<td>0.0</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Cameroon</td>
<td>0.0</td>
<td>2.6</td>
<td>0.0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Zambia</td>
<td>0.0</td>
<td>1.5</td>
<td>1.1</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Congo</td>
<td>0.01</td>
<td>2.4</td>
<td>0.2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Botswana</td>
<td>0.0</td>
<td>2.3</td>
<td>0.0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Mozambique</td>
<td>0.3</td>
<td>1.2</td>
<td>0.05</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Madagascar</td>
<td>0.1</td>
<td>1.3</td>
<td>0.0</td>
<td>1.4</td>
<td>0</td>
</tr>
<tr>
<td>Benin</td>
<td>0.0</td>
<td>1.1</td>
<td>0.0</td>
<td>1.1</td>
<td>0</td>
</tr>
<tr>
<td>Uganda</td>
<td>0.0</td>
<td>1.1</td>
<td>0.0</td>
<td>1.1</td>
<td>0</td>
</tr>
<tr>
<td>Other Africa</td>
<td>-0.6</td>
<td>18</td>
<td>0</td>
<td>18</td>
<td>-</td>
</tr>
<tr>
<td>Total Africa</td>
<td>142</td>
<td>927</td>
<td>547</td>
<td>1617</td>
<td>2</td>
</tr>
<tr>
<td>World Total</td>
<td>3575</td>
<td>9299</td>
<td>12111</td>
<td>24984</td>
<td>4</td>
</tr>
</tbody>
</table>

Uncertainty in fuel estimates is: gas = 15 %; liquid = 9 %; solid = 12 %
Total uncertainty is 6 - 10 %

[Other Africa: Burkina Faso, Burundi, Central African Republic, Chad, Djibouti, Equatorial Guinea, Eritrea, Gambia, the, Guinea, Guinea-Bissau, Lesotho, Liberia, Malawi, Mali, Namibia, Niger, Rwanda, Sierra Leone, Somalia, Swaziland, Tanzania, United Republic, Togo, Western Sahara]

Note: Negative values occur when exports exceed production and imports

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Table 2.5 Continued.

<table>
<thead>
<tr>
<th>Country</th>
<th>Tg CO₂/10⁶ Inhabitants</th>
<th>Emissions/GNP (Tg CO₂, per Billion US $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Africa</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>Egypt</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Nigeria</td>
<td>5</td>
<td>19</td>
</tr>
<tr>
<td>Algeria</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Libya</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>Morocco</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Tunisia</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Kenya</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Sudan</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Zaire</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ivory Coast</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mauritania</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Ethiopia</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Senegal</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Angola</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ghana</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Gabon</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Cameroon</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Zambia</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Congo</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Botswana</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Mozambique</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Madagascar</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Benin</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Uganda</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Other Africa</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Total Africa</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>World Total</td>
<td>4</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 2.6: CH\textsubscript{4} National Totals From Fossil Fuel Combustion and Emissions Per 10\textsuperscript{6} Inhabitants and Socio-economic Factors.

<table>
<thead>
<tr>
<th>Country</th>
<th>Gas\textsuperscript{1}</th>
<th>Liquid\textsuperscript{2}</th>
<th>Solid\textsuperscript{3}</th>
<th>Total\textsuperscript{4}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algeria</td>
<td>2137</td>
<td>0.15</td>
<td>0</td>
<td>2137</td>
</tr>
<tr>
<td>South Africa</td>
<td>71</td>
<td>0.02</td>
<td>1771</td>
<td>1842</td>
</tr>
<tr>
<td>Egypt</td>
<td>483</td>
<td>0.13</td>
<td>0</td>
<td>483</td>
</tr>
<tr>
<td>Libya</td>
<td>257</td>
<td>0.18</td>
<td>0</td>
<td>258</td>
</tr>
<tr>
<td>Nigeria</td>
<td>206</td>
<td>0.26</td>
<td>1</td>
<td>208</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>0</td>
<td>0.00</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Tunisia</td>
<td>8</td>
<td>0.001</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>Morocco</td>
<td>1</td>
<td>0.000</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Angola</td>
<td>6</td>
<td>0.000</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Mozambique</td>
<td>6</td>
<td>0.000</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Zambia</td>
<td>0</td>
<td>0.000</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Gabon</td>
<td>3</td>
<td>0.04</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Zaire</td>
<td>0</td>
<td>0.004</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Congo</td>
<td>0.2</td>
<td>0.024</td>
<td>0</td>
<td>0.2</td>
</tr>
<tr>
<td>Cameroon</td>
<td>0</td>
<td>0.015</td>
<td>0</td>
<td>0.02</td>
</tr>
<tr>
<td>Benin</td>
<td>0</td>
<td>0.001</td>
<td>0</td>
<td>0.001</td>
</tr>
<tr>
<td>Ivory Coast</td>
<td>0</td>
<td>0.001</td>
<td>0</td>
<td>0.001</td>
</tr>
<tr>
<td>Other Africa</td>
<td>0</td>
<td>0.001</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Total Africa</td>
<td>3178</td>
<td>1</td>
<td>1843</td>
<td>5023</td>
</tr>
<tr>
<td>World Total</td>
<td>79791</td>
<td>9</td>
<td>40780</td>
<td>120580</td>
</tr>
</tbody>
</table>

{Other Africa: Botswana, Burkina Faso, Burundi, Central African Republic, Chad, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gambia, The, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Namibia, Niger, Rwanda, Senegal, Sierra Leone, Somalia, Sudan, Swaziland, Tanzania, United Republic, Togo, Uganda, Western Sahara}

1. Uncertainty in gas fuel estimates is 38 %
2. Uncertainty in liquid fuel estimates is 34 %
3. Uncertainty in solid fuel estimates is 56 %
4. Uncertainty in total fuel estimates is 31-44 %

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Table 2.6 Continued.

<table>
<thead>
<tr>
<th>Country</th>
<th>Gg CH$_4$/106 inhabitants</th>
<th>Emission/GNP (Gg CH$_4$, per Billion US $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algeria</td>
<td>87</td>
<td>40</td>
</tr>
<tr>
<td>South Africa</td>
<td>53</td>
<td>21</td>
</tr>
<tr>
<td>Egypt</td>
<td>9</td>
<td>15</td>
</tr>
<tr>
<td>Libya</td>
<td>59</td>
<td>10</td>
</tr>
<tr>
<td>Nigeria</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>Tunisia</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Morocco</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Angola</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Mozambique</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Zambia</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Gabon</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Zaire</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Congo</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cameroon</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Benin</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ivory Coast</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Other Africa</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Total Africa</td>
<td>7</td>
<td>13</td>
</tr>
<tr>
<td>World Total</td>
<td>21</td>
<td>-</td>
</tr>
</tbody>
</table>

{ Other Africa: Botswana, Burkina Faso, Burundi, Central African Republic, Chad, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gambia, The, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Namibia, Niger, Rwanda, Senegal, Sierra Leone, Somalia, Sudan, Swaziland, Tanzania, United Republic, Togo, Uganda, Western Sahara}
Table 2.7: National Totals for NOx Emissions from Electricity Generation and Emissions Per 10^6 Inhabitants and Socio-economic Factors

<table>
<thead>
<tr>
<th>Country</th>
<th>Gg NOx</th>
<th>Gg NOx/ 10^6 inhabitants</th>
<th>Emission/GNP (Gg NOx, per Billion US $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Africa</td>
<td>484</td>
<td>14</td>
<td>5</td>
</tr>
<tr>
<td>Egypt</td>
<td>115</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Algeria</td>
<td>54</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Libya</td>
<td>49</td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>Morocco</td>
<td>28</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Nigeria</td>
<td>27</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Tunisia</td>
<td>18</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>14</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Ivory Coast</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Senegal</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mozambique</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Gabon</td>
<td>0.6</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Kenya</td>
<td>0.6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sudan</td>
<td>0.4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Zaire</td>
<td>0.3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ethiopia</td>
<td>0.25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cameroon</td>
<td>0.2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Angola</td>
<td>0.16</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Zambia</td>
<td>0.11</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ghana</td>
<td>0.10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Tanzania, United Republic</td>
<td>0.07</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Congo</td>
<td>0.02</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Benin</td>
<td>0.02</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Other Africa</td>
<td>15</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Total Africa</td>
<td>813</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>World Total</td>
<td>21737</td>
<td>4</td>
<td>-</td>
</tr>
</tbody>
</table>

(Estimates have an uncertainty of 8%)

[Other Africa: Botswana, Burkina Faso, Burundi, Central African Republic, Chad, Djibouti, Equatorial Guinea, Eritrea, Gambia, The, Guinea, Guinea-Bissau, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Namibia, Niger, Rwanda, Sierra Leone, Somalia, Swaziland, Togo, Uganda, Western Sahara]
Table 2.8: Demographic Data for Africa (Source: GIS World Demographic Tables)

<table>
<thead>
<tr>
<th>Country</th>
<th>Population</th>
<th>Pop Grw rate</th>
<th>Pop by 2000</th>
<th>Popdensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algeria</td>
<td>24453010</td>
<td>2.90</td>
<td>33488943</td>
<td>26.60</td>
</tr>
<tr>
<td>Angola</td>
<td>9694001</td>
<td>0.00</td>
<td>9694001</td>
<td>20.15</td>
</tr>
<tr>
<td>Benin</td>
<td>4593000</td>
<td>3.19</td>
<td>6487990</td>
<td>105.62</td>
</tr>
<tr>
<td>Botswana</td>
<td>1217000</td>
<td>3.09</td>
<td>1700875</td>
<td>5.41</td>
</tr>
<tr>
<td>Burkina Faso</td>
<td>8776001</td>
<td>2.74</td>
<td>11814948</td>
<td>82.91</td>
</tr>
<tr>
<td>Burundi</td>
<td>5299000</td>
<td>3.05</td>
<td>7374318</td>
<td>493.16</td>
</tr>
<tr>
<td>Cameroon</td>
<td>11554000</td>
<td>3.25</td>
<td>16425667</td>
<td>62.94</td>
</tr>
<tr>
<td>Central African Republic</td>
<td>2951000</td>
<td>2.82</td>
<td>4007031</td>
<td>12.28</td>
</tr>
<tr>
<td>Chad</td>
<td>5537000</td>
<td>2.54</td>
<td>7296271</td>
<td>11.16</td>
</tr>
<tr>
<td>Congo</td>
<td>2208000</td>
<td>3.17</td>
<td>3112338</td>
<td>16.73</td>
</tr>
<tr>
<td>Djibouti</td>
<td>409700</td>
<td>4.03</td>
<td>632718</td>
<td>45.74</td>
</tr>
<tr>
<td>Egypt</td>
<td>51390000</td>
<td>2.42</td>
<td>66851491</td>
<td>132.92</td>
</tr>
<tr>
<td>Equatorial Guinea</td>
<td>344000</td>
<td>2.35</td>
<td>444144</td>
<td>31.75</td>
</tr>
<tr>
<td>Eritrea</td>
<td>33000000</td>
<td>3.13</td>
<td>4631792</td>
<td>91.25</td>
</tr>
<tr>
<td>Ethiopia</td>
<td>53400000</td>
<td>3.20</td>
<td>75512339</td>
<td>125.62</td>
</tr>
<tr>
<td>Gabon</td>
<td>1105000</td>
<td>2.57</td>
<td>1460784</td>
<td>10.70</td>
</tr>
<tr>
<td>Gambia, The</td>
<td>848000</td>
<td>3.11</td>
<td>1187693</td>
<td>194.35</td>
</tr>
<tr>
<td>Ghana</td>
<td>14425000</td>
<td>3.15</td>
<td>20289781</td>
<td>156.62</td>
</tr>
<tr>
<td>Guinea</td>
<td>5547000</td>
<td>2.67</td>
<td>7412033</td>
<td>58.45</td>
</tr>
<tr>
<td>Guinea-Bissau</td>
<td>960000</td>
<td>2.11</td>
<td>1207875</td>
<td>68.84</td>
</tr>
<tr>
<td>Ivory Coast</td>
<td>11713000</td>
<td>4.26</td>
<td>18533740</td>
<td>94.07</td>
</tr>
<tr>
<td>Kenya</td>
<td>23277010</td>
<td>3.64</td>
<td>34492815</td>
<td>103.89</td>
</tr>
<tr>
<td>Lesotho</td>
<td>1722000</td>
<td>2.71</td>
<td>2310857</td>
<td>146.96</td>
</tr>
<tr>
<td>Liberia</td>
<td>2475000</td>
<td>2.83</td>
<td>3364289</td>
<td>57.55</td>
</tr>
<tr>
<td>Libya</td>
<td>4395000</td>
<td>3.47</td>
<td>6396137</td>
<td>6.48</td>
</tr>
<tr>
<td>Madagascar</td>
<td>11174000</td>
<td>2.86</td>
<td>15237733</td>
<td>49.29</td>
</tr>
<tr>
<td>Malawi</td>
<td>8230001</td>
<td>3.34</td>
<td>11812801</td>
<td>179.90</td>
</tr>
<tr>
<td>Mali</td>
<td>8212001</td>
<td>2.83</td>
<td>11162646</td>
<td>17.15</td>
</tr>
<tr>
<td>Mauritania</td>
<td>1954000</td>
<td>2.49</td>
<td>2561067</td>
<td>4.95</td>
</tr>
<tr>
<td>Morocco</td>
<td>24567010</td>
<td>2.50</td>
<td>32234046</td>
<td>142.50</td>
</tr>
<tr>
<td>Mozambique</td>
<td>15357000</td>
<td>2.73</td>
<td>20625686</td>
<td>49.62</td>
</tr>
<tr>
<td>Namibia</td>
<td>1300000</td>
<td>3.20</td>
<td>1838315</td>
<td>4.09</td>
</tr>
<tr>
<td>Niger</td>
<td>7479001</td>
<td>3.03</td>
<td>10385903</td>
<td>15.28</td>
</tr>
<tr>
<td>Nigeria</td>
<td>113665000</td>
<td>3.22</td>
<td>161075377</td>
<td>318.67</td>
</tr>
</tbody>
</table>
Table 2.8 Continued.

<table>
<thead>
<tr>
<th>Country</th>
<th>Population</th>
<th>Pop Gw rate</th>
<th>Pop by 2000</th>
<th>Popdensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rwanda</td>
<td>6893000</td>
<td>3.50</td>
<td>10063571</td>
<td>677.78</td>
</tr>
<tr>
<td>Senegal</td>
<td>7211000</td>
<td>3.03</td>
<td>10013737</td>
<td>94.95</td>
</tr>
<tr>
<td>Sierra Leone</td>
<td>4040000</td>
<td>2.56</td>
<td>5335062</td>
<td>145.84</td>
</tr>
<tr>
<td>Somalia</td>
<td>6089000</td>
<td>3.12</td>
<td>8537248</td>
<td>24.73</td>
</tr>
<tr>
<td>South Africa</td>
<td>34925010</td>
<td>2.70</td>
<td>46817844</td>
<td>74.07</td>
</tr>
<tr>
<td>Sudan</td>
<td>24423010</td>
<td>2.68</td>
<td>32669587</td>
<td>25.25</td>
</tr>
<tr>
<td>Swaziland</td>
<td>761000</td>
<td>3.48</td>
<td>1108677</td>
<td>113.55</td>
</tr>
<tr>
<td>Tanzania, United Republic</td>
<td>25627010</td>
<td>3.57</td>
<td>37693952</td>
<td>70.24</td>
</tr>
<tr>
<td>Togo</td>
<td>3507000</td>
<td>3.66</td>
<td>5207856</td>
<td>159.93</td>
</tr>
<tr>
<td>Tunisia</td>
<td>7988001</td>
<td>2.33</td>
<td>10291313</td>
<td>126.44</td>
</tr>
<tr>
<td>Uganda</td>
<td>16772000</td>
<td>3.40</td>
<td>24227621</td>
<td>184.15</td>
</tr>
<tr>
<td>Western Sahara</td>
<td>179000</td>
<td>-</td>
<td>-</td>
<td>1.74</td>
</tr>
<tr>
<td>Zaire</td>
<td>34442000</td>
<td>3.17</td>
<td>48548531</td>
<td>38.02</td>
</tr>
<tr>
<td>Zambia</td>
<td>7837001</td>
<td>3.66</td>
<td>11637860</td>
<td>26.96</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>9567001</td>
<td>2.80</td>
<td>12962837</td>
<td>63.43</td>
</tr>
</tbody>
</table>
Table 2.8 Continued.

<table>
<thead>
<tr>
<th>Country</th>
<th>Birth Rate</th>
<th>Death Rate</th>
<th>Fertility</th>
<th>Life Expectancy</th>
<th>GNP Per Capita</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algeria</td>
<td>36.5</td>
<td>7.7</td>
<td>5.27</td>
<td>64.77</td>
<td>2220</td>
</tr>
<tr>
<td>Angola</td>
<td>47.0</td>
<td>19.6</td>
<td>6.45</td>
<td>45.31</td>
<td>610</td>
</tr>
<tr>
<td>Benin</td>
<td>46.3</td>
<td>15.1</td>
<td>6.33</td>
<td>50.84</td>
<td>380</td>
</tr>
<tr>
<td>Botswana</td>
<td>36.9</td>
<td>6.5</td>
<td>4.98</td>
<td>67.15</td>
<td>1600</td>
</tr>
<tr>
<td>Burkina Faso</td>
<td>47.0</td>
<td>18.0</td>
<td>6.50</td>
<td>47.62</td>
<td>320</td>
</tr>
<tr>
<td>Burundi</td>
<td>46.5</td>
<td>15.7</td>
<td>6.80</td>
<td>49.27</td>
<td>220</td>
</tr>
<tr>
<td>Cameroon</td>
<td>44.0</td>
<td>12.4</td>
<td>6.41</td>
<td>56.72</td>
<td>1000</td>
</tr>
<tr>
<td>Central African Republic</td>
<td>41.9</td>
<td>15.0</td>
<td>5.68</td>
<td>50.47</td>
<td>390</td>
</tr>
<tr>
<td>Chad</td>
<td>44.0</td>
<td>19.0</td>
<td>5.94</td>
<td>46.35</td>
<td>190</td>
</tr>
<tr>
<td>Congo</td>
<td>47.2</td>
<td>15.0</td>
<td>6.47</td>
<td>53.50</td>
<td>940</td>
</tr>
<tr>
<td>Djibouti</td>
<td>46.1</td>
<td>17.0</td>
<td>6.60</td>
<td>47.90</td>
<td>1000</td>
</tr>
<tr>
<td>Egypt</td>
<td>33.2</td>
<td>8.7</td>
<td>4.46</td>
<td>63.01</td>
<td>630</td>
</tr>
<tr>
<td>Equatorial Guinea</td>
<td>41.6</td>
<td>19.2</td>
<td>5.50</td>
<td>46.34</td>
<td>390</td>
</tr>
<tr>
<td>Eritrea</td>
<td>50.5</td>
<td>19.2</td>
<td>7.50</td>
<td>47.62</td>
<td>-</td>
</tr>
<tr>
<td>Ethiopia</td>
<td>45.0</td>
<td>14.0</td>
<td>6.90</td>
<td>51.50</td>
<td>130</td>
</tr>
<tr>
<td>Gabon</td>
<td>41.5</td>
<td>15.4</td>
<td>5.57</td>
<td>52.92</td>
<td>2960</td>
</tr>
<tr>
<td>Gambia, The</td>
<td>47.8</td>
<td>20.4</td>
<td>6.50</td>
<td>43.95</td>
<td>240</td>
</tr>
<tr>
<td>Ghana</td>
<td>44.8</td>
<td>12.9</td>
<td>6.23</td>
<td>54.45</td>
<td>390</td>
</tr>
<tr>
<td>Guinea</td>
<td>47.9</td>
<td>22.1</td>
<td>6.50</td>
<td>43.01</td>
<td>430</td>
</tr>
<tr>
<td>Guinea-Bissau</td>
<td>45.4</td>
<td>24.0</td>
<td>6.00</td>
<td>39.75</td>
<td>180</td>
</tr>
<tr>
<td>Ivory Coast</td>
<td>49.4</td>
<td>13.8</td>
<td>7.28</td>
<td>52.92</td>
<td>790</td>
</tr>
<tr>
<td>Kenya</td>
<td>46.1</td>
<td>10.5</td>
<td>6.77</td>
<td>59.01</td>
<td>370</td>
</tr>
<tr>
<td>Lesotho</td>
<td>40.3</td>
<td>12.3</td>
<td>5.63</td>
<td>56.16</td>
<td>470</td>
</tr>
<tr>
<td>Liberia</td>
<td>44.2</td>
<td>16.0</td>
<td>6.33</td>
<td>50.31</td>
<td>500</td>
</tr>
<tr>
<td>Libya</td>
<td>43.5</td>
<td>8.7</td>
<td>6.74</td>
<td>61.65</td>
<td>5800</td>
</tr>
<tr>
<td>Madagascar</td>
<td>42.7</td>
<td>15.3</td>
<td>5.93</td>
<td>50.67</td>
<td>230</td>
</tr>
<tr>
<td>Malawi</td>
<td>54.0</td>
<td>19.4</td>
<td>7.60</td>
<td>47.40</td>
<td>180</td>
</tr>
<tr>
<td>Mali</td>
<td>50.1</td>
<td>19.0</td>
<td>7.02</td>
<td>47.64</td>
<td>270</td>
</tr>
<tr>
<td>Mauritania</td>
<td>47.4</td>
<td>19.0</td>
<td>6.50</td>
<td>46.39</td>
<td>490</td>
</tr>
<tr>
<td>Morocco</td>
<td>34.9</td>
<td>9.2</td>
<td>4.66</td>
<td>61.32</td>
<td>880</td>
</tr>
<tr>
<td>Mozambique</td>
<td>45.6</td>
<td>17.2</td>
<td>6.37</td>
<td>48.60</td>
<td>80</td>
</tr>
<tr>
<td>Namibia</td>
<td>42.8</td>
<td>11.6</td>
<td>5.92</td>
<td>57.14</td>
<td>1120</td>
</tr>
<tr>
<td>Niger</td>
<td>51.2</td>
<td>19.9</td>
<td>7.14</td>
<td>45.10</td>
<td>290</td>
</tr>
<tr>
<td>Nigeria</td>
<td>46.7</td>
<td>14.9</td>
<td>6.55</td>
<td>51.14</td>
<td>250</td>
</tr>
</tbody>
</table>
Table 2.8 Continued.

<table>
<thead>
<tr>
<th>Country</th>
<th>Birth Rate</th>
<th>Death Rate</th>
<th>Fertility</th>
<th>Life Expectancy</th>
<th>GNP Per Capita</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rwanda</td>
<td>53.6</td>
<td>17.8</td>
<td>8.00</td>
<td>48.97</td>
<td>320</td>
</tr>
<tr>
<td>Senegal</td>
<td>45.1</td>
<td>15.8</td>
<td>6.50</td>
<td>48.06</td>
<td>650</td>
</tr>
<tr>
<td>Sierra Leone</td>
<td>47.3</td>
<td>22.3</td>
<td>6.50</td>
<td>42.08</td>
<td>220</td>
</tr>
<tr>
<td>Somalia</td>
<td>48.4</td>
<td>18.4</td>
<td>6.77</td>
<td>47.53</td>
<td>150</td>
</tr>
<tr>
<td>South Africa</td>
<td>34.5</td>
<td>9.6</td>
<td>4.35</td>
<td>61.30</td>
<td>2530</td>
</tr>
<tr>
<td>Sudan</td>
<td>43.4</td>
<td>15.4</td>
<td>6.30</td>
<td>50.23</td>
<td>470</td>
</tr>
<tr>
<td>Swaziland</td>
<td>45.5</td>
<td>12.0</td>
<td>6.33</td>
<td>56.07</td>
<td>900</td>
</tr>
<tr>
<td>Tanzania, United Republic</td>
<td>47.7</td>
<td>13.1</td>
<td>6.67</td>
<td>53.68</td>
<td>120</td>
</tr>
<tr>
<td>Togo</td>
<td>48.9</td>
<td>14.1</td>
<td>6.63</td>
<td>53.53</td>
<td>390</td>
</tr>
<tr>
<td>Tunisia</td>
<td>30.4</td>
<td>7.0</td>
<td>4.00</td>
<td>66.21</td>
<td>1260</td>
</tr>
<tr>
<td>Uganda</td>
<td>50.9</td>
<td>16.4</td>
<td>7.30</td>
<td>48.62</td>
<td>160</td>
</tr>
<tr>
<td>Western Sahara</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Zaire</td>
<td>44.4</td>
<td>13.7</td>
<td>5.99</td>
<td>52.49</td>
<td>260</td>
</tr>
<tr>
<td>Zambia</td>
<td>48.9</td>
<td>12.6</td>
<td>6.65</td>
<td>53.71</td>
<td>390</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>37.5</td>
<td>7.3</td>
<td>5.12</td>
<td>63.42</td>
<td>650</td>
</tr>
</tbody>
</table>
Table 2. 10: An Assessment of Africa’s Contribution from Fossil Fuel Source

<table>
<thead>
<tr>
<th>Species</th>
<th>% Contribution to the Global Total Fossil Fuel Budget 1994</th>
<th>% Contribution to the Global Total All Anthropogenic Emissions 2020*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tg species/ yr 1994</td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>1617± 97</td>
<td>6 ± 0.4</td>
</tr>
<tr>
<td>CH₄</td>
<td>5 ± 2</td>
<td>4 ± 1.2</td>
</tr>
<tr>
<td>NOₓ</td>
<td>0.81± 0.07</td>
<td>4 ± 0.3</td>
</tr>
</tbody>
</table>

* The uncertainty is computed assuming fuel amount is known. Actual uncertainty could be much higher for future emissions.
Figure 2.1: Total Carbon Dioxide Emissions from the Use of Fossil Fuels in Africa: 1994
Figure 2.2: Carbon Dioxide Emissions from Gas Flaring in Africa: 1994
Figure 2.3: Fossil fuel types and relative contributions to Carbon dioxide emissions in African countries: 1994
Figure 2.4: Carbon Dioxide Emissions from the Use of Liquid Fossil Fuel in Africa: 1994
Figure 2.5: Carbon Dioxide Emissions from the Use of Gaseous Fossil Fuels in Africa: 1994
Figure 2.6: Carbon Dioxide Emissions from the Use of Solid Fossil Fuels in Africa: 1994

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 2.7: Total Regional Methane Emissions from the Use of Fossil Fuels in Africa: 1994
Figure 2.8: Emissions of Methane from the Use of Liquid Lossil Fuels in Africa: 1994
Figure 2.9: Emissions of Methane from the Use of Natural Gas Fossil Fuel in Africa: 1994
Figure 2.10: Emissions of Methane from the Use of Solid Fossil Fuels in Africa: 1994
Figure 2.11: Partitioning by Fuel Phase for Total Fossil fuel Methane Emissions in Africa: 1994
Figure 2.12: Emissions of NOx from Fossil Fuel Generation of Electricity in Africa: 1994
Figure 2.13: CO$_2$ Emissions from Consumption of Natural Gas Fuel in Africa: 1970-1995

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 2.14: CO$_2$ emissions from consumption of solid fuels in Africa 1970 - 1995

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 2.15: CO₂ Emissions from the Consumption of Liquid Fuels in Africa 1970 - 1995

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 2.16: Trends of Total fossil Fuel CO₂
Emissions for Africa
1970 - 1995
Even though Africa continues to show increasing total population, the increase in the average growth rate is decreasing.
Figure 2.18: CO$_2$ Emissions from Fossil Fuel Consumption in Africa under a No-Further Control Scenario (Procedure by Foell, 1995)

RCW - Rapidly Changing World

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Average Emissions Per Million People: 1 dot = 0.03 Tg

Figure 2.19: Total Fossil fuel Carbon Dioxide Emissions in Africa (Normalized by Population): 1994
Figure 2.20: Average Total fossil fuel CO2 Emissions Normalized by GNP Per Capita in Africa: 1994
Average Emissions: 1 dot = 0.2 Tg

Figure 2.21: Total Carbon Dioxide Emissions from the Use of Fossil Fuels in Africa (Normalized by None): 1994
BIOMASS BURNING IN AFRICA

3.1 Introduction

Africa is experiencing rapid population growth which is expected to increase the extent of biomass burning in frequency and scale. Recent studies have suggested that Africa may make the largest continental contribution of gaseous and particulate emissions due to biomass burning (Andreae et al., 1996, Levine et al., 1995; and Scholes 1995). Burning produces agents for depletion of ozone layer, and contributes to global warming, deforestation, acid precipitation, and production of chemically and radiatively active species- carbon dioxide, methane, nitric oxide, tropospheric ozone, methyl chloride and elemental carbon particulates (Levine et al., 1995). For these reasons, smoke aerosols are likely to have a noticeable impact on atmospheric chemistry, surface temperatures and hydrological processes over Africa, particularly in the dry season.

The goal of this chapter is to present the first regional and national inventory of estimates of gaseous and particulate emissions from Africa. Gases of interest shown to be important components of African fires (Cofer et al., 1995) include carbon dioxide (CO₂), carbon monoxide (CO), methane (CH₄), methyl chloride (CH₃Cl), methyl bromide (CH₃Br), oxides of nitrogen (NOₓ), non-methane hydrocarbons (NMHC'S), sulfur dioxide (SO₂), ammonia (NH₃), total particulate matter (TPM), particles< 2.5 μm, and carbon particles. This inventory has a 1°x1° latitude/longitude spatial resolution of biomass burning activity in Africa and provides estimates of emissions on a country-by-country basis. Emissions are calculated based on biomass burning data from Hao and Liu (1994). DMSP fire distribution data for 1986-87, and emission factors based on a series of field campaigns and laboratory measurements. Africa's contribution to global biomass burning emissions is included in the
assessment. The results are compared with previous estimates for continental emissions. The history and possible future trends of these emissions will also be discussed.

3.2 Background

Biomass burning is the burning of the world's vegetation and encompasses a wide range of burning phenomena. Forests, savannas, and agricultural lands are some of the most affected ecosystems (Levine, 1995; Caboon et al., 1996). Reasons for burning include clearing land and changing land use and clearing of vegetation to provide land for agricultural and grazing purposes (Granier et al., 1996). In addition, fire is used to control weeds, and to eliminate agricultural waste after harvest. Moreover, shifting agricultural practices are carried out in many third world countries. For example, in Zambia, the Chitemene practice, in which the fields are set ablaze at the end of the harvest season to eliminate stubble and agricultural waste, is widespread. Many fires are started every day which consume biomass matter for domestic heating and cooking.

Most biomass burning in the world takes place in savannas and nearly 66% of the world's savannas are located in Africa, so that Africa is referred to as the "Burn Center" of the planet (Levine et al., 1995). The term savanna refers to tropical and subtropical vegetation formations with a predominantly continuous grass cover, occasionally interrupted by trees and shrubs (Intergovernmental Panel on Climate Change, 1995). These formations exist in Africa, Latin America, Asia, and Australia. The growth of vegetation in savannas is controlled by alternating wet and dry seasons because most of the growth occurs during the wet season whereas man-made and/or natural fires are frequent and generally occur during the dry season. Fires have
historically been a prevalent phenomenon on the African continent. Early Portuguese explorers to southern Africa in the fifteenth century called the interior of South Africa "tera dos Fumos"—the land of smoke and fire (Trollope, 1996).

Africa’s capacity to support fires stems from the fact that climatic factors are the driving force of fire ecology. Naturally induced fires from lightning are frequent on the continent because Africa is highly prone to lightning storms. In addition anthropogenic activities enhance fire potential from the natural climatically induced extremes in wet periods. Thus fires can burn the plant fuels during the dry season that have been produced and accumulated during the wet season (Trollope, 1996). These climatic conditions are characteristic of the savannas of southern Africa, which receive a strictly summer rainfall followed by an extended dry winter period.

During the dry season, human induced vegetation fires are prevalent in the equatorial regions. Large areas are burned every year in South America and Africa (Konzelmann et al., 1996). Of all the continents, just as is the case with savanna, Africa has the greatest area in the tropics characterized by extensive fires that constitute the single largest source of biomass emissions worldwide (Levine et al., 1992; Crutzen et al., 1979). About 20% of Africa is humid savannas and nearly 15% is arid savannas (Hao et al., 1990). Recent estimates show that the biomass burned every year in Africa is about 390 million tonnes of dry matter for forest and 2430 million tonnes for savannas (Andreae et al., 1992). Other studies give the total figure of 2500 million tonnes (Hao and Liu, 1990), which represents almost 60% of the world’s biomass burning. More than 7.5 million square kilometers of savanna area are consumed in fires annually (Hao et al., 1990). As a result, Africa is thought to be the world’s leading contributor to pollution originating from the burning of vegetation (Hao et al., 1990; Cachier, 1992).
Globally, it is estimated that approximately 66% of the vegetation burned during the 1980's occurred in tropical Africa (World Resources Institute (WRI), 1990). Approximately 85% of biomass is associated with the burning of more than 440 x 10^6 ha of grassland savannas and savanna woodlands (Hao et al., 1990). The frequency of burning varies considerably in Africa depending on ecosystem type (Hao et al., 1996).

Available evidence increasingly indicates that biomass burning in its various forms represents a major perturbation of atmospheric chemistry, comparable in magnitude to the effects of fossil fuel combustion (Crutzen and Andreae, 1990). It has been suggested that large scale biomass burning in both tropical and savanna Africa will contribute to the pollution of both the regional and global atmosphere large quantities of CO₂, O₃, NOₓ, CH₃Cl and CH₃Br (Hao et al., 1996; Brocard et al., 1996; Piketh et al., 1996 Zepp et al., 1996). Remote sensing by satellites has revealed high concentrations of ozone and carbon monoxide in the inter-tropical area over the African continent, and over the Atlantic ocean area under the trade winds [(Zenker et al., 1996; Fishman et al., 1991, 1990; Thompson, 1996; Tyson et al., 1996). Experiments carried out as part of the Dynamics and Chemistry of the Atmosphere in Equatorial Forest [DECAFE] program showed strongly acidic precipitation (Lacaux et al., 1991) and high ozone and hydrocarbon concentrations (Cross et al., 1992, 1996). Acid deposition to the African equatorial forest of 0.74 kg H⁺ha⁻¹ yr⁻¹, with a biomass contribution of 80%, is higher than that of the Eastern United States with 0.67 kg H⁺ha⁻¹ yr⁻¹(Lacaux et al., 1996).

African savanna fires, largely human initiated, have been shown to have a significant impact on the downward surface short-wave irradiance on a regional scale through aerosols (Konzelmann et al., 1996; Cachier et al.; Ballentine et al.; 1996;
LeCanut et al., 1996). Biomass burning may thus directly affect the radiation budget of the planet. Savanna fires release large amounts of particles into the atmosphere, leading to causes an increased aerosol optical depth (LeCanut et al., 1996). These findings are indicative of pollution ascribed to fires on the African continent.

Biomass burning is currently considered to be the most dominant anthropogenic perturbation to atmospheric chemistry in the tropics, where nearly 80% of global burning takes place (Seiler and Crutzen, 1980). Savanna fires are estimated to contribute about 50-67% of tropical biomass fire emissions (Goldammer, 1990; Hao and Liu 1994). Because almost two-thirds of the world's savanna biome is located in Africa, the importance of understanding savanna burning in Africa is apparent.

The South African Fire-Atmosphere Research Initiative (SAFARI) was undertaken to assess the relationships between fires and savanna ecology, to characterize emissions from African savannas, and to study the transport of pyrogenic emissions across the subcontinent and adjacent oceanic areas. SAFARI represents the African component of the Southern Tropical Atlantic Regional Experiment (STARE), sponsored by the International Geosphere-Biosphere Program (IGBP)/International Global Atmospheric Chemistry Program (IGAC) (Lindesaay et al., 1996). The first STARE experiment was conducted during the August-October 1992 season and consisted of two major components, SAFARI-92 and TRACE-A (Transport and Atmospheric Chemistry near the Equator-Atlantic). The SAFARI component was principally an emissions characterization study. It defined the chemical composition of biomass fire released emissions directly over their source (African savanna) during active flame combustion, and also assessed the proportion of emissions associated with each combustion phase. The importance of this study was that it provided

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
emission ratios and emission factors which will be used to estimate emissions of gases and particulates in this study and other future studies (Harris et al., 1993). Observations of fires from space have proved useful in visualizing regional distribution patterns of fire trajectories of smoke transport (Goldammer et al., 1996; Kihn, 1996, Christopher et al., 1996)

Biomass in one form or another continues to be the predominant source of energy for at least half of the world's population, with extremely high dependence on this source of energy by African countries (Policy Options for stabilizing global climate, 1990). The removal of wood for fuel affects both forest and savanna ecosystems in Africa. Charcoal production is increasing as a result of urban growth in developing countries particularly in Africa.

High population growth in Africa over the last decade has been accompanied by rapid changes in land use practices. The deforestation rate has increased about 12% annually from 1980 to 1990 (Food and Agriculture Organization, 1993: Hao et al., 1994), and the fallow cycle of shifting cultivation has shortened from 10 years to 5 years (Hao et al., 1996)

3.3 Estimation Procedures

Understanding the geographical and temporal distribution of burning is critical for assessing the emissions of gases and particles to the atmosphere. For a first approximation, the total amount of biomass burned in an ecosystem can be calculated from measurements of the total land area burned annually, the average organic matter per unit area in the ecosystem, the fraction of above ground biomass relative to the total average biomass. Once the total amount of biomass is known, the total mass of
carbon release to the atmosphere during the burning can be estimated because \( \sim 45\% \) of biomass by weight is made up of carbon.

During complete combustion, biomass undergoes an oxidation process that yields water vapor and carbon dioxide according to the following reaction:

\[
\text{(CH}_2\text{O}) + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O}
\] (3-1)

However, in natural fires, insufficient oxygen supply causes incomplete combustion. This leads to the formation of incompletely oxidized compounds; carbon monoxide (CO), or reduced compounds such as methane (CH\(_4\)), non methane hydrocarbons (NMHC), and others.

The amount of biomass (\( M \)) burned in a particular ecosystem can be estimated by the following expression (Seiler and Crutzen, 1980):

\[
M = A \times B \times a \times b
\] (3-2)

where:
- \( M \) = total amount of biomass burned
- \( A \) = total land area burned annually (m\(^2/\text{yr.}\))
- \( B \) = average organic matter per unit area in the individual ecosystem (gdm/m\(^2\))
- \( a \) = fraction of the above ground biomass relative to the total average biomass \( B \)
- \( b \) = the burning efficiency of the above ground biomass.
A can be determined from satellite and remote sensing techniques and procedures, such as fire scars. Parameters B, a, and b are determined during biomass burn field measurements in diverse ecosystems (Levine, 1995) Field experiments to determine these parameters involve carrying out measurements before, during and after burning. A detailed outline of the procedures involved to determine these parameters is given (Delmas et al., 1995).

Once M is estimated, the amount of total carbon [M(C)] emitted to the atmosphere in grams can be estimated using the following expression:

\[ M(C) = 0.45M \]  
\[ \text{(3-3)} \]

where: \( M(C) = \text{amount of carbon} \)

The emission of any gaseous or particulate species from biomass burning depends on two parameters. (1) the amount of biomass material burned, and (2) the emission factor (EF) or emission ratio (ER). The EF which can generally be described as the proportion of a given compound released during the combustion, and is given as species/kg fuel. Emission ratios are typically estimated by measuring the increase in a given gas relative to the increase in CO\(_2\) in a smoke plume. This measurement is then converted to a dry - mass basis by assuming a carbon content in the fuel of 41-45% and an efficiency of conversion of fuel C to CO\(_2\) of 80-98%.
The Emission \((E_i)\) for combustion products is given for each gas by:

\[
E_i = EF_i \times M
\]

or

\[
E_i = M(\text{carbon released}) \times ER_i
\]

(which is summed over the vegetation classes)

The carbon released during burning is in the form of several gaseous and particulate compounds. The ratio of any carbon or nitrogen compound to CO\(_2\) produced in the burning can be determined from knowledge of an emission ratio (ER).

\[
ER = \frac{\Delta[X]}{\Delta[CO_2]} \quad (3-4)
\]

where: \(\Delta[X]\) = the concentration of the species \(X\) produced by biomass burning

\[
\Delta[X] = X^* - X \quad (3-5)
\]

where: \(X^*\) = the measured concentration of \(X\) in the biomass burn smoke
\(X\) = the background (out of plume) atmospheric concentration of the species.
\(\Delta[CO_2]\) = the concentration of CO\(_2\) produced by biomass burning

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
\[
\Delta[\text{CO}_2] = \text{CO}_2^* - \text{CO}_2
\]  

(3-6)

where: \(\text{CO}_2^*\) = the measured concentration of \(\text{CO}_2\) in the biomass burn smoke and \(\text{CO}_2\) is the background (out of plume) atmospheric concentration of \(\text{CO}_2\).

The ER and its variability is critical for any estimate of trace compound emissions from biomass burning. The emission ratio is highly dependent on both the type of combustion (especially the phases of combustion, flaming or smoldering) and the ecosystem.

3.4 Methods

Source Construction

The general scheme we designed and used to estimate emissions from the biomass burning source is outlined in Figure 3.1

DMSP Imagery

The annual fire distribution grid used in this study is a product of the nighttime low-light imagery acquired by the DMSP block 5 satellites during the years 1986 and 1987. The DMSP nighttime imagery of the earth records fire activity, city lights, lightning and auroras (Cahoon et al., 1994) Local midnight imagery was used to record the sources of light on the surface of the earth. City lights were easily isolated by subtraction because they do not change location in time. Throughout the years of study, visible imagery was obtained on average for every fourth day. The temporal distribution of the images through most months is good even though images were not spread out evenly. Daily imagery was examined for each month, and from
the spatial distribution of fires, the actual monthly burning was established. A composite was made from the monthly mosaics and this was used in this study.

The Defense Meteorological Satellite Program (DMSP) is a Department of Defense (DoD) program run by the Air Force Space and Missile Systems Center (SMC). The DMSP program designs, builds, launches, and maintains several near polar orbiting, sun synchronous satellites monitoring the meteorological, oceanographic, and solar-terrestrial physics environments.

DMSP satellites are in a near polar orbiting, sun synchronous orbit at an altitude of approximately 830 Km above the earth. Each satellite crosses any point on the earth twice a day and has an orbital period of about 101 minutes thus providing complete global coverage of clouds every six hours.

Each DMSP satellite monitors the atmospheric, oceanographic and solar-geophysical environment of the Earth. The visible and infrared sensors collect images of global cloud distribution across a 3,000 km swath during both daytime and nighttime conditions. The coverage of the microwave imagery and sounders are one-half the visible and infrared sensors coverage, thus they cover the polar regions above 60 on a twice daily basis but the equatorial region on a daily basis. The space environmental sensors record along track plasma densities, velocities, composition and drifts.

The data from the DMSP satellites are received and used at operational centers on a continual basis. The data are sent daily to the National Geophysical Data Center (NGDC), Solar Terrestrial Physics Division (STPD) for creation of an archive.
Global Wildfire Detection

The upwelling terrestrial light is measured in the 0.4-1.1 micrometer range at a resolution of 2.7 km. There is a high contrast between the background and light sources, such that the light sources can be qualitatively distinguished and mapped. Each DMSP image was mapped to form monthly composites. Cities are isolated, since their location does not vary from month to month, and are removed from the monthly composites, leaving only time varying sources. Throughout the study years, visible imagery is obtained for every fourth day. Although these images are not spread out evenly, the temporal distribution through most months is very good. Daily imagery was examined for each month and, given the daily spatial distribution of fires, each mosaic is representative of the actual burning throughout the month (Cahoon, et al., 1994)

Fire Pixel Counts and Resampling and distributing to 1°x1° Grid of Total Biomass Burned Distribution

The 1986-87 DMSP imagery annual composite of fire distribution in Africa (Figure 3.2) was converted from the raster image into a fire grid using GIS technology. The arc program in GIS converts the image into a geo-referenced grid map and assigns the fire pixels to their exact geographic location. The resulting grid was then mapped into 1°x1° grid. Using GIS spatial analyst, fire pixel counts were then evaluated for each 1°x1° grid box (Figure 3.3). An avenue generated script was used to calculate the sum of fire pixels in each 1°x1° grid box. These counts were weighted, with respect to a 5°x5° grid box which was divided into 25, 1°x1° grid boxes and weighing functions based on ratio distribution over a 5°x5° were assigned to each 5°x5° grid box. These counts were then used to resample Hao's biomass
burning data from the present 5°x5° grid to a 1°x1° grid. Instead of assuming that the entire 5°x5° grid box burns, the resampling and re-weighting only places burning in those 1°x1° grid box that actually experience fire activity.

Assignment of EF/ER to Reclassified Vegetation Distribution Map

African biomes that are either expansive or have enough supporting emission data to warrant separate classification were identified. These include, water, desert, and forests. Of these, water and desert are assumed to have no emission. The remaining biomes were mapped out on a grid using a simplified version of the 32-type Global Vegetation Index (Matthews, 1983; 1985).

The Vegetation map for Africa was compiled from GISS Matthew's vegetation (1°x1° grid Global vegetation distribution - 32 type) in ASCII grid (Figure 3.3). The global map was digitized and edge-matched using Geographic Information System (GIS) Technology to create a vegetation based map of the continent. The 32-type vegetation classes were reclassified into eleven broad types (Figure 3.4), each of which has a distinctive fuel type, fuel production and climate. The map was converted from ASCII format into a 1°x1° grid format using GIS, and this grid was reclassified by summarizing zones in GIS and appropriate emission factors were assigned to each 1x1 degree box.

The following species were estimated on the basis of EF: CO₂, NMHC's, CH₃Cl, CH₃Br, NH₃, and SO₂ (Table 3.1). Emission factors and Emission ratios were assembled from available literature and from field measurements from campaigns such as DECAFE and SAFARI'92, held in the savannas of West and Southern Africa respectively. Default values obtained from IPCC guides for greenhouse gas inventory compilation. Special field experiments have been carried
out to collect data representative of southern Africa, where much of the burning occurs. Field experiments yielded emission factors and emission ratios. The mean emission factors in each vegetation type are given in (Table 3.1)
Table 3.1 Mean Emission Factors:

<table>
<thead>
<tr>
<th>Compound</th>
<th>Savanna</th>
<th>Agricultural Residues</th>
<th>Forest/ Fuelwood</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>1640 ±40</td>
<td>1597±29</td>
<td>1679 ±43</td>
<td>Andreae et al., 1996</td>
</tr>
<tr>
<td>NMHC's</td>
<td>3.1</td>
<td>3.1</td>
<td>3.1 ±1.1</td>
<td>Andreae et al., 1996</td>
</tr>
<tr>
<td>CH₃Cl</td>
<td>0.11</td>
<td>-</td>
<td>-</td>
<td>Andreae, 1996</td>
</tr>
<tr>
<td>CH₃Br</td>
<td>0.002</td>
<td>-</td>
<td>-</td>
<td>Andreae et al., 1996</td>
</tr>
<tr>
<td>NH₃</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>Andreae et al., 1996</td>
</tr>
<tr>
<td>SO₂</td>
<td>0.6</td>
<td>-</td>
<td>-</td>
<td>Andreae et al., 1996</td>
</tr>
</tbody>
</table>

Detailed Emission factors are provided in Skunda, 1996

Note: These best guess emission factors were calculated based on information from SAFARI-92
The following species were estimated on the basis of ER (Table 3.2): CH4, CO, NOx, NMHC's, and TPM. Particulates <2.5 \( \mu \)m. Carbon particles.

Emission ratios used in this section and presented in the tables are derived from Crutzen and Andreae (1996), Andreae (1990), Scholes (1995), Skunda (1996), and the IPCC Greenhouse Gas Inventory Reference Manual reports data form, Delmas (1993), and Lacaux, et al. (1993). They are based on measurements in a wide variety of fires, including forest and savanna fires in the tropics and laboratory fires using grasses and agricultural wastes as fuel. In many cases these ratios are general averages for all biomass burning. Research will need to be conducted in the future to determine if more specific emission ratios, e.g., specific to the type of biomass and burning conditions, can be obtained. Also, emission ratios vary significantly between the flaming and smoldering phases of a fire. CO2, N2O, and NOx are mainly emitted in the flaming stage, while CH4 and CO are mainly emitted during the smoldering stage (Andreae et al., 1996). The relative importance of these two stages will vary between fires in different ecosystems and under different climatic conditions, and so the emission ratios will vary. As inventory methodologies are refined, emission ratios should be chosen to represent as closely as possible the ecosystem type being burned, as well as the characteristics of the fire.
Table 3.2: Mean Emission Ratios

Emission Ratios for CH₄, CO, NOₓ, NMHC's, TPM, Particulates <2.5 µm, and Carbon particles

<table>
<thead>
<tr>
<th>Compound</th>
<th>Savanna</th>
<th>Agricultural Residues</th>
<th>Forest/ Fuelwood</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₄</td>
<td>0.004 ±0.002</td>
<td>0.005 ±0.002</td>
<td>0.012 ±0.003</td>
<td>Delmas, 1993</td>
</tr>
<tr>
<td></td>
<td>0.004</td>
<td>-</td>
<td>-</td>
<td>Andreae et al., 1996</td>
</tr>
<tr>
<td>CO</td>
<td>0.06 ±0.002</td>
<td>0.06 ±0.002</td>
<td>0.06 ±0.002</td>
<td>Lacaux et al., 1993</td>
</tr>
<tr>
<td></td>
<td>0.028</td>
<td>-</td>
<td>-</td>
<td>Andreae et al., 1996</td>
</tr>
<tr>
<td>NOₓ</td>
<td>0.121 ±0.027</td>
<td>0.121 ±0.027</td>
<td>0.121 ±0.027</td>
<td>Crutzen and Andreae, 1990</td>
</tr>
<tr>
<td>NMHC's</td>
<td>0.006</td>
<td>-</td>
<td>-</td>
<td>Andreae et al., 1996</td>
</tr>
</tbody>
</table>

Particulates

| TPM        | 10 ±8.5           | 10                    | 7.9 ±3.2         | Andreae et al., 1996          |
| particles<2.5 µm | 7.2 ±3.8 | 6.4 ±3.2 | 3.6 ±1.2 | Andreae et al., 1996          |
| Total C particulates | 6.4 ±5.1 | 6.4 ±5.1 | 3.0 ±1.3 | Andreae et al., 1996          |
| N/C ratio by weight | 0.006 | 0.015 | 0.01 | Default IPCC, 1995 |

Detailed Emission ratios are provided in Skunda, 1996
Note: Ratios for carbon compounds, i.e., CH$_4$ and CO, are mass of carbon compound released (in units of C) relative to mass of total carbon released from burning (in units of C); those for the nitrogen compounds are expressed as the ratios of mass of nitrogen compounds relative to the total mass of nitrogen released from the fuel.

Once the carbon released from burning has been estimated, the emissions of CH$_4$, CO, and NO$_x$ can be calculated based on emission ratios.

Default value means a value that can be applied when there is not sufficient information to characterize an ecosystem, and this value has been adopted by the IPCC from scientists and is the best estimate value to minimize uncertainty. The amount of carbon released due to burning is multiplied by the emission ratios of CH$_4$ and CO relative to total carbon to yield emissions of CH$_4$ and CO (each expressed in units of C). The emissions of CH$_4$ and CO are multiplied by 16/12 and 28/12, respectively, to convert to full molecular weights. NMHC's could also be calculated in the same way. However, default values are not available. Therefore NMHC's were calculated using EF values.

To calculate emissions of NO$_x$, first the total carbon released is multiplied by the estimated N/C ratio of the fuel by weight to yield the total amount of nitrogen (N) released. The total N released was then multiplied by the ratios of emissions of NO$_x$ relative to the N content of the fuel to yield emissions of NO$_x$ (expressed in units of N). To convert to full molecular weights, the emissions of NO$_x$ were multiplied by 46/14.
The calculation for trace gas emissions from burning is summarized as follows:

\[
\text{CH}_4 \text{ Emissions} = \text{Carbon Released} \times (\text{emission ratio}) \times \frac{16}{12}
\]

\[
\text{CO Emissions} = \text{Carbon Released} \times (\text{emission ratio}) \times \frac{28}{12}
\]

\[
\text{NO}_x \text{ Emissions} = \text{Carbon Released} \times (N/C \text{ ratio}) \times (\text{emission ratio}) \times \frac{46}{14}
\]

Using the maps created above and the relevant emission factors, emission ratios, and the empirical relationships discussed in section 3.3, emissions for various greenhouse gases were derived for the appropriate 1°x1° grid cell.

National estimates:

Using GIS rezoning, cells were edge-mapped with country boundaries and results were recalculated and tabulated on a country by country basis (Table 3.4). Table 3.5 shows the Estimates for Emissions from African fires and comparison with other studies and Global estimates.

3.5 Results and Discussion

Figure 3.1 shows an annual composite of fire activity in Africa based on pixel counts from DMSP imagery data. From an examination of this figure, the severity and extremity of burning in Africa becomes obvious. A large percentage of the continent particularly the belt between 25 degrees South and 20 degrees north is affected annually by fire activity. Regions which show the highest fire frequency are Ivory Coast, Ghana, Nigeria, Central African Republic, South western Sudan, Southern
Zaire (now Congo), Southern Tanzania and eastern Mozambique border with Zimbabwe.

The spatial distribution of fire activity is consistent with the works of Cahoon et al., 1994, and that of Goldammer, 1991. Previous studies have indicated that fire activity is not expected to vary much from year to year (Cachier et al. 1996; Brocard et al. 1996). There is limited burning, almost insignificant in the desert areas in Northern Africa and South East Southern Africa. Areas of peak fire activity were found to be correlated with regions of high population density.

**Seasonal Variations in Biomass Burning Activity**

Analysis of monthly maps (Figures 3.6 through 3.17) of biomass burning show that during the first half of the year (January to June), most biomass burning activity is confined to the Northern Hemisphere. The months of March and April indicate the peak season for biomass burning north of the equator. Northern Hemisphere savannas, forests, and agricultural lands residues and firewood fire activity is extensive during the months of January to June. These results are consistent with DMSP satellite imagery data indicating that burning is prevalent in the Northern Hemisphere during this time of the year, which also happens to be the dry season in Northern Hemisphere. However, DMSP data shows January as the peak month for savanna fire activity, while monthly maps show March and April as peak months. This discrepancy can be explained by the fact that DMSP data does not incorporate total biomass burning for all sources, savanna, forest, agricultural residues and fuel wood. Most of the burning in the Northern hemisphere is concentrated in the 0° to 20° N belt.
During the first half of the year, the dry season is concentrated in the N. hemisphere and gradually shifts to the S. Hemisphere. By July, there is a noticeable drop in biomass burning activity in the N. Hemisphere. By August (Figure 3.13), biomass burning activity has become pronounced in the S. hemisphere. By this time, dry conditions are already prevailing in the Africa, south of the equator, and fire activity increases over the Southern African interior. The pattern of burning follows the ecosystem boundary between sub-humid broad leafed savanna on infertile soils and the equatorial tropical rain forest in North central Zaire (now Congo). Rainfall remains strongly seasonal permitting frequent fires.

From July (Figure 3.12) to November (Figure 3.16), burning increases in Southern Africa with peak activity in the months of September, October and November. These months are usually the warmest for the region and are the very dry season preceding the first rains. The data is consistent with the fact that burning frequency is expect to be at the climax as the dry season comes to an end. Peak activity is located in Southern Zaire, Northern Zambia, Zimbabwe/Mozambique border. As the dry season encroaches, extent of biomass burning frequency is noted to increase in Tanzania and Mozambique (Figures 3.13 - 3.16).

Figure 3.18 shows the annual distribution of instantaneous carbon dioxide emissions from biomass burning activities in Africa. Savanna biomes show areas of high emissions particularly around Senegal and Ivory Coast.

**Trace Gas and Particulate Emissions.**

Biomass burning in Africa is dominated by savanna fires (Figure 3.19). The relative contributions to total biomass burning in Africa of the different activities is 64% savanna, 28% forest, 7% fuelwood, and 1 agricultural residues. Consequently,
savanna emissions will dominate the nature of trace gas and particulate emissions from Africa.

Based on the estimates in table 3.5, Africa's contribution to total global biomass burning species emissions is high. Savanna fires dominate emissions in Africa. Savanna fires are characterized by clean, flaming combustion (Andreae et al., 1996) and hence the emissions of reduced trace gases such as (CO, CH₄, and NMHC) is less than would be expected from the fraction of global biomass burning that takes place in Africa. Africa contributes 30% CO (with range 12-48%), 17% CH₄ with range 8-25%), and 18% NMHC (with range 4-33%) of the total annual global emissions from biomass burning (Table 3.4).

In contrast, NOₓ which is favored by the flaming combustion in savanna fires has a 63% (with range 38-88%) global contribution (Table 3.4). Field experiments in Africa reported high NOₓ/ NMHC ratios in the savanna fire plumes as a result of the flaming dominated emissions profile. One consequence of this is that higher specific ozone production is expected over Africa because O₃ production is NOₓ-limited (Andreae et al., 1996)

Africa's methyl halide contribution to the global biomass burning budget is 25% methyl chloride (range 3-49%) and 26% methyl bromide (range 3-50%). It has been established that savanna fires contribute methyl halide emissions roughly proportional to their fraction of biomass burned (Andreae et al., 1995). Low emissions would be expected due to the small smoldering combustion, but this is compensated by the high halogen content of savanna biomass compared to, forest biomass (Andreae et al., 1996; Blake et al., 1996)

Africa's aerosol contribution stand at 27.6% TPM, and 29% (with range 6-52%) carbon particles. Since smoldering fires release more aerosols than flaming fires
(in terms of mass, but not in terms of the specific components like inorganic species or black carbon), a lower relative contribution from savanna fires to the total emissions would be expected. These results are much lower than those reported by Andreae et al., 1995 who argued that their high African aerosol contributions to the global budget was due to large uncertainties in emission factors. The lower results reported here are largely due to new data on emission factors. A percentage contribution of Africa's particles < 2.5 um could not be established as no information is available presently on global totals for this species. Recent studies suggest that aerosol emissions from biomass burning may be the second largest source of anthropogenic aerosols after the production of sulfates from $SO_2$ (Andreae et al., 1995)

From these estimates, Africa contributes nearly 31% (range 3-59%) to the NH$_3$ biomass burning budget. Unfortunately, the emission factor used to obtain this result is speculative, making estimates for this species highly uncertain. No reliable data on ammonia emissions was obtained during SAFARI-92. The values used here were a mean of the upper and lower limits of NH$_3$ emission ratios and factors from the literature.

Africa was found to contribute nearly 38% (with range 3-59%) to the global biomass burning sulfur dioxide (SO$_2$) budget. Sulfur occurs in plants as sulfate as well as a variety of sulfate esters and other sulfur compounds. During combustion, a large fraction of the sulfur content is released to the atmosphere. SAFARI-92 results suggest an 86% sulfur volatilization.
National Contributions

Table 3.3 lists African countries and their contributions to the budget of Carbon dioxide (CO2), carbon monoxide (CO), methane (CH4), methyl chloride (CH3Cl), methyl bromide (CH3Br), oxides of nitrogen (NOx), non-methane hydrocarbons (NMHC'S), sulfur dioxide (SO2), ammonia (NH3), and aerosols include Total particulate matter (TPM), particles< 2.5 um, and carbon particles from biomass burning. Countries not shown are grouped as other Africa.

For the purposes of my research, Africa was divided into four latitudinal belt regions (Figure 3.20)

The estimated pyrogenic emissions for the countries in Africa with sufficient data for the above method are listed in table 3.4. The results compared to the study in Southern African Countries by Scholes, Ward and Justice (1996) are significantly higher. The reasons for this discrepancy stems from the fact that the other study used modeled fuel loads and the area burned was estimated using detection by remote sensing. Zaire is the single largest emissions contributor and eight other important contributing countries are Sudan, Zambia, Nigeria, Tanzania, Ethiopia, Ghana, Mozambique, and ivory coast. Zaire lies in the ecosystem boundary between sub-humid broad leafed savanna on infertile soils and the equatorial tropical rain forest where biomass burning is frequent fires and DMSP imagery supports this. Because vast areas of Africa burn every year, the gross trace gas emissions from Africa are globally significant and dominate the greenhouse gas inventories of large but lightly industrialized countries such as Zaire, Angola, Tanzania and Zambia. Results show that Zaire, Sudan, Zambia and Tanzania dominate in emissions resulting from Biomass burning in Africa.
Region I (Countries Within the Latitudinal Belt 20° - 40° N )
(Algeria, Egypt, Libya, Morocco, Tunisia, and Western Sahara)

There is almost insignificant biomass burning activities in the countries lying within this belt. This region is primarily desert (Sahara Desert). The contributions of these desert countries to the African biomass burning emissions budget is insignificant. Nighttime photographs from a low light sensor on board the block 5 Defense Meteorological Satellite Program (DMSP) satellites to monitor fires in Africa show no fire activity in this belt (Cahoon et al., 1992). (see Figure 3.2)

Region II (Countries Within the Latitudinal Belt 5° - 20° N, but Westward of 25 Degrees Longitude )
(Benin, Burkina Faso, Cameroon, Central African Republic, Chad, Equatorial Guinea, Gambia -The, Ghana, Guinea, Guinea Bissau, Ivory Coast, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone, and Togo)

The DMSP imagery shows marked fire activity in this region, particularly in Ghana and Ivory coast. Nigeria, Ghana and Ivory Coast fall in 4, 7 and 9 positions in contributing the African biomass burning emissions budget. This western part (west of Ivory coast) can be described as dense and high grass dominated by scattered trees, where grass production is high and annual fire activity is severe. The area around Ivory coast, Ghana, and Nigeria is characterized by humid forests with derived savanna and sub-humid wooded savanna. These area exhibit fire patterns resulting from burning in highly populated regions, where the burning is controlled. large scale fires are frequent in the less populated areas of this region (Richardson, 1994; Menaut et al., 1991). Little fire activity occurs in the moist forest parts of this region. the
largest contributions per 1 x 1 degree grid for emissions are observed in Ivory coast and Nigeria.

Region III (Countries Within the Latitudinal Belt 5° - 20° N, but Eastward of 25 Degrees Longitude)

(Djibouti, Eritria, Ethiopia, Somalia, and Sudan)

The Northern region around the Sudan (Sahel region) is characterized by grassland with shrub cover. This region is widely used for cattle raising and the cattle usually trample the little vegetation there is (Menaut et al., 1991). Sudan (second highest in Africa as a whole) shows high emissions because of its large land mass area and there is prevalent fire activity in the southern Sudan savannas. This region has lower vegetation production but experiences severe drought periods (Matthews, 1985). There are vast open grasslands in this region which leaves wide land expanses for fire burns. Matthews describes the southern part of this region as drought-deciduous woodland. The southern region is also used for hunting and grazing while the remaining wide expanses of land are susceptible to burning. Emissions in these countries are maximal in the middle of the dry season, and this is consistent with open savanna and low population burning. There is also a wide expanse of grasslands with less than 10% woody cover. There is a high population density along the coast while the inland is sparsely populated. Ethiopia has high emissions in this region (sixth overall in Africa) Ethiopia suffers severe drought periods and large mass of dry vegetation quickly burn (Richardson, 1994). Somalia and Eritrea have minimum contributions.
Region IV (Countries Within the Latitudinal Belt 10° S- 5° N)
(Congo, Burundi, Kenya, Tanzania, Uganda, and Zaire)

Equatorial Africa is included in this belt. There is very little deforestation occurring in the equatorial rain forest and satellite imagery shows little or no fire activity in this region. Figure 3.1 shows very little fire occurrences in central Zaire and Congo) The population density is low here and fire activity occurs on the periphery of the forests. Emissions from this equatorial belt are at a minimum. DMSP images exhibit a large biennial behavior coinciding with the precipitation patterns of the region. However, countries within this belt still show high emissions, because of the diversity of their vegetation strata. Zaire has the highest total emissions in Africa because of its larger land area and its fire activities are more widely distributed and less intense. The northern part of Zaire falls in the burn season consistent with N hemisphere burning and the southern part falls into the S. hemisphere burn season. Zaire is the greatest single national source of gases and particulates from biomass burning in Africa largely because of extended burn seasons, large land mass area and widespread fire activity. Tanzania is overall fifth in emissions with Kenya and Uganda showing significant contributions.

Region V and VI (Countries Within the Latitudinal Belt 10° S- 35° S)
(Angola, Botswana, Lesotho, Madagascar, Malawi, Mozambique, Namibia, South Africa, Swaziland, Zambia, Zimbabwe)

In this region, Zambia, Mozambique and Botswana have the highest emissions (positions 3, 8, and 10 respectively in Africa), with Angola also contributing significantly. A key aspect of the Southern African hemisphere emissions are concentrated in a band that stretches across the subcontinent between 5
and 20 degrees south. This belt lies in the sub-humid broad leafed savannas on infertile soils. Although the rainfall is sufficient to generate substantial biomass, it remains strongly seasonal, allowing frequent fires. The infertility of the soils mean that the dry grass from the previous season must burn first to stimulate the growth of new grass. This practice is particularly common in Zambia it is referred to as the Chitemene practice. In rural Zimbabwe and Mozambique, the greater part of the population relies heavily on subsistence farming and the agricultural practices are still very much traditional. Lack of modern infrastructure means that the only way peasant farmers can clear vast land fields for crop growing is by setting them ablaze. In Zambia and Zimbabwe for example there are no enacted by-laws governing these seasonal field fires [personal communication with Dr. Daniel Mtetwa of the Forestry commission of Zimbabwe]. In southern Africa, Zambia has the highest emissions followed by Tanzania, Mozambique and Botswana. The modeling study of Scholes, 1995 suggest that Angola has the greatest contribution followed by Zambia and then Tanzania. A careful analysis of fire satellite imagery suggests that fire activity in Angola is less prominent than in the other three countries.

The western edge of South Africa and Namibia is either desert or shrub land (Fynbos). This region is what is referred to as the Kalahari desert. This region has an extended dry season lasting almost 7 months (June to December), with very little rain if any after that most of South Africa has low density vegetation and eastern south Africa is covered by grassland (Richardson, 1994). Central south Africa is covered by dwarf shrubs and some grassland. Because of the low productivity of this vegetation, widespread fires are uncommon here. Fire is also infrequent in the arid savannas of northern South Africa (Huntley, 1984) The burn season is from July to December. Most of the burning occurs between July and November. Nearly half of the burning
takes place in the broad leafed, low-nutrient savannas which dominate the zone between 5 and 18 degrees south. In eastern Southern Africa particularly in Mozambique and Zimbabwe, the thorny fine leafed savannas on fertile soils predominate. these two vegetation types dominate the emissions in the Southern hemisphere countries.

When emissions are compared with population density, more fire activity occurs in less populated regions than in more populated areas. this is largely because burning tends to be more controlled in populated areas where the greatest biomass burning activity is firewood consumption as opposed to uncontrolled burning in vast open areas. However, total national emissions are not correlated with neither population nor area. This analysis however does show that Zaire and Sudan with Africas largest areas have the highest emissions.

The results for total species emissions for the continent are comparable to those by Andreae et al., 1995. The results presented here are higher only because Andreae presents results for emissions from savanna biomass burning. This only accounts for a total of 62% of the total biomass burning in Africa since the study excludes Forest, Fuelwood and Agricultural residues. If the contribution from these other activities are subtracted, emissions are well within the margins of those by Andreae.

Scholes, 1995, presents estimates of CO₂, CH₄, CO, NOₓ and N₂O for countries in southern Africa. The results presented here are higher by factors ranging from 1.5 for Angola to 8 for Zimbabwe. This difference can be explained by the fact that Scholes models his estimates. The modeling estimates underestimate the total emissions from biomass burning because they do not consider biomass burned through land changes such as forest clearing, agricultural waste burning and fuel
wood consumption. There are also errors in the modeling methods in the amount of fuel wood removed by herbivory decay.

**Uncertainties**

Major uncertainties exist in the amount of biomass burned from Hao's dataset which was used to make the emissions estimates. In deriving this dataset, there were uncertainties in estimating the amount of biomass burned in the areas cleared by different land use practices, the fallow period, the above ground biomass density, and the temporal distribution of biomass burned. It is necessary that a high resolution biomass burned dataset be developed with better information so that estimating emissions and modeling the chemistry of the atmosphere and the global climate can be done more accurately. Reasonably accurate emission factors have been determined for many important species and were used in generating emissions estimates in this study. However, great uncertainty persists with regard to the amount of biomass burned for many regions.

Some of the areas in this study did not have enough emission factor and emission ratio data. The calculation of immediate trace gas emissions, based on the default emission ratios produces relatively crude estimates with substantial uncertainties. Use of specific emission ratios which vary by type of burning, region, etc. allows for more precise calculations. The use of default IPCC factors and the extrapolation of field factors into these biomes causes two problems: The IPCC method combines two concepts in the term "combustion efficiency": combustion completeness and combustion efficiency (Ward and Radke, 1993). The IPCC then goes on to base the emission factors on CO2 alone, but the emission factors are highly sensitive to combustion efficiency. Combustion efficiency is highly sensitive in the savannas (around 95%) because most of the fuel is consumed during the flaming
phase, which is highly oxygenated and therefore does not favor the reduced species. Combustion completeness on the other hand, is highly variable (50-98%) (Scholes, 1995) and strongly dependent on the fuel load, fuel type and the meteorological conditions prevailing during the time of the fire. For example, fallen tree litter is likely to burn more when there is fallen grass to fuel the fire. If the fuel load drops, fires become patchy and may go out particularly during lower night temperatures and increased humidity. These factors create errors in those regions where such data had to be used.

It is generally inappropriate to apply emission factors derived from one ecosystem type to another type (for example EF from forest or temperate grasslands to savannas). In general emission factors are dependent on the fire type, whether smoldering phase or flaming phase and these factors vary with ecosystem type. (for example, the emissions of smoldering-phase gases are much lower in savannas, and flaming phase emissions are higher. The type of emissions, i.e. whether reduced or oxidized is also dependent on this. The latitudinal belt 15 - 30 degrees South was seriously affected by drought in 1992 and continues to experience drought periods over time (Justice et al., 1996). Temporal resolution of biomass burning emissions is very difficult to establish at this time. Very little data is available on inter-annual variability of fires activity in Africa, and timing of fires has not been resolved either. The relationship between fires, rainfall and vegetation state needs to be established.

The calculations described here ignore the contemporary fluxes associated with past burning activities. These delayed releases are known to exist (IPCC, 1995), but are poorly understood at present.

Estimates of emissions from biomass burning confronts a serious data problem. Few of the figures used in current best estimates are known to better than
30% of their means. Some, such as fraction of biomass burned, populations in slashand-burn agriculture, and area burned are known to no better than ± 50%. The error in global estimates accumulates to embarrassing proportions as uncertain terms are compounded in chain multiplication (Robinson, 1989). Satellite and remote sensing will provide better data for estimates.

Combining Uncertainties

It is necessary to derive the overall uncertainty from the combination of emission factor and activity data uncertainties. The emission factor and activity data ranges are as estimates of the 95 per cent confidence interval, expressed as a percentage of the point estimate, around each of two independent components from statistically based calculations. To compute overall uncertainty, it is necessary to assume that the individual components used in the estimation procedures are statistically independent. This assumption is valid for the estimates presented here.

On this interpretation (for quoted ranges extending not more than 60 per cent above or below the point estimate) the appropriate measure of overall percentage uncertainty ($U_T$) for the emissions estimate is given by the square root of the sum of the squares of the percentage uncertainties associated with the emission factor ($U_{EF}$) and the activity data ($U_A$). That is, for each source category: (where the uncertainties are defined as $U_i$, the uncertainty in the activity factors and emission factors involved in the computation of estimates.

$$U_T = \pm \sqrt{\sum (U_i)^2} \text{ for } |U_i| < 60$$

where (For individual uncertainties greater than 60 per cent the sum of squares procedure is not valid). All that can be done is to combine limiting values to define an overall range, although this leads to upper and lower limiting values which
are asymmetrical about the central estimate (If uncertainties due to the emission factor and the activity data are $\pm E\%$ and $\pm A\%$ respectively, and the upper and the lower limits of overall uncertainty are $U\%$ and $L\%$ respectively, then $U\% = (E+A+E.A/100)$ and $L\%=(E+A-E.A/100)$). The calculated uncertainties are presented in Table 3.6.
Table 3.6: Uncertainties due to Emission factors and activity data for biomass burning estimates

<table>
<thead>
<tr>
<th>Species</th>
<th>source category</th>
<th>Uncertainty in Amount of Biomass burned</th>
<th>Uncertainty in Emission factor/ratio</th>
<th>Overall Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>biomass burning</td>
<td>50</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>CO2</td>
<td>savanna</td>
<td>50</td>
<td>2.4</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>forest/fuelwood</td>
<td>50</td>
<td>3.4</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>Agricultural</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>residues</td>
<td>50</td>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>CO</td>
<td>savanna</td>
<td>50</td>
<td>33</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>forest/fuelwood</td>
<td>50</td>
<td>33</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>agricultural</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>residues</td>
<td>50</td>
<td>33</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td>60</td>
</tr>
<tr>
<td>CH4</td>
<td>savanna</td>
<td>50</td>
<td>50</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td>forest/fuelwood</td>
<td>50</td>
<td>25</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>agricultural</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>residues</td>
<td>50</td>
<td>40</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td>50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Species</th>
<th>source category</th>
<th>Uncertainty in Amount of carbon released</th>
<th>Uncertainty in N/C ratio</th>
<th>Emission Ratio</th>
<th>Overall uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx</td>
<td>savanna</td>
<td>50</td>
<td>20</td>
<td>22</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td>forest/fuelwood</td>
<td>50</td>
<td>33</td>
<td>22</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>agricultural</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>residues</td>
<td>50</td>
<td>20</td>
<td>22</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>40</td>
</tr>
</tbody>
</table>

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Table 3.6 (Continued)

<table>
<thead>
<tr>
<th>Species</th>
<th>source category</th>
<th>Uncertainty in Amount of biomass burned</th>
<th>Uncertainty in Emission Factor</th>
<th>Overall Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMHC</td>
<td>biomass burning</td>
<td>50</td>
<td>57</td>
<td>76</td>
</tr>
<tr>
<td>NH₃</td>
<td>biomass burning</td>
<td>50</td>
<td>66</td>
<td>80</td>
</tr>
<tr>
<td>CH₃Cl</td>
<td>biomass burning</td>
<td>50</td>
<td>70</td>
<td>90</td>
</tr>
<tr>
<td>CH₃Br</td>
<td>biomass burning</td>
<td>50</td>
<td>75</td>
<td>90</td>
</tr>
<tr>
<td>TPM</td>
<td>savanna</td>
<td>50</td>
<td>85</td>
<td>93 - 178</td>
</tr>
<tr>
<td></td>
<td>forest/fuelwood</td>
<td>50</td>
<td>41</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>agricultural residues</td>
<td>50</td>
<td>85</td>
<td>93 - 178</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td>90</td>
</tr>
<tr>
<td>particles</td>
<td>savanna</td>
<td>50</td>
<td>53</td>
<td>73</td>
</tr>
<tr>
<td>&lt;2.5 μm</td>
<td>forest/fuelwood</td>
<td>50</td>
<td>33</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td>agricultural residues</td>
<td>50</td>
<td>53</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>carbon</td>
<td>savanna</td>
<td>50</td>
<td>78</td>
<td>89 - 167</td>
</tr>
<tr>
<td>particles</td>
<td>forest/fuelwood</td>
<td>50</td>
<td>43</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>agricultural residues</td>
<td>50</td>
<td>78</td>
<td>89 - 167</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td>80</td>
</tr>
<tr>
<td>SO₂</td>
<td>biomass burning</td>
<td>50</td>
<td>70</td>
<td>90</td>
</tr>
</tbody>
</table>

Total uncertainty if uncertainties for the individual fuels are mutually independent is given by:

\[ U_T = \pm \left[ \sum (f_i \sqrt{\sum (U_i)^2})^2 \right]^{1/2} \]
\( f_i \) is emissions from the \( i \)th fuel type divided by total emissions.

\[
( f_{\text{savanna}} = 0.64; f_{\text{forest}} = 0.28; f_{\text{fuelwood}} = 0.07; f_{\text{agricultural residues}} = 0.01 )
\]

It is valid to assume that individual fuels are mutually independent, because the emission factors and emission ratios are not related to the amount of biomass dry matter.

**Summary**

This study presents the first regional and national inventory of estimates of gaseous and particulate emissions from biomass burning in Africa. Trace gases estimated include, Carbon dioxide (CO\(_2\)), carbon monoxide (CO), methane (CH\(_4\)), methyl chloride (CH\(_3\)Cl), methyl bromide (CH\(_3\)Br), oxides of nitrogen (NO\(_x\)), non-methane hydrocarbons (NMHC'S), sulfur dioxide (SO\(_2\)), ammonia (NH\(_3\)), and aerosols include Total particulate matter (TPM), particles< 2.5 \(\mu\)m, and carbon particles. This inventory has a 1x1 degree latitude/longitude spatial resolution of biomass burning activity in Africa and provides estimates of emissions on a country-by-country basis. Emissions are calculated based on biomass burning data from Hao and Liu, 1994, DMSP fire distribution data for 1986-87, and emission factors based on a series of field campaigns and laboratory measurements. Africa’s contribution to global biomass burning emissions is included in the assessment. The results are compared with previous estimates for continental emissions.

A comprehensive national and regional database has been developed for the emissions of (gases) from biomass burning in Africa. The results show that Africa is the world’s single largest continental source of emissions due to biomass burning and that these emissions are likely to increase with time. Time increase is likely to result from the fact that demand for land use has increased substantially during the last decades the human population has grown 36% in Africa (FAO, 1991; US Bureau of
Savanna fires prevail in Africa. The peak of the burning occurs from March to June in the northern hemisphere and September to November in the southern hemisphere. The gross trace gas emissions from Africa are globally significant and dominate the greenhouse gas inventories of large but lightly industrialized countries such as Zaire, Angola, Tanzania and Zambia.

Biomass Burning in Africa is highly significant source of many trace gases and aerosol species. The regional and seasonal variation of emissions is mostly limited to the dry season and the occurrence of fires is mainly centered in the savanna and the tropical regions. Results show that Zaire, Sudan, Zambia and Tanzania dominate in emissions resulting from Biomass burning in Africa.

To accurately assess the impact of African Biomass burning on regional and global atmospheric chemistry, temporal and spatial estimates have to be made which can be used as inputs into regional and global chemistry and transport models. While reasonably accurate Emission factors and emission ratios have been determined for many important species and vegetation types, more field measurements are needed to obtain data characteristically representative of Northern and eastern Africa. Great uncertainty persists with regard to the amount of biomass burned for many regions.
Table 3.3: Estimated Biomass Burning Emissions of Trace Gases and Particulates from African Countries.

<table>
<thead>
<tr>
<th>Country</th>
<th>Species (Tg species yr$^{-1}$)</th>
<th>C</th>
<th>CO2</th>
<th>CO</th>
<th>CH4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zaire</td>
<td>150</td>
<td>502</td>
<td>38</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Tanzania, United Republic</td>
<td>57</td>
<td>193</td>
<td>16</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td>Zambia</td>
<td>66</td>
<td>224</td>
<td>16</td>
<td>0.62</td>
<td></td>
</tr>
<tr>
<td>Sudan</td>
<td>80</td>
<td>265</td>
<td>11</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>Mozambique</td>
<td>44</td>
<td>149</td>
<td>9</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td>Botswana</td>
<td>40</td>
<td>136</td>
<td>8</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td>Nigeria</td>
<td>59</td>
<td>196</td>
<td>8</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Ethiopia</td>
<td>47</td>
<td>158</td>
<td>6</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>Kenya</td>
<td>28</td>
<td>92</td>
<td>6</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>Ghana</td>
<td>45</td>
<td>150</td>
<td>6</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>Central African Republic</td>
<td>43</td>
<td>144</td>
<td>6</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>Namibia</td>
<td>38</td>
<td>131</td>
<td>6</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>Ivory Coast</td>
<td>42</td>
<td>141</td>
<td>6</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>Angola</td>
<td>29</td>
<td>100</td>
<td>4</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>Cameroon</td>
<td>33</td>
<td>110</td>
<td>4</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>Mali</td>
<td>23</td>
<td>79</td>
<td>4</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>Mauritania</td>
<td>19</td>
<td>67</td>
<td>4</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>Benin</td>
<td>29</td>
<td>97</td>
<td>4</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>Chad</td>
<td>24</td>
<td>82</td>
<td>4</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>Uganda</td>
<td>23</td>
<td>77</td>
<td>3</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>Niger</td>
<td>21</td>
<td>69</td>
<td>3</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>Burkina Faso</td>
<td>20</td>
<td>66</td>
<td>3</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>Congo</td>
<td>15</td>
<td>51</td>
<td>3</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>17</td>
<td>59</td>
<td>2</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>Madagascar</td>
<td>12</td>
<td>42</td>
<td>2</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>Senegal</td>
<td>14</td>
<td>46</td>
<td>2</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>Eritrea</td>
<td>6</td>
<td>21</td>
<td>0.8</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>Somalia</td>
<td>5</td>
<td>16</td>
<td>0.6</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Algeria</td>
<td>0.6</td>
<td>2</td>
<td>0.1</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>Egypt</td>
<td>0.01</td>
<td>0.03</td>
<td>0</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>Other Africa</td>
<td>90</td>
<td>302</td>
<td>20</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Total Africa</td>
<td>1120</td>
<td>3765</td>
<td>204</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

Uncertainty in: C = 50%; CO$_2$ = 40 - 50%; CO = 60%; CH$_4$ = 50%
<table>
<thead>
<tr>
<th>Country</th>
<th>CH$_3$Cl</th>
<th>CH$_3$Br</th>
<th>NMHC's</th>
<th>NH$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zaire</td>
<td>0.036</td>
<td>0.0007</td>
<td>1.03</td>
<td>0.33</td>
</tr>
<tr>
<td>Tanzania, United Republic</td>
<td>0.014</td>
<td>0.0003</td>
<td>0.39</td>
<td>0.13</td>
</tr>
<tr>
<td>Zambia</td>
<td>0.016</td>
<td>0.0003</td>
<td>0.45</td>
<td>0.15</td>
</tr>
<tr>
<td>Sudan</td>
<td>0.019</td>
<td>0.0003</td>
<td>0.55</td>
<td>0.16</td>
</tr>
<tr>
<td>Mozambique</td>
<td>0.010</td>
<td>0.0002</td>
<td>0.30</td>
<td>0.10</td>
</tr>
<tr>
<td>Botswana</td>
<td>0.010</td>
<td>0.0002</td>
<td>0.28</td>
<td>0.09</td>
</tr>
<tr>
<td>Nigeria</td>
<td>0.014</td>
<td>0.0002</td>
<td>0.40</td>
<td>0.13</td>
</tr>
<tr>
<td>Ethiopia</td>
<td>0.012</td>
<td>0.0002</td>
<td>0.33</td>
<td>0.11</td>
</tr>
<tr>
<td>Kenya</td>
<td>0.007</td>
<td>0.0001</td>
<td>0.20</td>
<td>0.06</td>
</tr>
<tr>
<td>Ghana</td>
<td>0.011</td>
<td>0.0002</td>
<td>0.31</td>
<td>0.10</td>
</tr>
<tr>
<td>Central African Republic</td>
<td>0.011</td>
<td>0.0002</td>
<td>0.30</td>
<td>0.10</td>
</tr>
<tr>
<td>Namibia</td>
<td>0.009</td>
<td>0.0002</td>
<td>0.26</td>
<td>0.08</td>
</tr>
<tr>
<td>Ivory Coast</td>
<td>0.010</td>
<td>0.0002</td>
<td>0.29</td>
<td>0.09</td>
</tr>
<tr>
<td>Angola</td>
<td>0.007</td>
<td>0.0001</td>
<td>0.20</td>
<td>0.07</td>
</tr>
<tr>
<td>Cameroon</td>
<td>0.008</td>
<td>0.0002</td>
<td>0.23</td>
<td>0.07</td>
</tr>
<tr>
<td>Mali</td>
<td>0.006</td>
<td>0.0001</td>
<td>0.16</td>
<td>0.05</td>
</tr>
<tr>
<td>Mauritania</td>
<td>0.005</td>
<td>0.0001</td>
<td>0.13</td>
<td>0.04</td>
</tr>
<tr>
<td>Benin</td>
<td>0.007</td>
<td>0.0001</td>
<td>0.20</td>
<td>0.07</td>
</tr>
<tr>
<td>Chad</td>
<td>0.006</td>
<td>0.0001</td>
<td>0.17</td>
<td>0.05</td>
</tr>
<tr>
<td>Uganda</td>
<td>0.006</td>
<td>0.0001</td>
<td>0.16</td>
<td>0.05</td>
</tr>
<tr>
<td>Niger</td>
<td>0.005</td>
<td>0.0001</td>
<td>0.14</td>
<td>0.05</td>
</tr>
<tr>
<td>Burkina Faso</td>
<td>0.0048</td>
<td>0.0001</td>
<td>0.14</td>
<td>0.04</td>
</tr>
<tr>
<td>Congo</td>
<td>0.004</td>
<td>0.0001</td>
<td>0.11</td>
<td>0.03</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>0.004</td>
<td>0.0001</td>
<td>0.12</td>
<td>0.04</td>
</tr>
<tr>
<td>Madagascar</td>
<td>0.003</td>
<td>0.0000</td>
<td>0.08</td>
<td>0.03</td>
</tr>
<tr>
<td>Senegal</td>
<td>0.003</td>
<td>0.0001</td>
<td>0.10</td>
<td>0.03</td>
</tr>
<tr>
<td>Eritrea</td>
<td>0.002</td>
<td>0.0000</td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td>Somalia</td>
<td>0.001</td>
<td>0.0000</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>Algeria</td>
<td>0.000</td>
<td>0.0000</td>
<td>0.004</td>
<td>0.001</td>
</tr>
<tr>
<td>Egypt</td>
<td>0.000</td>
<td>0.0000</td>
<td>0.0001</td>
<td>0.000</td>
</tr>
<tr>
<td>Other Africa</td>
<td>0.02</td>
<td>0.0004</td>
<td>0.61</td>
<td>0.20</td>
</tr>
<tr>
<td>Total Africa</td>
<td>0.27</td>
<td>0.005</td>
<td>7.70</td>
<td>2.49</td>
</tr>
</tbody>
</table>

Uncertainty in: CH$_3$Cl = 90%; CH$_3$Br = 90%; NMHC's = 80%; NH$_3$ = 80%.
Table 3.3 (continued)

<table>
<thead>
<tr>
<th>Country</th>
<th>NOx</th>
<th>SO2</th>
<th>TPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zaire</td>
<td>2.64</td>
<td>0.199</td>
<td>3.31</td>
</tr>
<tr>
<td>Tanzania, United Republic</td>
<td>1.14</td>
<td>0.076</td>
<td>1.27</td>
</tr>
<tr>
<td>Zambia</td>
<td>1.06</td>
<td>0.088</td>
<td>1.46</td>
</tr>
<tr>
<td>Sudan</td>
<td>0.68</td>
<td>0.106</td>
<td>1.77</td>
</tr>
<tr>
<td>Mozambique</td>
<td>0.59</td>
<td>0.059</td>
<td>0.97</td>
</tr>
<tr>
<td>Botswana</td>
<td>0.54</td>
<td>0.054</td>
<td>0.89</td>
</tr>
<tr>
<td>Nigeria</td>
<td>0.52</td>
<td>0.078</td>
<td>1.30</td>
</tr>
<tr>
<td>Ethiopia</td>
<td>0.43</td>
<td>0.063</td>
<td>1.05</td>
</tr>
<tr>
<td>Kenya</td>
<td>0.42</td>
<td>0.037</td>
<td>0.61</td>
</tr>
<tr>
<td>Ghana</td>
<td>0.40</td>
<td>0.060</td>
<td>1.00</td>
</tr>
<tr>
<td>Central African Republic</td>
<td>0.38</td>
<td>0.058</td>
<td>0.95</td>
</tr>
<tr>
<td>Namibia</td>
<td>0.26</td>
<td>0.051</td>
<td>0.85</td>
</tr>
<tr>
<td>Ivory Coast</td>
<td>0.38</td>
<td>0.057</td>
<td>0.94</td>
</tr>
<tr>
<td>Angola</td>
<td>0.24</td>
<td>0.039</td>
<td>0.64</td>
</tr>
<tr>
<td>Cameroon</td>
<td>0.29</td>
<td>0.044</td>
<td>0.74</td>
</tr>
<tr>
<td>Mali</td>
<td>0.15</td>
<td>0.031</td>
<td>0.52</td>
</tr>
<tr>
<td>Mauritania</td>
<td>0.08</td>
<td>0.026</td>
<td>0.43</td>
</tr>
<tr>
<td>Benin</td>
<td>0.26</td>
<td>0.039</td>
<td>0.65</td>
</tr>
<tr>
<td>Chad</td>
<td>0.20</td>
<td>0.033</td>
<td>0.54</td>
</tr>
<tr>
<td>Uganda</td>
<td>0.21</td>
<td>0.031</td>
<td>0.52</td>
</tr>
<tr>
<td>Niger</td>
<td>0.16</td>
<td>0.027</td>
<td>0.45</td>
</tr>
<tr>
<td>Burkina Faso</td>
<td>0.18</td>
<td>0.026</td>
<td>0.44</td>
</tr>
<tr>
<td>Congo</td>
<td>0.17</td>
<td>0.020</td>
<td>0.34</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>0.08</td>
<td>0.023</td>
<td>0.38</td>
</tr>
<tr>
<td>Madagascar</td>
<td>0.09</td>
<td>0.016</td>
<td>0.27</td>
</tr>
<tr>
<td>Senegal</td>
<td>0.12</td>
<td>0.019</td>
<td>0.31</td>
</tr>
<tr>
<td>Eritrea</td>
<td>0.06</td>
<td>0.008</td>
<td>0.14</td>
</tr>
<tr>
<td>Somalia</td>
<td>0.04</td>
<td>0.006</td>
<td>0.10</td>
</tr>
<tr>
<td>Algeria</td>
<td>0.01</td>
<td>0.0008</td>
<td>0.01</td>
</tr>
<tr>
<td>Egypt</td>
<td>0.00</td>
<td>0.0000</td>
<td>0.00</td>
</tr>
<tr>
<td>Other Africa</td>
<td>1.42</td>
<td>0.12</td>
<td>1.99</td>
</tr>
<tr>
<td>Total Africa</td>
<td>13.20</td>
<td>1.40</td>
<td>24.80</td>
</tr>
</tbody>
</table>

Uncertainty in: NOx = 40%; SO2 = 90; TPM = 90
Table 3.3 (continued)

<table>
<thead>
<tr>
<th>Country</th>
<th>Species (Tg species yr⁻¹)</th>
<th>Carbon particles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>particles &lt;2.5 μm</td>
<td></td>
</tr>
<tr>
<td>Zaire</td>
<td>2.46</td>
<td>2.32</td>
</tr>
<tr>
<td>Tanzania, United Republic</td>
<td>1.02</td>
<td>0.89</td>
</tr>
<tr>
<td>Zambia</td>
<td>1.06</td>
<td>1.02</td>
</tr>
<tr>
<td>Sudan</td>
<td>0.87</td>
<td>1.24</td>
</tr>
<tr>
<td>Mozambique</td>
<td>0.61</td>
<td>0.68</td>
</tr>
<tr>
<td>Botswana</td>
<td>0.54</td>
<td>0.62</td>
</tr>
<tr>
<td>Nigeria</td>
<td>0.65</td>
<td>0.91</td>
</tr>
<tr>
<td>Ethiopia</td>
<td>0.53</td>
<td>0.74</td>
</tr>
<tr>
<td>Kenya</td>
<td>0.41</td>
<td>0.43</td>
</tr>
<tr>
<td>Ghana</td>
<td>0.50</td>
<td>0.70</td>
</tr>
<tr>
<td>Central African Republic</td>
<td>0.48</td>
<td>0.67</td>
</tr>
<tr>
<td>Namibia</td>
<td>0.44</td>
<td>0.59</td>
</tr>
<tr>
<td>Ivory Coast</td>
<td>0.47</td>
<td>0.66</td>
</tr>
<tr>
<td>Angola</td>
<td>0.38</td>
<td>0.45</td>
</tr>
<tr>
<td>Cameroon</td>
<td>0.37</td>
<td>0.52</td>
</tr>
<tr>
<td>Mali</td>
<td>0.26</td>
<td>0.36</td>
</tr>
<tr>
<td>Mauritania</td>
<td>0.22</td>
<td>0.30</td>
</tr>
<tr>
<td>Benin</td>
<td>0.32</td>
<td>0.45</td>
</tr>
<tr>
<td>Chad</td>
<td>0.28</td>
<td>0.38</td>
</tr>
<tr>
<td>Uganda</td>
<td>0.26</td>
<td>0.36</td>
</tr>
<tr>
<td>Niger</td>
<td>0.23</td>
<td>0.32</td>
</tr>
<tr>
<td>Burkina Faso</td>
<td>0.22</td>
<td>0.31</td>
</tr>
<tr>
<td>Congo</td>
<td>0.20</td>
<td>0.24</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>0.19</td>
<td>0.27</td>
</tr>
<tr>
<td>Madagascar</td>
<td>0.14</td>
<td>0.20</td>
</tr>
<tr>
<td>Senegal</td>
<td>0.15</td>
<td>0.21</td>
</tr>
<tr>
<td>Eritrea</td>
<td>0.07</td>
<td>0.098</td>
</tr>
<tr>
<td>Somalia</td>
<td>0.05</td>
<td>0.072</td>
</tr>
<tr>
<td>Algeria</td>
<td>0.01</td>
<td>0.009</td>
</tr>
<tr>
<td>Egypt</td>
<td>0.00</td>
<td>0.0002</td>
</tr>
<tr>
<td>Other Africa</td>
<td>1.35</td>
<td>1.40</td>
</tr>
<tr>
<td>Total Africa</td>
<td>14.70</td>
<td>17.42</td>
</tr>
</tbody>
</table>

Uncertainty in: particles <2.5 μm = ±50%; Carbon particles = ±80%
Table 3.4: Estimates for Total Regional (Africa) Biomass Burning Emissions, Savanna Africa, All Biomass Burning (Global), and Percentage Contribution by Africa to the Global Budget of Biomass Burning Emissions.

<table>
<thead>
<tr>
<th>Species</th>
<th>Total Africa (current results)</th>
<th>Range</th>
<th>Global biomass burning (Literature)</th>
<th>Africa’s % contribution to global budget (Current)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon</td>
<td>1120</td>
<td>560 - 1679</td>
<td>4100</td>
<td>27</td>
<td>14 - 41</td>
</tr>
<tr>
<td>CO2</td>
<td>3765</td>
<td>2259 - 5271</td>
<td>13500</td>
<td>28</td>
<td>17 - 39</td>
</tr>
<tr>
<td>CO</td>
<td>204</td>
<td>82 - 327</td>
<td>680</td>
<td>30</td>
<td>12 - 48</td>
</tr>
<tr>
<td>CH4</td>
<td>7.2</td>
<td>4 - 11</td>
<td>43</td>
<td>17</td>
<td>8 - 25</td>
</tr>
<tr>
<td>NMHC's</td>
<td>7.7</td>
<td>2 - 14</td>
<td>42</td>
<td>18</td>
<td>4 - 33</td>
</tr>
<tr>
<td>NOx</td>
<td>13.2</td>
<td>8 - 18</td>
<td>21</td>
<td>63</td>
<td>38 - 88</td>
</tr>
<tr>
<td>CH3Cl</td>
<td>0.27</td>
<td>0.03 - 0.5</td>
<td>1.1</td>
<td>25</td>
<td>3 - 49</td>
</tr>
<tr>
<td>CH3Br</td>
<td>0.005</td>
<td>0.0005-0.01</td>
<td>0.02</td>
<td>26</td>
<td>3 - 50</td>
</tr>
<tr>
<td>SO2</td>
<td>1.5</td>
<td>0.1 - 3</td>
<td>4.8</td>
<td>31</td>
<td>3 - 59</td>
</tr>
<tr>
<td>NH3</td>
<td>2.5</td>
<td>0.5 - 4</td>
<td>6.7</td>
<td>37</td>
<td>7 - 67</td>
</tr>
<tr>
<td>Aerosols</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TPM</td>
<td>25</td>
<td>2 - 47</td>
<td>90</td>
<td>28</td>
<td>3 - 52</td>
</tr>
<tr>
<td>Particles</td>
<td>15</td>
<td>7 - 22</td>
<td>no data</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>&lt;2.5 μm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon</td>
<td>17</td>
<td>3 - 31</td>
<td>60</td>
<td>29</td>
<td>6 - 52</td>
</tr>
</tbody>
</table>

a. From Andreae et al., 1996.

NA- not applicable

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
DMSP Fire satellite Imagery annual composite

convert image to grid

1x1 degree grid fire pixel counts

Hao's dataset Total biomass burned, 5x5 degree grid (monthly/annual)

resample 5x5 grid to 1x1 grid

1x1 degree grid fire pixel counts

Total biomass burned (monthly/annual) redistributed and resampled to a 1x1 degree grid using DMSP 1x1 degree pixel counts.

Matthews 1x1 degree Global distribution of vegetation-(32 type)

32 type to 11 type

Matthews 1x1 degree Global distribution of vegetation-reclassified into 11 broad types

1x1 degree grid of EF/ER

Emission Factors and Emission Ratios (from literature)

1x1 degree grid of amount species emitted based on biomass burned and EF/ER

summarized by country

= Ei x M

emissions by country

Ei = M(carbon released) x ER

Figure 3.1: Biomass Burning Emissions Estimation Scheme
Figure 3.2: Nighttime Low-Light DMSP Imagery Annual Composite of Fires in Africa (1986-1987)
Figure 3.3: DMSP Annual Composite of Fire Distribution (1986-1987)
1 Degree by 1 Degree Grid
Figure 3.4: GISS Matthews Global Vegetation Index - 32 Type
<table>
<thead>
<tr>
<th>Key</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  tropical evergreen rainforest</td>
</tr>
<tr>
<td>2  trop/subtropical evergreen seasonal broad-leaved forest</td>
</tr>
<tr>
<td>3  subtropical evergreen rainforest</td>
</tr>
<tr>
<td>4  temperate/subpolar evergreen rainforest</td>
</tr>
<tr>
<td>5  temperate evergreen seasonal broadleaved forest, summer rain</td>
</tr>
<tr>
<td>6  evergreen broadleaved sclerophyllous forest, winter rain</td>
</tr>
<tr>
<td>7  tropical/subtropical evergreen needle-leaved forest</td>
</tr>
<tr>
<td>8  temperate/subpolar evergreen needle-leaved forest</td>
</tr>
<tr>
<td>9  tropical/subtropical drought-deciduous forest</td>
</tr>
<tr>
<td>10 cold-deciduous forest, with evergreens</td>
</tr>
<tr>
<td>11 cold-deciduous forest, without evergreens</td>
</tr>
<tr>
<td>12 xeromorphic forest/woodland</td>
</tr>
<tr>
<td>13 evergreen broadleaved sclerophyllous woodland</td>
</tr>
<tr>
<td>14 evergreen needleleaved woodland</td>
</tr>
<tr>
<td>15 tropical/subtropical drought-deciduous woodland</td>
</tr>
<tr>
<td>16 cold-deciduous woodland</td>
</tr>
<tr>
<td>17 evergreen broadleaved shrubland/thick, evergreen dwarf-shrubland</td>
</tr>
<tr>
<td>18 evergreen needleleaved or microphyllous shrubland/thicket</td>
</tr>
<tr>
<td>19 drought-deciduous shrubland/thicket</td>
</tr>
<tr>
<td>20 cold-deciduous subalpine/subpolar shrubland/dwarf shrub</td>
</tr>
<tr>
<td>21 xeromorphic shrubland/dwarf shrub</td>
</tr>
<tr>
<td>22 arctic/alpine tundra, mossy bog</td>
</tr>
<tr>
<td>23 tall/medium/short grassland. 10-40% woody cover</td>
</tr>
<tr>
<td>24 tall/medium/short grassland. &lt; 10% woody cover</td>
</tr>
<tr>
<td>25 tall/medium/short grassland. shrub cover</td>
</tr>
<tr>
<td>26 tall grassland. no woody cover</td>
</tr>
<tr>
<td>27 medium grassland. no woody cover</td>
</tr>
<tr>
<td>28 meadow, short grassland. no woody cover</td>
</tr>
<tr>
<td>29 forb formations</td>
</tr>
<tr>
<td>30 desert</td>
</tr>
<tr>
<td>31 ice</td>
</tr>
<tr>
<td>32 cultivation</td>
</tr>
</tbody>
</table>
Vegetation type
- Tropical - evergreen broad-leaved forest
- Tropical drought deciduous
- Xeromorphic woodland
- Evergreen woodland
- Broad-leaved shrubland
- Drought deciduous shrubland
- Xeromorphic shrubland
- Tall/medium/short grassland, 10-40% woody cover
- Tall/medium grassland no woody cover
- Meadow/short grassland, no woody cover
- Desert

Figure 3.5: Reclassified 1x1 degree grid; 11 broad vegetation types (based on distinct fuel type, fuel production, and climate).
Figure 3.6: 1x1 Degree Grid Showing Distribution of Total Monthly Biomass Burning in Africa

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 3.7: 1x1 Degree Grid Showing Distribution of Total Monthly Biomass Burning in Africa

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
March

Figure 3.8: 1x1 Degree Grid Showing Distribution of Total Monthly Biomass Burning in Africa

x 1000 tons dm/month
0 - 120
120 - 240
240 - 360
360 - 480
480 - 600
600 - 720
720 - 840
840 - 960
960 - 1120

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 3.9: 1x1 Degree Grid Showing Distribution of Total Monthly Biomass Burning in Africa
May

Figure 3.10: 1x1 Degree Grid Showing Distribution of Total Monthly Biomass Burning in Africa

x 1000 tons dm/ month

0 - 60
60 - 120
120 - 180
180 - 240
240 - 300
300 - 360

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 3.11: 1x1 Degree Grid Showing Distribution of Total Monthly Biomass Burning in Africa
July

Figure 3.12: 1x1 Degree Grid Showing Distribution of Total Monthly Biomass Burning in Africa

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 3.13: 1x1 Degree Grid Showing Distribution of Total Monthly Biomass Burning in Africa
September

Figure 3.14: 1x1 Degree Grid Showing Distribution of Total Monthly Biomass Burning in Africa

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 3.15: 1x1 Degree Grid Showing Distribution of Total Monthly Biomass Burning in Africa

October

x 1000 tons dm/ month

0 - 80
80 - 180
180 - 260
260 - 360
360 - 440
440 - 520
520 - 600
600 - 700
700 - 800

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 3.16: 1x1 Degree Grid Showing Distribution of Total Monthly Biomass Burning in Africa

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 3.17: 1x1 Degree Grid Showing Distribution of Total Monthly Biomass Burning in Africa

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 3.18: Annual Estimated Carbon Dioxide Emissions from Total Biomass Burning in Africa

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 3.19: Biomass Burning Activities in Africa

Biomass burning activity

<table>
<thead>
<tr>
<th>Activity</th>
<th>% Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td></td>
</tr>
<tr>
<td>Savanna</td>
<td></td>
</tr>
<tr>
<td>Fuelwood</td>
<td></td>
</tr>
<tr>
<td>Agriculture</td>
<td></td>
</tr>
</tbody>
</table>

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Africa is characterized by vast savanna biomes and distinct wet and dry seasons leading to widespread burning. These characteristics have been established to stimulate the production of soil biogenic NO$_x$ emissions. Additionally, Africa's population growth is expected to result in increased and improved agricultural infrastructure that will rely heavily on fertilizer usage for crop production. Biogenic soil-NO$_x$ emissions depend on a number of parameters, including soil temperature, soil moisture, soil nutrients, vegetation cover, N mineralization rates, and nitrification/denitrification and burning (Yienger and Levy, 1995). Most of these parameters are at a level conducive to enhanced emissions in Africa. Africa's climatology, and ecosystems will result in high soil biogenic NO$_x$ emissions leading to high ambient concentrations of NO$_x$, acid deposition and tropospheric ozone. Increasing levels of ozone can impact human health, and damage crops (Levine et al 1995).

This study estimates regional, global and ecosystem soil biogenic NO$_x$ emissions using a global-scale empirical model of soil biogenic NO$_x$ emissions that is temperature and precipitation dependent and uses a 6-hour averaged GCM output for meteorological forcing. The focus is on Africa's contribution in order to better understand its biogenic emissions. New features we incorporated into the model since Yienger and Levy (1995) include source inputs of mean NO$_x$ flux from recent field experiments in Africa to estimate emissions of NO$_x$ following burning (biomass burning stimulation). The model was designed and constructed by Jim Yienger and...
Hiram Levy, of the NOAA Geophysical Fluid Dynamics laboratory at Princeton University, Princeton, New Jersey. Estimates are presented for three case studies, (1) Past case-Pre industrial, (2) Present case, and (3) Future case of Soil -NOX emissions. The results will be categorized for each case by biome and region and include discussion of the importance of fertilizer use, fertilizer induced emissions, and total emissions.

The results are estimated using an empirical model of soil biogenic NOX emissions by relating emission to biome, soil temperatures, precipitation and fertilizer application. This model has been designed to be used with global datasets to provide reasonable emissions estimates by using data from field experiments and extrapolation provides reasonable estimates in regions with little or no data.

4.2 BACKGROUND

Recent research has established that oxides of nitrogen play an important role in regulating the chemistry of the troposphere. Generally, the oxides of nitrogen are expressed as NOX (NOX = [NO + NO2]) which has been directly linked to the oxidizing efficiency of the troposphere due to its ability to regulate the concentration of ozone (O3) and also that of the hydroxyl radical (OH) (Yinger and Levy, 1995). Nitric oxide (NO) is an important species in the photochemical production of ozone (O3) in the troposphere, the chemical production of nitric acid (HNO3) (a component of acid rain) and in the chemistry of the hydroxyl radical (OH), the major chemical scavenger in the troposphere (Levine et.al., 1995).

It has been established that fossil fuel NOX source is both strong and localized and dominates in industrialized areas (Logan, 1983) while the soil biogenic emission source dominates in less industrialized nations and may dominate in remote
tropical and agricultural areas (Yienger and Levy, 1995). There is a growing awareness of soil biogenic NOx, and papers have been published on emissions from grasslands, woodlands, savannas and forests. (Levine et al., 1995; Yienger and Levy, 1995)

In the last few decades, a number of studies provided estimates of factors regulating African biogenic NOx emissions. Results indicate that biogenic NOx emissions established that biogenic emissions are regulated by both soil moisture and soil nitrogen content, parameters that operate on different temporal and spatial scales (Parsons, 1996; Scholes, et al., 1996). In African savannas, soil moisture is largely determined by season, while nitrogen content is determined by both soil type and fire regime (Parsons, 1996; Fire in Southern African Savannas, 1997). A study of Biogenic NO emissions from savanna soils as a function of fire regime, soil type, soil nitrogen, and water status in Southern Africa was also conducted and many factors affecting emissions were established (Levine et al., 1996; Parsons et al., 1996).

Field measurements performed in southern African savannas showed that NO emissions were significantly enhanced by wetting and burning (Levine et al., 1996). The measurements showed that mean background NO emissions from dry sites ranged from 0.4 to 6.2 ng N m\(^{-2}\) s\(^{-1}\) and from the wetted sites ranged from 4.7-34 ng N m\(^{-2}\) s\(^{-1}\). After burning, the mean NO emissions from the dry sites increased and ranged from 13.3 to 15.2 ng N m\(^{-2}\) s\(^{-1}\) and from wetted sites increased, exceeding 60 ng N m\(^{-2}\) s\(^{-1}\). In most field measurements, emissions of NO\(_2\) were found to be below detectable limits (Levine et al., 1996).

Airborne observations from the Namibian savanna showed strong biogenic NO\(_X\) emissions following sporadic rainfall events, during and at the end of the dry season. These measurements show that wetting is as important a source as savanna
burning and may have important consequences for regional scale ozone formation. (Harris et al., 1996).

Major uncertainties underlie many aspects of our understanding of regional and global anthropogenic and natural contributions of soil biogenic NO\textsubscript{x} emissions. A number of studies have been carried out to estimate global NO\textsubscript{x} emissions (Yienger and Levy, 1995). But most of these studies have not incorporated all parameters suspected of regulating emissions. This study presents estimates of soil NO\textsubscript{x} emissions for Africa based on calculations using all known factors, and compares Africa's contribution with that of other continents. Africa's contributions to the global budget are discussed.

4.3 Major Parameters Affecting Biogenic Soil NO\textsubscript{x} Emissions

The Yienger and Levy model described below includes four key parameters: "Pulsing", nitrogen fertilizer stimulation, biomass burning stimulation and canopy reduction (Yienger and Levy, 1995). Each parameter is discussed briefly below.

1. Pulsing

If a very dry soil is wetted, a large burst or "pulse" in NO\textsubscript{x} emissions occurs and then decays rapidly over a time period following the wetting event. This pulse is thought to be caused by a release of built up inorganic nitrogen trapped on the dry soil and a concurrent reactivation of water stressed bacteria which then metabolize the excess nitrogen (Davidson et. al., 1992). The strongest impact is in the tropics where there are extended dry seasons followed by wet seasons. The first large scale observations of dry to wet season pulsing were made in Africa, with very strong emissions (20-40 ng N m\textsuperscript{-2} s\textsuperscript{-1}) from a 100 km\textsuperscript{2} area of savannas at the beginning of the wet season (Harris et al., 1993).
2. Nitrogen Fertilizer Stimulation

It is well established that adding N fertilizer to soils increases biogenic NOx emissions (Yienger and Levy, 1995). Biological nitrification and denitrification has been established to depend on the form of fertilizer used, either ammonium or nitrate (Yienger and Levy, 1995). Mixed forms, such as NH4NO3, generate the strongest emissions (Yienger and Levy, 1995). Response to fertilization has been shown to vary dramatically: some fields have prolonged periods of emission and others show initial sharp increases that decay over time. However, there is a general linear correlation between fertilizer use and emission. Soil emissions (NOx) are at a maximum during the summer in regions of intensive agriculture (Yienger and Levy, 1995).

3. Biomass Burning Stimulation

There is a general consensus that biomass burning may enhance soil emissions by a factor of 5-10 for several weeks following the burn. (Johnson et al., 1988, Anderson et al., 1988; Levine et al., 1990. Burning has been found to raise ammonium levels in soil nutrients (Levine et al., 1990), and this has been particularly pronounced in tropical savannas because a majority of annual burning occurs there (Menaut et al., 1991). There is also reason to believe that burning may possibly enhance pulsing. (Yienger and Levy, 1995), while measurements in Africa showed that dry savannas which were burned and then wetted had higher emissions than those which were just burned or wetted (Levine et al., 1996).
4. Canopy Reduction

Before escaping the plant canopy, some of the NO\(_x\) is lost by a process called "Canopy Reduction (CR)" (Yienger and Levy, 1995). CR is a combination of losses resulting from diffusion of NO\(_2\) through plant stomata and direct deposition of NO\(_2\) onto and through the cuticle (Yienger and Levy, 1995). During daytime, loss through the plant stomata dominates, while at night, loss by direct deposition dominates, because NO\(_2\) is more abundant at night. A detailed description of this parameter is given by Yienger and Levy, 1995.

4.4 Description of Yienger and Levy Model

General Circulation Model

The biogenic soil NO\(_x\) model utilized in this study is run using winds generated from the GFDL GCM (Manabe et al., 1974; Manabe and Holloway, 1975). The GCM computes wind fields, precipitation fields vertical and horizontal wind speed, and temperature every six hours. In the vertical, there are 11 pressure levels, and in the horizontal, each grid is approximately 1x1 degree. Of the 11 vertical levels (pressure levels, only the surface level, 990 mb is used in the biogenic source model. The GCM products are stored and then used by the biogenic source model each time it is run. A full year of meteorology from the GCM was saved in the form of 6-hour averaged wind fields and surface pressure.

The model stimulation starts by identifying global biomes that either are expansive or have enough supporting emission data to warrant separate classification. These include water, ice, desert, tundra, grassland, scrub land, woodland, deciduous forests, coniferous forests, drought- deciduous forests, rain forests, and agricultural
lands. Of these, water, ice, desert, and scrubland are assumed to have no NO\textsubscript{X} emission. The remaining biomes are mapped out on a 1x1 degree grid using a simplified version of the 36-type NASA/Goddard Institute for Space Studies (GISS) Global Vegetation Index [Matthews, 1983; Matthews, 1985]. Table 2 identifies which NASA/GISS classifications are grouped under each biome. World agriculture was presented as an overlaying grid with cultivation percentages defined for each grid box. These parameters are scaled so that the agricultural area in each country reflects statistics from the Food and Agricultural Organization of the United Nations (FAO). This reduces the NASA/GISS global agricultural area from $1.75 \times 10^{13}$ to $1.41 \times 10^{13}$ m\textsuperscript{2}.

The empirical relationships used to compute the emission are of the form

$$F = f_{w/d} \times P \times CR$$

(4-1)

where:

- $F$ = flux
- $f_{w/d}$ (soil temperature, $A_{w/d}(\text{Biome})$) = some function either constant, linear, or exponential
- $A_{w/d}(\text{Biome})$ = coefficient which distinguishes between biomes.
- $w/d$ = soil moisture state:
  - $w$ = wet
  - $d$ = dry
- $P$ (precipitation) = a scalar factor used to adjust the flux in the event of a pulse
- $CR$ (LAI, SAI) = a scalar reduction factor that accounts for uptake of NO\textsubscript{x} by the plant canopy.
The model calculates emissions every 6 hours for one year, using temperature and precipitation fields from a parent general circulation model (GCM). GCM data is required because synoptic scale observed temperature and precipitation data are not readily available and this time resolution is used to drive the pulsing scheme, estimate soil moistures, and reduce the systematic underestimation caused by applying long term averaged data to a non-linear temperature/NOx flux relationship. The GCM can generate synoptic scale features of the Earth's climate such as transient mid-latitude cyclones, and is also reliable for simulating the migration of the intertropical convergence zone (ITCZ), an important feature associated with wetting and drying in the tropics and is the major source of pulsing emissions. However, the GCM does not have diurnal isolation and can not realistically simulate atmospheric fluctuations with time scales less than 6 hours or spatial scales less than 300 km.

The emission model requires soil temperatures not readily obtainable from the GCM. The surface temperatures carried in the GCM do not include biome parameterization and therefore, cannot account for the large effect vegetation has on soil temperature. Instead, the lowest model level air temperatures are converted to soil temperatures as follows. In wet soils, the empirical relationships was used and in dry soils 5°C are added to the model temperature, based on field observations. Dry soils regardless of temperature, are relatively insignificant in the global budget. Below, the derivation of each component in the equation above is presented.

### 4.4.1 Pulsing

After every 6 hours, a grid box is defined as either wet or dry to determine whether or not to allow pulsing at the next step. A soil is considered dry in the sense that it will pulse when wetted, if it receives less than 1 cm of precipitation in the
previous 2 weeks. In the model, a soil will pulse if it receives sufficient rainfall. Below is the general pulsing scheme used in the model. In the model, a pulse will occur if a dry grid box receives sufficient rainfall. To parameterize the required rainfall, as well as the pulse's magnitude and duration, the model relies on qualitative fitting to experimentally documented pulses. Below is the general pulsing scheme used in the model.
Table 4.1 Four Step Pulse Scheme.

<table>
<thead>
<tr>
<th>Rain Rate, cm/day</th>
<th>Pulse Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.1</td>
<td>no pulse (assume evaporation)</td>
</tr>
<tr>
<td>0.1 &lt; rain &lt; 0.5</td>
<td>&quot;sprinkle,&quot; a 3-day pulse starting x 5 with exponential decay</td>
</tr>
<tr>
<td>0.5 &lt; rain &lt; 1.5</td>
<td>&quot;shower,&quot; 1-week pulse starting at x 10 with exponential decay</td>
</tr>
<tr>
<td>1.5 &lt; rain</td>
<td>&quot;heavy rain,&quot; 2-week pulse starting at x 15 with exponential decay</td>
</tr>
</tbody>
</table>

The model utilizes exponential decay because pulsing is correlated with soil drying and under ideal situations (i.e. constant sun, temperature, and relative humidity), soil moisture would decrease exponentially. Fitting exponential curves to these parameters, gives precipitation (P) values as:

No pulse

\[ P \text{ (precipitation)} = 1.0 \] \hspace{1cm} (4-2)

"Sprinkle"

\[ P \text{ (precipitation)} = 11.19 \times e^{-0.805[\text{day}^{-1}] \times t} \text{ (1< t< 3)} \] \hspace{1cm} (4-3)

"Shower"

\[ P \text{ (precipitation)} = 14.68 \times e^{-0.384[\text{day}^{-1}] \times t} \text{ (1< t< 7)} \] \hspace{1cm} (4-4)

"Heavy rain"

\[ P \text{ (precipitation)} = 18.46 \times e^{-0.208[\text{day}^{-1}] \times t} \text{ (1< t< 14)} \] \hspace{1cm} (4-5)
where \( t \) is days, with the pulse beginning at \( t = 1 \) and counting up through its duration. These functions provide scalar factors (between 1 and 15) which are applied directly in (4-1). There can be no pulse initiation in a "wet" soil but if the pulse-causing rain is substantial enough to change the moisture state from dry to wet, or if the moisture state changes amidst a pulse, then the pulse will still occur (or continue) and decay uninterrupted as described by (4-3), (4-4), or (4-5).

### 4.4.2 Temperature Dependencies, \( f_{w/d} \) (Soil Temperature, \( A_{w/d} \) (Biome)

The soil temperature/flux dependence diminishes from exponential to linear with decreasing soil moisture. It is not possible to explicitly include soil moisture in a soil temperature/flux relationship; however, one can fit a separate exponential for "wet" soils and linear form for "dry" soils. The "wet" category includes inundated soils and that neglect the possibility that saturation decreases emissions (except for a simple implicit treatment in tropical rain forests and rice fields to be described later) because this state is presently too difficult to resolve on a global scale. This omission may cause a slight overestimate of emission, but the error should be minimal because high evaporation rates in non-rain forest tropical biomes (i.e., most error would be during the tropical savanna wet season) routinely drop soil moistures to as low as 2%, even during the wet season.
(a) Wet Soils:

\[ f_w (\text{soil temperature}, \ A_w (\text{biome})) \text{ for three soil temperature intervals, cold-linear (0-10 °C), and optimal (>30 °C), are defined as:} \]

\[ 0.28 \times A_w (\text{biome}) \times T \]  

\[ f_w (T, A_w (\text{biome})) \text{ } [\text{ng N/m}^2 \text{s}] = A_w (\text{biome}) \times e^{(0.103 \pm 0.04) \times T} \]

\[ 21.97 \times A_w (\text{biome}) \]

where: \( A_w (\text{biome}) \) = "wet" biome coefficient analogous to the \( A \) in (1)

\[ T = \text{soil temperature in degrees Celsius.} \]

Assume emissions from wet soils between 10 ° and 30 °C are characterized by (1) and that \( k \) is a global constant. The weighted average \( k (0.103 \pm 0.04 \text{ one sigma}) \) of the data shows all reported exponential temperature dependencies, yields a general dependence. The range of 10 ° to 30 °C corresponds to the range at which all dependencies were consistent. For temperatures between 0 ° and 10 °C, a simple "cold-linear" relationship between the flux computed by the exponential at 10 °C and zero flux at 0 °C was derived. For temperatures above 30 °C, a temperature independent "optimal" flux as the flux computed by the exponential at 30 °C in (4-8) was defined, where 21.97 is merely the exponential term with 30 °C substituted in for temperature. Below 0 °C (it is assumed emissions are zero because they are insignificant for the purposes of this global source).
A_w (biome) coefficients were calculated for each biome (except for rain forests and agricultural soils) by applying available mean soil temperature and NO_x flux data to (4-6 to 4-8) and taking the mean of the subsequent set of ln (A_w (biome)) values.

For agricultural soils, A_w (agricultural) was made linearly depended on N fertilizer rate and constrain it to force a 2.5% loss of applied N fertilizer annually per grid box:

\[
A_w (\text{agriculture}) \ [\text{ng N / m}^2 \text{s}] = A_w (\text{grassland}) \ [\text{ng N / m}^2 \text{s}] + S \times \text{Fertrate} \ [\text{ng N / m}^2 \text{s}] \tag{4-9}
\]

where the "intercept" is A_w (grassland) and the slope S (ng N / m^2 s / Kg N / ha / month) is calculated for each grid box to force a 2.5% loss of fertilizer, because available estimates cluster around this percentage. The monthly fertilizer rates were derived by using FAO statistics of each country annual fertilizer use, and assuming that all fertilizer is broadcast uniformly during the growing season (defined as May-August for the northern temperate zone (above 30°N), November-February for the southern temperate zone (below 30°S), and year-round for the tropics (30°N-30°S). It was assumed that fertilization elevates soil nitrogen to constant levels during the growing season, and that during the off-season, no residual fertilizer remains, so that soils emit as grassland. While not physically true, this assumption is reasonable because off-season croplands have been shown to emit on the same order of magnitude as grassland. All crop types were treated the same with the exception of rice, which emits much less NO_x than other crops because of soil inundation. Based on research the model reduced the fertilizer loss rate and the background emission rate for rice by a factor of 30 and defined agriculture in the region 0°-35° N and 80°-
140°E to be all rice, and in the region 0°-35°N and 60°-80°E to be one-half rice. The former box covers the main rice-producing areas of southeast Asia and Japan, and the latter box covers the mixed growing region of central and eastern India.

(b) Dry Soils:

In dry soils the soil temperature/NOx flux correlation is weak to non existent. Therefore only two temperature regimes were defined for $f_d(T, A_d(biome))$: cold-linear (0-30°C) and optimal (>30°C):

$$f_d(T, A_d(biome)[\text{ng N/m}^2\text{s}] = A_d(biome) \times T / 30 \quad (4-11\text{a})$$

or

$$= A_d(biome) \quad (4-11\text{b})$$

where: $A_d(biome)$ = the "optional" flux, or the average of all fluxes recorded over 30°C, and T is soil temperature in degrees Celsius.

The "cold-linear" formulation is analogous to wet soils, except that the upper limit extends to the optimal temperature, thus cutting out the exponential dependence.

Computation of the $A_d(biome)$ is difficult because there are only scattered NOx measurements from dry grasslands (and one from a drought-deciduous forest). For natural biomes without dry data, the wet emission data were divided by three, assuming a moisture dependence consistent with that observed in grasslands. For dry agriculture, we use (4-6 to 4-8) because emission response to fertilizer in dry soils has not yet been examined and it is very possible that the grassland moisture dependence is not valid in this complex system. If agriculture follows the pattern observed in grassland and has lower "dry" emissions, the parameterization might be considered
high during dry periods. However, since annual emissions were set as a percentage of
the yearly applied fertilizer, this will act only to smooth out emissions over the year
and not actually cause an overall increase. Furthermore, it is probable that much of
the fertilized dry agricultural land would be irrigated.

(c) Tropical Evergreen Rain Forests:

Tropical rain forests are unique because of no correlation between temperature
and emission, even at temperatures well below 30°C Therefore we set $f_{w/d}$ (soil
temperature, $A_d$ (biome)) constant with respect to soil moisture condition: 8.6 ng
N/m$^2$s for dry soils and 2.6 ng N/m$^2$s for wet soils.

These values reflect the average rain forest emissions recorded during the wet
and dry season in Venezuela. The apparent inversion with other biomes (that is,
greater emissions in the dry season as opposed to the wet season) is a result of the
almost constant soil inundation during the wet season The dry season is drier, but
still somewhat rainy, consequently the soil moisture only drops to levels considered
optimal for NO$_x$ emission, somewhere between 10% and 18%. The model is forced to
emit at the dry soil rate for the five contiguous driest months, regardless of the actual
model soil moisture state. However, the soil still must meet the requirements for
pulsing.

4.4.3 Canopy Reduction, CR (LAI, SAI)

Canopy reduction is a function of five key variables, surface O$_3$, NO soil
emission, leaf resistance to deposition, canopy residence time and leaf area index
(LAI). Surface O$_3$ and NO emission determine the inter-canopy NO$_2$/NO$_x$ ratio, and
the other three determine the effect of the canopy for NO$_2$ uptake. However, the
scheme established is not practical for global inventories because it relies on
experimental measurements of vertical transfer rates and NO$_2$ deposition velocities. The only reliable parameters available globally, which are linked to CR, are leaf and stomatal areas. Therefore, the model ignores NO$_2$/NO$_x$ ratio, canopy residence time, and stomatal resistance, and models the canopy as a simple "gray absorber" of NO$_2$ dependent only on LAI and the product of LAI and the ratio of stomatal area to leaf area (product defined as the stomatal area index (SAI)). It is reasonable to assume the amount of NO$_x$ lost in a canopy is roughly dependent on the total leaf (cuticle) and stomatal area. For simplicity, the model uses an exponential decay model, assuming that stomata and cuticle absorb a constant fraction of NO$_2$ they encounter and are distributed uniformly throughout canopy. Then, considering an idealized case of only cuticle absorption at night and stomatal absorption during the day, the daily averaged flux escape efficiency, or CRF(LAI, SAI) was defined as:

$$F_{\text{from canopy}} = F_{\text{from soil}} \times [0.5e^{-(ks \times SAI)} + e^{-(kc \times LAI)}]$$

$$= F_{\text{from soil}} \times \text{CRF (LAI, SAI)}$$

(4-12)

where $ks$ and $kc$ = some "stomata" and "cuticle" absorptivity constants

and $[0.5e^{-(ks \times SAI)} + e^{-(kc \times LAI)}]$ is applied to (4-1) as CR(LAI, SAI) and was referred to as the Canopy reduction factor or CRF).

The rate of NO$_2$ consumption is controlled by inter-stomatal kinetics, which in turn is controlled by stomatal resistance to deposition, NO$_2$/NO$_x$ partitioning, and vertical transfer rates.
4.4.4 Biomass Burning Stimulation:

A change was made to the already existing model to incorporate biomass burning using better information that is now available from literature (Levine et al., 1996). From literature, biomass burning seems to stimulate emissions by at least an average factor of 3. In the absence of enough data, a factor of 5 or 10 had been suggested (Yienger and Levy, 1995).

Table 4.2: Biomass Burning Effect on Flux of Soil Biogenic NO\textsubscript{X} Emissions.

<table>
<thead>
<tr>
<th>Before Burning-Dry Sites</th>
<th>Before Burning-Wet Sites</th>
<th>After Burning-Dry Sites</th>
<th>After Burning-Wet Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Background NO\textsubscript{Emissions} ng N m\textsuperscript{-2} s\textsuperscript{-1}</td>
<td>0.4-6.2</td>
<td>4.7-34</td>
<td>13.3-15.2</td>
</tr>
</tbody>
</table>

The flux then becomes three times (Flux F = F x 3 in equation (4-1)) i.e., if the grid burns, then the emissions are stimulated by a factor of 3. A grid was defined to burn if its precipitation was less than 25 mm/ year.
4.5 EXPERIMENT CASE STUDIES

Cases 1, 2 and 3 give the best estimates for Past Case-Pre industrial. Present Case, and Future Case of Soil -NOX emissions. The results are categorized for each case by biome and region and include discussion of the importance of fertilizer use, fertilizer induced emissions, and total emissions. The importance of the biogenic source relative to other sources is discussed in Chapter 5. The Pre-industrial case (Case 1) was computed by replacing current agriculture in the world with the NASA/GISS pre industrial land types, and the future case (Case 3) was computed by raising fertilizer rates to projections of Lashof and Tirpak (1990).

4.6 RESULTS and DISCUSSION

The pattern of emissions presented here (Fig 4.1, 4.2 and 4.3) is in qualitative agreement with that of Yienger and Levy (1995). The computed annual emissions are slightly higher, however because Yienger and Levy did not include biomass burning stimulation in their primary function (Equation 4-1). This source was ignored due to lack of data needed to make a reliable parametization at the time of the study. Several recent global experiments have provided flux rates and emission factors which allow inclusion of this important effect in the calculations presented here.

Figures 4.1, 4.2, and 4.3 show annual global distribution of soil biogenic NOX emissions for the preindustrial, present case (1995), and future case (2020) respectively. Figures 4.4, 4.4, and 4.6 show monthly distribution of soil biogenic NOX emissions for the three cases studied for the month of January. July emissions for the three cases are highlighted in figures 4.7, 4.8, and 4.9. To better understand continental contributions to the soil biogenic NOX emissions, graphs were plotted in
Figures 4.10, 4.11, 4.12, showing individual continental sources by percentage contribution. Fertilizer induced continental contributions are shown in Figures 4.13 and 4.14 for 1995 and 2020. Biome source contributions are shown in figures 4.15, 4.16, and 4.17.

Case 1:

Pre industrial emissions of soil NO\textsubscript{X} (Fig 4.1) are mainly confined to the tropics. The computed global total of 4.5 Tg N/yr for the pre industrial case is less than the present day scenario if all fertilizer would be removed. This effect is due to anthropogenic conversion of low NO\textsubscript{X} emitting forests into higher emitting grasslands and pastures. Areas such as Africa and India have experienced the largest increases in conversion of biome types due to anthropogenic deforestation. Figure 4.15 shows the strongest biome emitters. Globally, Africa (32%), South East Asia (31%), and South America (19) were the strongest regional emitters (Figure 4.10).

Case 2:

The Present day emissions scenario is quite different from the Pre industrial case (Case 1). Massive changes in advances in agricultural technology prompted by large population increases have been accompanied by the increased use of fertilizer and biomass burning in which forest land is converted into pastures and fields. The world's forest and woodland areas have been reduced 15% since 1850, primarily to accommodate the expansion of cultivated lands (World Resources Institute and International Institute for Environment and Development, 1989). For example in western Africa, 70% of the forested area that existed at the beginning of the century has already been cleared. (Delmas et al., 1995)
Lower emitting forests are being constantly converted into higher emitting grasslands and pastures, particularly in South America, specifically Brazil. Africa and parts of South East Asia. While emissions from the three continents above have increased (Figure 4.2), the largest increases have been in Europe and North America, largely as a result of huge fertilizer usage. Globally, Africa (37%), South America (19%), and Europe (14%) were the strongest regional emitter (Figure 4.10). This can be attributed to the rice developments of the region. The high emissions from Europe are due to heavy fertilizer use. Forests and Tundra and natural biomes 30° poleward are all less important than tropical areas despite their huge landmass.

Case 3:

The pattern of emissions in the future case are similar to the present day case, but net annual emissions are expected to more than double those of the pre-industrial case by the year 2020, due to increasing use of fertilizer in business as usual scenario. Developing areas such as Africa, India and South America will experience the largest increase (figure 4.3). By 2020, Africa (33%), Europe (19%), and South America (17%) are predicted to be the strongest regional emitters (Figure 4.12).

In the tropics, emissions are strong because year round warmth stimulates vast savannas and rain forests, as well as scattered but not significant agriculture. The model generates three quarters of global pulsing emissions in the tropics, suggesting that the ITCZ migration allows a greater amount of land to dry out thoroughly before wetting than do mid-latitude transient disturbances. Savanna grasslands are the most important tropical biome and account for nearly half of all tropical soil biogenic NOX. Most of this comes from the large belt of African savannas between 0°-20°N, which forms the single largest continental-scale contributor in the world. A reduction in
tropical emissions is consistent with the reduction of tropical forests due to
deforestation activities.

The present contribution of Soil-NO\textsubscript{X} to the total NO\textsubscript{X} budget is quite
significant. In the tropics, the influence of the inter tropical convergence zone (ITCZ)
is especially evident in Africa. The wet savannas of the Northern Hemisphere account
for well over 75\% of the regions total NO\textsubscript{X} emissions source, whereas the lower
emitting dry season savannas account for only 15\%. This large difference is
enhanced by the inverse seasonality of the biomass burning NO\textsubscript{X} source (direct
emissions NO\textsubscript{X} from fire, which is different from biomass burning stimulation of
biogenic emissions), which is very strong in the dry season when the biogenic source
is very weak.

In all three cases, summer emissions are higher than winter emissions due to
stimulation by warm temperatures, heavy rainfall and biomass burning effects which
are all at an optimum during the summer months (Figures 4.4 to 4.9). July emissions
are higher than January emissions.

**Fertilizer induced emissions**

Figures 4.13 and 4.14 show regional contributions to the global budget of
fertilizer induced emissions of soil biogenic NO\textsubscript{X} for the present day (1995) and
future case (2020) respectively. Figure 4.13 shows that the chief fertilizer induced
emitters are Europe, North America and East Asia at 41\%, 20\% and 19\% of the
world’s use of fertilizer. This data is consistent with fertilizer usage by these well
developed regions. Africa clearly plays an insignificant role in this situation, with
fertilizer emissions at only 4\% (Figure 4.13). In the year 2020, the chief fertilizer
users and emitters will be Europe, South East Asia and East Asia at 37\%, 18\% and
18\% respectively (Figure 4.14). Again Africa is not expected to contribute
significantly in fertilizer induced emissions by the year 2020.
4.7 Uncertainties and Errors

A large number of assumptions and approximations were made estimating soil NOX biogenic emissions. The amount of data available at the time of computations although more than previous studies is still not sufficient enough to allow error limits to be assigned with reasonable scientific precision. However, the results are probably the best they can be at this time taking into consideration the limitations placed by lack of enough background data. Agriculture and tropical biomes present the largest biome related uncertainties. These biomes have a large spatial variation and a vast in area and have the least information to provide reliable estimations. At this time it would probably be correct to assume results are good to a factor of two.

Summary

In this study, estimates of regional, global and ecosystem soil biogenic NOX emissions are made using a global-scale empirical model of soil biogenic NOX emissions that is temperature and precipitation dependent and uses a 6-hour averaged GCM output for meteorological forcing. The focus is on Africa's contribution in order to better understand biogenic emissions from Africa. New features incorporated into the model since Yienger and Levy (1995) include biomass burning stimulation (the soil emissions following burning). The best annual estimate for world emissions is 8.7 Tg N (NOx) with a range of 6.5-10.9 Tg N annually. The results show that on a global scale Africa is the greatest continental soil biogenic NOX emitter contributing 37%. The other continents, South America, Europe, North America, South Asia, Australia and East Asia yield 19%, 14%, 9%, 7%, 7% and 6% respectively (Figure 4.11). The most strongly emitting biomes are tropical rain forests, agricultural activities and temperate regions, which accounted for 49%, 14%, and 21% of the
total emissions respectively (Figure 4.16). Biomass burning is significant in
enhancing soil biogenic emissions by stimulating emissions following burn periods.
By the year 2020, global emissions are estimated to increase to 12 Tg N annually,
with Africa still as the largest continental source at 32% (Figure 4.12)
Figure 4.1: Past Case Pre Industrial Annual Soil - NOX Emissions

units - grams N/m2

scale = 1 exp - 2    average = 1.754

GFDL/NOAA Global Chemical Transport Model
Figure 4.2: Present Day Case (1995) Annual Soil - NOx Emissions

units - grams-N/m2

scale = 1 x 10^{-2} \quad average = \quad 2.956

GFDL/NOAA Global Chemical Transport Model

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 4.3: Future Case (2020) Annual Soil - NO$_X$ Emissions

units - grams - N/m$^2$

scale = 1 exp -1   average = 0.363

GFDL/NOAA Global Chemical Transport Model

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 4.4: Past Case Pre Industrial January Soil - NO$_x$ Emissions

units: grams-N/m$^2$

scale = $1 \times 10^{-3}$ average = 1.404

GFDL/NOAA Global Chemical Transport Model

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 4.5: Present Day Case (1995) January Soil - NO$_x$ Emissions

units - grams-N/m$^2$

scale = $1 \times 10^{-3}$  average = 1.865

GFDL/NOAA Global Chemical Transport Model

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 4.6: Future Case (2020) January Soil - NO\textsubscript{x} Emissions

units = grams-N/m\textsuperscript{2}

scale = 1 \times 10^{-3} \quad \text{average} = 2.057

GFDL/NOAA Global Chemical Transport Model

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 4.7: Past Case Pre Industrial July Soil - NOx Emissions

units: grams-N/m2

scale = 1 exp -3  average = 1.703

GFDL/NOAA Global Chemical Transport Model

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 4.8: Present Day Case (1995) July Soil - NO\textsubscript{x} Emissions

(units: grams-N/m\textsuperscript{2})

scale = 1 \times 10^{-2} \quad average = 0.371

GFDL/NOAA Global Chemical Transport Model

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 4.9: Future Case (2020) July Soil - NOx Emissions

units - grams - N/m2

scale = 1 exp - 2    average = 0.521

GFDL/NOAA Global Chemical Transport Model

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 4.10: Total Global Biogenic Soil NOx Emissions
Regional Contribution

Africa 45%

Australia 6%

N. America 6%

Europe 7%

East Asia 3%

S. Asia 4%

S. America 26%

Pre-Industrial Case

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 4.11: Total Global Biogenic Soil- \( \text{NO}_x \) Emissions: Regional Contribution

- Africa: 37%
- Australia: 7%
- N. America: 9%
- Europe: 14%
- E. Asia: 6%
- South Asia: 8%
- S. America: 19%

Present Case- 1995
Figure 4.12: Total Global Biogenic Soil- NOx Emissions: Regional Contribution

Future Case- 2020
Figure 4.13: Total Global Fertilizer Induced Biogenic Soil- NO$_x$ Emissions: Regional Contribution

Present Case - 1995
Figure 4.14: Total Global Fertilizer Induced Biogenic Soil- $\text{NO}_x$ Emissions: Regional Contribution

- N. America: 12%
- Africa: 7%
- S. America: 3%
- S. Asia: 18%
- E. Asia: 18%
- Europe: 37%

Future Case - 2020
Figure 4.15: Sources of Biogenic Soil emissions
Biome Source Contribution

- Tropical Emissions: 66%
- Emissions During Pulsing: 21%
- Temperate Emissions: 14%

Pre-Industrial Case
Figure 4.16: Sources of Biogenic Soil- $\text{NO}_x$ Emissions-
Biome Source Contribution

- Tropical Emissions: 49%
- Emissions during Pulsing: 17%
- Fertilizer Induced Emissions: 13%
- Temperate Emissions: 21%

Present Case - 1995
Figure 4.17: Sources of Biogenic Soil NO\textsubscript{x} Emissions: Biome Source Contribution

- Tropical Emissions: 41%
- Temperate Emissions: 22%
- Fertilizer Induced Emissions (22%)
- Emissions During Pulsing: 15%

Future Case - 2020
Chapter 5

CONCLUSIONS

Introduction

This section covers the relative importance of the sources of gases and particulates in this study, in the form of relative contributions to the regional budget and an overall assessment of the importance of Africa as a regional and global source of atmospheric gases and particulates. Table 5.1 shows African fossil fuel, biogenic, biomass burning, total emissions, and all anthropogenic sources emissions (an assessment of Africa's importance as a regional and global source of trace gases and particulates).

Presently there are three major anthropogenic sources of atmospheric gases and particulates in Africa: fossil fuel consumption, soil biogenic emissions, and biomass burning. This research has established the order of importance of these sources on the African continent. Biomass burning predominates for all species investigated in this study. The biomass burning source is so important that more than 11% with a range of 8-14% of the world's total anthropogenic CO$_2$ production is from Biomass burning in Africa. The fossil fuel source is weak and the biogenic source, while being the strongest single continental source of soil biogenic NO$_x$, is relatively small compared to the biomass burning source. The fossil fuel source though small is localized and dominates in more industrialized countries (MIC), while the biomass burning source dominates in countries where climate, vegetation and socio factors are conducive to burning, particularly those lying in the savanna belt of Africa. The biogenic source is strong in tropical and agricultural lands.
Table 5.1: Continued. An Assessment of Africa's Importance as a Regional and Global Source of Trace Gases and Particulates. African Fossil Fuel, Biogenic, Biomass Burning, Total Emissions, and All Anthropogenic Sources Emissions

<table>
<thead>
<tr>
<th>Species</th>
<th>Total Africa Best Estimate</th>
<th>Total Africa Range</th>
<th>Total All anthropogenic sources</th>
<th>Africa's % contribution to the global budget</th>
<th>Africa's Global % Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2</td>
<td>5382</td>
<td>3767 - 6997</td>
<td>33700</td>
<td>16.0</td>
<td>11 -21</td>
</tr>
<tr>
<td>CO</td>
<td>204</td>
<td>82 - 326</td>
<td>1600</td>
<td>13</td>
<td>5 - 21</td>
</tr>
<tr>
<td>CH4</td>
<td>12</td>
<td>7 - 17</td>
<td>275</td>
<td>5</td>
<td>3 - 7</td>
</tr>
<tr>
<td>CH3Cl</td>
<td>0.27</td>
<td>0.05 - 0.49</td>
<td>1.1</td>
<td>25</td>
<td>3 - 48</td>
</tr>
<tr>
<td>CH3Br</td>
<td>0.005</td>
<td>0.0005 - 0.01</td>
<td>0.11</td>
<td>5</td>
<td>0.5 - 10</td>
</tr>
<tr>
<td>NMHC's</td>
<td>8</td>
<td>2 - 14</td>
<td>100</td>
<td>8</td>
<td>2 - 14</td>
</tr>
<tr>
<td>NOx</td>
<td>23</td>
<td>7 - 39</td>
<td>70</td>
<td>33</td>
<td>10 - 56</td>
</tr>
<tr>
<td>SO2</td>
<td>1.5</td>
<td>0.2 - 3</td>
<td>160</td>
<td>1</td>
<td>0.1 - 2</td>
</tr>
<tr>
<td>NH3</td>
<td>2.5</td>
<td>0.5 - 5</td>
<td>57</td>
<td>5</td>
<td>1 - 9</td>
</tr>
<tr>
<td>Aerosols</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TPM</td>
<td>25</td>
<td>3 - 48</td>
<td>390</td>
<td>7</td>
<td>1 - 13</td>
</tr>
<tr>
<td>particles</td>
<td>15</td>
<td>8 - 23</td>
<td>240</td>
<td>6</td>
<td>3 - 9</td>
</tr>
<tr>
<td>&lt;2.5 μm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon</td>
<td>17</td>
<td>3 - 31</td>
<td>90</td>
<td>20</td>
<td>4 - 36</td>
</tr>
</tbody>
</table>

1. Sources for this data are discussed in Andreae et al., 1996
Table 5.1: Continued. An Assessment of Africa’s Importance as a Regional and Global Source of Trace Gases and Particulates. African Fossil Fuel, Biogenic. Biomass Burning, Total Emissions, and All Anthropogenic Sources Emissions

<table>
<thead>
<tr>
<th>Species</th>
<th>Total Africa Range</th>
<th>Total All anthropogenic sources</th>
<th>Africa’s % contribution to the global budget</th>
<th>Africa’s Global % Contribution Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2</td>
<td>5382 3767 - 6997</td>
<td>33700</td>
<td>16.0</td>
<td>11 -21</td>
</tr>
<tr>
<td>CO</td>
<td>204 82 - 326</td>
<td>1600</td>
<td>13</td>
<td>5 - 21</td>
</tr>
<tr>
<td>CH4</td>
<td>12 7 - 17</td>
<td>275</td>
<td>5</td>
<td>3 - 7</td>
</tr>
<tr>
<td>CH3Cl</td>
<td>0.27 0.05 - 0.49</td>
<td>1.1</td>
<td>25</td>
<td>3 - 48</td>
</tr>
<tr>
<td>CH3Br</td>
<td>0.005 0.0005 - 0.01</td>
<td>0.11</td>
<td>5</td>
<td>0.5 - 10</td>
</tr>
<tr>
<td>NMHC’s</td>
<td>8 2 - 14</td>
<td>100</td>
<td>8</td>
<td>2 - 14</td>
</tr>
<tr>
<td>NOx</td>
<td>23 7 - 39</td>
<td>70</td>
<td>33</td>
<td>10 - 56</td>
</tr>
<tr>
<td>SO2</td>
<td>1.5 0.2 - 3</td>
<td>160</td>
<td>1</td>
<td>0.1 - 2</td>
</tr>
<tr>
<td>NH3</td>
<td>2.5 0.5 - 5</td>
<td>57</td>
<td>5</td>
<td>1 - 9</td>
</tr>
</tbody>
</table>

Aerosols

| TPM particles <2.5 μm | Carbon | 17 | 3 - 31 | 90 | 20 | 4 - 36 |

1. Sources for this data are discussed in Andreae et al., 1996
Africa as a Regional Source of Atmospheric Gases and Particulates.

The partitioning of biomass burning species emissions by source in order to evaluate the regional budget is very important. This research suggests that the biomass burning source is both strong and localized and dominates in Africa. The biomass burning source of gases and particulate in Africa which is dominated by savanna vegetation burning is increasingly important. There is a strong seasonal cycle of emissions between the Northern hemisphere (January to June) and Southern hemisphere (July to November). An assessment of Africa's regional budget illustrates the following interesting results:

A. Fossil Fuel Source

This study confirms that Africa is not an important source of global gases (CO$_2$, CH$_4$, and NO$_x$) from fossil fuel combustion or energy related sources. Total CO$_2$ emissions from fossil fuel combustion in Africa in 1994 were 1617 ± 97 Tg CO$_2$. This represents a 6 ± 0.4% of global fossil fuel carbon dioxide, and 5 ± 0.3% contribution to the global total all anthropogenic carbon dioxide budget. The estimate was slightly higher than the 3 % anticipated (Marland et al., 1995). Africa's contribution to the CO$_2$ global budget is expected to increase from 6% in 1994 to approximately 9% with a range of 8-10% by the year 2020. Chief national contributors to the regional CO$_2$ budget were, Algeria, Libya, Angola, South Africa, Morocco, and Egypt. As expected, high national emissions were directly linked to high GNP and higher population.

Partitioning by source for CO$_2$ to the African regional budget was 30% (with range 28-32%) fossil fuel and 70% (range 42-98%) biomass burning. While the biomass burning source is much stronger, the fossil fuel source is very important to global warming because it represents a net source of CO$_2$, about 5% (range 4-6%) of
global anthropogenic CO₂. The fossil fuel NOₓ is almost insignificant as NOₓ emissions are dominated by biomass burning source in Africa. Relative contributions to the African regional anthropogenic induced NOₓ emissions are: 4 ± 0.3 % fossil fuel. 77% biomass burning and 18% soil biogenic source. NOₓ emissions from fossil fuel electricity generation in 1994 for Africa were 813 ± 70 Gg NOₓ. In 1994, Africa was responsible for 4 ± 0.3 % of global fossil fuel NOₓ budget, and 1 ± 0.08 % of the global total anthropogenic NOₓ. The methane budget is also dominated by biomass burning with the relative proportions to the African regional budget standing at 41± 12% fossil fuel source and 59 ± 41% biomass burning source. In 1994, CH₄ emissions in Africa were 5 ± 2 Tg CH₄. Africa contributed 4 ± 1.2% to the global fossil fuel methane total. This fossil fuel source represents about 2 ± 0.6% of global anthropogenic total.

The production of other species from fossil fuel consumption in Africa is currently at insignificant contributions. It can be fairly assumed that nearly all anthropogenic CO, CH₃Cl, CH₃Br, NMHC's, SO₂, NH₃, and aerosols is from biomass burning. But NMHC's from biomass burning are a larger fraction of the global emissions than methane. While fossil fuel and energy related emissions in Africa will continue to increase, Africa will still not be major source in this area even by the year 2020. The fossil fuel and energy source dominates in the more industrialized countries (MIC) in Africa.

B. Biogenic source

Africa is an important source of biogenic soil NOₓ. Africa currently dominates the soil biogenic NOₓ source has done so even in pre industrial times and will continue to be the leading continental source even by the year 2020. The most
strongly emitting biomes were tropical rain forests, and savanna. Fertilizer induced emissions in Africa lag behind those of other continents as Africa’s consumes the least amount of fertilizer in the world (Lashof and Tirpak, 1990).

C. Biomass Burning Source

This research suggests that the biomass burning source is both strong and localized and dominates in Africa. The biomass burning source of gases and particulates in Africa is very important. The influence of gases and particulate emissions by the savanna vegetation burning is predominant. Biomass burning source is the strongest of all gaseous and particulate sources in Africa.

Africa as a Global Source of Atmospheric Gases and Particulates.

An overall assessment of Africa's contribution to the global species budget is presented in Table 5.1. An assessment of the Africa's contribution to the overall global trace gases and particulates yields both new findings and confirms some older speculations.

Africa is a significant global source of the following gases, CO$_2$, CO, CH$_3$Cl, NO$_x$, and carbon particulates (Table 5.1). From a global perspective, Africa's contribution to the anthropogenic carbon dioxide, carbon monoxide, and NO$_x$ budgets, is stronger than anticipated (Andreae et al., 1996; Zenker et al., 1996). The estimates presented here confirm suggestions that Africa might be a major source of methyl bromide and particulates (Rudolph, 1995; Remer, 1996).

Africa's global significance has been demonstrated to be overwhelming in this study, as more than 11% (range of 8-14%) of the world's total anthropogenic CO$_2$ production is from Biomass burning in Africa. Africa is a significant source of CO$_2$ emissions contributing more than 16% (range 11-21%) of the world's total anthropogenic carbon dioxide. The CO contribution is nearly 13% (range 5-21%).
These gases are likely to have a significant impact on both regional and global atmosphere, chemistry and climate (Whitlock et al. 1996). Africa's contribution to the problem of global warming could be quite significant. A better understanding of the impact on global chemistry and climate must be assessed using the information provided here as a source term in chemical transport models.

Net atmospheric CO$_2$ emissions from biomass burning

In computing net atmospheric CO$_2$ emissions due to biomass burning, the partitioning by source must be considered (The net atmospheric CO$_2$ emission is the amount of CO$_2$ released by biomass burning that is not reincorporated in the biosphere via photosynthesis). While this research indicates that the production of CO$_2$ from biomass burning is significant, the value reported is a gross amount of CO$_2$. The broad classes of biomass burning considered in this study are savanna, forest, agricultural residues, and fuelwood, and each one of these has a different impact on net CO$_2$ emissions and this will be discussed below. It is important to note that re-incorporation into the biosphere only pertains to CO$_2$, not the other gaseous emissions of biomass burning.

The burning of savanna areas in tropical and subtropical formations with continuous grass coverage results in the instantaneous emissions of carbon dioxide. However, the vegetation re-grows between burning cycles, so the carbon dioxide released into the atmosphere is reincorporated in the biosphere during the next vegetation growth period. Net CO$_2$ emissions are therefore assumed to be zero. For agricultural residue burning, the CO$_2$ released is not considered to be net emission because the biomass burned is generally replaced by re-growth over the subsequent year. An equivalent amount of carbon is removed from the atmosphere during this regrowth, to offset the total carbon released from combustion. Since savanna and
agricultural residues account for 64% and 1% (Figure 3.19) of total biomass burning in Africa. 65% of the emissions of CO2 are not net emissions.

This assumption has been made by assuming that the following issues are unimportant and can be assumed to have zero effect:

1. Some crop residues are removed from the fields and burned as a source of energy, especially in developing countries in Africa

2. Long term changes in soil carbon are certainly possible as a result of agricultural practices. In land use change and forestry, there is a general assumption that soil carbon is gradually lost from agricultural lands over many years after forests are cleared (IPCC, 1995). Depending on the specific agricultural and soil management practices (including burning), there may be a variety of effects on soil carbon. Repeated burning of savannas and crop residues in fields, for example, may cause an increase in the amount of carbon stored in the soil over time. This issue requires further research and may lead to more detailed emissions estimation methods in the future.

3. Agricultural practices such as overgrazing which degrade the productivity of grasslands or other agricultural lands, reduce the amount of aboveground biomass which re-grows. These could be considered sources of gradual emissions of carbon dioxide. This effect is not included in the basic calculations, but could be included in more refined calculations.

4. A similar long-term effect can be observed from savanna burning. If the savannas are burned too frequently, complete regrowth may not occur. In this situation, grasslands can degrade over time, resulting in long-term losses of both above ground and soil carbon.
5. Carbon might be sequestered through the use of agricultural residues to make durable products (e.g., bricks, composite boards). The assumption is that the carbon sequestered in such activities on an annual basis is small, and can be ignored in the calculations. As the stocks of such products are not significantly increasing or decreasing over time, ignoring them as net sources is acceptable.

Forest and Fuelwood

This category includes conversion of existing forests and natural grasslands to other land uses, such as agriculture. Forests can be cleared to convert land to a wide variety of other uses, including agriculture, highways, urban development, etc. In all cases there is a net carbon release to the atmosphere which should be accounted for in this calculation. The predominant current cause of forest clearing in Africa is conversion to pasture and cropland in the tropics (Levine 1995). This is accomplished by an initial cutting of undergrowth and felling of trees. The biomass may then be combusted in a series of on-site burns or taken off site to be burned as fuel, or perhaps used for forest products. Conversion of tropical forests to pasture and cropland accounts for the largest share of global forest clearing and resulting net CO\textsubscript{2} emissions. Fuelwood combustion also results in net emissions of CO\textsubscript{2}.

In this study an assumption was made that forest and fuelwood account for net CO\textsubscript{2} emissions. An overestimation will account for the underestimation in the zero net emissions for savanna and agricultural residues. In conclusion, based on these arguments, net CO\textsubscript{2} emissions from biomass burning in Africa will be from forest and fuelwood, are summarized as follows:

\[
\begin{align*}
\text{Net CO}_2 & \leq 0.35 \times 3764.7 = 1317.6 \text{ Tg CO}_2/\text{yr} \\
\text{Net CO}_2 & \leq 35\% \text{ of gross}
\end{align*}
\]
(Forest and fuelwood account for 28% and 7% of biomass burning in Africa respectively)

**Major Findings**

Africa contributes nearly a third of the world's anthropogenic NOx emissions. This gas is very important in regulating the oxidizing efficiency of the atmosphere, influences tropospheric ozone formation and stratospheric ozone depletion. Africa's contribution to these impacts is likely to be significant. The biogenic source and biomass burning source are the most important sources of this species in Africa.

Africa is a significant source of methyl chloride (CH$_3$Cl), contributing nearly a fourth of the global anthropogenic CH$_3$Cl. It has always been speculated that biomass burning might be responsible for about a fifth of the global methyl budget (Rudolph et al., 1995). The estimates reported here confirm the importance of Africa as a global methyl chloride source. Methyl chloride is an important source of chlorine, a major agent in ozone depletion.

Africa is a significant source of carbon particles contributing nearly one fifth to the world's global anthropogenic budget. Aerosols are important in affecting the radiative properties of the atmosphere.

Africa is not a significant source of CH$_4$, CH$_3$Br, NMHC's, SO$_2$, NH$_3$, TPM, and particulates <2.5 um (Table 5.1). These gases are produced in relatively smaller quantities in Africa and their global contribution is minimal. However they are very important in atmospheric chemistry considerations and their contribution though small should not be overlooked. For example, CH$_4$ is a more efficient absorber of thermal radiation than CO$_2$ even though the abundance of methane is 1/200 that of CO$_2$ (Lashof and Timpak, 1990), and the combined efficiency of the bromine removal cycles for ozone (HO$_2$ + BrO and ClO + BrO) is likely to be about 50% times greater.
than the efficiency of known chlorine removal cycles on an atom-for-atom basis (WMO, 1994).

Conclusions

This study has provided a comprehensive understanding of the importance of Africa as a regional and global source of atmospheric gases and particulates in Africa. The importance of Africa as a key global source of trace gases and aerosols has been underestimated in the past and this research offers a new picture of gaseous and particulate emissions from Africa and partitioning by source.

The first comprehensive national and regional database was developed for the emissions of gases and particulates from major sources in Africa. The results showed that Africa is the world's single largest continental source of emissions due to biomass burning and that these emissions are likely to increase with time. Increases in time are likely to result from the fact that demand for land use has increased substantially during the last two decades the human population has grown 36% in Africa (FAO, 1991; US Bureau of Census) and the annual deforestation rate has increased by 12% in tropical Africa (FAO, 1993). The results also showed that Africa is the greatest continental soil biogenic NOX emitter. We also showed that Africa is not an important source of global gases from fossil fuel combustion or energy related sources.

We have also conducted modeling studies for biogenic soil NOX emissions study estimated regional, global and ecosystem soil biogenic NOX based on a temperature and precipitation dependent model that uses a 6-hour averaged GCM output for meteorological forcing. The study established that on a global scale Africa was the greatest continental soil biogenic NOX emitter contributing almost 2/5 of the worlds total. The most strongly emitting biomes were tropical rain forests, and savannas of Africa. Biomass burning was established to be significant in enhancing

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
soil biogenic emissions by stimulating emissions following burn periods. By the year 2020, global emissions were estimated to increase to 11.82 Tg N annually (range 0-35 Tg N), with Africa still as the largest continental source.

This study presented the first regional and national inventory of estimates of gaseous and particulate emissions from biomass burning in Africa using satellite measurements to evaluate the extent of biomass burning and gaseous and particulate emissions resulting from this burning. This inventory provided a 1°x1° latitude/longitude spatial resolution of biomass burning activity in Africa and provides estimates of emissions on a country-by-country basis. Emission factors and ratios were based on a series of field campaigns and laboratory measurements. Africa’s contribution to global biomass burning emissions was established to overwhelmingly significant. We established that more than 11% (range 8-14%) of the world’s total anthropogenic CO2 production is from Biomass burning in Africa.

Africa was found to be a significant global source of the following gases, CO2, CO, CH3Cl, NOx, and carbon particulates, and found not to be an important source of Africa is not a significant source of CH4, CH3Br, NMHC’s, SO2, NH3, TPM, and particulates <2.5 um.

The relationships between population, GNP per Capita, and emissions is central to emissions trends. Increases in population, especially in Africa will result in significant increases in gaseous and particulate emissions from the continent and rising level of industrialization (higher GNP) will result in significant increases in emissions. Growth in GNP per capita outpaces growth in population in influencing levels of emissions. This study has shown that fossil fuel source is directly correlated with population and GNP. However, this research found no correlation between these two parameters and biomass burning emissions. It only established that regions of
higher population density have more controlled burning, but still, there is no relationship between the total population of a given country and its emissions from biomass burning. Forecasts of emissions are based on several assumptions concerning population increases, growths in per capita GNP, and per capita emissions. While future estimates should only be regarded as possible endpoints for present day activities, the increase in emissions is firmly established.

**Topics for Future Study**

The inventory of trace gas emissions for continental Africa developed in this study suggests a range of topics for further investigation. For effective policy decisions, we must quantify the sources, magnitude, and impacts of these emissions. In this study, we have compiled existing databases on fossil fuel use, conducted modeling studies for biogenic sources, and used satellite measurements to evaluate the extent of biomass burning and gaseous and particulate emissions resulting from this burning. The combination of these three processes in a comprehensive inventory of trace gas emissions from continental Africa on a country-by-country basis provides invaluable information for policy makers. For a global perspective, however, this approach would have to be applied to all of the continents. With the resulting inventory, the international community could move to develop cost-effective measures to reduce greenhouse gas emissions, and control other trace species that effect atmospheric composition, chemistry, climate, and air quality. The three-step process applied here, could provide important inputs to policy makers, if these methods are applied on a global scale.

From a regional perspective, the results from this study might be applied to help in forecasting changes in the regional climate of Africa. The rapid changes in
population and industrialization in Africa necessitate monitoring on a regional scale. While in situ monitoring over Africa would require a major investment in infrastructure, the combination of techniques provided in this study provide a reasonable first approximation of emissions. To improve these estimates, we must have better estimates of area burned, and more sophisticated diagnostic relationships between burning, emissions, and ecosystems. To obtain better estimates of area burned, improvements are needed in the satellite remote sensing techniques used. Better relationships between burning and the associated atmospheric chemistry requires a combination of laboratory studies and field programs in African biomes. Finally, the simple diagnostic relationships between biogenic emissions, biome, and meteorology are somewhat simplistic as this stage in their development and could use improvement.

To really assess the effect of emissions on regional and global climate, chemical transport models (CTM's) must be initialized with the improved emissions rates from studies such as the one presented here. The CTM's will provide life-cycle information on emissions, ultimate sinks of these species, and give some estimate on the net effects of emissions from Africa on the composition, chemistry, and climate on both continental and global scales.
REFERENCES


*Intergovernmental Panel on Climate Change*, Climate Change 1992, WMO/UN Environmental Programme.


Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.


Vita

Lawrence Mtetwa was born February 24, 1969 in Mt. Selinda, Zimbabwe. He graduated from Hartzell High School (A United Methodist Mission School) in Mutare, in the eastern Highlands of Zimbabwe in January of 1989. In 1987, he was an exchange student to the United States of America. In March of 1989, he enrolled at the University of Zimbabwe in Harare, Zimbabwe where he received a Bachelor of Science (Honors) in Chemistry in January of 1992. He worked there as a Teaching Assistant in 1992 before leaving for further studies in the United States of America in January of 1993. He attended Hampton University in Hampton, Virginia for the Master of Science in Chemistry from 1993 to 1994. In January of 1995 he became a doctoral candidate in Atmospheric Science, in the Applied Science department at the College of William and Mary in Williamsburg, Virginia. He was a Research Assistant with the Computer Sciences Corporation (Langley EOS/ DIS Distributed Active Archive Center) from February, 1995 to January, 1996 after which he became a Research Assistant in the Theoretical Studies Branch of the Atmospheric Science Division at the National Aeronautics and Space Administration (NASA) Langley Research Center where the research for this dissertation was conducted. He received a Master of Science in Applied Science (Atmospheric Science) from the College of William and Mary, Williamsburg, Virginia in May of 1997. He completed the requirements for a doctorate in Atmospheric Science in May, 1998.