Greenhouse Gas Inventory Reference Manual

First Draft

UNEP

WMO

IPCC Draft Guidelines for National Greenhouse Gas Inventories

IPCC/OECD
Joint Programme

Volume 3

IMPORTANT NOTICE

The material contained in this document is in draft, and is sent to you for comment as part of the IPCC review process. The document has not yet been approved by the IPCC and must not be published or cited as an official IPCC report.
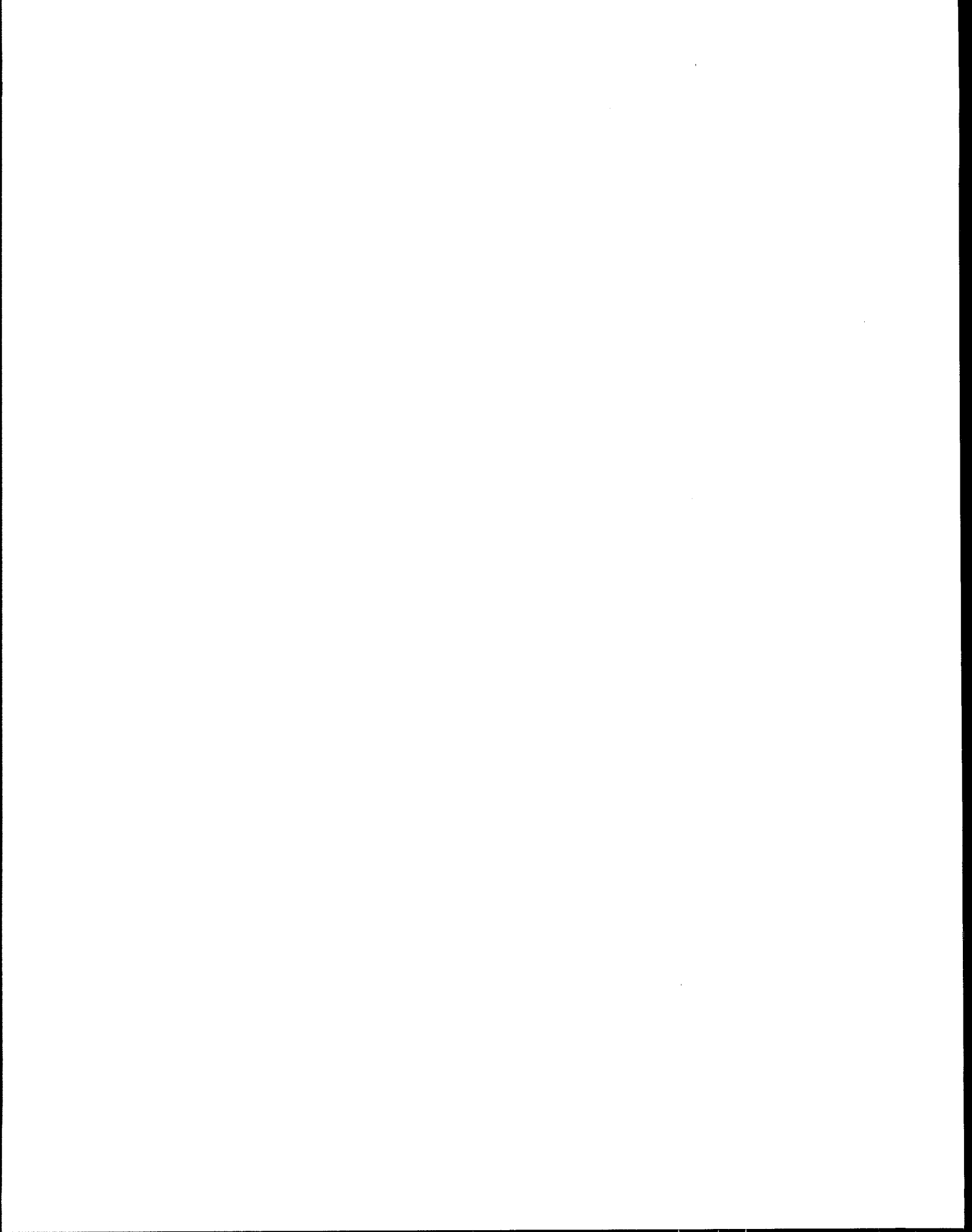
As a result of the review process this draft is expected to undergo amendment and correction before being presented for approval by IPCC WGI in September 1994 and by IPCC plenary in November 1994.

Material contained in this draft may be copied in whole or in part for review by others, but a copy of this notice should be attached to all such copies.

ACKNOWLEDGEMENTS

PREFACE

The signature of the UN Framework Convention on Climate Change (UNFCCC) by around 150 countries in Rio de Janeiro in June 1992 indicated widespread recognition that climate change is a potentially major threat to the world's environment and economic development. Human activities have substantially increased atmospheric concentrations of greenhouse gases, thus perturbing the earth's radiative balance. According to projections from climate models, a global rise of temperature is a likely consequence. The potential impacts of climate change such as sea level rises and changes in local climate conditions - such as temperatures and precipitation patterns - could have important negative impacts on the socio-economic development of many countries.

The ultimate objective of the Convention is the stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level is to be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change.. The Convention also calls for all Parties to the Conference to commit themselves to three objectives:

- To develop, update periodically, publish, and make available to the Conference of the Parties their national inventories of anthropogenic emissions of all greenhouse gases not controlled by the Montreal Protocol.

- To use comparable methodologies for inventories of greenhouse gas emissions and removals, to be agreed upon by the Conference of the Parties.

- To formulate, implement, publish and update regularly national programmes containing measures to mitigate climate change by addressing anthropogenic emissions.

By the time of the Second World Climate Conference in Geneva in October - November 1990, the need for a standard methodology for compiling national emission inventories was obvious. Under the auspices of the Organisation for Economic Cooperation and Development (OECD) and the International Energy Agency (IEA), with support from the USA, the UK and Norway, an initial compendium of methods (covering all gases except chlorofluorocarbons (CFCs) which were already accounted for under the Montreal Protocol). This document was discussed in detail by a meeting of experts (including many representatives of non-OECD countries) in Paris in February 1991. It was then adopted in a slightly modified form at the fifth session of the Intergovernmental Panel on Climate Change (IPCC) in March 1991 as the starting point for a set of IPCC guidelines to be used by countries drawing up national inventories of greenhouse gas emissions.

The *IPCC Guidelines for National Greenhouse Gas Inventories* consists of three volumes: the *Greenhouse Gas Inventory Reporting Instructions,* the *Greenhouse Gas Inventory Workbook* and

the *Greenhouse Gas Inventory Reference Manual*. The *Guidelines* are being distributed world-wide to national experts for review before adoption.

Further development of the methodology has been undertaken by the Scientific Assessment Working Group (WGI) of the IPCC, working in close collaboration with the OECD and the IEA under the IPCC/OECD programme on emissions inventories. The objectives of the programme are:

- Development and refinement of an internationally agreed methodology and software for calculation and reporting of national net emissions.

- Efforts to encourage widespread use of the methodology by countries participating in the IPCC and Parties to the UN Framework Convention on Climate Change.

- Establishment of procedures and a data management system for collection, review and reporting of national data.

In the Guidelines, default methods and assumptions have been developed for characterising the major sources and sinks of greenhouse gases. Countries have the option of using the various methods depending on their own needs and capabilities. Other more detailed methods are also discussed. However, the IPCC/OECD programme is developing a common reporting and documentation framework for all inventories. This will provide for comparison of these methodologically diverse national estimates. It is essential that guidelines for this methodology are internationally agreed upon, and this will be achieved through workshops and expert groups with a broad geographical base.

Additionally, the IPCC/OECD programme is charged with continuing to improve the methodology. This is being achieved through:

- expert groups which review and recommend changes to the method

- results from country studies

- comments and preliminary inventories from countries

- feedback from technical workshops held in Asia, Africa, Latin America and Central and Eastern Europe

About thirty five countries from all over the world have submitted their preliminary inventory data on anthropogenic greenhouse gas emissions and removals from different sources, using a range of approaches including the IPCC methodology. The results of all the above activities have been considered in developing the current *Guidelines*.

The IPCC/OECD programme gives technical support to the greenhouse gas inventory components of country study projects sponsored by UNEP, Asian Development Bank, individual countries etc.. Countries participating in these projects are developing national emission inventories. These country studies will contribute to:

- development of national capacity and capability (including improving baseline data)

- promulgation of the methodology

- realistic testing of the methodology and its guidelines in order to identify strengths and weaknesses

Over thirty countries are currently working on country studies with support from various sponsors.

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PART I
INTRODUCING THE
REFERENCE MANUAL

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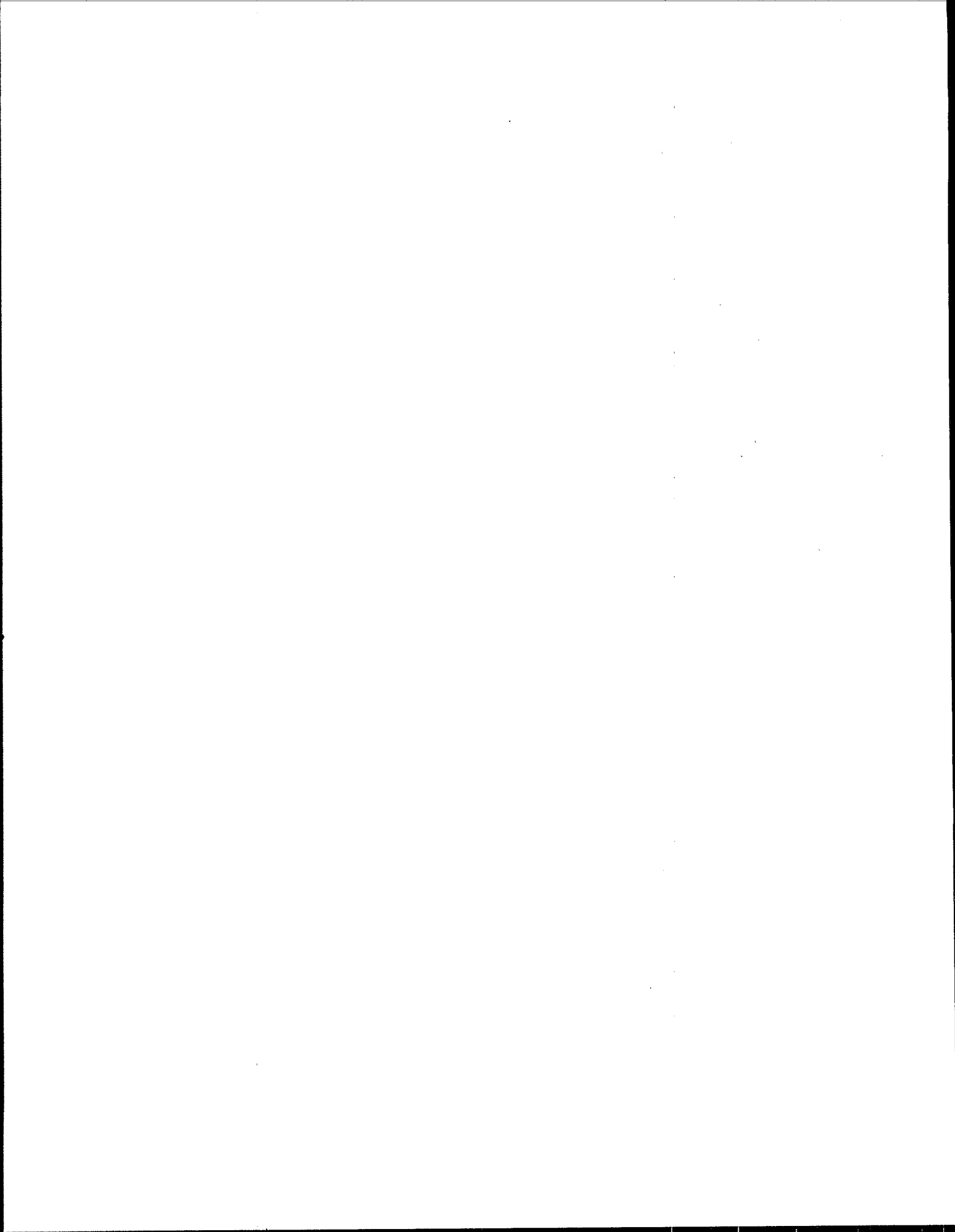
INTRODUCTION

This *Reference Manual* is one of three volumes of the *IPCC Draft Guidelines for National GHG Inventories*. It provides a compendium of information on the various human activities which cause greenhouse gas emissions to or removals from the atmosphere. It builds on work carried out in preparation of the OECD Report: *Estimation of Greenhouse Gas Emissions and Sinks, Final Report From the OECD Experts Meeting, 18-21 February 1991*, (OECD, 1991). In August 1991, the IPCC/OECD joint programme distributed this document as a starting point for development of guidelines for national inventories of greenhouse gases. In some sections for which no recent methodologies are available, it incorporates text with very little change from that document. In some areas, detail presented in the earlier report is summarized here. The OECD (1991) document remains a valuable reference document for national experts and others interested in the development of the IPCC National GHG Inventory Methods. In particular, detailed discussions of the reasoning behind some of the technical decisions made early in the IPCC/OECD programme can be found there.

Another major published resource document heavily used in the preparation of this *Manual* is the *Proceedings of an International IPCC Workshop on Methane and Nitrous Oxide, Amersfoort, NL, 3-5 February 1993* (van Amstel, 1993). To provide technical information for improvement of the early methods known to be weak, the IPCC/OECD programme established informal expert groups to work toward reaching international agreement on proposed revisions to the guidelines. A major landmark in this effort was the Amersfoort workshop sponsored by the Dutch government and hosted by the Netherlands National Institute of Public Health and Environmental Protection (RIVM). National experts presented their findings at the workshop and then discussions were held in working group sessions. The conclusions and recommendations have been drawn upon in the preparation of the *Guidelines*.

In preparing this document, the IPCC/OECD has also received valuable technical input from a number of other international workshops. The overall purpose of these workshops was to provide a forum for experts to discuss ways to improve the methodologies and reporting procedures and to ensure widespread participation in the development process. Many of the recommendations received have been incorporated into this revised Manual.

In general, the basic approach to estimating national emissions is similar across the various gases and human activities which are sources or sinks. Fundamentally, emissions are a product of activity data and emission factors.

Activity data are some quantitative measures of the level of the relevant human activity which occurs in the country (or region) of interest, during the inventory year. Activity data range from fuel combustion and industrial production statistics to numbers of domesticated animals of various types, to hectares of forest land converted to other uses.

Emission Factors are average relationships between a level of activity and the expected level of emissions which would result. Ideally they are derived from a number of data points of monitored emission levels from a single type of activity or technology being used in different places under different conditions.

In reality, these calculations are often more complicated than this would indicate, with several steps being involved in the calculation of each of the general terms - activity data and emission factors. But it is useful to keep this general structure in mind as it provides an organizing framework for all of the calculations and a means of evaluation and comparison.

The *Reference Manual* frequently provides a number of different possible methodologies or variations for calculating a given emission. In most cases these represent calculations of the same form but the differences are in the level of detail at which the original calculations are carried out. Wherever possible the methodology provides a "tiered" structure of calculations which describes and connects the various levels of detail at which national experts can work depending on the importance of the source category, availability of data, and other capabilities. All national experts are encouraged to work at the most detailed level which is possible and appropriate for their situation. The tiered structure ensures that estimates calculated at a very detailed level can be aggregated up to a common minimum level of detail for comparison with all other reporting countries.

The methodology is by necessity broken down into segments and presented category by category. It is important to recognize some key linkages and interactions among components. For example, calculations in land use change and forestry methods (chapter 5), energy (chapter 1) and agriculture (chapter 4) are connected with one another through the calculation of emissions from biomass as fuel. Several sub-categories within the energy chapter make use of common data elements which must be consistent. There are many other such examples which are noted in the appropriate sections of the *Manual.*

Reviewers and users of this document will recognize that a full scale final editing has not yet been completed. There are significant inconsistencies in formats and styles among the various chapters and sometimes even within chapters. For example while most of the document uses footnotes, there are a few sections which provide notes at the end of the chapter or page. These editing problems will be corrected during the review process. The IPCC/OECD programme elected to place emphasis on completing the technical update and to produce a review draft quickly rather than correcting all of the appearance problems at the draft stage.

Another known problem of a more technical nature is the inconsistency in treatment of full molecular weight of nitrogen oxides (NO_x). Nitrogen oxides as emitted consist of NO and NO_2. The convention among engineers working with emissions from industrial combustion is to assume that all of the N is emitted as NO_2. However, experts on emissions from biomass burning have generally adopted a different convention, assuming that all of the N is emitted as NO. In the document, both conventions are used in different sections, and noted in each case. The programme recognizes that this is an unsatisfactory compromise, as a particular term or formula must have only one meaning in order to ensure comparability. This problem will be corrected in the final *IPCC Guidelines.*

Conclusion

This *Guidelines* document draws on the input of expert groups and national experts from around the world. The methodologies presented offer a recommended process for estimating and tracking national emissions inventories. Along with offering the best current methodologies for developing consistent national inventories, these *Guidelines* discuss weaknesses in the existing methodologies and identify technical areas where additional work is needed to develop better methods in the future.

The chapters are divided by subject areas and correspond to the same subject chapters in the *Workbook*. This document should be used by national experts as a reference tool to accompany the *Workbook* and the *Reporting Instructions* when constructing and reporting national inventories of GHG emissions and removals.

References

OECD (1991) *Estimation of Greenhouse Gas Emissions and Sinks, Final Report from the OECD Experts Meeting, 18-21 February 1991*. The Organization for Economic Cooperation and Development, Paris. Revised August 1991.

van Amstel, A.R., (ed.) 1993. *Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control. Proceedings of an International IPCC Workshop, Amersfoort, NL. 3-5 February 1993.* RIVM Report no. 481507003. Bilthoven, NL. July.

1 USING THE IPCC GUIDELINES

This document is one volume of the *IPCC Guidelines for National Greenhouse Gas Inventories*. The series consists of three books:

- THE GREENHOUSE GAS INVENTORY REPORTING INSTRUCTIONS

- THE GREENHOUSE GAS INVENTORY WORKBOOK

- 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) provide step-by-step directions for assembling, documenting and transmitting completed national inventory data consistently, regardless of the method used to produce the estimates. These instructions are intended for all users of the IPCC Guidelines and provide the primary means of ensuring that all reports are consistent and comparable.

The *Workbook* (Volume 2) contains suggestions about planning and getting started on a national inventory for participants who do not have a national inventory available already and are not experienced in producing such inventories. It also contains step-by-step instructions for calculating emissions of carbon dioxide (CO_2) and methane (CH_4) (also some other trace gases) from six major emission source categories. It is intended to help experts in as many countries as possible to start developing inventories and become active participants in the IPCC/OECD programme.

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. It also provides summaries of the scientific basis for the inventory methods recommended and gives extensive references to the technical literature. It is intended to help participants at all levels of experience to understand the processes which cause greenhouse gas emissions and the estimation methods used in compiling inventories.

The three books are designed to be used together and include these features:

- all three volumes use an identical arrangement and numbering by source category for ease of cross reference

- all the books have a common index which allows you to follow up all references to a topic

  (The common index will be included in the final, approved version but not in the February 1994 review draft.)

- icons in the margin of each book indicate the source category

- colour coding on the page indicates source category.

  (Colour will be included in the final, approved version but not in the February 1994 review draft.)

Before you start...

This diagram explains the stages needed to make a national inventory which meets IPCC standards.

```
                    ┌─────────────────┐
                    │ Do you have a   │          Yes
                    │ detailed        │─────────────────────┐
                    │ National        │                      │
                    │ inventory?      │                      │
                    └─────────────────┘                      │
                            │                                │
                            │ No                             │
                            ▼                                ▼
                 ┌──────────────────┐          ┌──────────────────┐
                 │ Plan inventory   │          │ Aggregate/       │
                 │ assemble data    │          │ transform        │
                 │                  │          │ data and put     │
                 │                  │          │ into standard    │
                 │                  │          │ format           │
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                            ▼
   No     ┌─────────────────────────┐   Yes    ┌──────────────┐
 ┌────────│ Do you want to use      │─────────▶│ Use software │
 │        │ IPCC Computer Software? │          │ and workbook │
 ▼        └─────────────────────────┘          └──────────────┘
┌──────────────┐                                       │
│ Use manual   │                                       │
│ work sheets  │                                       │
│ in workbook  │                                       │
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 └────────▶│ Reporting            │◀───────────────────┘
           │ recommendations      │
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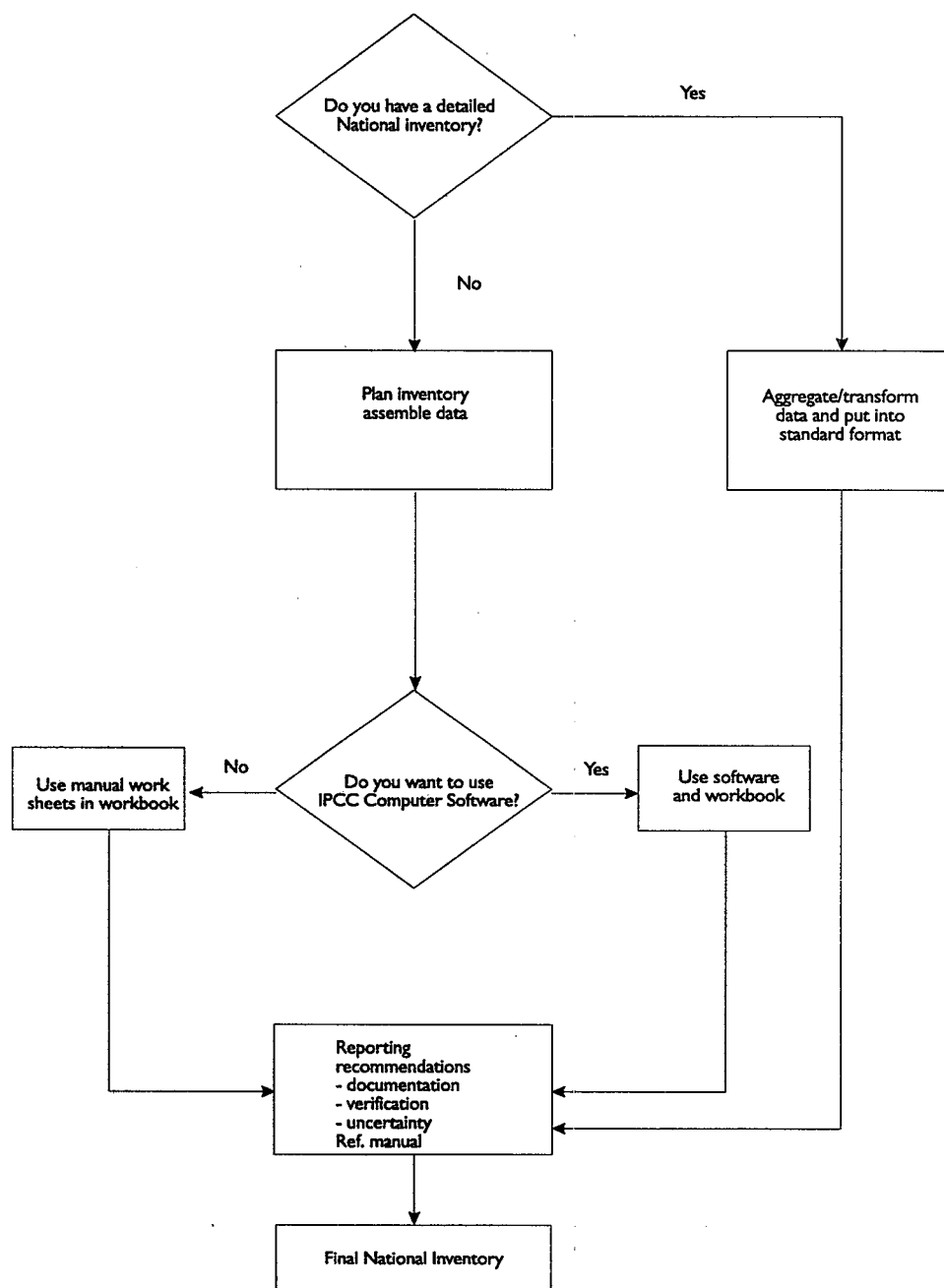
The stages are:

Question 1
Do you have a detailed national inventory?

Answer: Yes

If your country already has a complete national inventory, you should transform the data it contains into a form suitable for use by IPCC. This means transforming it into a standard format. In order to do this, use Volume 1 of the *IPCC Guidelines, Reporting Instructions*. This gives details of the way in which data should be reported and documented.

Answer: No

You should start to plan your inventory and assemble the data you will need to complete the Worksheets in this book. Refer to the *Getting Started* section of this *Workbook*.

Question 2
Do you want to use the IPCC computer software?

Answer: Yes

If you want to use the IPCC software, you will still follow the instructions are included in the *Workbook* to assemble the data you have collected into an inventory (see margin box). You will use the software instead of the printed worksheets to enter data.

Answer: No

If you do not use the IPCC software, use the *Workbook* and the Worksheets it contains to assemble the data you have collected into an inventory.

Finally...

Inventory data should be returned to IPCC in the form recommended in the *Reporting Instructions*. It is important that, where you have used a methodology other than the IPCC Default Methodology, it is properly documented. This will ensure that national inventories can be aggregated and compared in a systematic way in order to produce a coherent regional and global picture.

General Notes on the Guidelines

1   The flow diagram above is intended as a simple schematic to illustrate the different types of users (working at different levels of inventory detail) and how they should be able to use the various volumes of the Guidelines. You should recognise that reality is more complex than this simplest explanatory chart. Many countries may have some parts of the inventory complete at a high level of detail but may only be getting started on other parts. It is quite likely that some users will need to do several iterations of the thinking process reflected in the diagram with regard to different parts of their inventory.

2   Throughout the Guidelines there is an intentional double-counting of carbon released from human activities. On one hand, CO_2 is calculated based on the assumption that all of the carbon in original fuel, biomass,

soils etc. which oxidizes produces CO_2. For combustion sources, however, methods are also provided to estimate portions of the original carbon which are released as CH_4 and CO. The primary reason for double counting this is that carbon is that carbon released as CH_4 or CO is eventually converted to CO_2 in the atmosphere. This occurs in less than 15 years, which is short relative to the 100+ years lifetime of CO_2 in the atmosphere. Therefore carbon emitted as CH_4 and CO can have two effects. First, in the form initially emitted, and, second, as part of long term CO_2 accumulation in the atmosphere. In order to have a very precise estimate of the actual emissions of carbon species for a given year (i.e. as input to a complex atmospheric model) you should subtract carbon in reported CH_4 and CO from CO_2 to get net annual CO_2 emissions.

3 Many of the categories of greenhouse gas emissions and removals can only be estimated with large ranges of uncertainty. Quite naturally, some national experts have developed methods which are designed to produce ranges of estimates rather than point estimates for highly uncertain categories.. The IPCC Guidelines, however, require that users provide a single point estimate for each gas and emissions/removal category. This is simply to make the task of compilation, comparison and evaluation of national reports manageable. Users are encouraged to provide uncertainty ranges or other statements of confidence or quality along with the point estimates. The procedures for reporting uncertainty information are discussed in the *Greenhouse Gas Inventory Reporting Instructions*.

PART 2
SECTORS
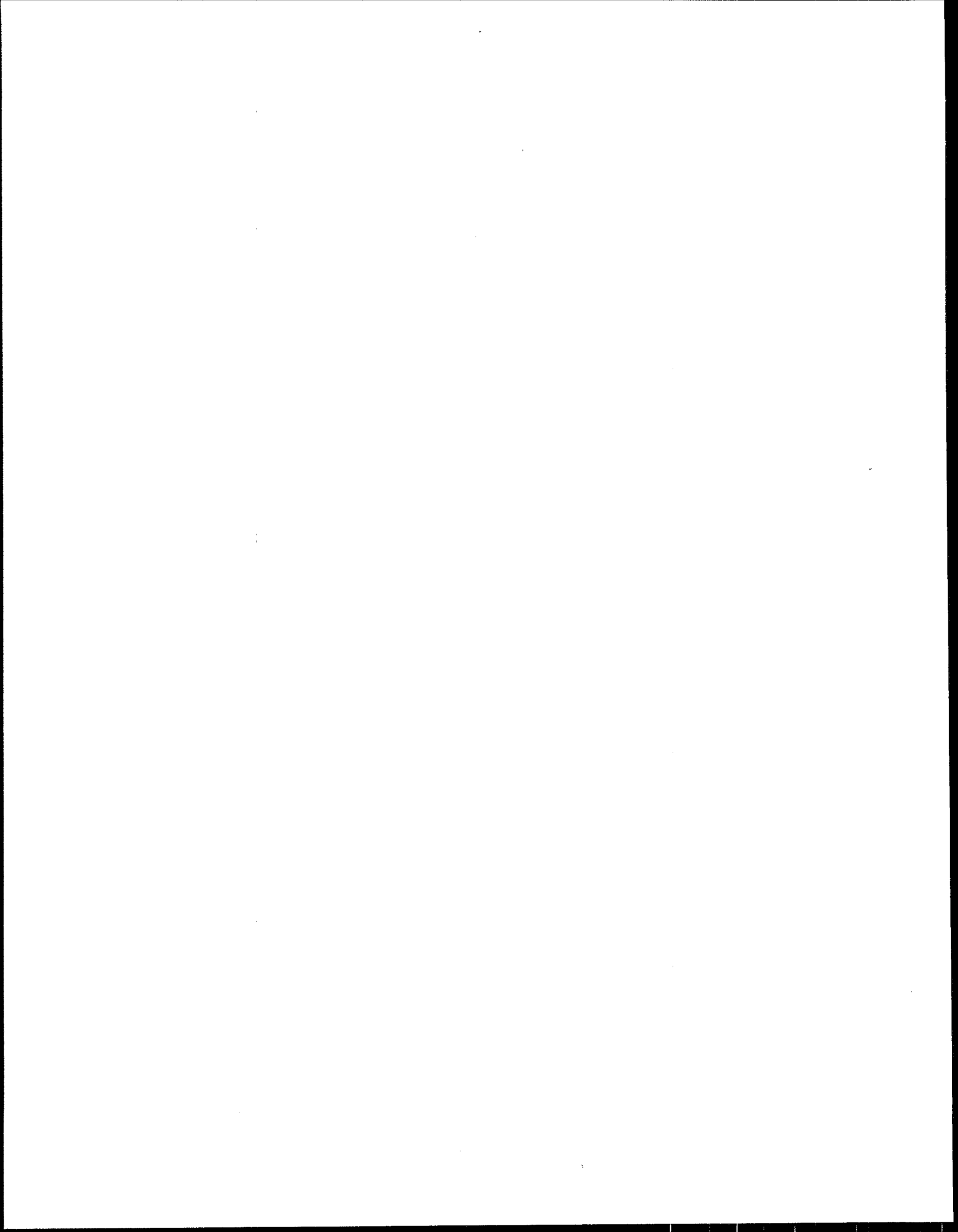
CHAPTER I
EMISSIONS FROM ENERGY
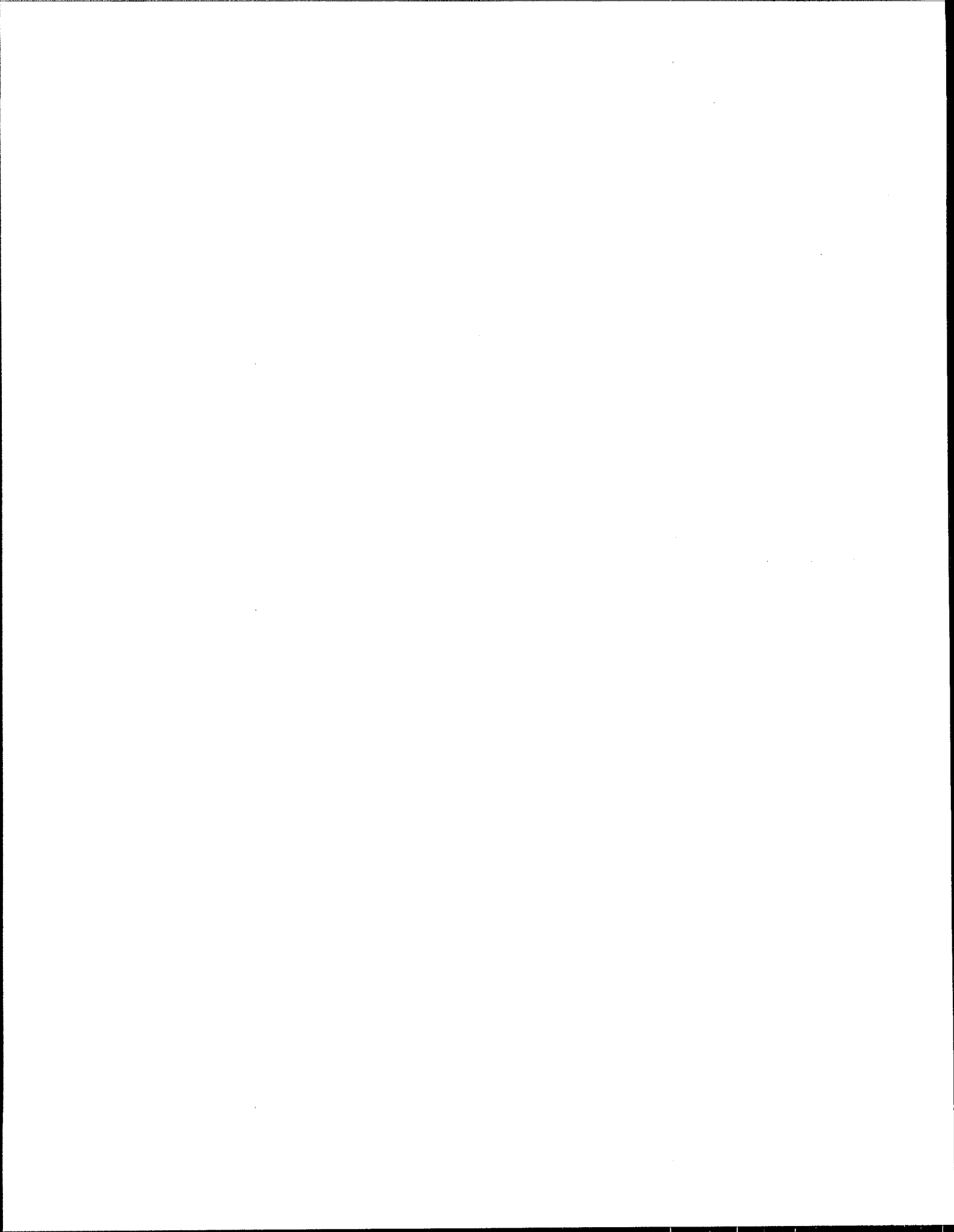
CHAPTER I   EMISSIONS FROM ENERGY

I.I   Introduction

This chapter discusses inventory methods for the energy sources of greenhouse gases, which include CO_2, CH_4, N_2O, NO_x, NMVOC and CO. Energy systems are extremely complex and pervasive components of national economies. The full range of greenhouse gases are emitted from a wide variety of different aspects of energy production, transformation handling and consumption activities. The various emissions from energy systems are organized in two main categories - 1) emissions from combustion, and 2) non-combustion, or "fugitive" emissions.

In dealing with fuel combustion emissions, CO_2 is discussed in a separate section because it can be calculated accurately at a highly aggregate level, unlike other gases. CO_2 emissions are primarily dependent on fuel properties. The IPCC reference method for CO_2 emissions from fuel combustion is a simple, accurate and internationally transparent approach which takes advantage of this fact. Non-CO_2 greenhouse gases are more related to technology and combustion conditions, and hence, must be estimated from detailed sectoral energy activity data.

CO_2 from energy activities can be estimated on a mass balance basis using information on the amount and carbon content of the fuels consumed. Primary energy data, with a few adjustments such as for non-oxidized products, serve as the basis of the inventory calculation. Energy data on all commercial fuels are widely available from internationally-validated data bases for individual countries of the world. These data provide an accurate starting point for the estimation of CO_2 inventories. However, since fuel qualities vary by region, so will emission factors. For global or regional estimations of CO_2, these variations are slight enough that they will not significantly affect inventories. However, wide variation among the types of fuels consumed within the primary fuel categories from one nation to another will affect the accuracy of each national inventory. For example, certain countries may depend on lignite, whereas others will use only bituminous coals. As discussed later, the variation in emission factors within fuel categories can be as high as 10%. As a result, national energy data and appropriate emission factors should reflect the actual mix of fuel types within each country.

Unlike CO_2, national inventories of CH_4, N_2O, NO_x, CO and NMVOCs all require more detailed information. This is due to the dependence of non-CO_2 emissions on several interrelated factors, including combustion conditions, technology, and control policies, as well as fuel characteristics. These other gases cannot be estimated on the same mass balance basis as used for CO_2, as the use of average emission factors for broad emission categories will introduce high levels of uncertainty. Average emission factors can represent a wide distribution of values even across a single source category or sub-category. CO_2 emissions can also be calculated at the more detailed level required for other gases. When national experts calculate other GHG emissions from energy combustion at a detailed level, they should use the same data to estimate CO_2 at the more detailed level as well. Comparison and reconciliation of the aggregate and detailed CO_2 emissions calculations can serve as a valuable verification process. Procedures for estimating CO_2 at both levels of detail are discussed in this chapter. For all emissions estimates, the range of uncertainty should be stated to the extent feasible. *Volume I: Reporting Instructions* discusses approaches for estimating and expressing uncertainty.

The non-CO_2 gases from energy are discussed according to two major combustion source categories: stationary sources and mobile sources. The use of these two main categories

is the most common method for the initial disaggregation of energy combustion activities. These two categories also best represent differences in the types of service, which also captures technology differences. A special section on traditional biomass fuels is included because they may need to be treated with a somewhat different approach from other stationary combustion sources. This is due to their dispersed nature and scarcity of data on this category.

Fugitive emissions are essentially intentional or unintentional releases of greenhouse gases during production including from venting and flaring, processing transmission and storage of fuels. The most significant greenhouse gas emissions in this category are methane emissions from coal mining and from oil and gas systems. There are also emissions of other gases, such as CO_2 and NMVOC as fugitive or by-product emissions from energy systems.

1.1.1 Organization of the Chapter

In addition to this introduction, this chapter is organized into six separate energy sections:

- **CO_2 emissions from fossil fuels:** CO_2 emissions from all combustion sources are estimated using an aggregate carbon balance approach to account for all carbon across all energy categories.

- **Non-CO_2 emissions from stationary sources:** Separated by common type of service sector, and further by technology, estimation of non-CO_2 emissions from stationary source activities focuses on large facilities for NO_x and on the commercial and residential sectors for CO and VOC.

- **Non-CO_2 emissions from burning of traditional biomass fuels:** A simplified approach is provided because data are often inadequate for estimating emissions from this category based on technology-specific emission factors. This approach is designed to be used with data obtainable in developing countries where traditional fuels make up a large fraction of total energy use.

- **Non-CO_2 emissions from mobile sources:** Mobile source activities are divided by transport mode, vehicle type and size to characterize a diverse range of engine types and their respective emission characteristics.

- **Fugitive emissions from coal production and handling activities:** Emissions are generated as a result of the production and handling of coal, primarily methane emissions from coal mining. Other emissions of GHG from coal mine and waste fires, are briefly discussed.

- **Fugitive emissions from oil and gas systems:** Methane emissions from natural gas flaring and venting, and from natural gas production, transmission and distribution are the most important for this category. CO_2 emissions from venting and flaring are included as are NMVOC emissions from production, processing and distribution of oil and oil products.

1.2 Emission Factor Data

Emissions of GHGs from fuel combustion and fuel supply activities are calculated by multiplying levels of activity by emission factors. Emission factors are usually presented in the form of mass of pollutant per unit of activity (e.g., g N_2O/GJ). The most commonly used activity measure for energy-related emissions is the amount of fuel combustion or, where fugitive emissions are concerned, the amount of fuel produced or distributed. In some cases other measures of activity are used, most notably in calculating emissions from the transport sector.

For CO_2 emission factors are a function of fuel quality, but for all other gases emission factors are also related to other factors (e.g., combustion technology, combustion conditions, control technology). A number of international and national sources of energy and industry emission factors exist largely as a result of international and national analyses of alternative control policies for SO_x, NO_x and NMVOC. A few sources have also recently emerged on various other GHGs. The more detailed factors (for gases other than CO_2) do not relate directly to national energy activity data described below, but require some additional information. The sources of emission factor data and procedures for making these linkages are discussed in the context of specific gases and source types, in the relevant sections which follow.

1.3 Energy Activity Data

Subject to the requirements outlined below and intended to ensure the comparability of country inventories, the IPCC approach to the calculation of emission inventories encourages the use of fuel statistics collected by an officially recognised, national body as this is usually the most appropriate and accessible activity data. In some countries, however, those charged with the task of compiling inventory information may not have ready access to the entire range of data available within their country and may wish to use data specially provided by their country to the international organisations whose policy functions require knowledge of energy supply and use in the world.

There are, currently, two main sources of international energy statistics: the International Energy Agency of the Organization for Economic Cooperation and Development (OECD/IEA), and the United Nations (UN). The primary energy data sources cited in this report include:

- From the OECD/IEA: Energy Statistics and Balances for Non-OECD Countries (OECD/IEA, 1993a); Energy Balances of OECD Countries (OECD/IEA, 1993b); and Energy Statistics (OECD/IEA, 1993c).

- From the United Nations: Energy Statistics Yearbook (UN, 1993).

There is a substantial amount of overlap among these two systems. The UN uses data supplied by the IEA for the countries of the OECD, and the IEA starts with the UN data for non-OECD countries when preparing its world energy data publication. While the UN data set starts with IEA data for OECD countries, in its book-form publications it reports slightly more detail by fuel. This is simply a preference for reporting, since all data points exist in the original IEA source and are available in machine-readable format (i.e., magnetic tape or computer diskette).

Another issue is the "official" nature of the statistics reported by each source. The UN data source represents the official energy profile of both OECD countries (via the IEA source) and the rest of the world, via their own national data collection and review procedures. Alternatively, the IEA begins with the UN data for non-OECD countries, compiles it in their format, and augments it with information not available to the UN, e.g., data from oil companies and other energy industries provided to the IEA. These additions to the basic UN data are checked for internal consistency and against other sources of data for the country, and when discrepancies exist, experts are contacted in the country

for an opinion as to which data to use. Coverage of the nations of the world in the IEA data is not complete.[1]

1.3.1 Comparability of Reporting

In order to meet the objectives of the IPCC/OECD programme, inventories submitted by parties to the agreement must be readily comparable. This requires a large measure of commonality of definitions of activities and fuel product groups and the use of a reporting discipline which makes evident the construction of the inventory from the activity data. Specific guidelines for reporting have been prepared. In order to reduce the uncertainty created by possibly different definitions, the IPCC methodology recommends the use of those utilised by the IEA for the regular collection of energy data from OECD member countries. The active cooperation between the UN Statistical Division (New York), the UNECE (Geneva), Eurostat and the IEA has ensured that there are now very few differences between the definitions employed by these organisations for the collection of their energy data. The IEA definitions may be found in *Energy Balances of OECD Countries 1990-91*.

The paragraphs above make clear that the reporting country, when constructing the inventory, is entitled to use national data from local sources or the national data as reported to the international organisations. If local data are used, this should be stated, identified and the reasons for preferring it to those provided to the international organisations discussed in the documentation accompanying the submission. The activity data used should also be reported.

A group of experts convened recently to discuss in detail the existing internationally compiled energy data bases and their use in estimating GHGs, primarily carbon dioxide.[2] This group included representatives of the two major data collection activities (UN and IEA), the IPCC/OECD programme and a number of experts who have used or currently are using these data for the purposes of estimating GHG emissions. The experts in this meeting confirmed that, of existing data sources, "the data bases of the UN Statistical Division in New York and of the IEA are the most comprehensive and provide the basis for others. There is good consistency between the UN data base, the IEA data base and other data bases such as those of the UN-ECE and CEC (EUROSTAT data set)."

An important result of the experts' meeting, which led to the IPCC methodology, was to highlight the importance of careful and comprehensive reporting of national energy data in relation to its use in GHG emissions estimation and analysis. Experts recommended that every effort be made to communicate to national agencies who provide energy data that this data plays a crucial role in international evaluation of national GHG emissions. It is hoped that this awareness will provide an additional motivation for national energy data sources to allocate adequate effort to the development and reporting of energy data so that comprehensive and high quality information will be available as input to GHG assessments. This recommendation is being conveyed through traditional channels to energy statistics sources and also reinforced through environmental channels such as the IPCC and INC.

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[1] Approximately 120 countries (of about 170 UN Member countries) are included in the IEA data, but the countries it includes account for about 98% of worldwide energy consumption and nearly all energy production.

[2] This meeting was convened by the International Atomic Energy Agency (IAEA), and detailed results are described in IAEA. 1993.

Inconsistent reporting standards among both national and international energy data sets can lead to differences that hinder comparison and comparable inventory development. At least five aspects of energy data reporting need to be checked prior to using data for greenhouse gas inventories:

■ Are energy data reported in terms of lower heat values (LHV) or higher heat values (HHV)?[3] Since most of the world uses lower heat values, the IPCC *Guidelines* use lower heating values.

■ Are waste or waste-derived fuels included if combusted for energy production? These fuels should be accounted for in the IPCC methodology, but are included with biomass fuels.

■ Is non-energy fuel usage (if non-oxidized) accounted for?[4]

■ How are international bunker fuels for air and ship transport treated?[5]

■ Are non-commercial fuels, including wood and other biomass fuels, included?[6]

Given responses to these questions, several adjustments may need to be made to the energy data being used in order to formulate a complete inventory of greenhouse gases. If published IEA data are being used the following corrections must be made:

1 Bunker fuels and vegetal fuels (both commercially-traded and traditional or non-commercial biomass fuels) need to be added to each country of origin. The IEA has some data on commercially-traded vegetal fuels, but traditional biofuels consumption, e.g., wood collected for cooking by individuals, is typically not included in official energy statistics.

2 Non-energy fuel use needs to be estimated and deducted from apparent energy consumption.[7] Adjustments also need to be made for the portion of non-energy uses that do not oxidize.

3 Vegetal fuels should be separated and added as a separate fuel group.

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[3] The IEA generally reports data in lower heat values. The difference between the lower and the higher heating value of a fuel is the heat of condensation of moisture in the fuel during combustion. The lower heating value excludes this. The IEA assumes that lower heating values are 5% lower than higher heating values for oil and coal and 10% lower for natural gas.

[4] This is normally reported in primary energy requirements but is not combusted and therefore does not contribute directly to greenhouse gas emissions.

[5] Bunker fuels are combusted at sea and by airplanes and therefore should be included in greenhouse gas estimations. The question is how to allocate emissions among nations or regions. As discussed later, the Paris workshop recommended that emissions from bunker fuels be estimated as a separate category under energy-related emissions, and that the issue of how to allocate these emissions be addressed and agreed upon internationally in follow-up efforts. Okken and Tiemersma (1984) provide an example of the contribution of shipping bunker fuels to the Netherlands' CO_2 budget.

[6] While some of these fuels (such as wood) may be included in national or international data sets, it is likely that they are underestimated due to poor record keeping and lack of statistical information for non-commercial fuels.

[7] IEA data on bunker fuels and non-energy fuel use represent only a partial accounting of these activities and would need to be supplemented with outside information. Specifically, non-energy natural gas products and aviation bunker fuels are not separated in the IEA statistics.

These adjustments can be quite significant to the energy balance and hence to the calculation of greenhouse gases. For example, in 1987 international bunker fuels for shipping represented about 3 per cent of the global oil requirement, but in some countries accounted for a much higher share. Non-commercial vegetal fuels in 1987 are estimated to represent less than 4% of total primary energy requirements (TPER) in the OECD and CPE, but nearly 22% for Developing Countries. Non-energy use of fuel products represented about 10% of the world oil TPER in 1987.[8]

1.4   Carbon Dioxide Emissions from Energy

In this section methodology for estimating CO_2 emissions from energy is discussed. Carbon dioxide (CO_2) is the most common greenhouse gas produced by anthropogenic activities, accounting for about 60% of the increase in radiative forcing since pre-industrial times. (IPCC, 1992) By far the largest source of CO_2 emissions is from the oxidation of carbon when fossil fuels are burned, which accounts for 70-90% of total anthropogenic CO_2 emissions. When fuels are burned, most carbon is emitted as CO_2 immediately during the combustion process. Some carbon is released as CO, CH_4, or non-methane hydrocarbons, which oxidize to CO_2 in the atmosphere within a period from a few days to 10-11 years. The IPCC methodology accounts for all of the carbon from these emissions in the total for CO_2 emissions. The other carbon-containing gases are also estimated and reported separately (see following sections for methodologies for estimating CH_4, CO, and non-methane VOCs).[9]

Fuel combustion is widely dispersed throughout most activities in national economies, and assembly of a complete record of the quantities of each fuel type consumed in each "end use" activity is a considerable task, which some countries have not yet completed. Fortunately, it is possible to obtain an accurate estimate of national CO_2 emissions by accounting for the carbon in fuels supplied to the economy. The supply of fuels is simple to record and is more likely to be available in many countries, than detailed end use consumption statistics. For this reason, the IPCC Reference Approach for estimating emissions of CO_2 from fossil fuels is somewhat different than the approach used for other greenhouse gases. For CO_2 emissions depend mostly on the basic fuel characteristics rather than on technology or emission controls (as with gases such as NO_x or CO).

The Reference Approach requires a careful accounting of fossil fuel production by energy type, carbon content of fossil fuels consumed, fossil fuel consumption by type, and production of products with long term carbon storage. In this respect the methodology for estimating CO_2 emissions represents more of a "top-down" approach compared to the "bottom-up" approach recommended for the other gases. This does not mean that a "bottom-up" approach used for other gases cannot also be followed for estimating CO_2

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[8] Also combustion of non-energy oil products, such as plastics or refuse-derived fuel, may not be consistently counted in the energy statistics compared to other solid fuels, nor would they be included in the base energy statistics if combusted without energy recovery. No global estimate of their significance is available.

[9] It is important to note, as discussed in the introduction to this document, that there is an intentional double counting of carbon emitted from combustion. This format treats the non-CO_2 gases as a subset of CO_2 emissions and ensures that the CO_2 emission estimates reported by each country represent the entire amount of carbon that would eventually be present in the atmosphere as CO_2. The reasons for this double counting are discussed in the introduction.

emissions. A method for estimating emissions with a "bottom-up" approach is briefly discussed later in this section. It is recommended that national experts who do detailed estimates of emissions of non-CO_2 gases, should also apply CO_2 emission factors at this detailed level. In all cases, experts should estimate CO_2 emissions from fuel combustion using the IPCC reference method also. This method provides the basis for international comparison, and all national estimates should be reconciled with the results of this approach.

For all calculations of CO_2 emissions from fuel combustion, emissions are directly related to the amount of fuel consumed and the carbon content of the fuel. Coal contains close to twice the carbon of natural gas and roughly 25 per cent more than crude oil per unit of useful energy. A number of complicating factors need to be considered carefully:

■ **Common Energy Units:** There is considerable variation in the energy content by weight of some fuels, especially coals. For comparison all energy data must first be converted to common energy units (e.g., gigajoules) before emission factors (or coefficients) are applied.

■ **Variations in Fuel Carbon:** For a given fuel type, even when quantified in energy units, the carbon per unit of useful energy varies. For example, not all coal types contain the same proportion of carbon. Generally speaking, the lower the quality of the coal (such as sub-bituminous coal and lignite), the higher the carbon emission factor (i.e., carbon per unit of energy).[10] There are similar carbon differences among the different types of liquids and gases.

■ **Unoxidized Carbon:** When energy is consumed not all of the carbon in the fuel oxidizes to CO_2. Incomplete oxidation occurs due to inefficiencies in the combustion process that leave some of the carbon unburned or partially oxidized as soot or ash.

■ **Stored Carbon:** Not all fuel supplied to an economy is burned for heat energy. Some is used as a raw material (or feedstock) for manufacture of products such as plastics, fertilizer, or in a non-energy use (e.g. bitumen for road construction, lubricants). In some cases, as in fertilizer production, the carbon from the fuels is oxidized quickly to CO_2 once applied and exposed to air. In other cases, as in road construction, the carbon is stored (or sequestered) in the product, sometimes for as long as centuries. The amounts stored for long periods are called *stored carbon* (or sequestered carbon), and should be deducted from the carbon emissions calculation. Estimation of stored carbon requires data on fuel used as feedstock and/or quantities of non-fuel energy products produced. The calculations are discussed within each of the alternative approaches presented in this section.

■ **Bunker Fuels:** Bunker fuels refer to quantities of fuels used for international marine or aviation purposes. The IPCC methodology accounts for these fuels as part of the energy balance of the country in which they were **delivered** to ships or aircraft. Thus the CO_2 emissions from combustion of those fuels would also appear in the country of delivery, even though most of the actual emissions occur outside its boundaries. This is done to ensure that all fuel use is accounted for in the methodology. However. for informational purposes, the quantities and types of fuels delivered for international bunker purposes should be separately subtotaled.

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[10] The major exception to this relationship is anthracite or very hard coal, which typically has a higher carbon emission coefficient than bituminous coal.

- **Biomass Fuels:** Biomass fuels are included in the national energy and emissions accounts for completeness, as an information item. These emissions should not be included in the summation of national CO_2 emissions from energy. If biomass is being regrown at roughly the same rate as it is being harvested on an annual basis, the net flux of CO_2 to the atmosphere is zero. If energy use, or any other factor, is causing a long term decline in the total carbon embodied in standing biomass (e.g. forests), this net release of carbon should be evident in the calculation of CO_2 emissions described in the *Land Use Change and Forestry* chapter.

All of the above issues are addressed within each of the alternative approaches presented in the remainder of this section.

1.4.1 Approaches For Estimating CO_2 Emissions

The conceptual approach for estimating CO_2 emissions from energy consumption is well-known and straightforward. The basic calculations can be characterized as six fundamental steps that explicitly identify all of the factors necessary to measure CO_2 emissions from energy consumption:

1   Estimating consumption of fuels by fuel product type.

2   Converting fuel data to energy units (if necessary).

3   Selecting carbon emission factors for each fuel product type and total carbon potentially released from use of the fuels.

4   Estimating the amount of carbon stored in products for long periods of time.

5   Accounting for carbon not oxidized during combustion.

6   Converting emissions as carbon to full molecular weight of CO_2.

There are three basic approaches for estimating CO_2 emissions discussed in this document that vary primarily according to the level of detail at which these six steps are carried out. The methods are:

1   **The IPCC Reference Approach: Detailed Fuels.** The Detailed Fuels approach is the basic methodology recommended by the IPCC and requires information on several different types of energy products. This approach is sometimes referred to as "top-down" estimation since a country only needs information on the quantities of fuels produced domestically, and flowing into and out of the country. Accounting for actual consumption of fuels at the sectoral or sub-national level is not required.

2   **Detailed Technology Based Calculation: "Bottom-Up" Method.** Most countries would ultimately like more detail on emissions of CO_2 by energy using sub-sector than provided in the reference approach. This information is clearly necessary for evaluating policy options for reducing GHG emissions. In addition, if national experts are calculating emissions of non-CO_2 GHGs from energy combustion, they are very likely working at a much finer level of energy use and technology detail. It is desirable to estimate CO_2 emissions and other gases at the same levels of detail for consistency purposes. The basic calculations to estimate CO_2 can be applied a very detailed level, including by sector and fuel types consumed in specific end-uses. This level of calculation is called "bottom-up" because it is very data-intensive, requiring a substantial amount of information about national energy consumption patterns in each sector of a nation's economy. Some of the additional complexities which must be addressed at this level are discussed briefly at the end of this section. If national experts use this approach, it is recommended that they also use the IPCC reference

approach and reconcile any differences between results at the two levels of detail. This can be a very useful verification exercise.

3 **Aggregate Fuel Approach.** The aggregate fuel approach only requires information on the generic types of fossil fuels consumed in each country, specifically the quantities of solid, liquid, and gaseous fossil fuels consumed, and the amount of biomass consumed. No further detail on fuel product types is used in this approach. Since most countries have access to energy data that is more detailed than these general categories, this overly simplified approach is not recommended by the IPCC unless the reference approach cannot be implemented. Discussion of this aggregate fuels approach can be found in Annex A. As an alternative to the IPCC reference approach, this level of detail still allows a country to estimate CO_2 emitted, due to consumption of various types of fossil fuels, but at a very aggregate, and less accurate level.

I.4.2 IPCC Reference Approach: Detailed Fuels

The Reference Approach is based on an accounting of the carbon in fuels supplied to the economy. It involves the careful estimation of each country's production of fuels, imports of fuels and refined products, exports of fuels and refined products, and changes in the stock levels for these fuels and products within the country. It makes use of a simple assumption: once carbon is brought into a national economy in fuel, it is either saved in some way (e.g., in increases if fuel stocks, stored in products, left unoxidized in ash) or it must be released to the atmosphere. It is not necessary to know exactly how the fuel was used or what intermediate transformations it underwent in order to calculate the carbon released.

Carbon accounting is based mainly on the total supply of primary fuels and the net quantities of secondary fuels brought into a country. Using these values apparent consumption (i.e., energy supply) can be estimated   Once apparent consumption is estimated, subsequent steps account for carbon emission factors and other adjustments for the stored carbon, fraction oxidized, and other complications discussed in the introduction to this section.

ESTIMATE FUEL COMBUSTION

The first step of the IPCC Reference Approach is to estimate apparent consumption of fuels within the country. This requires a balance of primary fuels produced, plus imports, minus exports, and net changes in stocks. stock change.[11] In this way carbon is "transferred" into the country from energy production and imports (adjusted for stock changes) and transferred out of the country through exports. In this accounting system for fuels supplied it is important to distinguish between *primary fuels* (i.e., fuels which are found in nature such as coal, crude oil, natural gas), and *secondary fuels* or fuel products, such as gasoline and lubricants, which are derived from primary fuels.

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[11] This approach is similar to, but not as detailed as, standard energy balance accounting. Energy balances, by their nature, are an attempt to reconcile supply (apparent consumption) with observed consumption where all the end-use sectors are separately identified. The Reference Approach includes only the data necessary to account for carbon flows into and out of a country. Therefore, the level of detail needed for this approach to CO_2 emissions estimation is not as great as for a complete national energy balance.

To calculate the supply of fuels to the country, the following data are required for each fuel and inventory year:

■ the amounts of primary fuels produced (production of secondary fuels and fuel products is excluded)

■ the amounts of primary and secondary fuels and fuel products imported

■ the amounts of primary and secondary fuels and fuel products exported

■ the net increases or decreases in stocks of fuels

Production data would be provided for the primary (untreated) fuels, including crude oil, natural gas liquids (NGL), coking coal, steam coal, sub bituminous coal, lignite (brown coal), peat, and natural gas. These production data would define the initial amount of carbon available for consumption in a country from which CO_2 emissions are generated. To determine the net amount of carbon consumed, i.e., apparent consumption, any exports of these fuels would be subtracted and any imports added. Adjustments for stock changes are also needed. The apparent consumption of primary fuels is, therefore, calculated as:

> Production + Imports - Exports - Stock Change.

An increase in stocks is a positive stock change. As this is subtracted in the equation, a positive stock change results in a decrease in apparent consumption. A stock reduction is a negative stock change which, when subtracted in the equation, causes an increase in apparent consumption.

Flows of secondary fuels should be added to primary apparent consumption. The production (or manufacture) of secondary fuels should be ignored in the calculations of apparent consumption since the carbon in these fuels will already have been accounted for in the supply of primary fuels from which they were derived (e.g., the estimate for apparent consumption of crude oil already contains the carbon from which gasoline would be refined). However, information on production of some secondary fuel products is required in a later step to adjust carbon stored in these products. Flows of secondary fuels are calculated as:

> Imports - Exports - Stock Change.

Note that this calculation can result in negative numbers for Apparent Consumption. This is a perfectly acceptable result for the purposes of this calculation since it indicates a net export or stock increase in the country *when domestic Production is not considered.*

This procedure, in effect, calculates the supply of primary fuels to a country, with adjustments for net imports (imports-exports) and stock changes in secondary fuels.

Since carbon content typically varies by fuel type, data should be reported for detailed categories of fuel and product types as shown in Table 1-1. The table also illustrates the inputs and calculations recommended for the IPCC Reference Approach. The data are specified in the form available in the OECD/IEA *Energy Statistics* (1993). As discussed above, biomass fuels and bunker fuels have been included in the emission inventory calculations for information only. These subtotals are not added to the totals calculated for fuels above the line.

TABLE 1-1
IPCC REFERENCE APPROACH
ENTRIES AND CALCULATIONS FOR STEPS (1) AND (2)

Fuel	(1) Production	(2) Imports	(3) Exports	(4) Stock Change	(5) Apparent Cons.[1]	(6) Conver. Factor	(7) Apparent Cons. (GJ=10^5)
A) Liquid Fossil					sum()[2]		sum()
Primary Fuels							
1) Crude Oil	input	input	input	input	calc	input	calc
2) N.Gas Liquids	input	input	input	input	calc	input	calc
Secondary Fuels/Products							
3) Gasoline	NA	input	input	input	calc	input	calc
4) Kerosene	NA	input	input	input	calc	input	calc
5) Jet Fuel	NA	input	input	input	calc	input	calc
6) Gas/Diesel Oil	NA	input	input	input	calc	input	calc
7) Residual Fuel Oil	NA	input	input	input	calc	input	calc
8) LPG	NA	input	input	input	calc	input	calc
9) Naphtha	NA	input	input	input	calc	input	calc
10) Bitumen	NA	input	input	input	calc	input	calc
11) Lubricants	NA	input	input	input	calc	input	calc
12) Petroleum Coke	NA	input	input	input	calc	input	calc
13) Refinery F-stocks	NA	input	input	input	calc	input	calc
14) Other Oil	NA	input	input	input	calc	input	calc
B) Solid Fossil					sum()		sum()
Primary Fuels							
15) Coking Coal	input	input	input	input	calc	input[4]	calc
16) Steam Coal	input	input	input	input	calc	input[4]	calc
17) Lignite	input	input	input	input	calc	input[4]	calc
18) Sub-bit. Coal	input	input	input	input	calc	input[4]	calc
19) Peat	input	input	input	input	calc	input	calc
Secondary Fuels							
20) BKB & Patent Fuel	NA	input	input	input	calc	input	calc
21) Coke	NA	input	input	input	calc	input	calc
C) Gaseous Fossil				sum()		sum()	
22) Nat. Gas(Dry)	input	input	input	input	calc	input	calc
Total					sum()[3]		sum()
Information Entries (Not Summed)							
Biomass					sum()		sum()
23) Solid Biomass	input	input	input	input	calc	input	calc
24) Liquid Biomass	input	input	input	input	calc	input	calc
Bunkers - (Fuel Used for International Transport)							
Total					sum()		sum()
Jet Fuel Bunkers	NA	NA	NA	NA	input	input	calc
Gas/Diesel Oil Bunkers	NA	NA	NA	NA	input	input	calc
Resid. Fuel Oil Bunkers	NA	NA	NA	NA	input	input	calc
"Other Oil" Bunkers	NA	NA	NA	NA	input	input	calc

TABLE 1-1 (CONTINUED)
IPCC REFERENCE APPROACH
ENTRIES AND CALCULATIONS FOR STEPS (3) - (6)

Fuel	(7) Apparen Cons (GJ)	(8) Carbon Emission Factor[5] (Kg C/GJ)	(9) Potential Emissions[6] (Gg C)	(10) Carbon Stored (Gg C)	(11) Net Carbon Emissions (Gg C)	(12) Adjusted Carbon Emissions (Gg C)	(13) CO_2 Emissions (Gg CO2)
A) Liquid Fossil	sum()		sum()	sum()	sum()	sum()	sum()
Primary Fuels							
1) Crude Oil	calc	20.0	calc		calc	calc	calc
2) N. Gas Liquids	calc	15.2	calc		calc	calc	calc
Secondary Fuels/Products							
3) Gasoline	calc	18.9	calc		calc	calc	calc
4) Kerosene	calc	19.5	calc		calc	calc	calc
5) Jet Fuel calc	19.5	calc		calc	calc	calc	
6) Gas/Diesel Oil	calc	20.2	calc		calc	calc	calc
7) Residual Fuel Oil	calc	21.1	calc		calc	calc	calc
8) LPG	calc	17.2	calc	Table 1-4	calc	calc	calc
9) Naphtha	calc	NA(20.0)	calc	Table 1-4	calc	calc	calc
10) Bitumen	calc	22.0	calc	Table 1-4	calc	calc	calc
11) Lubricants	calc	NA(20.0)	calc	Table 1-4	calc	calc	calc
12) Petroleum Coke	calc	27.5	calc		calc	calc	calc
13) Refinery F-stocks	calc	NA(20.0)	calc		calc	calc	calc
14) Other Oil	calc	NA(20.0)	calc		calc	calc	calc
B) Solid Fossil	sum()	sum()	sum()	sum()	sum()	sum()	
Primary Fuels							
15) Coking Coal	calc	25.8	calc	Table 1-4	calc	calc	calc
16) Steam Coal	calc	25.8	calc		calc	calc	calc
17) Lignite	calc	27.6	calc		calc	calc	calc
18) Subbit. Coal	calc	26.2	calc		calc	calc	calc
19) Peat	calc	28.9	calc		calc	calc	calc
Secondary Fuels/Products							
20) BKB & Pat. Fuel	calc	NA(25.8)	calc		calc	calc	calc
21) Coke	calc	29.5	calc		calc	calc	calc
C) Gaseous Fossil	sum()		sum()	sum()	sum()	sum()	sum()
22) Natural Gas (Dry)	calc	15.3	calc	Table 1-4	calc	calc	calc
Total[7]	sum()		sum()	sum()	sum()	sum()	sum()
Information Entries (Not Summed)							
Biomass Total	sum()		sum()		sum()	sum()	sum()
23) Solid Biomass	calc	29.9	calc		calc	calc	calc
24) Liquid Biomass	calc	NA(20.0)	calc		calc	calc	calc
Bunkers - (Fuel Use in international Transport)							
Total	sum()		sum()		sum()	sum()	sum()
Jet Fuel Bunkers	calc	19.5	calc		calc	calc	calc
Gas/Diesel Oil Bunkers	calc	20.2	calc		calc	calc	calc
Resid. Fuel Oil Bunkers	calc	21.1	calc		calc	calc	calc
Other Oil Bunkers	calc	NA(20.0)	calc		calc	calc	calc

TABLE 1-1 (CONTINUED)
EXPLANATORY NOTES

calc = value to be calculated,   NA = not applicable

TABLE I-I (CONTINUED)
EXPLANATORY NOTES

calc = value to be calculated,   NA = not applicable

[1] Apparent Consumption equals production plus imports minus exports minus stock changes. Apparent Consumption includes energy use for bunkers, although the subset of each category consumed as bunker fuels should be calculated separately to allow for differential treatment at a later date.

[2] Apparent Consumption for the aggregate categories of Liquid Fossil, Solid Fossil, Gaseous Fossil, and Biomass Fuels equal the sum of Apparent Consumption over the fuel types within the appropriate categories.

[3] Total should include Liquid, Solid, and Gaseous Fossil Fuel subtotals only. Biomass and Bunkers subtotals are for informational purposes only. and should not be included in the totals.

[4] If data is in 10^3 mt, separate conversion factors are available for Production, Imports, Exports, and Stock Changes in Table I-2. Each of these entries should be multiplied by the appropriate conversion factor. Then, the results should be summed to find Apparent Consumption in GJ (Col. 7).

[5] NA = Carbon Emission Factor (CEF) not available; value in parenthesis is a default value until a fuel-specific CEF is determined. For oil products the default value is the emission for crude oil; for coal products the default value is the emission factor for steam coal. All values taken from Grubb (1989), except LPG, which was taken from Marland and Pippin (in press), and subbituminous coal which was taken from Bowling (1989).

[6] calc = calculation to be made by respondent; in this case, Consumption (column 1) is multiplied by the Carbon Emission Factor (column 2) and converted to Gg.

[7] Total includes Liquid Fossil, Solid Fossil, and Gaseous Fossil subtotals only. Biomass emissions are not considered "net" emissions, and bunker data is already included in the totals for the fuel types from which it is derived. Separate biomass and bunker fuel totals are provided for information only.

CONVERT FUEL DATA TO COMMON ENERGY UNITS (IF NECESSARY)

Fuel statistics are needed on an <u>energy basis</u> (preferably in gigajoules; I gigajoule = 10^9 joules) for accurate estimation of CO_2 emissions. In the OECD/IEA *Energy Statistics*, and in many other energy data compilations, production and consumption of solid and liquid fuels are specified in 10^3 metric tons (10^3 mt). To convert metric tons to gigajoules, conversion factors must be applied. For unrefined fuels, energy content per tonne of fuel can vary widely from country to country. Default conversion factors for a number of countries based on IEA energy data. These values to convert from 10^3 metric tons to gigajoules are in Table I-2. Note that in many cases different conversion factors are given for production, imports and exports in a given country. These can be used to convert each of these categories separately in the calculation of apparent consumption. For stock changes national experts can use a weighted average of the different conversion factors, or use the one which represents the largest quantity of total apparent consumption for that coal type. For refined products the conversion factors from 10^3 metric tons to gigajoules do not normally vary by country and global default values are provided in Table I-3.[12]

National experts may use more detailed locally available conversion factors. In this case, the conversion factors used should also be reported and documented. If original data are expressed in other energy units such as British thermal units (Btu's), million tons of oil equivalent (Mtoe), they should be converted to gigajoules using standard conversion factors. If energy data are already available in gigajoules, no conversion is necessary and column 6 of Table I-I can be ignored.

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[12] The IEA has agreed to provide the relevant energy statistics data, along with the appropriate conversion factors, to any interested countries upon request. The IEA will provide data combining the fuel product detail found in the *Energy Statistics* (OECD/IEA, 1993) publication with the common energy unit format found in the *Energy Balances* publication.

TABLE 1-2

1990 COUNTRY-SPECIFIC CONVERSION FACTORS

(Gigajoule per metric ton)

	Albania	Algeria	Angola Cabinda	Argen-tina	Arme-nia	Azer-baijan	Bahrain	Bangla-desh	Bela-russia	Benin	Bolivia
Oil											
Crude Oil	41.45	43.29	42.75	42.29	-	42.08	42.71	42.16	42.08	42.58	43.33
NGL	-	43.29	-	42.50	-	-	42.71	42.71	-	-	43.33
Coal											
Hard Coal											
Production	-	25.75	-	24.70	-	-	-	-	-	-	-
Imports	27.21	25.75	-	30.14	18.58	18.58	-	20.93	25.54	-	-
Exports	-	-	-	24.70	18.58	18.58	-	-	25.54	-	-
Brown Coal and Sub-Bituminous Coal											
Production	9.84	-	-	-	-	-	-	-	-	-	-
Imports	-	-	-	-	14.65	14.65	-	-	14.65	-	-
Exports	9.84	-	-	-	14.65	14.65	-	-	14.65	-	-
Coal Products											
Patent Fuel/BKB	-	-	-	-	29.31	29.31	-	-	29.31	-	-
Coke	27.21	27.21	-	28.46	25.12	25.12	-	-	25.12	-	-

	Brazil	Brunei	Bulgaria	Came-roon	Chile	China	Colo-mbia	Congo	Cuba	Cyprus	Czech Republic
Oil											
Crude Oil	42.54	42.75	42.62	42.45	42.91	42.62	42.24	42.91	41.16	42.48	41.78
NGL	45.22	42.75	-	-	42.87	-	41.87	-	-	-	-
Coal											
Hard Coal											
Production	18.42	-	24.70	-	28.43	20.52	27.21	-	-	-	24.40
Imports	30.56	-	24.70	-	28.43	20.52	-	-	25.75	25.75	23.92
Exports	-	-	-	-	-	20.52	27.21	-	-	-	27.98
Brown Coal and Sub-Bituminous Coal											
Production	-	-	7.03	-	17.17	-	-	-	-	-	12.26
Imports	-	-	-	-	-	-	-	-	-	-	-
Exports	-	-	-	-	-	-	-	-	-	-	15.26
Coal Products											
Patent Fuel/BKB	-	-	20.10	-	-	-	-	-	-	-	21.28
Coke	28.30	-	27.21	-	28.43	28.47	20.10	-	27.21	-	27.01

Crude oil conversion factors are based on weighted average production data.

The conversion factors are those used by the IEA in the construction of energy balances.

Source: OECD/IEA, 1993.

TABLE 1-2 (CONTINUED)
1990 COUNTRY-SPECIFIC CONVERSION FACTORS

(Gigajoule per metric ton)

	Ecuador	Egypt	Estonia	Ethiopia	Gabon	Georgia	Ghana	Guate-mala	Hong Kong	Hungary	India
Oil											
Crude Oil	42.45	42.54	-	42.62	42.62	42.08	42.62	42.45	-	40.36	42.79
NGL	42.45	42.54	-	-	-	-	-	-	-	45.18	43.00
Coal											
Hard Coal											
Production	-	-	-	-	-	18.58	-	-	-	16.42	19.98
Imports	-	25.75	18.58	-	-	18.58	25.75	-	25.75	26.33	25.75
Exports	-	-	18.58	-	-	18.58	-	-	-	24.15	19.98
Brown Coal and Sub-Bituminous Coal											
Production	-	-	14.65	-	-	-	-	-	-	10.55	9.80
Imports	-	-	14.65	-	-	14.65	-	-	-	9.91	-
Exports	-	-	14.65	-	-	14.65	-	-	-	-	-
Coal Products											
Patent Fuel/BKB	-	-	20.10	-	-	29.31	-	-	-	21.44	20.10
Coke	-	27.21	25.12	-	-	25.12	-	-	27.21	30.11	-

	Indonesia	Iran	Iraq	Israel	Ivory Coast	Jamaica	Jordan	Kazakh-stan	Kenya	Kuwait	Kyrgy-zstan
Oil											
Crude Oil	42.66	42.66	42.83	42.54	42.62	42.16	42.58	42.08	42.08	42.54	42.08
NGL	42.77	42.54	42.83	-	-	-	-	-	-	42.62	-
Coal											
Hard Coal											
Production	25.75	25.75	-	-	-	-	-	18.58	-	-	18.58
Imports	25.75	25.75	-	26.63	-	25.75	-	18.58	25.75	-	18.58
Exports	25.75	-	-	-	-	-	-	18.58	-	-	18.58
Brown Coal and Sub-Bituminous Coal											
Production	-	-	-	-	-	-	-	14.65	-	-	14.65
Imports	-	-	-	-	-	-	-	14.65	-	-	14.65
Exports	-	-	-	-	-	-	-	14.65	-	-	14.65
Coal Products											
Patent Fuel/BKB	-	-	-	-	-	-	-	29.31	-	-	29.31
Coke	27.21	-	-	-	-	-	-	25.12	-	-	25.12

Crude oil conversion factors are based on weighted average production data.

The conversion factors are those used by the IEA in the construction of energy balances.

Source: OECD/IEA, 1993.

TABLE 1-2 (CONTINUED)
1990 COUNTRY-SPECIFIC CONVERSION FACTORS

(Gigajoule per metric ton)

	Latvia	Leb-anon	Libya	Lithu-ania	Malaysia	Malta	Mexico	Moldava	Mor-occo	Mozam-bique	Myan-mar
Oil											
Crude Oil	-	42.16	43.00	42.08	42.71	-	42.35	-	43.00	-	42.24
NGL	-	-	-	-	43.12	-	46.81	-	-	-	42.71
Coal											
Hard Coal											
Production	-	-	-	-	25.75	-	24.72	-	23.45	25.75	25.75
Imports	18.58	-	-	18.59	25.75	25.75	30.18	18.58	27.63	25.75	25.75
Exports	18.58	-	-	18.59	25.75	-	22.41	18.58	-	-	-
Brown Coal and Sub-Bituminous Coal											
Production	-	-	-	-	-	-	-	-	-	-	8.37
Imports	14.65	-	-	14.65	-	-	-	14.65	-	-	-
Exports	14.65	-	-	14.65	-	-	-	14.65	-	-	-
Coal Products											
Patent Fuel/BKB	29.31	-	-	29.31	-	-	-	29.31	-	-	-
Coke	25.12	-	-	25.12	27.21	-	27.96	25.12	27.21	-	27.21

	Nepal	Neth. Antilles	Neutral Zone	Nigeria	North Korea	Oman	Paki-stan	Panama	Para-guay	Peru	Philip-pines
Oil											
Crude Oil	-	42.16	42.12	42.75	42.16	42.71	42.87	42.16	42.54	42.75	42.58
NGL	-	-	-	-	-	-	-	-	-	42.75	-
Coal											
Hard Coal											
Production	-	-	-	25.75	25.75	-	18.73	-	-	29.31	20.10
Imports	25.12	-	-	-	25.75	-	27.54	25.75	-	29.31	20.52
Exports	-	-	-	25.75	25.75	-	-	-	-	-	-
Brown Coal and Sub-Bituminous Coal											
Production	-	-	-	-	17.58	-	-	-	-	-	8.37
Imports	-	-	-	-	-	-	-	-	-	-	-
Exports	-	-	-	-	-	-	-	-	-	-	-
Coal Products											
Patent Fuel/BKB	-	-	-	-	-	-	-	-	-	-	-
Coke	-	-	-	27.21	27.21	-	-	-	-	27.21	27.21

Crude oil conversion factors are based on weighted average production data.

The conversion factors are those used by the IEA in the construction of energy balances.

Source: OECD/IEA, 1993.

TABLE 1-2 (CONTINUED)
1990 COUNTRY-SPECIFIC CONVERSION FACTORS

(Gigajoule per metric ton)

	Poland	Qatar	Romania	Russia	Saudi Arabia	Senegal	Sing- apore	South Africa	South Korea	Slovak Republic	Sri Lanka
Oil											
Crude Oil	41.27	42.87	40.65	42.08	42.54	42.62	42.71	44.13	42.71	41.78	42.16
NGL	-	43.00	-	-	42.62	-	-	-	-	-	-
Coal											
Hard Coal											
Production	22.95	-	16.33	18.58	-	-	-	25.09	19.26	-	-
Imports	29.41	-	25.12	18.58	-	-	-	-	27.21	23.92	25.75
Exports	25.09	-	-	18.58	-	-	-	25.09	-	-	-
Brown Coal and Sub-Bituminous Coal											
Production	8.36	-	7.24	14.65	-	-	-	-	-	12.26	-
Imports	-	-	7.24	14.65	-	-	-	-	-	-	-
Exports	9.00	-	-	14.65	-	-	-	-	-	15.26	-
Coal Products											
Patent Fuel/BKB	20.93	-	14.65	29.31	-	-	-	-	-	21.28	-
Coke	27.76	-	20.81	25.12	-	-	27.21	-	-	27.01	-

	Sudan	Syria	Taiwan	Tajik- istan	Tanz- ania	Thai- land	Trini- dad / Tobago	Tunisia	Turk- meni- stan	Ukraine	Utd Arab Emir- ates
Oil											
Crude Oil	42.62	42.04	41.41	42.08	42.62	42.62	42.24	43.12	42.08	42.08	42.62
NGL	-	-	-	-	-	46.85	-	43.12	-	-	-
Coal											
Hard Coal											
Production	-	-	25.96	18.58	25.75	-	-	-	-	21.59	-
Imports	-	-	27.42	18.58	-	26.38	-	25.75	18.58	25.54	-
Exports	-	-	-	18.58	-	-	-	-	18.58	21.59	-
Brown Coal and Sub-Bituminous Coal											
Production	-	-	-	-	-	12.14	-	-	-	14.65	-
Imports	-	-	-	14.65	-	-	-	-	14.65	14.65	-
Exports	-	-	-	14.65	-	-	-	-	14.65	14.65	-
Coal Products											
Patent Fuel/BKB	-	-	-	29.31	-	-	-	-	29.31	29.31	-
Coke	-	-	-	25.12	27.21	27.21	-	27.21	25.12	25.12	-

Crude oil conversion factors are based on weighted average production data.

The conversion factors are those used by the IEA in the construction of energy balances.

Source: OECD/IEA, 1993.

TABLE 1-2 (CONTINUED)
1990 COUNTRY-SPECIFIC CONVERSION FACTORS

(Gigajoule per metric ton)

	Uruguay	Uzbek-istan	Venez-uela	Viet Nam	Yemen	Former Yugo-slavia	Zaire	Zambia	Zim-babwe
Oil									
Crude Oil	42.71	42.08	42.06	42.61	43.00	42.75	42.16	42.16	-
NGL	-	-	41.99	-	-	-	-	-	-
Coal									
Hard Coal									
Production	-	18.58	25.75	20.91	-	23.55	25.23	24.71	25.75
Imports	-	18.58	-	-	-	30.69	25.23	-	25.75
Exports	-	18.58	25.75	20.91	-	-	-	24.71	25.75
Brown Coal and Sub-Bituminous Coal									
Production	-	-	-	-	-	8.89	-	-	-
Imports	-	14.65	-	-	-	16.91	-	-	-
Exports	-	14.65	-	-	-	16.90	-	-	-
Coal Products									
Patent Fuel/BKB	-	29.31	-	-	-	20.10	29.31	-	-
Coke	-	25.12	27.21	27.21	-	26.90	27.21	-	27.21

Crude oil conversion factors are based on weighted average production data.

The conversion factors are those used by the IEA in the construction of energy balances.

Source: OECD/IEA, 1993.

TABLE 1-2 (CONTINUED)
1990 COUNTRY-SPECIFIC CONVERSION FACTORS

(Gigajoule per metric ton)

	Australia	Austria	Belgium	Canada	Den-mark	Finland	France	Ger-many	Greece	Iceland	Ireland	Italy
Oil												
Crude Oil	43.21	42.75	42.75	42.79	42.71	42.66	42.75	42.75	42.75	-	42.83	42.75
NGL	45.22	45.22	-	45.22	-	-	45.22	-	45.22	-	-	45.22
Refinery Feedst.	42.50	42.50	42.50	42.50	42.50	42.50	42.50	42.50	42.50	-	42.50	42.50
Coal												
Coking Coal												
Production	28.34	-	-	28.78	-	-	28.91	28.96	-	-	-	-
Imports	-	28.00	29.31	27.55	-	34.33	30.50	28.96	-	27.44	29.10	30.97
Exports	28.21	-	-	28.78	-	-	..	28.96	-	-	-	-
Bituminous Coal and Anthracite												
Production	24.39	-	25.00	28.78	-	-	26.71	24.96	-	-	26.13	26.16
Imports	-	28.00	25.00	27.55	26.09	26.38	25.52	26.52	27.21	25.85	29.98	26.16
Exports	25.65	-	25.00	28.78	26.09	-	26.43	31.71	-	-	26.13	-
Sub-Bituminous Coal												
Production	17.87	-	18.06	17.38	-	-	..	-	-	-	-	-
Imports	-	-	-	-	-	-	..	-	-	-	-	-
Exports	-	-	18.20	-	-	-	..	-	-	-	-	-
Brown Coal												
Production	9.31	10.90	-	14.25	-	-	17.94	8.41	5.74	-	-	10.47
Imports	-	10.90	21.56	-	-	-	17.94	14.88	-	-	19.82	10.47
Exports	-	10.90	-	14.25	-	-	..	8.40	-	-	-	-
Coal Products												
Patent Fuel/BKB	21.00	19.30	23.81	-	18.27	-	28.80	20.64	15.28	-	20.98	..
Coke	25.65	28.20	29.31	27.39	31.84	28.89	28.71	28.65	29.30	26.65	32.66	29.30

The conversion factors for oil and coal are those used by the IEA in the construction of energy balances.

The conversion factors for coal product groupings listed are calculated from the conversion factors of their constituents.

Source: OECD/IEA, 1993.

TABLE 1-2 (CONTINUED)
1990 COUNTRY-SPECIFIC CONVERSION FACTORS

(Gigajoule per metric ton)

	Japan	Luxem-bourg	Nether-lands	NZ	Norway	Port-ugal	Spain	Sweden	Switzerl and	Turkey	UK	USA
Oil												
Crude Oil	42.62	-	42.71	43.12	42.96	42.71	42.66	42.75	42.96	42.79	42.83	42.71
NGL	46.05	-	45.22	46.05	45.22	-	45.22	-	-	-	46.89	45.22
Refinery Feedst.	42.50	-	42.50	44.80	42.50	42.50	42.50	42.50	42.50	42.50	42.50	42.50
Coal												
Coking Coal												
Production	30.63	-	-	28.00	-	-	29.16	-	-	33.49	29.27	29.68
Imports	30.23	-	29.30	28.00	-	29.30	30.14	30.00	-	33.49	30.07	-
Exports	-	-	-	28.00	-	-	-	-	-	-	29.27	29.68
Bituminous Coal and Anthracite												
Production	23.07	-	-	26.00	28.10	-	21.07	14.24	-	29.30	24.11	26.66
Imports	24.66	29.30	29.30	-	28.10	26.59	25.54	26.98	28.05	27.21	26.31	27.69
Exports	-	-	29.30	-	28.10	-	23.00	26.98	28.05	-	27.53	28.09
Sub-Bituminous Coal												
Production	-	-	-	21.30	-	17.16	11.35	-	-	-	-	19.43
Imports	-	-	-	-	-	-	11.35	-	-	-	-	-
Exports	-	-	-	-	-,	-	-	-	-	-	-	-
Brown Coal												
Production	-	-	-	14.10	-	-	7.84	-	-	9.63	-	14.19
Imports	-	20.03	20.00	-	-	-	-	8.37	-	12.56	-	-
Exports	-	-	20.00	-	-	-	-	-	-	-	-	14.19
Coal Products												
Patent Fuel/BKB	27.05	20.10	23.53	-	-	-	20.31	20.10	21.76	20.93	26.26	-
Coke	28.64	28.50	28.50	-	28.50	28.05	30.14	28.05	28.05	29.28	26.54	27.47

The conversion factors for oil and coal are those used by the IEA in the construction of energy balances.

The conversion factors for coal product groupings listed are calculated from the conversion factors of their constituents.

Source: OECD/IEA, 1993.

TABLE I-3
CONVERSION FACTORS FOR OTHER
PRODUCTS

Factors ($GJ/10^3$ tonnes)

Refined Petroleum Products	
Gasoline (aviation and auto)	44800
Kerosene	44750
Jet Fuel	44590
Gas/Diesel Oil	43330
Residual Fuel Oil	40190
LPG	47310
Naphtha	45010
Bitumen	40190
Lubricants	40190
Petroleum Coke	40190
Refinery Feedstocks	44800
Other Oil Products	40190
Other Products	
Coal Oils and Tars	
derived from Coking Coal	28000

Source: OECD/IEA, Paris, 1993.

SELECT AVERAGE CARBON EMISSION FACTORS BY FUELS AND ESTIMATE POTENTIAL CARBON RELEASES

CO_2 emission estimates also need to consider that the amount of carbon per unit of energy varies considerably both among and within primary fuel types:

■   For natural gas, the carbon emission factor depends on the composition of the gas which, in its delivered state, is primarily methane, but can include small quantities of ethane, propane, butane, and heavier hydrocarbons. Natural Gas flared at the production site will usually be "wet", i.e. containing far larger amounts of non-methane hydrocarbons. The carbon emission factor will be correspondingly different.

■   For crude oil, Marland and Rotty (1984) suggest that the API gravity acts as an indicator of the carbon/hydrogen ratio. Carbon content per unit of energy is usually less for light refined products such as gasoline than for heavier products such as residual fuel oil.

■   For coal, carbon emissions per ton vary considerably depending on the coal's composition of carbon, hydrogen, sulfur, ash, oxygen, and nitrogen. While variability of carbon emissions on a mass basis can be considerable, carbon emissions per unit of energy (e.g., per gigajoule) vary much less (with lower ranked coals such as subbituminous and lignites usually containing slightly more carbon than higher-ranked coals; anthracite is an exception since it typically contains more carbon than bituminous coal).

TABLE 1-4

CARBON EMISSION COEFFICIENTS FOR FUELS FROM DIFFERENT STUDIES

(kg C/gigajoule,"net" heating value basis)[1]

Study	Anthracite	Bit. Coal	Sub-Bit. Coal	Lignite	Peat
Marland & Rotty (1984)		25.5[1]			
Marland & Pippin (1990)		25.4[1]			
Grubb (1989)	26.8[1]	25.8[1]		27.6[1]	28.9[1]
OECD (1991)		25.8[2]			

Study	Crude Oil	Gasoline	Kerosene	Diesel/Gas-Oil	Fuel Oils	NaturalGas
Marland & Rotty (1984)	21.0[1]				15.2[1]	
Marland & Pippin (1990)	21.0[1]	19.4[1]	19.4[1]	19.9[1]	21.1[1,3]	15.3[1]
Grubb (1989)	20.0[1]	18.9[1]	19.5[1]	20.0[1]	21.1[1]	15.3[1]
OECD (1991)	20.0					15.3

[1] Values were originally based on "gross" heating value; they were converted to "net" heating value by assuming a 5% difference in heating value for coal and oil, and 10% for natural gas. These percentage adjustments are the IEA assumptions on how to convert from gross to net heating values.

[2] Average value for all coal: sub-bituminous through anthracite.

[3] Midpoint of range from 20.7 for light fuel oil (#4 fuel oil) to 21.6 for residual fuel oil (#6 fuel oil).

Estimates of carbon emission factors for fuels from several studies are summarized in Table 1-4. The largest differences in emission factors between the studies occur with bituminous coal and oil, although these differences are relatively minor.

One approach for estimating the carbon emission factors was presented in Marland and Rotty (1984). For natural gas, the carbon emission factor was based on the actual composition of dry natural gas. They estimated the composition for natural gas from 19 countries based on sampling data and then calculated a weighted average global gas composition, breaking the gas out into methane, ethane, propane, other hydrocarbons, CO_2, and other gases. The composition of the gas then determined both the heating value of the gas and the carbon content. The carbon emission factor of the gas (kg C/gigajoule, using gross "calorific" units[13]) was expressed using the following relationship:

$$C_g = 13.708 + (0.0828 \times 10^{-3}) \times (H_v - 37,234)$$

where C_g is the carbon emission factor of the gas in kg C/gigajoule (GJ) and H_v is the heating value of the gas (heating value in "gross" calorific units, see OECD/IEA, 1990b) in kJ/meter^3. The coefficients of the equation (13.708, 0.0828 $\times$ 10^{-3}, and 37,234) were estimated using regression analysis based on data from the 19 countries. The carbon content of oil was estimated to be a function of the API gravity: using an estimate of world average API gravity of 32.5° $\pm$ 2°, they estimated a composition of 85% $\pm$ 1% carbon.

[13] Two ways are used to express the energy content of fuels: gross calorific value and net calorific value, sometimes expressed as high heating value and low heating value. The IPCC methodology requires that all energy data be expressed using net calorific (or lower heating) value.

Converting this to units of carbon per gigajoule yielded an estimate of 21.0 kg C/GJ on a net heating value basis (assuming 42.62 gigajoules per tonne, higher heating value, as reported in Marland & Rotty, 1984). For coal, the literature suggested that the carbon content of coal was predominantly a function of the energy content and that the carbon content on a per ton coal-equivalent basis was around 74.6% ± 2% (Marland and Rotty 1984). The carbon emission factor was estimated to be 25.5 kg C/GJ.

The approach used by M.J.Grubb (1989) to estimate carbon emission factors is very similar but based on more recent research. All carbon emission factors were originally reported on a "gross" heating value basis, but are converted here to a net heating value basis. He provides carbon factors for methane, ethane, propane, and butane and using data from Marland and Rotty (1984), he estimates an average emission factor for natural gas of 15.3 kg C/GJ ± 1%. For oil and some refined petroleum products the estimates are based on data from the literature, as summarized in Table 1-4. The carbon emission factor of coal, excluding anthracite, was defined as:

$$C_c = 32.15 - (0.234 \times H_v)$$

where C_c is the carbon emission factor in kg C/GJ and H_v is the heating value of the coal ("gross" calorific value) when the heating value is from 31 to 37 GJ/ton on a dry mineral matter free (dmf) basis. Anthracites fall outside this range and are estimated using a value of 26.8 kg C/GJ.

Since the publication of the original OECD Background Document (OECD 1991), additional information has been made available on carbon emission factors. Key points from this new information are summarized below (all factors are in lower heating value):

- At an IPCC-sponsored workshop in October 1992 (IPCC/OECD, 1993), experts recommended several revised emission factors based on national inventory submissions to the OECD:

Oven or Gas Coke	29.5 kg C/GJ
Natural Gas Liquids	15.2 kg C/GJ
Petroleum Coke	27.5 kg C/GJ
Refinery Gases	18.2 kg C/GJ
Wood	29.9 kg C/GJ
Blast Furnace Gas[14]	66 kg C/GJ
Coke Oven Gas[15]	13 kg C/GJ
Bitumen	22 kg C/GJ

- Of the country submissions received by the IPCC/OECD programme to date only Canada has reported a specific emission factor for subbituminous coals. This was a value of 27.1 kg C/GJ (Jaques, 1992). Detailed analysis conducted in the United States reported an average value of 26.2 kg C/GJ (USDOE/EIA, 1992). Based on these two results, it appears that the value previously recommended in OECD (1991) should be lowered. Because the U.S. analysis is documented in a detailed report, and

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[14] This emission factor would only be necessary if a bottom-up methodology were being used (e.g., see Approach #3).

[15] This is the mid-point of a range of values.

U.S. production of subbituminous coals is much higher than in Canada, the new recommended default value is 26.2 kg C/GJ.

- A number of countries have provided emission factors for jet fuel including those reported in IPCC/OECD (1993) and more recent reports. Based on a weighted average of these values the recommended emission factor for jet fuel is 19.5 kg C/GJ.

The IPCC Reference Approach relies primarily on the emission factors from Grubb (1989), with additions from other studies as discussed above, to estimate total potential carbon. The suggested carbon emission factors are listed in Step 3 of Table 1-1, Column 8. Table 1-1, Step 3, also provides the calculations needed to estimate the total carbon that could potentially be released from the use of fuels. The basic methodology is:

> Total Carbon (Gg C) =
> Apparent Energy Consumption (by fuel type in GJ)
> X Carbon emission factor (by fuel type in kg C/GJ), added across all fuel types

Apparent consumption of the fuels is estimated in Step 2 of Table 1-1 (Column 7). The carbon emission factors for the fuels are average values based on net calorific value (lower heating value). As noted, this approach relies on carbon emission factors from Grubb (1989), adjusted for net calorific value, plus factors recently available from other studies. This approach has been recommended by the IPCC because it explicitly treats each major fuel type differently according to its carbon emission factor. However, while carbon emission factors are available for most fuel types, some gaps in the data still remain. It is also possible that the default values provided here are not as accurate as country-specific factors that may be available. To the extent that other assumptions are used, countries should note the differences with the default values and provide documentation supporting the values used in the national inventory calculations.

ESTIMATE CARBON STORED IN PRODUCTS

After estimating the total carbon contained in the fuels, the next step is to estimate the amount of carbon from these fuels that is stored (or sequestered) in non-energy products and the portion of this carbon expected to oxidize over a long time period (e.g., greater than 20 years). All of the fossil fuels are used for non-energy purposes to some degree. Natural gas is used for ammonia production. LPGs are used for a number of purposes, including production of solvents and synthetic rubber. A wide variety of products are produced from oil refineries, including asphalt, naphthas, and lubricants. Coal is used to produce coke; two by-products of the coking process include crude light oil and crude tar, which are used in the chemical industry.

Not all non-energy uses of fossil fuels, however, result in the sequestering of carbon. For example, the carbon from natural gas used in ammonia production is oxidized quickly. Many products from the chemical and refining industries are burned or decompose within a few years, while the carbon in coke is oxidized when used. Several approaches for estimating the portion of carbon stored in products are reviewed in Box 2-1.

Box 2-1
Approaches for Estimating Carbon Stored in Products

The approach used by Marland and Rotty (1984) relied on historical data for determining non-energy applications and varied depending on fossil fuel type. For natural gas they assume that close to 1/3 of the carbon used for non-energy purposes (equivalent to 1% of total carbon from natural gas production) does not oxidize over long periods of time. For oil products they assume that some portion of LPG, ethane, naphthas, asphalt, and lubricants do not oxidize quickly. Specifically, they assume that about 50% of LPG and ethane from gas processing plants is sold for chemical and industrial uses and that 80% of this amount, or 40% of all LPG and ethane, goes into products that sequester the carbon. About 80% of the carbon in naphthas is assumed to end up in products such as plastics, tires, and fabrics and oxidize slowly. All of the carbon in asphalt is assumed to remain unoxidized for long periods, while about 50% of the carbon in lubricants is assumed to remained unoxidized. For coal they assume that on average 5.91% of coal going to coke plants ends up as light oil and crude tar, with 75% of the carbon in these products remaining unoxidized for long periods.

M.J.Grubb (1989) basically uses the Marland and Rotty (1984) approach, but suggests several changes, including higher estimates of methane losses during production and transportation of natural gas to market and a wide range of estimates concerning the fraction of carbon in refinery products that remain unoxidized. He does use Marland and Rotty's estimate of the amount of carbon in coal that does not oxidize, but also quantifies the amount of carbon emissions from SO_2 scrubbing (in which CO_2 is released during the chemical interactions in the desulfurization process) using the formula: (% sulfur by weight) X (coal consumption) X 12/32.

Okken and Kram (1990) introduce the concept of actual and potential emissions of CO_2 where potential emissions are defined as carbon that is stored in products from non-energy uses or by-products from combustion and actual emissions as all carbon from fuels that are emitted immediately or within a short period of time. Actual emissions plus potential emissions equal total carbon in the fuels. They assume that carbon from the following non-energy uses of fossil fuels oxidizes quickly: fertilizer production (ammonia), lubricants, detergents, volatile organic solvents, etc. Carbon from the following non-energy uses of fossil fuels remains stored for long periods of time (in some cases, hundreds of years): plastics, rubber, asphalt, bitumen, formaldehyde, and silicium carbide.

For the IPCC Reference Approach, the suggested formula for estimating carbon stored in products for each country is:

$$
\text{Total Carbon Stored =}
$$
$$
(\text{Non-energy Use, } 10^3 \text{ mt}) \times (\text{Conversion Factor, GJ}/10^3 \text{ mt}) \times (\text{Emission Factor, kg C/GJ}) \times
$$
$$
(\text{\% Stored), by product type}
$$

This approach is slightly revised from the original methodology in OECD (1991). The main changes are converting all values to gigajoules rather than leaving all values in metric tonnes and using an emission factor rather than an assumption for percent carbon content. The resulting carbon estimates from non-energy uses would be considered "potential" emissions, and are assigned to the country that produces the products. Most of the suggested categories conform to those used by Marland and Rotty (1984) and include naphthas, bitumen (asphalt), lubricants, LPG, and crude light oil and crude tar. The data available from the UN reports (e.g., 1990) correspond to these categories, with the exception of crude light oil and tar, which is not reported.

In addition, recent information has suggested some other modifications to the approach originally proposed in OECD (1991). These recommended modifications include:

- Naphtha will be stored when used as a feedstock in the petrochemical industry. However, in many countries naphtha is not always used as a feedstock. As the original methodology was based on total consumption of naphtha and not just that portion intended for use as a feedstock, it has been recommended that the methodology be changed to include only naphtha used as a feedstock. Furthermore, available evidence from Western European countries indicates that approximately 75% of naphtha used as feedstock is transformed into intermediate products in the petrochemical industry. The value of 75% is slightly lower than the 80% value originally assumed, which was based on U.S. information only.

- Gas/Diesel oil may also be used as a feedstock. This category was not included originally in the methodology, but is added here. Evidence from Western European countries indicates that about 50% of gas/diesel oil used as feedstock is transformed into intermediate products in the petrochemical industry.

The assumptions of 75% for naphtha as a feedstock and 50% for gas/diesel oil as a feedstock should be viewed as potential overestimates since not all of the carbon from the intermediate products will be stored. For example, carbon emissions may occur due to losses in the production of final products or incineration of final products. At this time these percentages can be used as the upper bound when determining stored carbon.

This suggested approach for estimating carbon stored in products is illustrated in Table 1-5. Whenever possible, countries should substitute assumptions that are more representative of practices within their own countries and provide documentation for these assumptions. The resulting estimates from Table 1-5 (Column 7) should be subtracted from potential emissions to determine net emissions of carbon that could be oxidized. This calculation is done by entering the values from Table 1-5 (Column 7) for the relevant fuels/products into Table 1-1 (Column 11). In Table 1-1, carbon stored in products is subtracted from total carbon in the fuels to get net carbon emissions.

TABLE 1-5
ESTIMATION OF CARBON STORED IN PRODUCTS

	1	2	3	4	5	6	7
	Estimated Fuel Quantities	Conversion Factor	Fuel Quantities	Emission Coefficient	Estimated Carbon Stored	Potential Carbon Stored	Percent Carbon Stored
[1]Product/Fuel	(Original Units)	GJ/Units	(GJ)	(Kg/GJ)	(Gg)	(%)	(Gg)
Lubricants	calc[2]	Table 1-3	calc[3]	Table 1-1	calc[4]	50%	calc[5]
Bitumen	calc	Table 1-3	calc	Table 1-1	calc	100	calc
Coal Oils and Tars from Coking Coal	calc	Table 1-3	calc	Table 1-1[6]	calc	75	calc
Naphtha as Feedstock	calc	Table 1-3	calc	Table 1-1	calc	75	calc
Gas/Diesel Oil as Feedstock	calc	Table 1-3	calc	Table 1-1	calc	50	calc
Gas as Feedstock	calc	Table 1-3	calc	Table 1-1	calc	33	calc
LPG as Feedstock	calc	Table 1-3	calc	Table 1-1	calc	80	calc

[1] This is only a partial list of products/fuels which accounts for the majority of carbon stored. Where data is available for other fuels, the estimation of stored carbon is strongly encouraged.

[2] Production plus Imports minus Exports minus Stock Change, or Feedstock Use.

[3] Apparent Consumption (Col. 3) equals Apparent Consumption (Col. 1) times a Conversion Factor (Col. 2).

[4] Potential Carbon Stored (Col. 5) equals Apparent Consumption (Col. 3) times an Emission Coefficient (Col. 4).

[5] Carbon Stored (Col. 7) equals Potential Carbon Stored (Col. 5) times Actual Percent Carbon Stored (Col. 6).

[6] Use the emission coefficient for coking coal (25.8 Kg C/GJ)

ESTIMATE CARBON OXIDIZED FROM ENERGY USES

As described earlier, not all carbon is oxidized during the combustion of fossil fuels. The amount of carbon that falls into this category is usually a small fraction of total carbon, and a large portion of this carbon oxidizes in the atmosphere shortly after combustion. Based on work by Marland and Rotty (1984), the IPCC has been recommending that 1% of the carbon in fossil fuels would remain unoxidized. This assumption was based on the following findings from Marland and Rotty for the amount unoxidized:

- For natural gas less than 1% of the carbon in natural gas is unoxidized during combustion and remains as soot in the burner, stack, or in the environment.

- For oil 1.5% ±1% passes through the burners and is deposited in the environment without being oxidized. This estimate is based on 1976 U.S. statistics of emissions of hydrocarbons and total suspended particulates.

- For coal 1% ±1% of carbon supplied to furnaces is discharged unoxidized, primarily in the ash.

However, several countries have commented that the amount of carbon remaining unoxidized is more variable than indicated by the 1% assumption across all fuels. For example, it has been noted that the amount of unburnt carbon varies depending on several factors, including type of fuel consumed, type of combustion technology, age of the equipment, and operation and maintenance practices, among other factors.

Information submitted by the Coal Industry Advisory Board of the OECD (Summers 1993), provided the following observations for coal combustion technologies:

- Unoxidized carbon from electric power stations in Australia averaged about 1%. Test results from stoker-fired industrial boilers, however, were higher, with unoxidized carbon amounting to 1% to 12% of total carbon with coals containing from 8-23% ash. As average values, 2% carbon loss was suggested for best practices, 5% carbon loss for average practices, and 10% carbon loss for worst practices. In those cases when coal is used in the commercial or residential sectors, carbon losses would be on the order of 5-10% (Summers, 1993).

- In related work British Coal has provided information on the percentage of unburnt carbon for different coal combustion technologies:

Pulverised Coal	1.6%
Travelling Grate Stoker	2.7-5.4%
Underfeed Stoker	4.0-6.6%
Domestic Open Fire	0.6-1.2%
Shallow Bed AFBC	Up to 4.0%
PFBC/CFBC	3.0%

- Evaluations at natural gas-fired boiler installations indicate that combustion efficiency is often 99.9% at units reasonably well-maintained.

It is clear from the available information that a single global default assumption of 1% unoxidized carbon is not always accurate. While some additional information is available to refine the assumptions for this portion of the methodology, most of the new information requires some level of detail on the type of technology in which the fuel is combusted or information on which sector is consuming the fuel. For this approach, the methodology only requires data on the amount of fuels consumed in a country, not data by technology type or sector of the economy. As a result, based on the information available at this point, the default values presented in Table 1-6 are recommended for the percentage of unoxidized during combustion by fuel. It should be recognized that the value for coal is highly variable based on fuel quality and technology types. National experts are encouraged to vary this assumption if they have data on these factors which indicates that different average values for their countries are appropriate. It is clear from the information available at this time that additional research should be conducted on this topic.

TABLE 1-6
CARBON OXIDIZED DURING COMBUSTION

RECOMMENDED DEFAULT ASSUMPTIONS

	percent
Liquid Fuels	99%
Solid Fuels	98%
Gaseous Fuels	99.5%

Net carbon emissions (column 12 in Table 1-1) are then multiplied by the fraction of carbon oxidized (column 13 of Table 1-1), and then summed across all fuel types, to determine the total amount of carbon oxidized from the combustion of the fuel. Next, to express the results as Carbon Dioxide (CO_2), there is one more step. Total carbon oxidized should be multiplied by the molecular weight ratio of CO_2 to C (44/12) to find total carbon dioxide emitted from fuel combustion.

1.4.3 Detailed Technology Based Calculations

This section briefly discusses procedures already used by some countries for estimating CO_2 emissions from fuel consumption at a more detailed and data-intensive level. This is a "bottom-up" approach in that emissions are estimated by sector of economic activity and/or by type of technology in which the fuel is consumed. The results for a wide range of "end-uses" and transformation activities must be summed to arrive at total national emissions. This discussion does not represent step by step guidance, but rather an initial conceptual discussion, that raises some issues which should be considered.

A greater level of detail than is provided by the IPCC Reference Approach may ultimately be needed by most, if not all, countries participating in international climate change discussions. Such detail is important for analysis of policy options for reducing emissions, which are frequently related to specific end uses rather than aggregate fuel use. As discussed in the next three sections, a more detailed approach is needed to credibly estimate emissions of several non-CO_2 greenhouse gases from energy combustion. Countries which have developed detailed energy and technology data for calculating emissions of NO_x, CO, etc., will very likely want to ensure that CO_2 emissions estimates are consistent and comparable. For this reason many countries may wish to utilize a detailed approach for CO_2 along with their detailed calculations for other GHG's from energy. This current discussion is intended to assist those countries which are trying to build CO_2 estimates into their existing detailed calculation procedures by indentifying some of the calculation issues which will have to be resolved.

This very detailed technology based approach does not provide a completely satisfactory result for two reasons. First it is extremely data intensive and may not be possible for the full range of IPCC countries in a reasonable time horizon. Second, even the most detailed technology based estimates produced in some countries, do not always carry with them the data necessary to conect emissions with economic subsectors of interest. In the future, the IPCC/OECD programme plans to provide more detailed guidance on practical application of a more detailed sectoral approach which will be less detailed than the technology based estimates but will still provide emissions broken down by economic sectors and sub-sectors of concern.

The detailed technology based calculations should be essentially the same as those carried out in the Reference Approach, but should be carried out at a finer level of resolution.

The formula is:

> fuel consumption (actual now rather than apparent) expressed in energy units (GJ) at the level of transformation or end use sub-sector and possibly by specific technology/process
>
> x carbon emission factor
>
> x fraction oxidized

Stored carbon would be calculated as is done in the reference approach although this, too, may be done at a finer level of product/process detail.

These steps are also conceptually quite similar to the calculations used to estimate emissions other than CO_2 from stationary and mobile source combustion. The methodologies for estimating emissions from these sources are discussed in detail in the following three sections. The Reference Approach for CO_2 only requires data by fuel type at the national level, but for the detailed calculations, national experts would be required to provide data on energy consumption patterns at a much greater level of detail. Once countries have obtained the activity data required for estimating detailed "bottom-up" inventories of NO_x, CO, etc., from combustion in stationary and mobile sources (i.e., fuel consumption data by sector by technology type), CO_2 emissions can also be estimated as part of the inventory estimates for these other gases. The amount of fuel consumed for each disaggregated category can be multiplied by an appropriate emissions factor to determine potential carbon emissions from fuel combustion. The fraction oxidized must also be accounted for each category.

There are some important complexities which must be recognized in working from the "bottom-up". Theoretically, it should make no difference in a country's total CO_2 emission estimate if the Detailed Technology Based Approach or the Reference Approach is applied since the amount of fuel consumed, and hence the amount of carbon oxidized, should be the same with both approaches. Differences may result, however, if the source activity data or emission factor data are not the same between the two approaches. These differences could be the result of:

- Actual differences may be due to better estimation methods with one approach (e.g., a country may choose alternative emission coefficients using the Detailed Technology Based Approach that are thought to more closely represent fuel qualities for a particular application)

- Statistical inconsistencies may exist between two different data sets (e.g., estimates of national coal consumption do not match).

- A special problem may be in accurately accounting for losses of carbon in transformation processes (as discussed below).

- Stored carbon (or non-fuel use) should be accounted for in much the same way as in the reference approach. However, this may produce somewhat different results if carried out at a finer level of detail.

The most important value of the Reference Approach is that it provides a simple, transparent and verifiable means of accounting for all of the carbon in fuels which could potentially be emitted to the atmosphere. Because of all of the above complexities, and others, it may not always be the case that adding up the fuel used from detailed data sets will account for all of the carbon in original fuels. For this reason, countries calculating their emissions at the Detailed Technology Based level should cross-check their emission estimates by also using the Reference Approach for verification, and reconcile any major differences.

Some of these difficulties at the detailed technology based level are discussed conceptually below related to specific aspects of the calculations. If national experts have or are developing detailed inventories of other gases they are encouraged to incorporate CO_2 estimates in this process as well. Experts should read through the stationary combustion and mobile combustion sections and should incorporate as much of the CO_2 estimation as possible in the same calculations. The emission factors necessary to apply the Detailed Technology Based Approach for CO_2 emissions are repeated in the relevant sections.

ESTIMATING FUEL COMBUSTION BY SECTOR AND TECHNOLOGY TYPE

In this approach countries would estimate fuel consumption for at least the same fuel categories specified for the Reference Approach. A few additional fuel types such as Blast Furnace Gas and Refinery Gas may need to be added to account for all of the fuels in the form of their end use. The concept of "apparent consumption" used in the Reference Approach allows users to ignore some of the details in fuel transformations. For example, while we know that in fact crude oil is not actually consumed as an end use fuel, we also know that all the carbon in the original crude oil is emitted to the atmosphere unless a) it is converted to a non-fuel product (stored carbon), or b) it is incompletely oxidized and remains as ash at a combustion or transformation step.

When working at the detailed level, countries would estimate actual fuel consumption for these fuel categories rather than apparent consumption. Moreover, rather than determining total national fuel consumption for these categories, a country would need to determine the amount of fuel consumed in each sector in order to estimate emissions for each sector of the economy. It may be necessary to account for actual consumption of specific fuels in various end use subcategories, further broken down by specific processes and technologies. Then one needs to work backwards to arrive at the total amounts of fuel carbon supplied to an economy.

A major area of difficulty in this process is accounting for the carbon released in transformation of energy from one form to another. The largest emissions from the energy transformation sub-sector are associated with electric power generation, in which fossil fuels are converted into electricity. These emissions are treated exactly like end use fuel combustion emissions in most detailed inventories so this component should be relatively straightforward.

Other transformations such as the refining of crude oil into oil products and the production of coke from coal can be more complicated and may be difficult to fully account for in the "bottom-up" approach. A simple input-output analysis may be helpful in accounting for the carbon releases during transformation steps. For example, a refinery (or for all refineries of a specific type) is a complex set of processes, but can be considered as a single box. Total carbon in the form of crude oil (and possibly other input energy forms) can be estimated. Total carbon out of the box in the form of secondary fuels or fuel products can be estimated. Any carbon disposed of in the form of wastes (such as ash), which represent stable long term storage, can be estimated. Any carbon not accounted for in one of these output forms must be assumed to have oxidized as a result of the transformation process.

Primary fuels that are not combusted directly, would thus not appear in end use combustion, although they may be considered as input to the input-output analysis of transformation steps. In both transformation and in some end use applications, the detailed technology based level will require explicit accounting of some intermediate products -e.g., blast furnace gas, refinery gas - which can be ignored in the Reference

Approach. At a minimum it is recommended that countries using the Detailed Technology Based Approach report emissions by the major fuel-consuming sectors defined in *Volume 1: Reporting Instruction.*

- Energy and Transformation Industries
  - Industry
  - Transport
  - Commercial/Institutional
  - Residential
  - Agriculture/Forestry
  - Other
  - Biomass Burned for Energy (Unallocated to any of the other sectors listed above)

Within each consuming sector emission estimates could also be developed according to the technology type in which the fuel was consumed. The following sections on stationary and mobile source combustion list possible technology source categories that could be estimated. Additional work needs to be done to further define a comprehensive set of appropriate categories.

CONVERTING TO COMMON ENERGY UNITS

This is handled exactly as in the Reference Approach. Wherever detailed fuel consumption data are collected in original physical units such as 10^3 mt or other energy units such as tons of oil equivalent (toe), they should be converted to gigajoules (GJ) using the same conversion procedures discussed in the Reference Approach.

CARBON EMISSIONS FACTORS

Once fuel consumption data are provided in GJ for the relevant sectors and/or technology types, these consumption estimates can be multiplied by the appropriate carbon emission factors to determine potential carbon emissions in kilograms (kg). The default carbon factors are the same as those used in the Reference Approach since the carbon content of specific fuel types does not change by sector or technology application. For example, if bituminous coal is used in an industrial boiler, a country could use the same emission factor for bituminous coal it would select under the Reference Approach. This does not mean that a country may not vary the emission factor from one application to another if it has reason to believe that the fuel qualities may differ. For example, if it is known that bituminous coal consumed in the industrial sector has significantly different fuel qualities than the average bituminous coal consumed in the country, then a country may wish to specify an alternative emission factor. Unless such information is available, however, the default emission factors used in the Reference Approach are acceptable.

These factors are provided again in the following sections on stationary and mobile source combustion. In some cases the factors are also converted to different forms (e.g. kg total CO_2/GJ, g CO_2/km) where these are more appropriate for specific end uses. Countries using alternative emission factors should note these differences and report the reasons for using an alternative factor.

As in the IPCC Reference Approach, bunker fuel and biomass fuel and CO_2 subtotals are for informational purposes only, and should not be added to overall totals. They should be shown as separate information totals when reporting.

ADJUSTMENTS FOR CARBON UNOXIDIZED

As discussed above under the Reference Approach, the amount of carbon that may remain unoxidized from combustion activities can vary for many reasons, including type of fuel consumed, type of combustion technology, age of the equipment, and operation and maintenance practices, among other factors. Since the Detailed Technology Based Approach relies on fuel consumption data on a more disaggregated level, it is possible to specify the assumptions for unoxidized carbon by application. Unless other data are available, as default values countries should use the assumptions recommended in the Reference Approach: 2% of carbon in fuel consumed is unoxidized for coal, 1% for oil-derived fuels and 0.5% for natural gas. In addition, the following assumptions (from Summers, 1993) are recommended:

- For stoker-fired industrial boilers an average value for carbon unoxidized is 5%. If countries believe that their operation and maintenance procedures achieve maximum efficiency, a 2% carbon loss is suggested. If these procedures are believed to lead to very poor efficiency, then a 10% carbon loss is recommended.

- In those cases when coal is used in the commercial or residential sectors, the assumption for unoxidized carbon should be 5%.

Clearly, much additional research needs to be done in this area. These adjustments are suggested as initial default values. As more work is done, countries are encouraged to report any additional information they may have to refine understanding of the amount of carbon unoxidized in various applications.

CARBON STORED

Calculations of stored carbon for countries choosing to use a detailed technology based approach should be more straightforward since the country would already be collecting fuel consumption data at a disaggregated level. The methodology for calculating stored carbon (non-fuel uses) is the same as the procedures used in the Reference Approach. That is, fuel quantities for which carbon may be stored should be estimated, then converted to GJ, multiplied by the carbon emission factor to determine potential emissions, and then multiplied by the actual share of carbon stored to determine the carbon stored for each fuel. It may be that national experts working at a detailed technology based level may account for non-fuel uses for a more detailed level of products and processes. In this case, default factors may not apply, and fractions of carbon actually stored and in some cases carbon emission factors will have to be supplied by the national experts.

The adjustments for stored carbon (deductions of Gg CO_2 stored) would have to be made to the appropriate sector for which emissions are being estimated. In most cases, these adjustments are made to emission estimates from the industrial sector since most uses for which potential storage of carbon have been identified are from this sector. Countries should explicitly identify the sectoral category to which they have assigned the estimates of stored carbon.

CONVERTING TO CO_2 EMISSIONS

This is also similar to the Reference Approach. For some end use categories emission factors may be provided directly as kg CO_2/Gj. Wherever emissions have been calculated as carbon, the must be expressed as <u>Carbon Dioxide (CO_2)</u>. To convert to CO_2, total carbon oxidized should be multiplied by the molecular weight ratio of CO_2 to C (44/12) to find total carbon dioxide emitted from fuel combustion.

1.5   Greenhouse Gas Emissions from Stationary Combustion

1.5.1 Overview

This section discusses greenhouse gas emissions (CO_2, NO_x, N_2O, CO, CH_4, and NMVOCs) from energy consumption in stationary sources. This section focuses on emissions from commercial fuel consumption, which includes virtually all fossil fuel combustion, but also includes the portion of biomass fuels traded commercially and used in large scale technology applications. These biomass emissions are estimated in exactly the same manner as fossil fuel combustion emissions, except for CO_2 emissions[16]. A large share of total global biomass fuel consumption, however, is not accounted for in commercial energy statistics. GHG emissions from this "traditional" biomass fuel use, primarily in developing countries, are calculated differently and discussed in the next section of this chapter.

Emissions of non-CO_2 greenhouse gases across activities (sectors, sub-sectors) will depend upon fuel, technology type, and pollution control policies. Emissions will also vary more specifically with size and vintage of the combustion technology, its maintenance, and its operation. As discussed in the previous section, CO_2 emissions are not technology-dependent, although these emissions can be estimated by technology using a "bottom-up" approach, as described in this section.

In addition to CO_2, stationary fuel combustion is a major component of total NO_x emissions in most countries. As defined here (i.e., excluding "traditional" biomass), this category generally contributes a smaller but still significant share of national emissions of CO and NMVOC. With the exclusion of "traditional" biomass, the stationary combustion category is generally a small contributor to total N_2O and CH_4, but these two gases are nonetheless discussed in some detail because of their priority status within the IPCC/OECD programme.

Organization of this section

The next sub-section provides a general discussion of the emissions calculation method common to the estimation of all GHGs from detailed fuel combustion data. This includes discussion of data needed including extensions required based on energy data discussed earlier, and highlights the importance of fuel and technology specific emission factors in this approach. The following sub-section provides a series of tables of representative emission factors which illustrate the range of technologies of concern and the variations of emission rates across these technologies.

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[16] CO_2 emissions resulting from biomass fuel consumption should not be included in a national energy emission totals to avoid double counting CO_2. This double-counting would occur either because: (1) biomass fuels may have been produced on a sustainable basis, particularly for commercial consumers, such that no net increase in CO_2 occurs, or (2) production of CO_2 from due to extraction of biomass fuels from existing stocks on a non-sustainable basis would be captured as part of emissions which are calculated as described in the Land Use Change and Forestry chapter in this manual. The IPCC method recommends that countries estimate CO_2 emissions from biomass fuel consumption and report this as an information item.

Two additional sub-sections, discuss each of the relevant gases of interest is discussed briefly. This discussion is presented in two parts - dealing with direct GHGs (CO_2, N_2O and CH_4), and indirect GHGs (NO_x, CO, and NMVOC) respectively. The priority area of work for the IPCC/OECD programme in the initial stages was methodologies for direct GHGs. Thus, improvements in methods for these gases are discussed in some detail. For CO_2 some additional discussion is provided to assist national experts who wish to do these calculations at a "bottom-up" level of detail. N_2O and CH_4 from stationary combustion are relatively minor as shares of total emissions. Nonetheless, as priority gases, a review of recent research results is included for each.

For indirect gases, the IPCC/OECD programme has not carried out any original methods development work. However, these gases are traditional air pollutants, as well as indirect GHGs, and have been the focus of a great deal of ongoing work outside the IPCC/OECD programme. The discussion of these gases, is primarily oriented toward identification of comprehensive, up-to-date references which have been published by other inventory programmes, including CORINAIR, and programmes of individual countries.

Finally, the last subsection discusses some priorities for future work.

1.5.2 Recommended Methodology

General Method

Estimation of emissions from stationary sources can be described using the following basic formula:

$$Emissions = \sum (EF_{abc} \times Activity_{abc})$$

where:

EF = Emission Factor (g/GJ);

Activity = Energy Input (GJ);

a = Fuel type;

b = Sector-activity; and

c = Technology type.

Total emissions for a particular nation is the sum across activities, technologies and fuels of the individual estimates.

Emission estimation is based on at least three distinct sets of assumptions or data: 1) emission factors; 2) energy activities; and 3) relative share of technologies in each of the main energy activities. Sources of the emission factors and energy activities data that are relevant internationally are described briefly below and suggestions on appropriate use of such data are made.

Technology share or technology splits for each of the various energy activities are needed at least on a national level for non-CO_2 greenhouse gas estimation since emission levels are affected by the technology type. Unfortunately, there are no complete international sources of data on technology splits and, as a result, each nation will need to develop its own technology splits for each energy activity.

The main steps in the inventory method can be summarized as follows:

1   Determine source of, and the form of, the best available, internationally verifiable, national (or sub-national) energy activity data;

2   Based on a survey of national energy activities, determine the main categories of emission factors;

3   Compile best available emission factor data for the country, preferably from national sources. If no national source is available, select from the options described here. Selection among the options should be based on an assessment of the similarity of the country to the source of original measurements for types of technology and operating conditions across main energy activities. The selection should also consider the extent to which control technologies may be in place and the ability to clearly separate and understand control policy assumptions that may be embedded in the emission factor data.

4   Based on the form of the selected emission factor data, develop assumptions regarding the technology categories to be used in the national inventory;[17]

5   Using these assumptions on technology categories, develop estimates, main activity by main activity, of each of the greenhouse gases.

6   Sum the individual activity estimates to arrive at the national inventory total for the greenhouse gases.

Data Needs

A considerable amount of detailed and specialized data is required to construct a national inventory of GHGs from stationary fuel combustion. At minimum, the following types of data are needed:

■   **Energy Activity Data:**

Energy data sources are discussed in the introduction. The same basic energy information is needed in estimating other GHGs from fuel combustion.

International sources or locally available sources of energy activity data can be used, provided that the definitions and formats specified in the IPCC methodology are used to ensure comparability and transparency. However, national sources will be needed for activity data relating to specific technologies. It should be noted, that in many countries, energy consumption data may be available in truly "bottom-up" data collection efforts, associated with major programmes to develop detailed emissions. That is, energy consumption data may be collected, along with technology information on a source by source, region by region, or other disaggregated level. It is, of course, highly desirable to have actual data on fuel use by technology type, rather than having to allocate down from national statistics. It is important. however, in this situation, to carefully reconcile total national energy accounts with "bottom-up" fuel use data to ensure that all fuel combustion is being accounted for and none is double counted.

■   **Technology Splits for Energy Data**

National data or assumptions on the technology shares of each of the main source sector categories that have been identified as important in each country are necessary to create the linkage between national energy balances and the emission factors. Again, this may be bases on "bottom-up" data collection at as detailed a level as individual sources, or it may

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[17] This may also require assumptions about the control technologies in place.

be more of a top down allocation based on statistical sampling, or engineering judgement. The objective is to match up fuel use, by fuel type, with specific technologies or classes of technologies, for which credible emission factors for non-CO_2 gases can be provided.

■   **Emission Factor Data**

Emission factors represent the average emission performance of a population of similar technologies. Emission factors for all non-CO_2 greenhouse gases from combustion activities vary to lesser or greater degrees with:

- fuel type;

- technology;

- operating conditions; and

- maintenance and vintage of technology.

Good emission factors for gases other than CO_2 are therefore usually technology specific, but may still represent a wide distribution of possible values. In addition to technology type, the impacts of equipment vintage, operating conditions, maintenance conditions, and pollution control also affect emission factors. When available, the standard deviation of the emission factor should be used to show the range of possible emissions factors, and hence emissions, for each particular energy activity.[18]

There already exists a considerable body of literature and other data bases on emission factors, particularly for the indirect GHGs (NO_x, CO, and NMVOC) which are of great interest as local and regional air pollutants, in addition to their affect on global radiative forcing of the atmosphere. In addition to the basic emissions for specific technology types, in some cases adjustments for control technologies may be needed. Accounting for controls is particularly critical to estimation of emissions from large stationary sources in OECD countries, but probably has a minor effect on emission estimates for the rest of the world since control technologies are not typically used in these countries (See OECD/IEA, 1991).

Some tables of representative emission factors by main technology and fuel types were presented in the previous preliminary methodology manual (OECD, 1991) distributed by the IPCC. This information is still useful in illustrating the range and variation of sources and emission rates, and is reproduced in the next section. More detail on current emission factors and references is presented in the gas-by-gas discussions which follow after the next section.

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[18] Unfortunately, the standard deviation of emission factors is rarely reported with emission factor data. One study shows that when considered, variation of emissions factors within an energy activity vary widely, from 20 to more than 50 per cent (Eggleston and McInnes, 1987).

1.5.3 Illustrative Emission Factor Data

Some tables of representative emission factors for NO_x[19], CO, CH_4, N_2O, and NMVOCs by main technology and fuel types (based on Radian, 1990) were presented in the previous preliminary methodology manual (OECD, 1991) distributed by the IPCC. This information is still useful in illustrating the range and variation of sources and emission rates, and is reproduced in Tables 2-8 to 2-12 for the major sectoral categories.[20] All factors are expressed on a grams per gigajoule of energy input basis (unless stated otherwise) and are stated on a full molecular weight basis assuming that all NO_x emissions are emitted as NO_2. These data are taken from Radian (1990) and show uncontrolled emission factors for each of the technologies indicated. These emission factor data therefore do not include the level of control technology that might be in place in some countries. For instance, for use in countries where control policies have significantly influenced the emission profile, either the individual factors or the final estimate will need to be adjusted.

It may be necessary to make adjustments to "raw" emission estimates to account for control technologies, in place. Alternative control technologies, with representative percentage reductions, are shown in Tables 2-13 to 2-16 (Radian, 1990) for the main control technologies applicable to each sector. These lists reflect technologies in use for large stationary sources in OECD countries. Preliminary indications are that, in the rest of the world, control technologies are not typically used (See OECD/IEA, 1991). These data should be used in combination with the uncontrolled emission factors to develop a "net" representative emission factor for each of the technologies to be characterized in the national emission profile; alternatively, the total emission estimate could be adjusted downward according to the indicated percentage reduction.

Table 1-17 provides the fuel property assumptions upon which the Radian data are based.

The emission factor data in these tables is provided primarily for illustrative purposes. These factors could be used as a starting point or for comparison by national experts working on detailed "bottom-up" inventories. However, much more detailed data are available and should also be consulted in this process. More detail on current emission factors and references is presented in the gas-by-gas discussions in the next two sections.

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[19] The convention in this document is that NO_x emissions from fossil fuel combustion are expressed on a full molecular basis assuming that all NO_x emissions are emitted as NO_2. It should be noted that this is inconsistent with the convention reflected in the methods on NO_x emissions from traditional biomass burning, which are expressed on a full molecular weight basis assuming the emissions are all in the form of NO. This is a convention common in literature on biomass burning. This inconsistency should be reconciled in future versions of the methodology.

[20] Little reliable information on N_2O and NMVOCs emission factors was available at the time these tables were developed. Some more recent information is presented or reference later in this section.

TABLE 1-7
UTILITY BOILER SOURCE PERFORMANCE

Source	Emissions Factors (g/GJ energy input)[1]				
	CO	CH4	NOx	N2O	NMVOCs
Natural Gas - Boilers	19	0.1	267	N/A	N/A
Gas Turbine Combined Cycle	32	6.1	187	N/A	N/A
Gas Turbine Simple Cycle	32	5.9	188	N/A	N/A
Residual Oil Boilers	15	0.7	201	N/A	N/A
Distillate Oil Boilers	15	0.03	68	N/A	N/A
Shale Oil Boilers	15	0.7	201	N/A	N/A
MSW - Mass Feed[2]	98	N/A	140	N/A	N/A
Coal - Spreader Stoker	121	0.7	326	0.8	N/A
Coal - Fluidized Bed Combined Cycle	N/A	0.6	N/A	N/A	N/A
Coal - Fluidized Bed	N/A	0.6	255	N/A	N/A
Coal - Pulverized Coal	14	0.6	857	0.8	N/A
Coal - Tangentially Fired	14	0.6	330	0.8	N/A
Coal - Pulverized Coal Wall Fired	14	0.6	461	0.8	N/A
Wood-Fired Boilers[2]	1,473	18	112	N/A	N/A

[1] Values were originally based on "gross" (or higher) heating value; they were converted to "net" (or lower) heating value by assuming that net heating values were 5% lower than gross heating values for coal and oil, and 10% lower for natural gas. These percentage adjustments are the OECD/IEA assumption on how to convert from gross to net heating values.

[2] Emission factors were adjusted to lower heating value assuming a 5% difference in energy content between lower heating value and higher heating value.

Source: Radian, 1990.

TABLE 1-8
INDUSTRIAL BOILER PERFORMANCE

Source	Emissions Factors (g/GJ energy input)[1]				
	CO	CH4	NOx	N2O	NMVOCs
Coal-Fired Boilers	93	2.4	329	N/A	N/A
Residual Oil-Fired Boilers	15	2.9	161	N/A	N/A
Natural Gas-Fired Boilers	17	1.4	67	N/A	N/A
Wood-Fired Boilers[2]	1,504	15	115	N/A	N/A
Bagasse/Agricultural Waste-Fired Boilers[2]	1,706	N/A	88	N/A	N/A
MSW - Mass burn[2]	96	N/A	140	N/A	N/A
MSW - Small Modular[2]	19	N/A	139	N/A	N/A

[1] Values were originally based on "gross" (or higher) heating value; they were converted to "net" (or lower) heating value by assuming that net heating values were 5% lower than gross heating values for coal and oil, and 10% lower for natural gas. These percentage adjustments are the OECD/IEA assumption on how to convert from gross to net heating values.

[2] Emission factors were adjusted to lower heating value assuming a 5% difference in energy content between lower heating value and higher heating value.

Source: Radian, 1990.

TABLE 1-9
KILNS, OVENS, AND DRYERS SOURCE PERFORMANCE

Industry	Source	Emissions Factors (g/GJ energy input)[1]				
		CO	CH4	NOx	N2O	NMVOCs
Cement, Lime	Kilns - Natural Gas	83	1.1	1,111	N/A	N/A
Cement, Lime	Kilns - Oil	79	1.0	527	N/A	N/A
Cement, Lime	Kilns - Coal	79	1.0	527	N/A	N/A
Coking, Steel	Coke Oven	211	1	N/A	N/A	N/A
Chemical Processes, Wood, Asphalt, Copper, Phosphate	Dryer - Natural Gas	11	1.1	64	N/A	N/A
Chemical Processes, Wood, Asphalt, Copper, Phosphate	Dryer - Oil	16	1.0	168	N/A	N/A
Chemical Processes, Wood, Asphalt, Copper, Phosphate	Dryer - Coal	179	1.0	226	N/A	N/A

[1] Values were originally based on "gross" (or higher) heating value; they were converted to "net" (or lower) heating value by assuming that net heating values were 5% lower than gross heating values for coal and oil, and 10% lower for natural gas. These percentage adjustments are the OECD/IEA assumption on how to convert from gross to net heating values.

Source: Radian, 1990.

TABLE 1-10
RESIDENTIAL SOURCE PERFORMANCE

Source	Emissions Factors (g/GJ energy input)[1]				
	CO	CH4	NOx	N2O	NMVOCs
Wood Pits[2]	4,949	200	147	N/A	N/A
Wood Fireplaces[2]	6,002	N/A	116	N/A	N/A
Wood Stoves[2]	18,533	74	200	N/A	N/A
Propane/Butane Furnaces	10	1.1	47	N/A	N/A
Coal Hot Water Heaters	18	N/A	158	N/A	N/A
Coal Furnaces	484	N/A	232	N/A	N/A
Coal Stoves	3,580	N/A	179	N/A	N/A
Distillate Oil Furnaces	13	5	51	N/A	N/A
Gas Heaters	10	1	47	N/A	N/A

[1] Values were originally based on "gross" (or higher) heating value; they were converted to "net" (or lower) heating value by assuming that net heating values were 5% lower than gross heating values for coal and oil, and 10% lower for natural gas. These percentage adjustments are the OECD/IEA assumption on how to convert from gross to net heating values.

[2] Emission factors were adjusted to lower heating value assuming a 5% difference in energy content between lower heating value and higher heating value.

Source: Radian, 1990.

TABLE 1-11
COMMERCIAL SOURCE PERFORMANCE

Source	Emissions Factors (g/GJ energy input)[1]				
	CO	CH4	NOx	N2O	NMVOCs
Wood Boilers[2]	199	15	33	4.3	N/A
Gas Boilers	9.6	1.2	48	2.4	N/A
Residual Oil Boilers	17	1.6	155	46.5	N/A
Distillate Oil Boilers	16	0.6	64	15.7	N/A
MSW Boilers[2]	19	N/A	463	N/A	N/A
Coal Boilers	195	10	236	59.1	N/A
Shale Oil Boilers	17	1.6	186	46.5	N/A
Open Burning - MSW	42 kg/Mg	6.5 kg/Mg	3 kg/Mg	N/A	N/A
Open Burning - Agriculture	58 kg/Mg	9 kg/Mg	N/A	N/A	N/A
Incineration - high efficiency	5 kg/Mg	N/A	1.5 kg/Mg	N/A	N/A
Incineration - low efficiency	10 kg/Mg	N/A	1 kg/Mg	N/A	N/A

[1] Values were originally based on "gross" (or higher) heating value; they were converted to "net" (or lower) heating value by assuming that net heating values were 5% lower than gross heating values for coal and oil, and 10% lower for natural gas. These percentage adjustments are the OECD/IEA assumption on how to convert from gross to net heating values.

[2] Emission factors were adjusted to lower heating value assuming a 5% difference in energy content between lower heating value and higher heating value.

Source: Radian, 1990.

TABLE 1-12
UTILITY EMISSION CONTROLS PERFORMANCE

Technology	Efficiency Loss[1] (%)	CO Reduction (%)	CH4 Reduction (%)	NOx Reduction (%)	N2O Reduction (%)	NMVOCs Reduction (%)	Date Available[2]
Low Excess Air (LEA)	-0.5	+	+	15	N/A	N/A	1970
Overfire Air (OFA) - Coal	0.5	+	+	25	N/A	N/A	1970
OFA - Gas	1.25	+	+	40	N/A	N/A	1970
OFA - Oil	0.5	+	+	30	N/A	N/A	1970
Low NOx Burner (LNB) - Coal	0.25	+	+	35	N/A	N/A	1980
LNB - Tangent. Fired	0.25	+	+	35	N/A	N/A	1980
LNB - Oil	0.25	+	+	35	N/A	N/A	1980
LNB - Gas	0.25	+	+	50	N/A	N/A	1980
Cyclone Combustion Modification	0.5	N/A	N/A	40	N/A	N/A	1990
Ammonia Injection	0.5	+	+	60	N/A	N/A	1985
Selective Catalytic Reduction (SCR) - Coal	1	8	+	80	N/A	N/A	1985
SCR - Oil, AFBC	1	8	+	80	N/A	N/A	1985
SCR - Gas	1	8	+	80	60	N/A	1985
Water Injection - Gas Turbine Simple Cycle	1	+	+	70	N/A	N/A	1975
SCR - Gas Turbine	1	8	+	80	60	N/A	1985
CO2 Scrubbing - Coal	22.5	N/A	N/A	N/A	N/A	N/A	2000
CO2 Scrubbing - Oil	16.0	N/A	N/A	N/A	N/A	N/A	2000
CO2 Scrubbing - Gas	11.3	N/A	N/A	N/A	N/A	N/A	2000
Retrofit LEA	-0.5	+	+	15	N/A	N/A	1970
Retrofit OFA - Coal	0.5	+	+	25	N/A	N/A	1970
Retrofit OFA - Gas	1.25	+	+	40	N/A	N/A	1970
Retrofit OFA - Oil	0.5	+	±	30	N/A	N/A	1970
Retrofit LNB - Coal	0.25	+	+	35	N/A	N/A	1980
Retrofit LNB - Oil	0.25	+	+	35	N/A	N/A	1980
Retrofit LNB - Gas	0.25	+	+	50	N/A	N/A	1980
Burners Out of Service	0.5	+	+	30	N/A	N/A	1975

[1] Efficiency loss as a percent of end-user energy conversion efficiency (ratio of energy output to energy input for each technology) due to the addition of an emission control technology. Negative loss indicates an efficiency improvement.

[2] Date technology is assumed to be commercially available.

Note: A "+" indicates negligible reduction.

Source: Radian, 1990.

TABLE 1-13
INDUSTRIAL BOILER EMISSION CONTROLS PERFORMANCE

Technology	Efficiency Loss[1] (%)	CO Reduction (%)	CH4 Reduction (%)	NOx Reduction (%)	N2O Reduction (%)	NMVOCs Reduction (%)	Date Available[2]
Low Excess Air (LEA)	-0.5	+	+	15	N/A	N/A	1970
Overfire Air (OFA) - Coal	0.5	+	+	25	N/A	N/A	1970
OFA - Gas	1.25	+	+	40	N/A	N/A	1970
OFA - Oil	0.5	+	+	30	N/A	N/A	1970
Low NOx Burner (LNB) - Coal	0.25	+	+	35	N/A	N/A	1980
LNB - Oil	0.25	+	+	35	N/A	N/A	1980
LNB - Gas	0.25	+	+	50	N/A	N/A	1980
Flue Gas Recirculation	0.5	+	+	40	N/A	N/A	1975
Ammonia Injection	0.5	+	+	60	N/A	N/A	1985
Selective Catalytic Reduction (SCR) - Coal	1	8	+	80	N/A	N/A	1985
SCR - Oil, AFBC	1	8	+	80	N/A	N/A	1985
SCR - Gas	1	8	+	80	60	N/A	1985
Retrofit LEA	-0.5	+	+	15	N/A	N/A	1970
Retrofit OFA - Coal	0.5	+	+	25	N/A	N/A	1970
Retrofit OFA - Gas	1.25	+	+	40	N/A	N/A	1970
Retrofit OFA - Oil	0.5	+	+	30	N/A	N/A	1970
Retrofit LNB - Coal	0.25	+	+	35	N/A	N/A	1980
Retrofit LNB - Oil	0.25	+	+	35	N/A	N/A	1980
Retrofit LNB - Gas	0.25	+	+	50	N/A	N/A	1980

[1]Efficiency loss as a percent of end-user energy conversion efficiency (ratio of energy output to energy input for each technology) due to the addition of an emission control technology. Negative loss indicates an efficiency improvement.

[2]Date technology is assumed to be commercially available.

Note: A "+" indicates negligible reduction.

Source: Radian, 1990.

TABLE 1-14
KILN, OVENS, AND DRYERS EMISSION CONTROLS PERFORMANCE

Technology	Efficiency Loss[1] (%)	CO Reduction (%)	CH4 Reduction (%)	NOx Reduction (%)	N2O Reduction (%)	NMVOCs Reduction (%)	Date Available[2]
LEA - Kilns, Dryers	-6.4	+	+	14	N/A	N/A	1980
LNB - Kilns, Dryers	0	+	+	35	N/A	N/A	1985
SCR - Coke Oven	1.0	8	+	80	60	N/A	1979
Nitrogen Injection	N/A	N/A	N/A	30	N/A	N/A	1990
Fuel Staging	N/A	N/A	N/A	50	N/A	N/A	1995

[1]Efficiency loss as a percent of end-user energy conversion efficiency (ratio of energy output to energy input for each technology) due to the addition of an emission control technology. Negative loss indicates an efficiency improvement.

[2]Date technology is assumed to be commercially available.

Note: A "+" indicates negligible reduction.

Source: Radian, 1990.

TABLE 1-15
RESIDENTIAL AND COMMERCIAL EMISSION CONTROLS PERFORMANCE

Technology	Efficiency Loss[1] (%)	CO Reduction (%)	CH4 Reduction (%)	NOx Reduction (%)	N2O Reduction (%)	NMVOCs Reduction (%)	Date Available[2]
Catalytic Woodstove	-44	90	90	-27	N/A	N/A	1985
Non-Catalytic Modified Combustion Stove	-30	15	50	-5	N/A	N/A	1985
Flame Ret. Burn. Hd.	-9	28	N/A	N/A	N/A	N/A	
Heed. Mix. Burn. Hd.	-7	43	N/A	44	N/A	N/A	
Integr. Furn. Syst.	-12	13	N/A	69	N/A	N/A	
Blueray Burn./Furn.	-12	74	N/A	84	N/A	N/A	
M.A.N. Burner	-13	N/A	N/A	71	N/A	N/A	1980
Radiant Screens	-7	62	N/A	55	N/A	N/A	
Secondary Air Baffle	N/A	16	N/A	40	N/A	N/A	
Surface Comb. Burner	N/A	55	N/A	79	N/A	N/A	
Amana HTM	-21	-55	N/A	79	N/A	N/A	
Modulating Furnace	-7	N/A	N/A	32	N/A	N/A	
Pulse Combuster	-36	N/A	N/A	47	N/A	N/A	
Catalytic Combuster	-29	N/A	N/A	86	N/A	N/A	
Replace Worn Units	N/A	65	N/A	N/A	N/A	N/A	
Tuning, Seasonal Maintenance	-2	16	N/A	N/A	N/A	N/A	
Red. Excess. Firing	-19	14	N/A	N/A	N/A	N/A	
Red fir with new ret b	-40	14	N/A	N/A	N/A	N/A	
Pos. Chimney Dampers	-8	11	N/A	N/A	N/A	N/A	
Inc. thermal anticip.	-1	43	N/A	N/A	N/A	N/A	
Night therm. cutback	-15	17	N/A	N/A	N/A	N/A	
Low Excess Air	-0.8	N/A	N/A	15	N/A	N/A	1970
Flue Gas Recirculation	0.6	N/A	N/A	50	N/A	N/A	1975
Over-fire Air	1	N/A	N/A	20	N/A	N/A	1970
Over-fire Air	1	N/A	N/A	30	N/A	N/A	1970
Low NOx Burners	0.6	N/A	N/A	40	N/A	N/A	1980
Low NOx Burners	0.6	N/A	N/A	50	N/A	N/A	1980

[1]Efficiency loss as a percent of end-user energy conversion efficiency (ratio of energy output to energy input for each technology) due to the addition of an emission control technology. Negative loss indicates an efficiency improvement.

[2]Date technology is assumed to be commercially available.

Note: A "+" indicates negligible reduction.

Source: Radian, 1990.

TABLE 1-16
FUEL PROPERTIES[1]

Fuel	Heating Value (GJ/tonne)[2]	Carbon (wt percent)
GAS		
Butane/Propane	45.7	82.0
Coke Oven Gas	36.7	56.1
Methane (pure)	45.0	75.0
Natural Gas	46.0	70.6
Process Gas	48.6	70.6
LIQUID		
Crude Shale Oil	40.9	84.5
Diesel/Distillate	42.9	87.2
Gasoline	116.9 MJ/gal	85.7
Jet A	41.0	86.1
Methanol	56.1 MJ/gal	37.5
Residual Oil	40.9	85.6
SOLID		
Bagasse/Agriculture	8.6	22.6
Charcoal	27.6	87.0
Coal	22.0	65.0
MSW	10.7	26.7
Wood	10.1	27.0

[1] Values were originally based on "gross" (or higher) heating value; they were converted to "net" (or lower) heating value by assuming that net heating values were 5% lower than gross heating values for coal and oil, and 10% lower for natural gas. These percentage adjustments are the OECD/IEA assumption on how to convert from gross to net heating values.

[2] Unless otherwise indicated.

Source: Radian, 1990.

1.5.4 Discussion Of Direct GHGs

In the initial stages of the IPCC/OECD programme it was recognized that work on both methods development and national inventories needed to be prioritized, as it was not possible to deal with all of the gases and sources simultaneously. The direct greenhouse gases were established as the priority, with priority within this category in the following order: CO_2, methane and nitrous oxides (IPCC/OECD, 1991). CO_2 from fuel combustion has been discussed in detail in the previous section. It is discussed again here briefly to emphasize the possible linkage of detailed CO_2 calculations with the detailed approach required for estimation of other GHGs from combustion.

Methods for estimating emissions of methane and nitrous oxide are not yet well established, but are evolving rapidly based on a great deal of research underway within the global change research community and elsewhere. For this reason, expert groups have been established to recommend improvements in estimation methods for a variety of source categories - including fuel combustion - which produce these gases. Information developed by these groups provides some improvements in emission estimation methods as described below.

Carbon Dioxide (CO$_2$): The IPCC Reference Approach to estimation of CO$_2$ emissions from fuel combustion is described in the previous section. This method is designated as a reference method because it is transparent, easy to implement, and produces very reliable and comparable estimates for all IPCC countries. It is also clear that more detailed information on CO$_2$ emissions by source type can be useful to most countries. Countries which have detailed data bases for estimating emissions of non-CO$_2$ gases are encouraged to also estimate CO$_2$ emissions at a "bottom-up" level of detail based on the data developed to estimate non-CO$_2$ emissions.

Specifically, in order to estimate non-CO$_2$ emissions using the emission factors provided in Tables 2-9 to 2-13, countries will need to determine the amount of energy consumed by sector, technology type, and fuel type. Since the fuel type is known, the carbon emission coefficients provided in Table 1-1 by fuel type could, in theory, be applied to the total amount of input energy for each fuel/technology type by sector to determine total carbon consumed for that category. To determine total CO$_2$ emissions, one would sum across all technology/fuel combinations and all sectors, and then follow the steps outlined in the CO$_2$ section including adjusting for any carbon unoxidized during combustion (see Table 1-7). It would also be necessary to account for non-energy uses emitting carbon (see Table 1-6), in order to ensure that total carbon in fuels is covered.

As noted in the previous section, there may be some variations in the carbon emission factors (due to variations in fuel quality), and very likely will be differences in fraction oxidized for different technologies. If more detailed factors are available based on local conditions and measurements, these should be used (and documented). In addition, as discussed in the previous section, there are a number of complex accounting problems which can be ignored at the "top-down" level, but have to be addressed at a "bottom-up" level of detail. These are especially difficult in accounting for all of the carbon released during transformation of energy from one form to another (e.g., refining of crude oil). The IPCC Guidelines do not yet provide detailed guidance for dealing with these complexities. Rather, it is recommended that national experts currently working at the detailed use their own judgement to deal with the detailed questions which must be answered at the "bottom-up" level. It is also strongly recommended that all countries also prepare estimates using the IPCC Reference Approach and reconcile the results. This will help identify any carbon in original fuels (e.g., transformation losses) which may not have been accounted for in the detailed "bottom-up" accounts.

Methane (CH$_4$): CH$_4$ is produced from fuel combustion in small quantities due to incomplete combustion of hydrocarbons in fuel. In large, efficient combustion facilities, the emission rate is very low. In smaller combustion sources, emissions rates can be higher, particularly where smoldering combustion conditions occur. In global terms, total emissions from this source category (here defined to exclude "traditional" biomass burning discussed in the next section) are believed to be small relative to other anthropogenic source categories. Nevertheless, because of the importance of this gas, these emissions are being studied carefully.

In a background paper prepared for the informal experts group, Berdowski, et al., (1993) summarized the average emission rates for fuel combustion within broad subsectors. The highest rates of methane emissions from fuel combustion are reported for residential applications, where coal and "traditional" biomass fuels are used in small stoves for cooking and heating. Emissions from "traditional" fuels such and fuelwood and agricultural residues are discussed in the next section. Emissions from coal use in residential stoves can also be quite high relative to other combustion applications, as shown in Table 1-18. This table gives average emission factors for broad classes of combustion. It is clear that actual emissions would vary within each category by technology type, fuel quality, and operating conditions. However, the very aggregated information presented is sufficient to show that

methane emissions from fossil fuel combustion in large scale utility and industrial applications are low, with utility emission rates being less than 1% of average rates for residential coal combustion.

Based on the average emission factors in the above table, Berdowski, et al., (1993) estimate global emissions from residential coal use to be in the range of 2.5-5.0 Tg/year, despite the fact that residential coal use is common in only a few countries. The total emissions from utility and industrial coal use and all other fossil fuel use was estimated to be less than 1.5 Tg/year. Despite the fact that large amounts of fuel are used in these latter applications, the very low average emission rates result in very small contributions to total emissions.

TABLE 1-17
GLOBAL EMISSION FACTORS AND EMISSIONS OF METHANE FROM COMBUSTION OF SOLID FUELS.

Fuel (type)	Emission factor (g/GJ)		
	Utilities	Industry	Residential
Coal	1	10	300 (range 200-400)
Residual oil	3	3	-
Distil. oils	-	1	7
Natural gas, LPG	1	4	3

Table adapted for Berdowski, et al., 1993

References: For residential coal use, USEPA, 1985; Zeedijk, 1986. All other categories from Veldt, 1991.

Nitrous Oxide (N_2O): N_2O is produced from combustion of fuels, although this source category (stationary combustion, excluding "traditional" biomass burning) is presently considered to be minor, relative to other anthropogenic source categories. The mechanisms that cause the formation of N_2O during the combustion of fossil fuel are now fairly well understood (see De Soete, 1993). The basic knowledge on both gas phase and heterogeneous N_2O chemistry is well able to explain and to forecast at least in a qualitative manner N_2O emissions from different combustion sources and flue gas treatment techniques.

Nitrous oxide (N_2O) is produced directly from the combustion of fossil fuels. Gas phase N_2O chemistry is relatively well understood as it is part of NO kinetics and N_2O appears as a by-product of the so-called fuel-NO mechanism. For combustion temperatures well below 1000 K or above 1200 K the emission factor for N_2O is almost zero or negligible; in the temperature range between about 800 and 1100 K N_2O emissions are reaching the highest levels with a maximum around 1000 K. Increasing the oxygen concentration or the pressure tends to increase the emissions.

Fundamental studies of non-catalytic heterogeneous reactions on the formation and destruction of N_2O only started in recent years, so the available experimental data is still rather scarce. The main mechanisms for the N_2O chemistry appear to be: destruction of N_2O on bound carbon atoms, the formation of N_2O from char bound nitrogen atoms, and the formation of N_2O from NO and reduced sulfates. Catalytic N_2O chemistry may play a role in the following cases:

■ at overall reducing conditions (catalysts in spark ignition cars and trucks),

■ at overall oxidizing conditions (de-NO_x-techniques such as Selective Catalytic Reduction [SCR], emission abatement of diesel engines and lean-burn spark ignition engines), and

■ catalytic formation and destruction (e.g. during fluidized bed combustion caused by the presence of CaO).

Recent re-evaluation of available emission factor data from fuel combustion showed that in measurements before July 1988 often a so-called artefact appeared stemming from the presence of NO_x and SO_2 in samples, which resulted in erroneous emission factors which were much too high, thereby highly overestimating the importance of this source category (Muzio and Kramlich, 1988). Since the recognition of this artefact in June 1988 new measurements have lead to new reliable emission factors from different conventional stationary combustion sources (De Soete, 1993).

Emission factors can be limited to one value per fuel type for all applications, since relevant knowledge is now readily available. (see De Soete (1993) and references therein) Advanced (Pressurized) Fluidized Bed Combustion [(P)FBC] emissions are dependent on the rank of the coal: brown coal produces less emissions than bituminous coal. The emission factors for waste combustion and especially for sludge incineration are very high, with a tendency to increase when FBC technology is applied.

Combustors with application of catalytic reduction techniques for emission abatement (e.g. SCR or Non-Catalytic Selective Reduction [NCSR] of NO_x) also have estimated emission factors. NCSR experiments suggest that the application of this control technology increases the emission factor for N_2O; for SCR no differences are observed. In the case of NCSR the N_2O emissions are higher from urea or cyanuric acid injection than in the case of ammonia injection. These control technologies may not only be applied on large scale facilities exploited by utilities or industry, but may also be applied in modern woodstoves. Due to the uncertainty for the last categories at present an uncertainty range for these sources is most appropriate. Default uncertainty ranges still have to be determined, but a preliminary range is presented in this report.

Default emission factors and uncertainty ranges are shown in Table 1-19. When a country has its own locally determined emission factors, these are of course preferred above the default factors reported here. However, care should be taken that no artefact data were used in deriving the factors.

Reliable emission factors for non-commercial fuel combustion in particular fuelwood and charcoal are currently not yet available because of lack of data on emission measurements for these combustion technologies. This refers amongst others to fuelwood, charcoal (production and use in residential, commercial and industrial sectors), crop residues and dung. Published data are scarce and the representativeness for global application is questionable. Also, in the preparation of national inventories care should be taken to avoid double counting, since emissions of fuelwood use may also be included in the category of biomass burning. (Olivier, 1993)

TABLE I-18
ESTIMATED DEFAULT EMISSION FACTORS FOR STATIONARY COMBUSTION FACILITIES.

Technology	Emission factors (g N_2O/GJ energy input) (or g N_2O/ton waste)	Uncertainty range (ibidem)
Conventional facilities, uncontrolled		
Coal	1.4	0-10
Oil	0.6	0-2.8
Gas	0.1	0-1.1
Conventional facilities, controlled		
Selective catalytic reduction (SCR) of NOx	see uncontrolled	see uncontrolled
NCSR	NA	10-100[***]
Other combustion facilities:		
Fluidized bed combustion - hard coal [**]	NA	10-95[**]
FBC - brown coal, peat, wood [**]	NA	10-30[**]
Gas turbines - oil, gas	NA	0-5[*]

N.B.   NA = Not Available

[**] If the combustion temperature exceeds 1000 °C one may use a range of 0-10.

[***] Preliminary estimate with NH_3 injection at lower end and with urea injection at higher end of range.

Source: De Soete (1993) and references therein.

I.5.5 Discussion Of Indirect GHGs

The IPCC/OECD programme has not yet addressed the indirect GHGs in detail. This is consistent with the initial priorities within the IPCC/OECD programme. As noted above, fuel combustion is a major source for all of these gases. Because they are important contributors to a range of local and regional, as well as global atmospheric pollution problems, NO_x, CO and NMVOC have been widely studies and reported. The Radian data cited above reflect estimates of performance ranges of main combustion technologies in place worldwide, as of 1990. They are still considered to be reasonably representative. However, since in most instances the data are based on measurement samples taken from the United States, they represent averages of operating conditions, sizes and vintages of units found there. In all cases they are averages over a range of technologies, fuel qualities, and operating conditions.

More detailed alternative emission factor source data representative of the precise technologies and other conditions in a particular country would always be desirable. National experts working on detailed emission of non-CO_2 GHGs (particularly the indirect gases) should consult the extensive literature on emission factors and other estimation procedures which has been developed by other inventory programmes outside of the framework of the IPCC/OECD programme. As distinguished from the Radian emission factors, these data generally contain more technology detail, and are further detailed by sizes of the various technologies. There is also a slight difference in the

technology representation, but this may be more a terminology than a technical difference. The specific nature of these control assumptions should be known and carefully matched with actual conditions in the specific country in selecting the specific factors to be used.

Some key examples of data sources are:

■ The CORINAIR Inventory: Default Emission Factors Handbook (Bouscaren, 1992);

■ U.S. EPA's Compilation of Air Pollutant Emissions Factors (AP-42), 4th Edition 1985, (U.S. EPA, 1985), and Supplement F, (U.S. EPA, 1993);

■ Criteria Pollutant Emission Factors for the 1985 NAPAP Emissions Inventory (Stockton and Stelling, 1987)

■ Proceedings of the TNO/EURASAP Workshop (TNO Inst. of Environmental Sciences, 1993)

◢ Emissions Inventory Guidebook (European Environment Agency, forthcoming)

■ EMEP and CORINAIR Emission Factors and Species Profiles for Organic Compounds. (Veldt, 1991);

■ Other National Compilations of Emission Factors Include

-   Netherlands   Bakkum, et al., 1987, Okken, 1989
-   Norway   Statens forurensningstilsyn, 1990
-   Germany   Brieda, 1989, Fritsche, 1989, Rentz et al., 1988,
    Walbeck, et al., 1988
-   Japan   JAERI, 1988
-   United Kingdom   Essleston and McInnes, 1987

Nitrogen Oxides (NO_x): Electricity generation and industrial fuel combustion activities are similar in that they provide combustion conditions conducive to NO_x formation. NO_x emissions depend in part on the nitrogen contained in the fuel (this may be especially important for coal), but more importantly on the firing configuration of the technology. Excess air and high temperatures contribute to high NO_x emissions. Such conditions are highly variable by type of boiler; for instance, for oil-fired plants, tangential burner configurations generally have lower emission coefficients than horizontally opposed units. Also, the size of the boiler will affect the NO_x emission rate due to the lower temperatures of smaller units.

Usage of the technology can also significantly alter the pattern of NO_x emissions. Measurements of emissions show a 0.5% to 1.0% decrease in NO_x emission rates for every 1.0% decrease in load from full load operation. That is, as the usage rate increases, so does the emission rate associated with the facility.

Finally, control policies and related technological changes to meet emission limits directly influence NO_x emissions. Emissions from large facilities can be reduced by up to 60% by straightforward adjustments to the burner technology.[21] These adjustments are often standard in new facilities, but may not exist in older facilities in many OECD countries and may be especially rare in non-OECD countries. NO_x controls may also increase the rate of CO emissions. Information on the stock of combustion facilities, their vintage, and level of control are therefore necessary to accurately estimate emissions from large combustion facilities.

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[21] This can be done, for example, by limiting the excess air in combustion or by staging the combustion process.

NO_x emissions from small combustion facilities (small industry, commercial and residential) tend to be much less significant than for large facilities due to lower combustion temperatures. Nevertheless, emissions will depend on the specific combustion conditions of the activity in question, and an effort should be made to carefully characterize the type of activity, on average, in order to select appropriate emission factors.

For many years, NO_x has been the target of environmental policies for its role in forming ozone (O_3), as well as for its direct acidification effects. As a result, NO_x emission inventories and related data such as emission factors are more widely available than those for the other non-CO_2 greenhouse gases considered here. The sources listed above provide a large number of emission factors depending on technology, fuel characteristics, operating conditions, size, vintage, etc.

Carbon Monoxide (CO): By comparison to NO_x, combustion conditions in large facilities are less conducive to formation and release of CO emissions. CO is an unburnt gaseous combustible that is emitted in small quantities due to incomplete combustion. It have also been the target of emission control policies in some countries and hence must be estimated with these controls in mind. It is directly influenced by usage patterns, technology type and size, vintage, maintenance and operation of the technology. Emissions can vary by several orders of magnitude, for example, for facilities that are improperly maintained or poorly operated, such as may be the case for many older units. Similarly, during periods of start-up, combustion efficiency is lowest, and CO emissions are higher than during periods of full operation.

Size of the unit may indicate that combustion is less controlled and hence the CO emission coefficients for smaller units are likely to be higher than for large plants. Also wood stoves, due to their largely inefficient combustion of the fuel, have particularly high emission rates of CO. For these reasons, an understanding of commercial and residential activities are key to the estimation of CO from stationary sources, particularly in non-OECD countries where residential consumption of wood and other vegetal fuels is commonly high.

CO emissions from stationary sources are estimated in the same way as for NO_x emissions. Detailed energy data provide the basis for estimation, but there may be significant variation in the precise size and type of combustion technologies in place. A main combustion source of CO is the residential sector, where there is great variation in technology by geographic region due to a variety of manufacturers as well as unconventional combustion modes that may be found throughout the world. This may be especially the case for wood fuel use[22] -- an area where data are weak both on total energy consumption and characterization of the range of technologies in use in different regions of the world.

With these notes of caution in mind, another data source for CO emission factors from stationary sources is provided in L'Office Federal de la Protection de L'Environment, Bern, Switzerland (OFPE, 1987). This source is based on other European sources; it does

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[22]Some wood fuel use which is covered in commercial energy statistics and for which technology and emission factor data are known, may be included in the calculation described in this section. For developing countries, however, there is frequently a large share of "traditional" biomass use, which is generally not included in commercial energy statistics, and data on the mix of specific technologies used is lacking. For these countries an optional simpler method of calculating emissions from "traditional" biomass fuel use is provided in the next section. National experts must take care to ensure that there is not double counting, if more than one method is used.

provide a range for each of the activity categories for CO emission factors when combined with the Radian factors above.

Non-Methane Volatile Organic Compounds (NMVOC): As with CO, combustion conditions in large facilities are less conducive to formation and release of NMVOC emissions. VOCs are also unburnt gaseous combustibles that are emitted in small quantities due to incomplete combustion. They have also been the target of emission control policies in some countries and hence must be estimated with these controls in mind. They are directly influenced by usage patterns, technology type and size, vintage, maintenance and operation of the technology. Emissions can vary by several orders of magnitude, for example, for facilities that are improperly maintained or poorly operated, such as may be the case for many older units. Similarly, during periods of start-up, combustion efficiency is lowest, and NMVOC emissions are higher than during periods of full operation.

Size of the unit may indicate that combustion is less controlled and hence the NMVOC emission coefficients for smaller units are likely to be higher than for large plants. Also wood stoves, due to their largely inefficient combustion of the fuel, have particularly high emission rates of VOCs. For these reasons, an understanding of commercial and residential activities are key to the estimation of these greenhouse gases, particularly in non-OECD countries where residential consumption of wood and other vegetal fuels is commonly high.

Extensive emission factor data for non-methane volatile organic compounds (NMVOCs) from energy combustion sources are available from most of the sources listed above. In some older sources total volatile organic compounds, including methane have been considered together. The recent work of the CORINAIR programme, the U.S. EPA sources cited above, and most other more current sources distinguish both NMVOC and methane in emission factors and emission estimates. Analysts should be careful to understand the exact category of pollutant being specified when selecting emission factor data. There is considerable uncertainty in most available information on NMVOC emissions as is the case for methane.

The CORINAIR and U.S. EPA factors show rough agreement on most categories of fuel combustion, though both acknowledge considerable uncertainty. These data highlight the importance of small combustion facilities as the main energy-related source of emissions, but emission factor data for small facilities is also particularly unreliable. In any case, a review of the literature confirms that NMVOCs from energy combustion (excluding traditional biomass fuels) is a relatively minor source of the total NMVOC emissions in any given country or region.

1.5.6 Priorities For Future Work

Data for Non-OECD Regions of the World

A high priority for follow-up work is to develop representative energy technology and emission factor data for developing countries and other non-OECD regions of the world. Emission factor data are likely to differ significantly among OECD and non-OECD regions due to differences in types of fuels, combustion technologies, their vintage, their size and operating conditions.

Uncertainty in Emission Factor Data

Emission factor data are normally presented as single point estimates. In fact, emission factors are characterized by a great deal of variation around these point estimates.

Therefore, it would be preferable to have emission factor data presented with appropriate ranges, as well as with accompanying statistics such as representative operating conditions. These statistics should help relate the range of emission factors to the associated operating conditions.

Priorities by Gas

Emission factor data are particularly weak for N_2O, CH_4, NMVOC and CO. Monitoring and measurement studies for these gases to improve the base emission factor data would further the development of complete greenhouse gas inventories. The extent to which it is necessary to fill data gaps depends upon the importance of these greenhouse gases in national inventories.

However, CH_4 and N_2O emissions from stationary combustion sources (excluding "traditional" biomass fuel burning) are a small share of total emissions, although a few specific technologies appear to have higher emission rates and may warrant extensive study.

Similarly, NMVOC and CO can be quite significant in areas where wood or vegetal fuels make up a major share of total energy consumption. Again, these are areas with substantial "traditional" biomass fuel consumption, discussed in the next section.

Development of Simplified Workbook Methods

As noted several times in this chapter, the non-CO_2 gases do not lend themselves to simple "top-down" aggregate emissions estimation. Nonetheless, the IPCC and parties to the Framework Convention on Climate Change are committed to providing methods which are both comprehensive over all GHGs and accessible to all participating countries. Further work is needed to define default methods for estimating the non-CO_2 gases from fuel combustion. This may require development of a "mid-level" approach which incorporates more detail than the national top down CO_2 approach, but provides an intermediate level of detail which can capture the most important variations by technology without going directly to the most detailed level of technology information which may be difficult for some countries to obtain.

Reconciling Energy and ISIC Categories with Engineering-Technology Category Definitions

A priority for those countries where extensive emission data bases are being developed is a means of relating categories used in IEA energy statistics, as well as more detailed ISIC categories to standard engineering-technology or process category definitions. One key example is the ongoing effort to reconcile the proposed IPCC source category structure with the engineering/technology based structure in CORINAIR. This is discussed in *Volume I: Reporting Instructions*.

1.6 Burning Traditional Biomass Fuels

1.6.1 Overview

For all burning of biomass fuels, the IPCC methodology requires that net CO_2 emissions are treated as zero in the energy sector. Some biomass fuels are sustainably produced, in which case the actual net emissions are zero. However, even if all or part of the biomass fuel burned is extracted unsustainably from existing biomass stocks (e.g., forests), it would be difficult to determine, at the point of combustion, what fraction actually represents net emissions. Therefore, net CO_2 emissions, which are reflected in reductions in biomass stocks, are accounted for in the Land Use Change and Forestry section of the methodology.[23] However, other (non-CO_2) gases are emitted from burning of biomass fuels. Emissions of these gases (e.g., methane - CH_4, carbon monoxide - CO, nitrous oxide - N_2O, and oxides of nitrogen - NO_x) are net emissions and are accounted for as energy emissions. This section provides a method for calculating emissions of these non-CO_2 gases from burning of traditional biomass fuels.

Burning of "traditional biomass" is intended to include all traditional, small-scale use of biomass fuels, such as cook stoves and open fires. It also includes the production as well as consumption of charcoal in small scale traditional processes. In these conditions, emissions can be estimated using emission ratios of CH_4 and other gases to total carbon oxidized in the biomass, as is done in the various non-energy types of open burning. Non-CO_2 trace gas emissions from commercial use of biomass in large-scale combustion facilities or other technologies for converting energy, are treated elsewhere in the energy combustion chapter. This is because the recommended methods for calculating emissions for these source types are different from this proposed method for traditional, small-scale bioenergy use. Emissions from large-scale facilities are very much a function of the particular technology used and are treated very much like emissions from stationary fossil fuel combustion -- with specific emission factors for each technology/fuel combination. Emissions from traditional biomass fuel use also vary significantly based on technology, operating conditions, etc. However, available data often does not support a technology specific approach for traditional biomass fuel use. Therefore, the emission ratios approach is provided as a common method for crude estimation which can be used by all national experts.

This separation between commercial and traditional biomass does introduce the possibility of double counting some biomass energy use. Care should be taken to ensure that the "commercial" component of bioenergy use is carefully defined and deducted from total bioenergy consumed before doing the calculations of emissions from traditional biomass fuel use described in this section. It should also be noted that other possibilities for double counting of emissions from biomass fuels exist in the methodology. Agricultural residues and dung are two of the traditional fuels included in this section. Both are also sources of

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[23] For policy analysis purposes in the energy sector, it may be very important to consider the net CO_2 emissions from biomass fuel burning as an energy related emission. This can facilitate the comparison of biomass fuel combustion with other energy options on the basis of CO_2 or total GHG emissions. It is possible to reallocate the implied CO_2 emissions to biomass burning for such analytic purposes. However, it is essential, for consistency, that all **national inventories** be reported as specified in the *IPCC Guidelines*, that is, no net CO_2 emissions are counted for biomass burning.

emissions calculated in the agriculture section. Some portion of agricultural residues may be burned in the fields and produce the same set of trace gases in that situation. Dung is treated as a potential source of methane emissions from anaerobic decomposition in the calculation of emissions from animal wastes. In both cases it is the responsibility of users of this methodology to ensure that these materials are allocated to their different uses and not counted in both places.

For traditional biomass fuels, the approach is essentially the same as that used for non-CO_2 trace gases from all burning of unprocessed biomass, such as field burning of agricultural residues and savanna burning (Chapter 4: Agriculture) and open burning of cleared forests (Land use change and forestry, Chapter 6). For all these activities there is a common approach in the proposed methodology, in that crude estimates of non-CO_2 trace gas emissions can be based on ratios to the total carbon released. The carbon trace gas releases (CH_4 and CO) are treated as direct ratios to total carbon released. To handle nitrogen trace gases ratios of nitrogen to carbon in biomass fuels are first used to derive total nitrogen released. Then emissions of N_2O and NO_x are based on ratios to total nitrogen released. Default values for non-CO_2 trace gas emission ratios are provided, including ranges which emphasize their uncertainty. However, the basic calculation methodology requires that users select a best estimate value.[24]

1.6.2 Recommended Methodology

Calculations: There are two basic components to the calculation. First, it is necessary to estimate the amount of carbon released to the atmosphere from biomass fuel burning. These carbon releases are not **net** emissions, but are needed to derive non-CO_2 trace gas emissions which are net emissions. The activity data required are the annual consumption of the various types of biomass fuels. Box 1 provides some suggestions for developing these data. Based on the type of fuel burned, the amount of carbon released can be calculated (a reflection of carbon content and combustion efficiencies, see Table A). The second component is the same as for other biomass burning categories -- emission ratios are applied to estimate the amount of non-CO_2 trace gas released based on the amount of carbon released (Box 2)

Part 1: Total Carbon Released. First, for combustion by fuel, the mass of fuel as dry matter is converted to carbon units, and second, an efficiency of burn is assigned. The general equation for estimating CO_2 emissions is:

> Emissions from Biomass Fuel (by type) = Total Fuel Consumed (10^3 mt dm)
> X Carbon Fraction X Fraction Oxidized (combustion efficiency)

For emissions from charcoal production a single factor is applied based on total carbon released in charcoal production. One estimate indicates that the amount of carbon released during charcoal production roughly equals the carbon in charcoal consumed. In other words, roughly half of the original carbon in the wood is lost during charcoal

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[24] Emissions inventory developers are encouraged to provide estimates of uncertainty along with these best estimate values where possible, or to provide some expression of the level of confidence associated with various point estimates provided in the inventory. Procedures for reporting this uncertainty or confidence information are discussed in *Volume 1: Reporting Instructions.*

manufacture.[25] Therefore, to account for this release, as a default value, one could simply use the estimated release of carbon from charcoal burning as the estimate of carbon released from charcoal production.

Part 2: Non-CO$_2$ Trace Gas Emissions. Once the carbon released from biomass fuel burning has been estimated, the emissions of CH$_4$, CO, N$_2$O, and NO$_x$ can be calculated as follows.[26] The amount of carbon released due to burning is multiplied by the emission ratios of CH$_4$ and CO relative to total carbon emissions to yield total 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.

Box 1
FUEL CONSUMPTION ACCOUNTING

For traditional biomass fuel use, direct consumption statistics are often incomplete or unavailable. Large amounts of traditional fuels used may not be traded through normal commercial fuel markets. Instead they may be traded in the informal sector or directly gathered by consumers. In this situation, it is often considered more accurate to base fuel consumption estimates on surveys of household and small commercial fuel use patterns. In many countries, such surveys have produced rules of thumb concerning per capita use of traditional fuels (charcoal, fuelwood, dung, etc.). Survey results may be available as national averages, or broken down between rural and urban populations, or by region within countries. Users of this methodology may determine this to be the most reliable approach for all or part of biomass fuel consumption. In that case, available values for per capita consumption of biomass fuels should be documented and multiplied by population to obtain total consumption values by fuel type.

To calculate emissions of N$_2$O and NO$_x$, first the total carbon released is multiplied by the estimated N/C ratio of the fuel by weight (default values for biomass fuels are provided in table A) to yield the total amount of nitrogen (N) released. The total N released is then multiplied by the ratios of emissions of N$_2$O and NO$_x$ relative to the N content of the fuel to yield emissions of N$_2$O and NO$_x$ (expressed in units of N). To convert to full molecular weights, the emissions of N$_2$O and NO$_x$ are multiplied by 44/28 and 30/14, respectively.[27]

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[25] Delmas, 1993. Based on measurements indicating that 26% by weight of input fuelwood (dm) was produced as charcoal, with 87% carbon. This results in about 1/2 the carbon in original biomass remaining in charcoal, with 1/2 released during charcoal production. Hall (1993) suggests much different values assuming that only 12.5% of dry biomass in original wood is produced as charcoal and that carbon content of traditionally produced charcoal ranges from 60-80%. This would indicate that less than 25% of carbon in original dry biomass is incorporated into charcoal produced. Thus, 75+% of carbon is released in production. Additional work is needed to resolve these differences.

[26] From Crutzen and Andreae, 1990.

[27] There is an inconsistancy in the methodology in the treatment of the full molecular weight of NO$_x$. In fossil energy and industry discussions NO$_x$ is expressed as though all of the N were in the form of NO$_2$. In biomass burning literature, (e.g., Crutzen and Andreae, 1990) NO$_x$ is often discussed as though the emissions were in the form of NO. Therefore, the biomass burning discussions in these Guidelines convert NO$_x$-N to full weight using the conversion factor (30/14) for NO. All other references to NO$_x$ are based on the full weight of NO$_2$ (i.e., the conversion factor from NO$_x$-N would be 46/14).

The non-CO_2 trace gas emissions from burning calculation is summarized as follows:

CH_4 Emissions = (carbon released) × (emission ratio) × 16/12

CO Emissions = (carbon released) × (emission ratio) × 28/12

N_2O Emissions = (carbon released) × (N/C ratio) × (emission ratio) × 44/28

NO_x Emissions = (carbon released) × (N/C ratio) × (emission ratio) × 30/14

TABLE 1-19
BIOMASS FUELS DEFAULT DATA

Fuel Type	Carbon Fraction[1]	Nitrogen-Carbon (N/C) Ratio[2]	Combustion Efficiency[1]
Fuelwood	0.45-0.5	0.01	87
Charcoal Consumption	0.87	?	88
Charcoal Production[3]	0.45-0.5	0.01	30
Dung	0.36-0.42	?	85
Agricultural Residues[4]	0.4-0.48	0.01-0.02	88

Sources: [1] Delmas and Ahuja, 1993; [2] Crutzen and Andreae, 1990. [3] Delmas, 1993b

[4] These are general default values for crop residues. Specific carbon fraction and N/C ration data for residues from individual crops are provided in the agricultural burning discussion in chapter 4. If consumption data on biomass fuels are specific by crop type, these crop specific values can be used.

BOX 2
TRACE GAS EMISSIONS RATIOS

Emissions of CH_4, CO, N_2O and NO_x from burning of traditional biomass fuels (and other types of biomass burning associated with forest clearing and agriculture) are generally estimated by first calculating the total carbon emitted (mostly as CO_2) from combustion and applying a series of ratios. First, a ratio of nitrogen to carbon in fuel is applied to estimate total nitrogen released. Then specific ratios of CH_4 and CO to total carbon, and N_2O and NO_x to total nitrogen are used to estimate these trace gas emissions. Crutzen and Andreae (1990) provided a range of values considered representative of biomass burning generally.

Compound	Ratios	
CH_4	0.01	(0.007 - 0.013)
CO	0.10	(0.075 - 0.125)
N_2O	0.007	(0.005 - 0.009)
NO_x	0.121	(0.094 - 0.148)

Source: Crutzen and Andreae, 1990

More recently, Lacaux et al.(1993) have suggested a lower emissions ratio range for CO: 0.06 (0.04-0.08).

Delmas (1993a) and Delmas and Ahuja (1993) have developed more specific ratios for CH_4 from different types of biomass burning, including values for specific biomass fuels and open burning from forest clearing and agriculture. Delmas and Ahuja, 1993, also provide a ratio for estimating methane from the charcoal production process. This value is much higher than the Crutzen and Andreae range for relatively open burning, and should be used to estimate what could be a significant methane source in many countries. Fuel values are shown below.

Fuel Type	Ratio - C-CH_4/total C
Fuelwood	0.012 (0.009-0.015)
Agricultural Residues	0.005 (0.003-0.007)
Dung	0.017
Charcoal combustion	0.005 (0.0014-0.0085)
Charcoal production	0.063 (0.04-0.09)

These more recent values are considered more accurate than the Crutzen and Andreae ranges where available for individual components of biomass burning.

1.7   Greenhouse Gas Emissions from Mobile Combustion

1.7.1 Overview

This section discusses emissions of greenhouse gases from mobile sources, including carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), methane (CH_4), nitrous oxide (N_2O), and non-methane volatile organic compounds (NMVOCs). Emissions from mobile sources are most easily estimated by major transport activity, i.e., road, air, rail, and ships. Several major fuel types need to be considered, including gasoline, diesel, jet fuel, aviation fuel, natural gas, liquified petroleum gas, and residual fuel oil. Road transport accounts for the majority of mobile source fuel consumption (e.g., 82% in 1988 for the OECD), followed by air transport (about 13%). This suggests that the primary emphasis in developing emission inventories should be placed on road vehicles, followed by aircraft.

As a one of the major energy consuming sectors, globally and in most countries, transport is a significant source of CO_2 emissions. As discussed previously, these emissions should be accounted for in the "top-down" IPCC Reference Approach to CO_2 from fuel combustion described earlier. However, it is also useful to develop more detailed information about the role of specific end use activities, such as mobile sources, in causing CO_2 emissions. National experts are therefore encourage to also calculate CO_2 emissions at a more detailed level (as described in this section for transport) and to aggregated these estimates up for comparison with the Reference Method. Therefore, the discussion in this section includes information needed to estimate CO_2 emissions as well as other gases at a detailed level.

Motor vehicles release a large portion of total anthropogenic NO_x emissions. These emissions are related to air-fuel mixes and combustion temperatures, as well as pollution control equipment. For uncontrolled vehicles, NO_x emissions from diesel-fueled vehicles are generally lower than from gasoline-fueled vehicles and lower from heavy duty vehicles (HDV) on an emissions per ton/kilometer basis than light duty vehicles (LDV). HDV still contribute significant emissions and are more difficult to control than light duty vehicles.

The majority of CO emissions from fuel combustion comes from motor vehicles. CO emissions are a function of the efficiency of combustion and post-combustion emission controls. Emissions are highest when air-fuel mixtures are "rich," with less oxygen than required for complete combustion. This occurs especially in idle, low speed, and cold start conditions in spark ignition engines.

CH_4 and NMVOC emissions are a function of the methane content of the motor fuel, the amount of hydrocarbons passing unburnt through the engine, and any post-combustion control of hydrocarbon emissions, such as use of catalytic converters. In uncontrolled engines, emissions of unburned HC, including CH_4, are lowest when the combustion conditions (quantity of hydrogen, carbon, and oxygen present) are exactly right for complete combustion. They are generally highest in low speed and engine idle conditions. Poorly tuned engines (typical of many developing countries) may have particularly high output of total HC, including CH_4. Emissions are also dependent on engine type, emission controls and the fuel combusted.

N_2O emissions from vehicles have only recently been studied in detail. Emissions from this source are still thought to be small relative to total anthropogenic emissions. Emission rates are, however, substantially higher when some emission control technology

(especially catalysts on road vehicles) are used, and this could cause the total emissions to grow in the future.

Emission control policies adopted in many OECD member countries, will substantially reduce CO, NMVOC, CH_4, and NO_x emissions per automobile in these countries, but may cause N_2O emissions to increase.

Organization of this section

The next sub-section provides a discussion of the basic inventory methodology recommended for this mobile source emissions. Following illustrative information on emission factors is provided. This is summarized from a 1991 document, but useful in illustrating the range of mobile source types of concern and rates of emissions of various gases. Subsequently, some more recent information, developed by expert advisory groups to the IPCC/OECD programme, is provided on two direct GHGs - N_2O and CH_4. A short subsection discusses indirect GHGs - NO_x, CO and NMVOC. No new work has been done within the IPCC/OECD programme on these gases, but considerable detailed information is available from other national and international emissions inventory programmes. Some key references to this body of technical work are provided. A final sub-section suggests some priorities for future work on GHG emissions from mobile sources.

1.7.2 Basic Inventory Method: Mobile Source Emissions

Estimation of mobile source emissions is a very complex undertaking that requires consideration of many parameters, including information on such factors as:

- transport class

- fuel consumed

- operating characteristics

- emission controls

- maintenance procedures

- fleet age

- other factors

The need for data on several parameters and the wide variety of conditions that can affect the performance of each category of mobile sources makes it very difficult to generalize the emission characteristics in this area. This area is so complex that is difficult even for countries with extensive experience to develop highly-precise emission inventories.

Nevertheless, a basic emission estimation methodology was developed and included in the in the report of the OECD Experts Meeting in which was circulated to IPCC national experts as a starting point for the methods development programme (OECD, 1991). This basic discussion is still useful and repeated with few changes in this section. The method is consistent with the calculations carried out in those countries which already have detailed mobile source emissions inventory data bases. It is presented in a somewhat simplified, aggregate form to assist countries, with limited experience estimating emissions from mobile sources, in getting started.

In order to develop estimates for greenhouse gas emissions from mobile sources, basic information is required on the types of fuels consumed in the transport sector, the

combustion technologies that are used to consume the fuels, operating conditions during combustion, and the extent of emission control technologies employed during and after combustion. The basic calculation for estimating these emissions can be expressed as:

$$\text{Emissions} = \sum (EF_{abc} \times \text{Activity}_{abc})$$

where: EF = emissions factor

Activity = amount of energy consumed or distance traveled for a given mobile source activity

a = fuel type (diesel, gasoline, LPG, bunker, etc.)

b = vehicle type (e.g., passenger, light duty or heavy duty for road vehicles)

c = emission control

Based on this formula, the following basic steps are required to estimate mobile source emissions:

■ Determine the amount of energy consumed by fuel type for all mobile sources using national data or, as an alternative, IEA or UN international data sources (all values should be reported in gigajoules).

■ For each fuel type, determine the amount of energy that is consumed by each vehicle type, e.g., light-duty gasoline vehicles, etc. (all units are in gigajoules). If distance traveled is the basis, determine the total distance traveled by each vehicle type. In this case; the energy consumption associated with these distance travelled figures should be calculated and aggregated by fuel for comparison with national energy balance figures. If necessary, further subdivide each vehicle type into uncontrolled and key classes of emission control technology.

■ Multiply the amount of energy consumed, or the distance traveled, by each vehicle, or vehicle/control technology, category by the appropriate emission factor for that category. Data presented in the next section (Illustrative Emission Factors) can be used as a starting point. However, national experts are encouraged to consult other data sources referenced in this chapter and locally available before determining appropriate factors for a particular country.

■ Emissions can be summed across all fuel and technology type categories, including for all levels of emission control, to determine total emissions from mobile source-related activities.

Regardless of the specific methodology that is used to determine emissions, it is important to remember that there is a substantial amount of uncertainty surrounding the estimation of emissions from mobile sources. National experts are encouraged to provide indications of uncertainty in their estimates as described in *Volume 1: Reporting Instructions*.

Data Sources

Emission factors (such as those in Tables 2-20 through 2-31) can only be used if energy consumption can be adequately characterized by the fuel and vehicle/control technology categories. For example, for transportation needs, information is required on the percentage of light-duty versus heavy-duty vehicles by fuel type (gasoline- versus diesel-fueled) and the extent of emission controls for each category. There is no single data source that comprehensively provides all relevant information. There are several sources, however, that can help to determine this information.

For example, activity data on vehicle fleet characteristics will be needed. There are two main international sources of data available on transport, both of which are recommended to be used as the international point of reference. For road transport, both the UNECE (*Annual Bulletin of Transport Statistics for Europe*, e.g., 1989, Geneva) and the International Road Federation (*World Road Statistics*, e.g., 1990, Washington, D.C.) provide annual data on various aspects of vehicle fleets and traffic conditions. While the former is more detailed for the various modes of transport, it is available for Europe only. The latter is worldwide in coverage but provides only a few key statistics. These include data on vehicles in use, road traffic, motor fuels, and data on the flows of vehicles produced and sold (imports and exports) among countries. Individual regional and national data sources can also be used and may in fact be more disaggregate and up-to-date than these international data sources.

Information on energy consumption in the transport sector is also needed to determine emissions. As discussed earlier, the most reliable sources for international energy statistics are the International Energy Agency and the UN Statistical Division, where data on transport activities are detailed by fuel type and basic transport mode. These data are available for most mobile source energy consumption in the world. National energy data sources may be preferable to these international sources but the reporting definitions and conventions of the IEA energy balance should be used to summarise these energy data. This provides a check for internal consistency of the energy assumptions used to estimate emissions from mobile source combustion.

1.7.3 Illustrative Emission Factors

This section summarizes results of a detailed analysis of mobile source emission factors for gases contributing to global warming which was carried out in 1991. A more detailed discussion of the methods and assumptions used can be found in OECD 1991. It has not been possible, in the preparation of this *Reference Manual*, to update this earlier analysis in a systematic way. The results are still useful in illustrating the range of emission rates from different types of vehicles and how those rates vary by vintage and control technology. It is also very useful in providing side by side expressions of the same emission factors in three different forms. Therefore, the results are summarized in this section, as originally presented, for illustrative purposes.

However, for actual calculations of national emissions, users are encouraged to also consult a range of more recent and more detailed information sources. Particularly for indirect GHGs, more comprehensive and up-to-data sources as well are available based on programmes outside the GHG emissions area. More recent data on some gases, and references to other detailed data sources are provided in the gas by gas subsections later in this section.

Emission factor estimates are presented for CO_2, CO, NO_x, N_2O, methane, and non-methane VOCs for several classes of highway vehicles, railway locomotives, ships and boats, farm and construction equipment, and aircraft. All emission factor data are stated on the basis of full molecular weight of the respective pollutant; NO_x factors are stated as NO_2.

Road Vehicles - Conventional Fuels

Technical Approach

The emissions estimates for NO_x, CO, methane, and NMVOC from highway vehicles are based on the U.S. EPA's MOBILE4 model (EPA, 1989). MOBILE4 calculates exhaust emission factors for U.S. vehicles using gasoline and diesel fuel, based on the year in which

they were manufactured. For gasoline vehicles, it also calculates VOC emissions due to evaporative, running, and refueling losses (VOC emissions from diesel vehicles due to these causes are negligible).

Assumptions

Specific U.S. model years were used to represent the different possible control technologies. Emissions were calculated for a five year old vehicle of each type (approximately halfway through their useful lives). Similarly, emissions estimates for advanced-technology vehicles were based on 1990 model vehicles, calculated in 1995. Table 1-20 shows the correspondence between technology types and the U.S. model years used to represent them in the model. The conditions chosen for the modeling were "typical" values of 75 °F, with a diurnal range from 60 to 85 °F (24±8 °C), and Reid vapor pressure of gasoline at 9.0 PSI (62 kPa). Average speed was taken as the MOBILE4 default of 31.4 km/hr, typical of uncongested urban driving. An effective inspection/ maintenance and anti-tampering program, was assumed to be in place.

Since MOBILE4 does not estimate N_2O or CO_2 emissions, these were estimated separately. CO_2 emissions were calculated from typical fuel economy data for U.S. vehicles for representative model years in which the technology was used together with the average carbon content for each type of fuel.[28] Fuel economy estimates for heavy-duty gasoline and diesel trucks, are from Machiele, (1988), and from Weaver and Turner (1991) for other vehicle classes. The specific fuel economy value assumed for U.S. vehicles in each case is shown in the tables. The estimated vehicle fuel economies were also used to calculate fuel-specific (g/kg fuel) and energy-specific (g/MJ)[29] emission factors for all of the pollutants. The CO_2 factors on an energy input (g/MJ) were taken from Grubb (1989); all other emission factors are from Turner and Weaver (1991). Since emissions and fuel consumption tend to vary in parallel (vehicles and operating modes causing high emission rates also tend to result in high fuel consumption, and vice versa), these energy-specific emission factors are expected to be more generally applicable than the factors in grams/km.

N_2O emissions factors were developed based on the limited available test data. Prigent and Soete (1989), Dasch (1991), Ford (1989-1991), and Warner-Selph and Smith (1991) gave N_2O emissions for light-duty gasoline vehicles which were divided into four groups of technologies: uncontrolled, oxidation catalyst, early three-way catalyst, and modern three-way catalyst technologies. For light-duty gasoline trucks and motorcycles, fuel-specific N_2O emissions were assumed to be the same as for the corresponding passenger car technology. No data on N_2O emissions from heavy-duty gasoline trucks were available, but they were assumed to emit at the same rate per unit of fuel burned as passenger cars having similar technology. However, since these trucks undergo a heavier duty cycle, and experience fewer cold-starts, it was considered more appropriate to use N_2O emission factors based on the U.S. highway fuel economy test (HFET) rather than the cold-start FTP procedure. Fuel-specific N_2O emissions for passenger cars in the HFET procedure were obtained from the same data sources listed above. Dietzmann, Parness, and Bradow (1980) reported N_2O emission factors for heavy-duty diesel vehicles. No N_2O emissions data

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[28]As is the convention throughout these *Guidelines*, CO_2 emissions are calculated to include the carbon emitted as CO and as VOC. The rationale for this approach is explained in the Introduction.

[29] MJ=megajoule=10^6 joules. Energy-specific emission factors were based on the lower heating value of the fuel in each case.

were available for light-duty diesel vehicles, but they were assumed to have the same fuel-specific emission rates as for diesel passenger cars.

Results of this analysis are presented by categories defined by the U.S. EPA as listed below:

Table 1-21: Light-duty gasoline passenger cars - vehicles with rated gross weight less than 8,500 lb (3,855 kg) designed primarily to carry 12 or fewer passengers. Five levels of gasoline-vehicle control technology are shown:

1   Uncontrolled (still typical of most vehicles around the world)

2   Non-catalyst emission controls - including modifications to ignition timing and air-fuel ratio to reduce emissions, exhaust gas recirculation (EGR), and air injection into the exhaust manifold.

3   Oxidation catalyst systems normally including many of the same techniques, plus a two-way catalytic converter to oxidize HC and CO.

4   "Early" three-way catalyst results representative of vehicles sold in the U.S. in the early to mid '80s, which were mostly equipped with carburetors having electronic "trim".

5   "Advanced" three-way catalyst values based on current U.S. technology vehicles, using electronic fuel injection under computer control.

Table 1-22: Light-duty gasoline trucks - vehicles having rated gross vehicle weight less than 8,500 lb (3,855 kg), and which are designed primarily for transportation of cargo or more than 11 passengers at a time, or which are equipped with special features for off-road operation. They include most pickup trucks, passenger and cargo vans, four-wheel drive vehicles, and derivatives of these. The technology classifications used are the same as those for gasoline passenger vehicles.

Table 1-23: Heavy-duty gasoline vehicles - manufacturer's gross vehicle weight rating exceeding 8,500 lb (3,855 kg). This includes large pickups, vans and specialized trucks using pickup and van chassis, as well as the larger "true" heavy-duty trucks, which have gross vehicle weights of eight short tons or more. In the U.S., the large pickups and vans in this category greatly outnumber the heavier trucks, so that the emission factors calculated by MOBILE4, and fuel economy estimates, are more representative of these vehicles. Three levels of emission control technology are shown:

1   Uncontrolled.

2   Non-catalyst emission controls, including control of ignition timing and air-fuel ratio to minimize emissions, EGR, and air injection into the exhaust manifold to reduce HC and CO emissions.

3   Three-way catalyst technology presently used in the U.S. includes electronically-controlled fuel injection, EGR, air injection, and electronic control of ignition timing, as well as the catalyst itself.

Table 1-24: Light-duty diesel passenger cars - a diesel passenger car designed primarily to carry fewer than 12 passengers, with gross vehicle weight less than 8,500 lb (3,855 kg). Three levels of emission control technology are shown:

1   Uncontrolled

2   Moderate emissions control (achieved by changes in injection timing and combustion system design).

3   Advanced emissions control utilizing modern electronic control of the fuel injection system, and exhaust gas recirculation.

Table 1-25: Light-duty diesel trucks - light-duty diesel trucks defined like their gasoline counterparts, including weight, utility, and off-road operation features. The technology classifications are the same as those for diesel passenger cars.

Table 1-26: Heavy-duty diesel vehicles - the classification for heavy-duty diesel vehicles is the same as for gasoline vehicles, but the characteristics of the U.S. vehicle fleets are different. Heavy-duty diesel vehicles are primarily large trucks, with gross vehicle weight ratings of 10 to 40 tons. Therefore, the MOBILE4 emission factors are more representative of large trucks (and buses) than the smaller pickup and van-type vehicles, and this is reflected in the fuel economy estimates. Three levels of control are presented:

1   Uncontrolled.

2   Moderate control (typical of 1983 U.S. engines).

3   Advanced control (for engines meeting U.S. 1991 emissions standards)

Table 1-27: Motorcycles - The MOBILE4 emission factors for these vehicles are based on the U.S. motorcycle population, which probably reflects higher average power ratings and fuel consumption than for many developing countries. The factors for uncontrolled motorcycles include a mixture of two-stroke and four-stroke engines, with the VOC emissions due primarily to the two-strokes, and the NO_x to the four-stroke engines. The factors for motorcycles with non-catalyst emission controls reflect four-stroke engines only, as U.S. emission control regulations have essentially eliminated two-stroke engines from the market.

MOBILE4

Emission factors for certain greenhouse gas emissions from road vehicles can be developed using the MOBILE4 computer model.[1] This model was the basis for most of the emission factors presented in Tables 2-21 to 2-27, and can be used to calculate average emission rates for any selected calendar year (from 1960 to 2020) essentially by aging the fleet and weighting the emission factors by the shares of distance travelled by vehicles of various ages. The emission factors are estimated as a function of several parameters, including: vehicle type; model year (technology); vehicle age and accumulated mileage; percent of driving in cold start, hot start or stabilized conditions;

average speed; ambient temperatures; fuel volatility; and tampering rates with emission control systems. Since *these variables can be manipulated by the user, the conditions can be altered to reflect conditions in a variety of geographic regions and regulatory situations.

MOBILE4 calculates emission factors for total and non-methane hydrocarbons (HC and NMHC), NO_x and CO, and two fuels (gasoline and diesel). The emissions performance in MOBILE4 for vehicles under various conditions is estimated based on years of extensive testing of vehicles in use in the United States. The user can specify input data for the particular region or country, and emission factors that are tailored to that particular region will be estimated.

Several notes of caution need to be given on the use of MOBILE4 for development of greenhouse gas emission factors. First, the pollutant coverage is incomplete (including only NO_x, CO, VOC, and NMVOCs with methane as a calculated result of the difference between NMVOC and VOC).

Second, alternative fuel vehicles are not yet incorporated into the model. Supplementary information must therefore be used to develop these factors should the fuel mix in transport activities require them. Any assumptions used to build these factors should be as comparable as possible with those for conventional motor fuels.

Third, special attention must be given to the definition of MOBILE4 fleet assumptions to include two-stroke engines in order to make the results useful to many non-OECD nations. A substantial portion of the automobile fleets in countries of Eastern Europe and perhaps in other parts of the non-OECD world are two-stroke engines. These engine types have a substantially different emission profile than the standard (Otto) gasoline or four-stroke engine which is predominant in the OECD. Fleet data on two-stroke engine vehicle stocks will therefore be a first priority in understanding the necessary modifications to MOBILE4 emission factor estimates, which have been largely developed for OECD countries and regions.

[1] The MOBILE4 Model and its *User's Guide can be obtained from the U.S. National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia, 22161, United States.*

TABLE 1-20 EMISSION CONTROL TECHNOLOGY TYPES AND U.S. VEHICLE MODEL YEARS USED TO REPRESENT THEM	
Technology	**Model Year**
Gasoline Passenger Cars and Light Trucks	
Uncontrolled	1963
Non-catalyst controls	1972
Oxidation catalyst	1978
Early three-way catalyst	1983
Advanced three-way catalyst	1990
Heavy-Duty Gasoline Vehicles	
Uncontrolled	1968
Non-catalyst control	1983
Three-way catalyst	1991
Diesel Passenger Cars and Light Trucks	
Uncontrolled	1978
Moderate control	1983
Advanced control	1990
Heavy Duty Diesel Vehicles	
Uncontrolled	1968
Moderate Control	1983
Advanced control	1991
Motorcycles	
Uncontrolled	1972
Non-catalyst controls	1990

TABLE 1-21						
ESTIMATED EMISSIONS FACTORS FOR GASOLINE PASSENGER CARS						
	EMISSIONS					
	NOx	CH4	NMVOC	CO	N2O	CO2
Advanced Three-Way Catalyst Control; Assumed Fuel Economy: 11.9 km/l						
Total - g/km	0.50	0.020	0.66	3.14	0.019	200
Exhaust	0.50	0.020	0.26	3.14	0.019	200
Evaporative			0.11			
Refueling			0.15			
Running loss			0.14			
g/kg fuel	7.94	0.32	10.48	49.87	0.30	3172
g/MJ	0.18	0.0072	0.24	1.13	0.0069	69.3
Early Three-Way Catalyst; Assumed Fuel Economy: 9.4 km/l						
Total - g/km	0.52	0.04	0.67	3.12	0.046	254
Exhaust	0.52	0.04	0.25	3.12	0.046	254
Evaporative		0	0.12			
Refueling		0	0.16			
Running loss		0	0.14			
g/kg fuel	6.49	0.50	8.36	38.93	0.57	3172
g/MJ	0.15	0.0113	0.19	0.88	0.0130	69.3
Oxidation Catalyst; Assumed Fuel Economy: 6.0 km/l						
Total - g/km	1.59	0.09	1.75	12.98	0.027	399
Exhaust	1.59	0.09	1.13	12.98	0.027	399
Evaporative		0	0.19			
Refueling		0	0.21			
Running loss		0	0.22			
g/kg fuel	12.63	0.71	13.90	103.07	0.21	3172
g/MJ	0.29	0.0162	0.32	2.34	0.0049	69.3
Non-Catalyst Control; Assumed Fuel Economy: 6.0 km/l						
Total - g/km	1.97	0.174	3.15	23.8	0.005	399
Exhaust	1.97	0.174	2.14	23.8	0.005	399
Evaporative		0	0.45			
Refueling		0	0.29			
Running loss		0	0.27			
g/kg fuel	15.64	1.38	25.01	188.99	0.04	3172
g/MJ	0.36	0.0314	0.57	4.30	0.0009	69.3
Uncontrolled; Assumed Fuel Economy: 6.0 km/l						
Total - g/km	2.14	0.174	6.33	40.62	0.005	399
Exhaust	2.14	0.174	4.36	40.62	0.005	399
Evaporative		0	1.37			
Refueling		0	0.28			
Running loss		0	0.32			
g/kg fuel	16.99	1.38	50.27	322.56	0.04	3172
g/MJ	0.39	0.0314	1.14	7.33	0.0009	69.3

TABLE 1-22
ESTIMATED EMISSION FACTORS FOR LIGHT-DUTY GASOLINE TRUCKS.

	NOx	CH4	NMVOC	CO	N2O	CO2
EMISSIONS						
Advanced Three-Way Catalyst Control; Assumed Fuel Economy: 9.4 km/l						
Total - g/km	0.67	0.04	0.75	4.68	0.024	254
Exhaust	0.67	0.04	0.4	4.68	0.024	254
Evaporative		0	0.1			
Refueling			0.2			
Running loss			0.04			
g/kg fuel	8.36	0.50	9.36	58.40	0.30	3172
g/MJ	0.19	0.0113	0.21	1.33	0.0068	69.3
Early Three-Way Catalyst; Assumed Fuel Economy: 6.8 km/l						
Total - g/km	1.00	0 aa.07	1.17	9.23	0.063	350
Exhaust	1.00	0.07	0.78	9.23	0.063	350
Evaporative		0	0.13			
Refueling		0	0.21			
Running loss		0	0.04			
g/kg fuel	9.08	0.64	10.62	83.76	0.57	3172
g/MJ	0.21	0.0144	0.24	1.90	0.0130	69.3
Oxidation Catalyst; Assumed Fuel Economy: 5.1 km/l						
Total - g/km						
Exhaust	1.62	0.09	1.95	12.15	0.031	466
Evaporative	1.62	0.09	1.22	12.15	0.031	466
Refueling		0	0.22			
Running loss		0	0.29			
g/kg fuel		0	0.22			
g/MJ	11.03	0.61	13.27	82.70	0.21	3172
Non-Catalyst; Assumed Fuel Economy: 5.1 km/l	0.25	0.0139	0.30	1.88	0.0048	69.3
Total - g/km						
Exhaust	2.82	0.174	4.55	28.81	0.006	466
Evaporative	2.82	0.174	3.01	28.81	0.006	466
Refueling		0	0.9			
Running loss		0	0.34			
g/kg fuel		0	0.29			
g/MJ	19.19	1.18	30.97	196.09	0.04	3172
Uncontrolled; Assumed Fuel Economy: 5.1 km/l	0.44	0.0269	0.70	4.46	0.0009	69.3
Total						
Exhaust	2.63	0.174	8.54	44.55	0.006	466
Evaporative	2.63	0.174	4.98	44.55	0.006	466
Refueling		0	2.92			
Running loss		0	0.32			
g/kg fuel		0	0.32			
g/MJ	17.90	1.18	58.13	303.23	0.04	3172
	0.41	0.0269	1.32	6.89	0.0009	69.3

TABLE 1-23 ESTIMATED EMISSION FACTORS FOR HEAVY-DUTY GASOLINE VEHICLES						
	EMISSIONS					
	NOx	CH4	NMVOC	CO	N2O	CO2
Three-Way Catalyst Control; Assumed Fuel Economy: 2.9 km/l						
Total - g/km	2.64	0.099	1.57	8.43	0.006	832
Exhaust	2.64	0.099	0.689	8.43	0.006	832
Evaporative			0.323			
Refueling			0.342			
Running loss			0.22			
g/kg fuel	10.07	0.38	5.99	32.16	0.02	3172
g/MJ	0.23	0.01	0.14	0.73	0.0005	69.3
Non-Catalyst Control; Assumed Fuel Economy: 2.8 km/l						
Total - g/km	3.45	0.174	5.04	40.23	0.006	843
Exhaust	3.45	0.174	2.16	40.23	0.006	843
Evaporative			2.2			
Refueling			0.36			
Running loss			0.32			
g/kg fuel	12.98	0.65	8.12	151.32	0.02	3172
g/MJ	0.29	0.01	0.18	3.44	0.0005	69.3
Uncontrolled; Assumed Fuel Economy: 2.0 km/l						
Total - g/km	5.71	0.373	18.16	143.14	0.009	1,165
Exhaust	5.71	0.373	11.54	143.14	0.009	1,165
Evaporative			5.74			
Refueling			0.55			
Running loss			0.32			
g/kg fuel	15.54	1.02	49.44	389.68	0.02	3172
g/MJ	0.35	0.02	1.12	8.86	0.0005	69.3

TABLE 1-24
ESTIMATED EMISSION FACTORS FOR DIESEL PASSENGER CARS

	EMISSIONS					
	NOx	CH₄	NMVOC	CO	N₂O	CO₂
Advanced Control; Assumed Fuel Economy: 10.6 km/l						
Total - g/km	0.65	0.01	0.29	0.86	0.007	258
g/kg fuel	8.04	0.12	3.59	10.64	0.08	3188
g/MJ	0.19	0.003	0.084	0.25	0.0019	73.3
Moderate Control; Assumed Fuel Economy: 6.8 km/l						
Total - g/km	0.93	0.01	0.29	0.86	0.010	403
g/kg fuel	7.36	0.08	2.30	6.81	0.08	3188
g/MJ	0.17	0.002	0.054	0.16	0.0019	73.3
Uncontrolled; Assumed Fuel Economy: 5.1 km/l						
Total - g/km	1.02	0.01	0.52	1.06	0.014	537
g/kg fuel	6.05	0.06	3.09	6.29	0.08	3188
g/MJ	0.14	0.001	0.073	0.15	0.0019	73.3

TABLE 1-25
ESTIMATED EMISSION FACTORS FOR LIGHT-DUTY DIESEL TRUCKS

	EMISSIONS					
	NOx	CH₄	NMVOC	CO	N₂O	CO₂
Advanced Control; Assumed Fuel Economy: 7.7 km/l						
Total - g/km	0.76	0.01	0.42	0.98	0.009	358
g/kg fuel	6.77	0.09	3.74	8.73	0.08	3188
g/MJ	0.16	0.0021	0.09	0.21	0.0019	73.3
Moderate Control; Assumed Fuel Economy: 5.1 km/l						
Total - g/km	1.04	0.01	0.42	0.98	0.014	537
g/kg fuel	6.17	0.06	2.49	5.82	0.08	3188
g/MJ	0.15	0.0014	0.06	0.14	0.0019	73.3
Uncontrolled; Assumed Fuel Economy: 4.3 km/l						
Total - g/km	1.45	0.02	0.83	1.61	0.017	559
g/kg fuel	7.17	0.10	4.11	7.96	0.08	3188
g/MJ	0.17	0.00	0.10	0.19	0.0019	73.3

TABLE I-26
ESTIMATED EMISSION FACTORS FOR HEAVY DUTY DIESEL VEHICLES

	NOx	CH₄	NMVOC	CO	N₂O	CO₂
				EMISSIONS		
Advanced Control; Assumed Fuel Economy: 2.8 km/l						
Total - g/km	5.01	0.06	1.26	6.8	0.025	982
g/kg fuel	16.27	0.19	4.09	22.09	0.08	3188
g/MJ	0.38	0.005	0.10	0.52	0.0019	73.3
Moderate Control; Assumed Fuel Economy: 2.8 km/l						
Total - g/km	11.94	0.07	1.7	8.28	0.025	991
g/kg fuel	38.41	0.23	5.47	26.64	0.08	3188
g/MJ	0.90	0.01	0.13	0.63	0.0019	73.3
Uncontrolled; Assumed Fuel Economy: 2.2 km/l						
Total - g/km	16.79	0.1	2.99	8.54	0.031	1249
g/kg fuel	42.86	0.26	7.63	21.80	0.08	3188
g/MJ	1.01	0.01	0.18	0.51	0.0019	73.3

TABLE I-27
ESTIMATED EMISSION FACTORS FOR MOTORCYCLES

	NOx	CH₄	NMVOC	CO	N₂O	CO₂
				EMISSIONS		
Non-catalytic Control; Assumed Fuel Economy: 14.9 km/l						
Total - g/km	0.53	0.15	2.2	13.2	0.002	160
g/kg fuel	10.52	2.98	42.9	261	0.04	3188
g/MJ	0.24	0.07	0.97	5.9	0.0009	69.3
Uncontrolled; Assumed Fuel Economy: 12.8 km/l						
Total - g/km	0.19	0.329	6.5	23.8	0.002	186
g/kg fuel	3.23	5.60	111	405	0.04	3172
g/MJ	0.07	0.13	2.5	9.2	0.0009	69.3

Road Vehicles - Alternative Fuels

Alternative motor vehicle fuels such as natural gas, LP gas, methanol, and ethanol are presently being used in a limited way, and are the subjects of a great deal of research and development effort aimed at increasing their usage in the future. This section presents some preliminary estimates of the emissions to be expected from vehicles using these fuels, based on fuel properties and the limited emissions data available.[30]

Natural gas

Because natural gas is mostly methane, natural gas vehicles (NGVs) have lower exhaust NMVOC emissions than gasoline vehicles, but higher emissions of methane. There are no evaporative or running-loss emissions, refueling emissions and cold-start emissions are

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[30]Actual emission levels from these vehicles may be very different, and further testing is needed to confirm these estimates.

low, and have leaner fuel-air ratios. These conditions reduces both NMVOC and CO emissions relative to gasoline vehicles. CO_2 emissions from NGVs will be lower than for gasoline vehicles, since natural gas has a lower carbon content per unit of energy. It possible to attain increased efficiency by increasing the compression ratio. Optimized heavy-duty NGV engines can approach diesel efficiency levels. NO_x emissions from uncontrolled NGVs may be higher or lower than comparable gasoline vehicles, depending on the engine technology. NGV NO_x emissions are more difficult to control using three-way catalysts. N_2O emissions from NGVs were not included.

Table 1-28 shows three types of NGVs: passenger cars, gasoline-type heavy-duty vehicles, and diesel-type heavy-duty vehicles.[31] Two sets of emission factors are shown for each: uncontrolled (typical of a simple natural gas conversion, without catalytic converter or optimization for emissions) and advanced control (reflecting an engine and catalytic converter factory-produced and optimized for natural gas). The estimates for the passenger car and gasoline-type heavy duty vehicle are based on a gasoline-type engine, converted to use natural gas. For the uncontrolled vehicles, no changes in the engine are assumed beyond the fitting of a natural gas mixer and modified spark timing such that the efficiency would be the same. For the vehicles with advanced control, a higher compression ratio is assumed to give 15% better fuel efficiency.

For the diesel-type heavy-duty vehicles, the engine assumed is a diesel-type engine, converted to lean, Otto-cycle operation using natural gas. The uncontrolled case reflects no further optimization beyond the conversion, while the controlled case includes extensive combustion optimization for NO_x control and an oxidation catalytic converter.

LP gas

LPG is primarily propane (or a propane/butane mixture) rather than methane which affects the composition of exhaust VOC emissions, but otherwise it similar to NG. Evaporative and refueling emissions are virtually zero, and CO and exhaust NMVOC emissions are usually lower than gasoline vehicles. The CO_2 emissions should be somewhat lower than gasoline, due to the lower carbon-energy ratio, and the higher octane allows some increase in efficiency, although less than for natural gas. NO_x emissions from LPG vehicles tend to be higher than for gasoline, but can also be controlled using three-way catalysts. N_2O emissions were not included.

Table 1-29 shows four categories of LPG vehicles. The engines and technologies considered are the same as those for natural gas, except that the lean, diesel-derived natural gas engine with propane is not considered.

Methanol and ethanol. The two alcohols have similar properties, and are discussed together. Development efforts have focussed primarily on mixtures of alcohols with gasoline, in flexible fuel vehicles, capable of running on any combination of gasoline and up to 85% methanol or ethanol. Engines and emission control systems are similar to those for advanced-technology gasoline vehicles, and the overall energy efficiency and emissions properties are similar. Table 2-30 shows estimated emissions for a vehicle of this type using M85 (85% methanol/15% gasoline) fuel. Also shown are some rough emissions estimates for heavy-duty vehicles equipped with methanol or ethanol engines.

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[31]The emissions considered are only those of the vehicle itself--additional emissions due to, e.g., compression or liquefaction of gas for storage on the vehicle, leakage from pipelines, etc. are not included, nor are the potential emissions credits due to, e.g. production of methane from biomass. This is consistent with the treatment of emissions from vehicles using oil based fuels.

TABLE I-28 ESTIMATED EMISSION FACTORS FOR LIGHT- AND HEAVY-DUTY NATURAL GAS VEHICLES						
EMISSIONS						
	NOx	CH4	NMVOC	CO	N2O	CO2
Passenger Car						
Advanced Control; Assumed Fuel Economy: 14.9 km/M³						
g/km	0.5	0.7	0.05	0.3	N/A	133
g/kg fuel	10.3	14.5	1.0	6.2	N/A	2750
g/MJ	0.21	0.29	0.02	0.12	N/A	56.1
Uncontrolled; Assumed Fuel Economy: 6.5 km/M³						
g/km	2.1	3.5	0.5	4.0	N/A	305
g/kg fuel	19.0	31.6	4.5	36.1	N/A	2750
g/MJ	0.38	0.63	0.09	0.72	N/A	56.1
Heavy-Duty Vehicles: Stoichiometric Engine (compare with gasoline)						
Advanced Control; Assumed Fuel Economy: 3.6 km/M³						
g/km	2.6	3.0	0.20	1.0	N/A	550
g/kg fuel	13.0	15.0	1.0	5.0	N/A	2750
g/MJ	0.26	0.30	0.02	0.10	N/A	56.1
Uncontrolled; Assumed Fuel Economy: 2.2 km/M³						
g/km	5.7	10.0	1.4	12.0	N/A	900
g/kg fuel	17.4	30.6	4.3	36.7	N/A	2750
g/MJ	0.35	0.61	0.09	0.73	N/A	56.1
Heavy-Duty Vehicles: Lean Burn Engine (compare with diesel)						
Advanced Control; Assumed Fuel Economy: 2.4 km/M³						
g/km	4.0	4.0	0.40	1.5	N/A	825
g/kg fuel	13.3	13.3	1.3	5.0	N/A	2750
g/MJ	0.27	0.27	0.03	0.10	N/A	56.1
Uncontrolled; Assumed Fuel Economy: 2.0 km/M³						
g/km	23.0	10.0	2.0	8.0	N/A	990
g/kg fuel	63.9	27.8	5.6	22.2	N/A	2750
g/MJ	1.28	0.56	0.11	0.44	N/A	56.1

TABLE 1-29						
ESTIMATED EMISSION FACTORS FOR LIGHT- AND HEAVY-DUTY LP GAS VEHICLES.						
	EMISSIONS					
	NOx	CH$_4$	NMVOC	CO	N$_2$O	CO$_2$
Passenger Car						
Advanced Control						
g/km	0.5	0.02	0.25	0.3	N/A	170
g/kg fuel	8.8	0.4	4.4	5.3	N/A	3000
g/MJ	0.19	0.01	0.10	0.11	N/A	63.1
Uncontrolled						
g/km	2.1	0.18	3.5	8.0	N/A	356
g/kg fuel	17.7	1.5	29.5	67.5	N/A	3000
g/MJ	0.38	0.03	0.64	1.45	N/A	63.1
Heavy-Duty Vehicles: Stoichiometric Engine (compare with gasoline)						
Advanced Control						
g/km	2.6	0.1	0.70	1.0	N/A	695
g/kg fuel	11.2	0.4	3.0	4.3	N/A	3000
g/MJ	0.24	0.01	0.07	0.09	N/A	63.1
Uncontrolled						
g/km	5.7	0.4	8.0	24.0	N/A	1020
g/kg fuel	16.8	1.2	23.5	70.6	N/A	3000
g/MJ	0.36	0.03	0.51	1.52	N/A	63.1

TABLE 1-30 ESTIMATED EMISSION FACTORS FOR LIGHT- AND HEAVY-DUTY METHANOL VEHICLES						
	EMISSIONS					
	NOx	CH4	NMVOC	CO	N2O	CO2
Passenger Car (M85 Fuel)						
Advanced Control						
g/km	0.5	0.02	0.66	3.14	N/A	183
g/kg fuel	4.5	0.2	5.9	28.0	N/A	1632
g/MJ	0.19	0.01	0.25	1.19	N/A	69.7
Heavy-Duty Vehicle - Methanol-Diesel Engine - M100 Fuel						
Advanced Control						
g/km	4.0	0.1	1.50	4.0	N/A	908
g/kg fuel	6.1	0.2	2.3	6.1	N/A	1375
g/MJ	0.30	0.01	0.11	0.30	N/A	68.8

Non-Road Mobile Sources

Emission factors are provided for major non-road vehicle source categories including farm and construction equipment, railway locomotives, boats, and ships (all primarily equipped with diesel engines), jet aircraft, and gasoline-fueled piston aircraft in Table 1-31.

Emission factors for diesel engines used in railway locomotives, farm equipment such as tractors and harvesters, construction equipment such as bulldozers and cranes, and diesel boats, are from Weaver (1988). These estimates are specific to the U.S., may be applicable to other regions as well. N_2O emission factors for off-road diesels are assumed to be the same as those for heavy-duty on-highway diesel engines.

Large ocean-going cargo ships are driven primarily by large, slow-speed and medium-speed diesel engines, and occasionally by steam turbines and gas turbines (the latter in high pow- er-weight ratio vessels such as fast ferries and warships). The number of vessels equipped with steam or gas-turbine propulsion is small, however, since these vessels are unable to compete with the more efficient diesels in most applications. The results shown for NO_x and CO are from Hadler (1990)[32]. N_2O emissions for these engines were assumed to be the same, on a fuel-specific basis, as those for other heavy-duty diesels, and VOC emissions from these large diesels are probably negligible.

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[32]Other sources consulted for comparison are Melhus (1990), Bremnes (1990), Alexandersson (1990)

TABLE 1-31 ESTIMATED EMISSION FACTORS FOR NON-HIGHWAY MOBILE SOURCES						
UNCONTROLLED EMISSIONS						
	NOx	CH4	NMVOC	CO	N2O	CO2
OCEAN GOING SHIPS						
g/kg fuel	87	n/a	n/a	1.9	0.08	3212
g/MJ	2.1	n/a	n/a	0.046	0.002	77.4
BOATS						
g/kg fuel	67.5	0.23	4.9	21.3	0.08	3188
g/MJ	1.6	0.005	0.11	0.50	0.002	73.3
LOCOMOTIVES						
g/kg fuel	74.3	0.25	5.5	26.1	0.08	3188
g/MJ	1.8	0.006	0.13	0.61	0.002	73.3
FARM EQUIPMENT						
g/kg fuel	63.5	0.45	9.6	25.4	0.08	3188
g/MJ	1.5	0.011	0.23	0.60	0.002	73.3
CONSTRUCTION AND INDUSTRIAL EQUIPMENT						
g/kg fuel	50.2	0.18	3.9	16.3	0.08	3188
g/MJ	1.2	0.004	0.09	0.38	0.002	73.3
JET AND TURBOPROP AIRCRAFT						
g/kg fuel	12.5	0.087	0.78	5.2	n/a	3149
g/MJ	0.29	0.002	0.018	0.12	n/a	71.5
GASOLINE (PISTON) AIRCRAFT						
g/kg fuel	3.52	2.64	24	1034	0.04	3172
g/MJ	0.08	0.06	0.54	24	0.0009	69.3

Data on emissions from aircraft are limited or presented in forms which are difficult to compare. The factors shown for aircraft were developed by Radian (1990) - for jet (turbine) emissions based on a Pratt and Whitney JT-17 engine (one of the most commonly used types), and for small gasoline-fueled piston aircraft based on a Cessna engine. These are considered very approximate. For the gasoline piston engines, fuel-specific N_2O emissions were assumed to be similar to those for uncontrolled passenger cars.

1.7.4 Recent Information Updates

Methane

As background for an expert group meeting to advise the IPCC/OECD programme, Berdowski, Olivier and Veldt (1993) provided some updated emission factors for methane, in general derived from total VOC factors and studies on VOC profiles. In Table 1-32 the emission factor estimate for each fuel and vehicle type is summarized. Some of these factors are presented in a somewhat different format, but are generally very similar to those presented in the previous section, where they overlap. Some factors, notably for uncontrolled gasoline road vehicles are somewhat higher in the more recent material. The expert group in its report (Berdowski, et al., 1993) emphasized that uncertainties in all CH_4 estimates to date are large, and that no fully satisfactory set of emission factors is currently available for use in national inventory development.

Highest emission factors for CH_4 appear for (uncontrolled) gasoline vehicles (cars, light and heavy duty vehicles), and for consumption of aviation gasoline (avgas) which is generally used by general aviation aircraft (e.g. business aircraft). All factors are averages including all transport modes of a specific vehicle (e.g. city traffic, highways; cruise flights, take-off, landing, etc.). Uncertainty ranges are difficult to specify, since factors are derived by taking a fraction of total VOC emission factors, both introducing uncertainties. In addition, estimating global averages of total VOC, and thus methane, factors is an other cause of uncertainty. Mobile sources, in particular gasoline consumption, are a source category which is of some importance, and the uncertainty of which may be quite large.

TABLE 1-32 GLOBAL METHANE EMISSION FACTORS FOR MOBILE SOURCES				
Mode/vehicle type		Fuel type	Emission factor ****)		References
			(g/GJ)	(g/kg)	
Cars/ LDV-Freight	4-stroke, uncontr.	gasoline	57	2.5	*)
	2-stroke, uncontr.	gasoline	50	2.2	*)
	4-stroke, 3-way cat.	gasoline	7	0.3	*)
		diesel	5	0.2	*)
		LPG	13	0.6	*)
	3-way cat.	natural gas	290	14.5	Olivier, 1991
		alcohol	10	0.2	Radian 1990 ***)
HDV (Freight)		gasoline	57	2.5	*)
		diesel	5	0.2	*)
Rail, water		diesel, res. oil	5	0.2	*) **)
		coal	17	0.5	*) **)
		biomass	50	0.5	*) **)
Aircraft		jetfuel	2	0.1	Olivier, 1991 Radian, 1990
		avgas	60	2.6	Radian, 1990

Notes:

LDV   = Light Duty Vehicle (car, van); HDV = Heavy Duty Vehicle (trucks)

*)   Emission factors derived from VOC factors and studies on VOC profiles.

**)   Emission factor derived from boiler emissions.

***) Emission factor for methanol.

****)   Emission factor all mode average (including all transport phases e.g. highways,

        city traffic; cruise flight, take-off etc.). Original factors are in g/kg [marked *)].

Nitrous Oxide

An expert group convened to advise the IPCC/OECD programme on N_2O from combustion concluded that the basic estimation methodology previously recommended by the OECD (1991) was generally still appropriate, though future imporvements should be considered in characterizing catalyst equipped road vehicles. (Olivier, 1993)   This is especially important as vehicles equipped with *new* catalysts have emission factors which are 4 to 5 times higher than those of uncontrolled vehicles (De Soete, 1993); and emission factors of vehicles with *medium aged* catalysts (about 25 000 km) are 10 to 16 times higher than uncontrolled vehicles (De Soete, 1993; Baas, 1991). In principle, an improved methodology for estimating N_2O emissions from catalyst controlled gasoline cars would be a further distinction between:

(a)   cars equipped with a new catalyst (e.g. < 15 000 km)

(b)   cars equipped with aged catalysts (e.g. > 15 000 km).

(c)   cars with malfunctioning catalysts.

However, since in practice the fraction of catalyst equipped cars which has a "new" catalyst will be quite small, these refinement will likely result in a minor correction of the factors used for category (b) to be used as average figures for the whole fleet including all vintages

of catalyst equipped cars of a specific type as defined under category 2. Also the fraction of the catalyst car fleet with malfunctioning catalysts will generally not be known as are the appropriate N_2O emission factors for this category. Some countries may improve the calculations by distinguishing between various types of catalysts or between different parts of the driving cycle - when activity data are available of course.

For non-catalyst equipped vehicles the estimated emission factors for gasoline and diesel cars reported in the Revised IPCC/OECD Report of August 1991 are in line with the ranges reported in the evaluation by De Soete (1993) and Baas (1991). For other fuels such as LPG, natural gas, and biofuels (e.g. ethanol and methanol) default emission factors - expressed as g/GJ -for different types of road vehicles still have to be determined. In Table 1-33 the estimated emission factors and uncertainty ranges are shown for a number of types of road vehicles, where the figures in the column "emission factor" are preliminary estimates for the vehicle fleet in the USA. For default emission factors of catalyst equipped cars it is recommended to use a value within the uncertainty range shown in the table.

For non-road vehicles (ships, locomotives and off-road vehicles e.g. for farming and construction) emission factors have been assumed to be the same as for heavy duty diesel trucks. For gasoline piston aircraft fuel-specific emission factors were assumed to be similar to those for uncontrolled gasoline passenger cars; for jet aircraft no N_2O estimated emission factors are available. Table 1-34 shows the estimated emission factors for these categories.

Indirect Greenhouse Gases

The IPCC/OECD programme has not yet addressed the indirect GHGs in detail. This is consistent with the initial priorities within the programme. As noted above, mobile source combustion is a major contributor to all of these gases. Because they are important contributors to a range of local and regional, as well as global atmospheric pollution problems, NO_x, CO and NMVOC have been widely studies and reported. The illustrative data cited above reflect estimates of average emission rates for main transport sub-categories worldwide, as of 1991. They are still considered to be reasonably representative. However, the data are based on analyses done for the United States vehicle fleets, and they may be less representative elsewhere. In all cases they are averages over a range of vehicle and control technologies, and operating conditions.

TABLE 1-33
ESTIMATED EMISSION FACTORS AND UNCERTAINTY RANGES FOR ROAD VEHICLES.

Vehicle type	Emission factors* (g N_2O/km) (g N_2O/GJ energy input)		Uncertainty range** (g N_2O/km)(g N_2O/GJ energy)	
Gasoline car	NA/0.005	NA/0.9	0.004-0.06	1.5-22
Gasoline car, 2 stroke engine	NA	NA	NA	NA
Diesel car	NA/0.014	NA/1.9	0.02-0.06	8-25
LPG car	N/A	NA	NA	NA
Natural gas (CNG) car	NA	NA	NA	NA
Motor cycle	NA/0.002	NA/0.9	NA	NA
Biofuel car (ethanol, methanol)	NA	NA	NA	NA
Passenger, controlled:				
Non-catalytic controlled gasoline car	NA/0.005	NA/0.9	NA	NA
Oxidation catalyst gasoline car	NA/0.027	NA/4.9	NA	NA
Early 3-way catalyst gasoline car	NA/0.046	NA/13.0	NA	NA
Advanced 3-way catalyst gasoline car	NA/0.019	NA/6.9	NA	NA
Aged catalyst gasoline car	NA	NA	0.05-0.32	18-120
Moderate controlled diesel car	NA/0.01	NA/1.9	NA	NA
Advanced controlled diesel car	NA/0.007	NA/1.9	NA	NA
Catalyst equipped LPG car	NA	NA	NA	NA
Catalyst equipped methanol car	NA	NA	NA/0.002-0.004	NA/0.2-0.4***
Non-catalytic controlled motor cycle	NA/0.002	NA/0.9	NA	NA
Freight, uncontrolled:				
Low-duty gasoline vehicles	NA/0.006	NA/0.9	0.004-0.06	1.5-22
Low-duty diesel vehicles	NA/0.017	NA/1.9	0.02-0.06	8-25
Low-duty LPG vehicles	NA	NA	NA	NA
Low-duty CNG vehicles	NA	NA	NA	NA
Heavy-duty gasoline vehicles	NA/0.009	NA/0.5	NA	NA
Heavy-duty diesel vehicles	NA/0.031	NA/1.9	NA	NA
Heavy-duty LPG vehicles	NA	NA	NA	NA
Heavy-duty CNG vehicles	NA	NA	NA	NA
Freight, controlled:				
Non-catalyst LD gasoline truck	NA/0.006	NA/0.9	NA	NA
Oxidation catalyst LD gasoline truck	NA/0.031	NA/4.8	0.03-0.084	12-35
Early 3-way catalyst LD gasoline truck	NA/0.063	NA/13.0	NA	NA
Advanced 3-way catalyst LD gasoline truck	NA/0.024	NA/6.8	NA	NA
Moderate controlled LD diesel truck	NA/0.014	NA/1.9	NA	NA
Advanced controlled LD diesel truck	NA/0.009	NA/1.9	NA	NA
Catalyst equipped LD LPG truck	NA	NA	NA	NA
Non-catalyst controlled HD gasoline truck	NA/0.006	NA/0.5	NA	NA
Oxidation catalyst HD gasoline truck	NA	NA	NA	NA
3-way catalyst HD gasoline truck	NA/0.006	NA/0.5	NA	NA
Moderate controlled HD diesel truck	NA/0.025	NA/1.9	NA	NA
Advanced controlled HD diesel truck	NA/0.025	NA/1.9	NA	NA

N.B. NA = Not Available

* Preliminary estimate for US vehicles.

** Assumed fuel economy: 12 km/l gasoline; 15 km/l diesel.

*** Preliminary estimate for Japanese vehicles.

source: emission factor estimates for US vehicles: EPA (1989); Prigent and De Soete (1989); Dasch (1990); Ford (1989-1991); Warner-Selph and Smith (1991);

uncertainty range: De Soete (1993), Baas (1991)

controlled methanol cars: Iwasaki et al. (1990), Susuki et al. (1992).

TABLE 1-34
ESTIMATED DEFAULT EMISSION FACTORS AND UNCERTAINTY RANGES FOR NON-ROAD TRANSPORT.

Activity	Emission factor (g N_2O/kg)	Uncertainty range (g N_2O/kg)
Sea ships (diesel)	2*	NA
Ships (int. nav.)(diesel)	2*	NA
Locomotives (diesel)	2*	NA
Off-road vehicles** (diesel)	2*	NA
Aircraft (jet fuel)	NA	NA
Aircraft (aviation gasoline)	0.9*	NA

N.B.   NA = Not Available

*   * Preliminary estimate (assumed to be similar to HD diesel vehicles and uncontrolled gasoline passenger cars).

*   ** e.g. farm and construction equipment.

source: See note

More detailed alternative emission factor source data representative of the precise vehicle types, control technologies and other conditions in a particular country would always be desirable. National experts working on detailed emissions of non-CO_2 GHGs (particularly the indirect gases) should consult the extensive literature on emission factors and estimation procedures which has been developed by other inventory programmes outside of the framework of the IPCC/OECD programme. As distinguished from the illustrative emission factors, these data generally contain more vehicle and control technology detail, and are further detailed by operating conditions (e.g., catalyst vintages, driving cycles). The specific nature of these assumptions should be known and carefully matched with actual conditions in the specific country in selecting the specific factors to be used.

Some key examples of data sources are:

■   The CORINAIR Inventory: Default Emission Factors Handbook (Bouscaren, 1992);

■   CORINAIR Working Group on Emission Factors for Calculating 1990 Emissions from Road Traffic, Volume 1: Methodology and Emission Factors (Eggleston, et al., 1992)

■   CORINAIR Working Group on Emission Factors for Calculating 1990 Emissions from Road Traffic, Volume 2: COPERT Model, Users Mannuel (Andrias, et al., 1992)

■   Emissions Inventory Guidebook (European Environment Agency, forthcoming)

■   U.S. EPA's Compilation of Air Pollutant Emissions Factors: Highway Mobile Vehicles (AP-42), 4th Edition 1985,   (U.S. EPA, 1985);

■   U.S. EPA's Mobile4 Model and User's Guide. U.S. NTIS (1991)

■   Criteria Pollutant Emission Factors for the 1985 NAPAP Emissions Inventory (Stockton and Stelling, 1987)

1.7.5 Priorities For Future Work

Access to Exisiting Data: There is a significant amount of past and on-going work in the area of mobile source emissions estimation that could be very useful for all countries. Major references are cited in the previous section. However, at this time there is no simple mechanism for published information, and especially underlying data bases be disseminated it to other interested countries. The IPCC/OECD Programme should address information exchange more explicitly, in conjunction with other interested organizations and programmes, possibly resulting in a clearinghouse or some other mechanism to improve access to such information.

Data for Non-OECD Regions of the World: Most of the information which does exist on emissions performance of vehicles, is based on data collected in the OECD countires. A critical need is for measurement data to determine the characteristics of vehicle fleets in non-OECD countries and to develop adjusted emission factors if necessary.

Key Emission Factor Uncertainties: At this moment there are some key areas for which available emission factors are not adequate for to support national inventory development. Expert groups have identified several specific categories for priority work:

CH_4 uncontrolled gasoline road vehicles particularly as affected by age and maintenance

N_2O -   biofuels for all applications

        ships, aircraft and rail

        gasoline and diesel vehicles (with and without catalyst control)

        LPG, natural gas and biofuels used for road transport (with and without catalyst control)

1.8   Fugitive Emissions from Coal Mining, Handling and Utilization

1.8.1 Overview

This section covers "fugitive" emissions of greenhouse gases (GHGs) from production, processing, handling and utilization of coal. Conceptually, this includes all emissions from coal-related activities which are not the result of combustion of coal as a fuel. Thus, intentional or unintentional releases of gases such as methane in mining are included here, as are emissions from inadvertent combustion of coal in coal mine fires. By far the most important component of this sub-category is methane (CH_4) emissions from coal mining and handling. The bulk of this section, deals with these emissions. Two other fugitive emission sources are discussed briefly at the end of the section. These are CO_2 from burning coal mines and waste piles, and CO_2 from SO_2 scrubbing. There are very likely other fugitive emissions associated with the coal fuel cycle. If important sources are identified, these will be considered for inclusion in future editions of the *Guidelines*.

1.8.2 CH₄ From Coal Mining And Handling

The process of coal formation, commonly called coalification, inherently generates methane and other byproducts. The formation of coal is a complex physio-chemical process occurring over millions of years. The degree of coalification (defined by the rank of the coal) determines the quantity of methane generated and, once generated, the amount of methane stored in the coal is controlled by the pressure and temperature of the coal seam and other, less well-defined characteristics of the coal. The methane will remain stored in the coal until the pressure on the coal is reduced, which can occur through the erosion of overlying strata or the process of coal mining. Once the methane has been released, it flows through the coal toward a pressure sink (such as a coal mine) and into the atmosphere (Boyer, 1990). Methane emissions from coal mining in 1990 contributed an estimated 23 to 39 Tg of methane (USEPA, 1993a; CIAB, 1992; Airuni, 1992).

The amount of CH_4 generated during coal mining is primarily a function of coal rank and depth, gas content, and mining methods, as well as other factors such as moisture. Coal rank represents the differences in the stages of coal formation and is dependent on pressure and temperature of the coal seam; high coal ranks, such as bituminous, contain more CH_4 than low coal ranks, such as lignite. Depth is important because it affects the pressure and temperature of the coal seam, which in turn determines how much CH_4 is generated during coal formation. If two coal seams have the same rank, the deeper seam will hold larger amounts of CH_4 because the pressure is greater at lower depths, all other things being equal. As a result, the methane emission factors for surface mined coal are assumed to be lower than for underground mining.

In most underground mines, methane is removed by ventilating large quantities of air through the mine and exhausting this air (typically containing a concentration of 1 percent methane or less) into the atmosphere. In some mines, however, more advanced methane recovery systems may be used to supplement the ventilation systems and ensure mine safety. These recovery systems typically produce a higher concentration product, ranging from 35% to 95% methane. In some countries, some of this recovered methane is used as an energy source, while other countries vent it to the atmosphere. Recent technological innovations are increasing the amount of medium- or high-quality methane that can be recovered during coal mining and the options available to use it. Thus, methane emissions could be reduced from this source in the future.

In surface mines, exposed coal faces and surfaces, as well as areas of coal rubble created by blasting operations, are believed to be the major sources of methane. As in underground mines, however, emissions may come from the overburden (in limited cases where these strata contain gas), which is rubblized during the mining process, and underlying strata, which may be fractured and destressed due to removal of the overburden. Because surface mined coals are generally lower rank and less deeply buried, they do not tend to contain as much methane as underground mined coals. Thus, emissions per ton of coal mined are generally much lower for surface mines. Research is underway in the United States and elsewhere to increase the understanding of CH_4 emissions from surface mines (Kirchgessner, 1992; USGS, 1993).

A portion of the CH_4 emitted from coal mining comes from post-mining activities such as coal processing, transportation, and utilization. Coal processing involves the breaking, crushing, and thermal drying of coal, making it acceptable for sale. Methane is released mainly because the increased surface area allows more CH_4 to desorb from the coal. Transportation of the coal contributes to CH_4 emissions, because CH_4 desorbs directly from the coal to the atmosphere while in transit (e.g., in railroad cars). Utilization of metallurgical coal also emits methane. For instance, in metallurgical coke production, coal

is crushed to a particle size of less than 5 mm, vastly increasing the surface area of the coal and allowing more CH_4 to desorb. During coking process, methane, carbon dioxide, and other volatile gases are released. In modern coke ovens, this gas is typically collected and utilized as a fuel source, but in older coke ovens, particularly those used in less developed regions, coke gas is vented to the atmosphere (Boyer, 1990; coke production is covered in Chapter 3).

Some methane is also released from coal waste piles and abandoned mines. Coal waste piles are comprised of rock and small amounts of coal that are produced during mining along with marketable coal. There are currently no emission measurements for this source. Emissions are believed to be low, however, because much of the methane would likely be emitted in the mine and the waste rock would have a low gas content compared to the coal being mined. Emissions from abandoned mines may come from unsealed shafts and from vents installed to prevent the buildup of methane in mines. There is very little information on the number of abandoned mines, and data are currently unavailable on emissions from these mines. Most available evidence indicates that methane flow rates decay rapidly once deep mine coal production ceases (Williams and Mitchell, 1992; Creedy, 1991). In some abandoned mines, however, methane can continue to be released from surrounding strata for many years. In Belgium, France, and Germany, for example, several abandoned mines are currently being used as a source of methane which can be added to the gas system (Smith and Sloss, 1992; KfA, 1993). Due to the absence of measurement data for both coal waste piles and abandoned mines, no emissions estimates have been developed for these sources.

Review of Previous Methane Emission Estimation Studies

Over the years, a variety of methane emissions estimates have been developed for coal mining, as shown in Table I. As the table shows, the variation in estimates has been quite large, although more recent studies are showing more similar results. Many of the emission studies conducted to date have confronted difficulties in developing estimation methodologies that have resulted in the widely varying estimates and large uncertainties. These difficulties include:

- Absence of data on which to base estimates: Many methane emission estimation studies were developed without access to detailed data on methane emissions associated with various components of the coal cycle. For certain sources such as surface mines and post-mining activities, moreover, reliable emissions measurements are still lacking.

- Use of national data to develop global estimates: Some studies have relied on data from a single country to estimate global methane emissions from coal mining. This approach can introduce large errors into the estimates due to the difficulty of generalizing from one country's coal and mining conditions to other countries. Mining experience has shown that there are frequently significant differences in methane emission factors within countries, coal basins, and even coal mines for a variety of geologic and other reasons.

- Failure to include all possible emission sources: Some studies prepared to date have only estimated underground coal mining emissions from ventilation systems and have not included degasification system emissions or post-mining emissions. In addition, many estimates have assumed emissions from surface mines to be negligible and have not included this source. At this point, moreover, there are still potential emission sources such as abandoned mines for which emissions cannot be estimated due to the absence of necessary data.

■   <u>Overreliance on statistical estimation methodologies:</u> Several studies have attempted to estimate global emission factors using statistical models that relate methane emissions to various coal properties. For the most part, these models have proven unreliable when estimates are compared to those developed using more detailed country-specific information. The principal problem with using statistical methodologies is the number of variables that can affect methane emissions. Mining experience has shown that a complete understanding of methane emissions requires detailed examination of coal and geological characteristics and that methane emissions can be highly variable within mines, basins and countries. Collecting comprehensive data and developing statistical models of methane emissions that can reliably predict methane emissions on a global basis is thus extremely difficult.

In general, the results of the more recent country-specific and global methane emission studies are likely to be more reliable than previous efforts. For several of the major coal producing countries, for example, detailed data on methane emissions from underground mine ventilation and degasification systems are reported to central institutes and are publicly available. More recent studies have been able to use this available data from several countries in preparing and validating their estimates of methane emissions from underground mines. Data is still lacking on emissions from surface mines and post-mining activities, however, and thus even the emission estimates from more recent studies should be considered uncertain.

Suggested Emission Estimation Methods

Methane emission estimates should be developed for the three principal sources of methane emissions: underground mines, surface mines, and post-mining activities. To assist in developing these estimates, the IPCC recommends use of a "tiered" approach for estimating emissions. For each source, two or more approaches (or "tiers") are presented for estimating emissions, with the first tier requiring basic and readily available data and higher tiers requiring additional data. The selection among the tiers will depend upon the quality of the data available in the country.

Underground Mining

Methane emissions from underground mines should include estimated emissions from ventilation systems and from degasification systems, if any of a country's mines use degasification systems to supplement ventilation. In the approaches outlined below, methods of estimating emissions from both of these sources are presented.

Three possible methodological approaches are suggested by the IPCC, with the choice among them depending upon the availability of data and the degree to which coal mining is considered a significant source of emissions by particular countries. For those countries with comparatively large methane emissions from coal mining, the use of more detailed estimation methodologies may be warranted. In smaller coal producing countries, however, the most simple approach may provide a reasonably accurate first approximation of CH_4 emissions from underground mines.

TABLE 1-35			
SUMMARY OF EMISSIONS ESTIMATES FROM SELECTED STUDIES			
Study Author	Emissions Estimate (Tg)	Year of Estimate	Methodological Issues
Koyama (1963)	20	1960	Hard coal only; no emissions estimates for surface mining or post-mining activities. 1960 coal production data.
Hitchcock & Wechsler (1972)	8 - 28	1967	Post-mining not included; Source of emission factors, particularly low end, unspecified. 1967 coal production data.
Seiler (1984)	30	1975	Based on Koyama, with 1975 coal production data.
Crutzen (1987)	34	n/a	Source of emission factors unclear. Hard coal only; no emissions estimates for surface mining or post-mining activities.
Okken & Kram (1989)	15 - 45	n/a	Source of emission factors unclear. Hard coal only; no emissions estimates for surface mines or post-mining activities.
Zimmermeyer (1989)	24	n/a	Only underground mining considered; no emissions estimates for surface mines or post-mining activities.
Seltzer & Zittel (1990)	23	n/a	Adjusted Zimmermeyer by: (1) including surface mines; (2) assuming that 15 percent of underground mining emissions (3.6 Tg) not emitted to the atmosphere due to methane utilization.
Barns & Edmonds, USDOE (1990)	25	1986	Assumed mathematical relationship between coal rank and depth and that in-situ methane content was equal to the mining emission factor.
Boyer, USEPA (1990)	33 - 64	1988	Statistical approach related methane emissions to in situ methane content. Correlation based on U.S. data only. Large uncertainty in application of results for global estimates.
Hargraves (1990)	29	n/a	Method based on current methane production rates due to continued coalification.
Airuni (1992)	28	1990	Methodology unspecified.
CIAB (1992)	24	1990	Country specific data used where available for underground mines. Surface and post-mining emissions developed using low emission assumptions. No uncertainty analysis.
USEPA (1993a)	23 - 39	1990	Country specific data used where available for underground mines. Global average emission factors for rest of countries for underground mines and for all surface mining and post-mining emissions.

The first tier approach--called the Global Average Method--uses a pre-determined range of emission factors (based on experience in a number of countries) to estimate emissions. The most complex, third tier, approach--called the Mine Specific Method--develops emissions estimates using detailed emission data for most, if not all, of a country's underground coal mines. In between these two methods is an intermediate, second tier,

approach--called the Basin or Country Average Method--in which more limited information, including either measurements from a subset of mines or geological and other data, can be used to refine the range of possible emission factors presented in the Global Average Method. Each of these approaches is described in more detail below.

Tier I: Global Average Method

The simplest method for estimating methane emissions is to multiply underground coal production by a factor or range of factors representing global average emissions from underground mining, including both ventilation and degasification system emissions. This method may be selected in cases where total coal production from underground mines is available but more detailed data on mining emissions, geological conditions, coal characteristics, and the like are not. The emission estimates generated using this method should be presented as a range to reflect the high degree of uncertainty associated with it. The Tier I Equation is shown below.

EQUATION I

  TIER I: GLOBAL AVERAGE METHOD -- UNDERGROUND MINES

Low CH_4 Emissions =   Low CH_4 Emission Factor
  (tonnes)   (m^3 CH_4/tonne of coal mined)

                                             x Underground Coal Production

                                             (tonnes)

                                             x Conversion Factor

High CH_4 Emissions =   High CH_4 Emission Factor
  (tonnes)   (m^3 CH_4/tonne of coal mined)

                                             x Underground Coal Production

                                             (tonnes)

                                             x Conversion Factor

Where:

• Low CH_4 Emission Factor = 10 m^3/tonne

• High CH_4 Emission Factor = 25 m^3/tonne

• Conversion Factor converts the volume of CH_4 to a weight measure based on the density of methane at 20C and I atm, which is:

$$1.49 \times 10^9 \, m^3 \text{ per I million metric tons}$$

In the original IPCC methodology, a single emission factor of 27.1 m^3 of methane per tonne of coal mined was recommended for all underground mining. This factor included both emissions from mining and from post-mining emissions associated with underground coal production.[33]

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[33] Due to a mistake in OECD (1991), it appeared that this factor did not include emissions from mine degasification systems and post-mining activities. In fact, however, this emission factor did include these two additional emission sources.

Based on more recent studies and additional country-specific emission data, the IPCC recommends revising this emission factor to reflect some additional issues. First, use of a range of emission factors is suggested to reflect the large variation possible in methane emissions from underground mines in different coal basins and countries. Second, this emission factor should represent only those emissions associated with underground mining (ventilation and degasification systems); post-mining emissions should be handled separately.

The IPCC recommends revised global average emission factors of 10 to 25 m^3/tonne of coal mined (not including post-mining activities). This range reflects the findings of various country studies, as shown in Table 1-36. As more detailed emissions data are published by various countries, the factors can be further revised, if necessary.

Tier 2: Country or Basin Average Method

The suggested Tier 2 approach--called the "Country or Basin Average Method"--can be used to refine the range of emission factors used for underground mining by incorporating some additional country or basin-specific information. Basically, this method enables a country with limited available data to determine a more appropriate and most likely narrower range of emission factors for their underground mines. For many countries, it is expected that this range will fall within the global average emission factor range of 10 to 25 m^3/tonne. The range of possible emission factors is not constrained under the Tier 2 approach, however, and some countries may find that their underground mining emission factors lie outside the global average emission factor range.

To implement the Tier 2 approach, national experts must examine measurement data from at least a limited number of underground coal mines in their country or region. Using this data, either statistical analysis or expert judgement should be applied to develop a reasonable range of emission factors for the country or region.[34] Making this estimate will require judgment on the part of the estimator regarding the adequacy of the available data and its uncertainty. If sufficient expertise is not available to make such judgments, it is recommended that the Tier 1 approach (the Global Average Method) be used to prepare emissions estimates.

TABLE 1-36 ESTIMATED UNDERGROUND EMISSION FACTORS FOR SELECTED COUNTRIES		
Country	Emissions Factors (m^3/ton)	Source
Former Soviet Union	17.8 - 22.2	USEPA, 1993a
United States	11.0 - 15.3	USEPA, 1993b
Germany (East & West)	22.4	Zimmermeyer, 1989
United Kingdom	15.3	BCTSRE, 1992
Poland	6.8 - 12.0	Pilcher, 1991
Czechoslovakia	23.9	Bibler, 1992
Australia	15.6	Lama, 1992

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[34] If measurement data is available for most or all or a country's underground coal mines, the Tier 3 approach--called the "Mine Specific Method"--should be used to estimate emissions.

In some cases, measurement data on emissions from mines may be unavailable but a country will still seek to develop a narrower estimate based on other types of available data. In such cases, a country may seek to develop a simple emissions model based on physical principals or make judgments based on an evaluation of available data. Among the key types of data that should be considered in such a model or evaluation are:

- the gas content of the coal, which contributes to the total amount of methane available for emission during mining;

- the frequency of coal within the strata above and below the mined coal seam, which also contributes to the total amount of methane available for emission during mining; and,

- the method of mining, which determines the amount of ground that is disturbed by mining the coal and the extent to which the methane contained in the mined coal seam and the coal seams in the surrounding strata is liberated during mining.

It should be noted that while the Tier 2 approach can provide some additional information about methane emissions in a particular country or coal basin, the estimates will still be quite uncertain because of the absence of comprehensive and reliable emissions data. This approach should thus be used only in cases where there is a strong need to make an estimate that is narrower than the Tier 1 (Global Average Method) and not enough data are available to prepare an estimate using the Tier 3 (Mine Specific Method) described in the next section. It should further be noted that these narrower estimates will not necessarily be more accurate than those developed under Tier 1 because they have not been developed or verified with comprehensive measurement data.

In all cases where the Tier 2 approach is used, a detailed discussion of the types of data available and the manner in which it was used to determine the refined range of emission factors should be presented, so as to allow for the independent verification of estimates and ensure comparability with estimates being prepared by other countries.

Tier 3: Mine Specific Method

Because methane is a serious safety hazard in underground mines, many countries have collected data on methane emissions from mine ventilation systems, and some also collect data on methane emissions from mine degasification systems. Where such data are available, the more detailed Tier 3 approach--called the "Mine Specific Method"--should provide the most accurate estimate of methane emissions from underground mines. Since these data have been collected for safety, not environmental reasons, however, it is necessary to ensure that they account for total emissions from coal mines. The key issues that should be considered when using mine safety data, as well as the recommendations of the IPCC for resolving them, are shown in Table 1-37.

Treatment of Methane Utilization

All of the methods described above, with the possible exception of the Mine Specific Method, assume that all of the methane liberated by mining will be emitted to the atmosphere. In many countries, however, some of the methane recovered by mine degasification systems is used as fuel instead of being emitted. Wherever possible, the emission estimates should be corrected for the amount of methane that is used as fuel, by subtracting this amount from total estimated emissions.

In several countries, data on the disposition of methane recovered by degasification systems (i.e., whether it is used or emitted to the atmosphere) can be obtained from the coal industry or energy ministries. Poland, for example, reports that its mine degasification systems recovered 286 million m^3 of methane in 1989, of which 201 million m^3 was used and the remaining 85 million m^3 was emitted to the atmosphere (Polish Central Mining

Institute, 1990). Regardless of the method used to develop the emissions estimates, the Polish emission estimate should be adjusted to reflect the use of methane by subtracting 201 m³ from total emissions.

In some countries, data on the disposition of methane recovered by degasification systems may not be reported, but it may still be possible to estimate utilization amounts. In some cases, for example, it may be possible to collect utilization data from end-users of the methane if such data are unavailable from the mining industry. It may also be possible to estimate utilization amounts based on information about the specific utilization options being employed (i.e., if the methane is being used to fuel a gas turbine of a specific size).

TABLE 1-37 KEY ISSUES FOR CONSIDERATION WHEN USING TIER 3 -- MINE SPECIFIC METHOD		
ISSUE	DESCRIPTION	RECOMMENDATION
Where and how are ventilation system emissions monitored?	When used to develop overall methane emission estimates, the optimal location for ventilation air monitors is at the point where ventilation air exhausts to the atmosphere.	If ventilation emissions are not monitored at the point of exhaust, emission data should be corrected based on estimated additional methane emissions between the point of measurement and the point of exhaust to the atmosphere.
Are ventilation system emissions monitored and/or reported for all mines?	In some countries, emissions are only reported for "gassy mines".	Estimates should be developed for non-gassy mines as well. Estimates can be prepared using information about the definitions of gassy and non-gassy mines and data on the total number of mines and the coal production at these mines.
Are methane emissions from degasification systems reported?	Some countries collect and report methane emissions from ventilation and degasification systems, while others only report ventilation system emissions. Both emission sources must be included in emissions estimates.	If degasification system emissions are not included, those mines with degasification systems should be identified and estimates prepared on emissions from their degasification systems. Emissions estimates can be based on knowledge about the efficiency of the degasification system in use at the mine or the average efficiency of degasification in the country.

The data sources for any adjustments to emissions that are made to reflect the utilization of methane should be clearly specified to ensure the independent verification of the emissions estimates developed. If data are unavailable, no adjustment for utilization should be made.

Surface Mining

Two possible approaches for estimating methane emissions from surface mining are suggested by the IPCC. For the most part, these approaches resemble those developed for underground mining, but the results will be much more uncertain due to the absence of emissions data. If emissions measurements are developed in the future, it should be possible to refine these estimation methodologies.

Tier 1: Global Average Method

As for underground mining, the simplest Tier 1 approach for surface mines--called the "Global Average Method"--is to multiply surface coal production by a range of emission factors representing global average emissions, as shown in the equation below.

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┌─────────────────────────────────────────────────────────────────────┐
│                            EQUATION 2                                 │
│              TIER 1: GLOBAL AVERAGE METHOD -- SURFACE MINES           │
│                                                                       │
│  Low CH4 Emissions  =    Low CH4 Emission Factor                      │
│     (tonnes)             (m³ CH₄/tonne of coal mined)                 │
│                          x Surface Coal Production                    │
│                          (tonnes)                                     │
│                          x Conversion Factor                          │
│                                                                       │
│  High CH₄ Emissions =    High CH₄ Emission Factor                     │
│     (tonnes)             (m³ CH₄/tonne of coal mined)                 │
│                          x Surface Coal Production                    │
│                              (tonnes)                                 │
│                          x Conversion Factor                          │
│                                                                       │
│  Where:                                                               │
│                                                                       │
│  ■  Low CH⁴ Emission Factor  = 0.3 m³/tonne                          │
│                                                                       │
│  ■  High CH₄ Emission Factor = 2.0 m³/tonne                          │
│                                                                       │
│  ■  Conversion Factor converts the volume of CH₄ to a weight measure  │
│     based on the density of methane at 20C and 1 atm, which is:       │
│                                                                       │
│             1.49 x 10⁹ m³ per 1 million metric tons                  │
│                                                                       │
└─────────────────────────────────────────────────────────────────────┘
```

In the original IPCC methodology, an average emission factor of 2.5 m^3/tonne was recommended (OECD, 1991), based on the results of Boyer (1990).[35] Based on more recent analyses and additional studies, a revised emission factor range of 0.3 to 2.0 m^3/tonne is recommended by the IPCC, not including post-mining emissions (USEPA, 1993a; CIAB, 1992; BCTSRE, 1992; CMRC, 1992; Kirchgessner, 1992).

Given the lack of information and measurements on methane emissions from surface mines, this range must be considered extremely uncertain, and it should be refined in the future as more data become available.

Tier 2: Country or Basin Specific Method

A second tier estimation of methane emissions--called the "Country or Basin Specific Method"--can be used if additional information is available on in-situ methane content and other characteristics of a country's surface mined coals. This approach enables a country to develop emission factors that better reflect specific conditions in their countries. Depending on the degree of detail desired, emissions can be estimated for specific coal basins or countries, using the equation below.

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[35] In OECD (1991), it mistakenly appears that the surface mining emission factor does not include emissions from post-mining activities. In fact, the factor of 2.5 m3/ton includes both direct emissions from surface mining and those from post-mining activities.

EQUATION 3
TIER 2: COUNTRY OR BASIN SPECIFIC METHOD -- SURFACE MINES

CH$_4$ Emissions = [In-Situ Gas Content
(tonnes)   (m^3 CH$_4$/tonne)

                 x Surface Coal Production

                 (tonnes)

                 x Conversion Factor]

       +   [Assumed Emission Factor for Surrounding Strata

                 (m^3/tonne)

                 x Surface Coal Production

                 (tonnes)

                 x Conversion Factor]

Where:

n   In-Situ Gas Content and Assumed Emission Factor for Surrounding Strata are described in the text.

n   Conversion Factor converts the volume of CH$_4$ to a weight measure based on the density of methane at 20C and 1 atm, which is:

            1.49×10^9 m^3 per 1 million metric tons

In Equation 3, <u>In-Situ Gas Content</u> represents the methane actually contained in the coal being mined, as determined by measuring the gas content of coal samples. Average values for a coal mine, coal basin or country could be developed, depending on the level of detail in the estimate. For surface mines, unlike underground mines, it is frequently assumed that all of the methane contained in the coal is released during mining and that post-mining emissions from surface mined coals are effectively zero (BTSCRE, 1992; CIAB, 1992; CMRC, 1992). Some countries may choose to modify this assumption based on their specific conditions. Care should be taken, however, to ensure that estimates of any emissions assumed to occur during post-mining activities are subsequently prepared.

<u>Assumed Emission Factor for Surrounding Strata</u> represents the possibility that more methane will be emitted during surface mining than is contained in the coal itself because of emissions from the strata below (or in limited cases, above) the coal seam. Some countries have assumed that there are not emissions from surrounding strata associated with surface mined coals (BTSCRE, 1992; CMRC, 1992). If available information indicates that there are gas bearing strata surrounding the mined coal seam and that these strata are emitting their gas in conjunction with the mining, however, countries should include these emissions in their estimates.

Emission factors for the surrounding strata can be developed using one of two approaches. Ideally, the assumed emission factor should be based on an evaluation of the gas content of the surrounding strata and verified by measurements. If such data are unavailable, an alternative method of developing an emission factor is to assume that some multiple of the gas content of the mined coal is emitted by the surrounding strata. It should be noted that the alternative approach is highly speculative, however, given the lack of data upon which to base such assumptions.

Post-Mining Activities

Like surface mining emissions, there are currently few measurements of methane emissions from post-mining activities. In fact, many past studies have overlooked this emission source, while others have developed only rudimentary estimation methodologies. Two possible approaches for estimating emissions from post-mining activities are recommended by the IPCC.

Tier 1: Global Average Method

For the most simple estimates, a global average emission factor can be multiplied by coal production for underground and surface mining, as shown in the equation below. It is important to distinguish between underground and surface mined coals because the gas contents are likely to be very different and hence emissions could vary significantly.

EQUATION 4
TIER 1: GLOBAL AVERAGE METHOD -- POST-MINING ACTIVITIES

Low CH_4 Emissions =   Low CH_4 Emission Factor

(tonnes)   (m^3 CH_4/tonne of coal mined)

            x Underground Coal Production

            (tonnes)

            x Conversion Factor

High CH_4 Emissions =   High CH_4 Emission Factor

(tonnes)   (m^3 CH_4/tonne of coal mined)

            x Surface Coal Production

            (tonnes)

            x Conversion Factor

Where:

- Underground Low CH_4 Emission Factor = 0.9 m^3/tonne
- Underground High CH_4 Emission Factor = 4.0 m^3/tonne
- Surface Low CH_4 Emission Factor = 0 m^3/tonne
- Surface High CH_4 Emission Factor = 0.2 m^3/tonne
- Conversion Factor converts the volume of CH_4 to a weight measure based on the density of methane at 20C and 1 atm, which is:

        1.49×10^9 m^3 per 1 million metric tons

<u>Underground Mined Coals:</u> The IPCC recommends emission factors of 0.9 to 4 m^3/ton for underground mined coal, based on recent studies (CIAB, 1992; BCTSRE, 1992; USEPA, 1993a).

<u>Surface Mined Coals:</u> Emission factors of 0 to 0.2 m^3/ton are recommended by the IPCC for post-mining activities involving surface mined coal (CIAB, 1992; CMRC, 1990; USEPA, 1993a).

Tier 2: Country or Basin Specific Method

Emissions estimates can be refined if additional data are available on coal characteristics. This method may be preferable if higher tier methods have been used to estimate

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EQUATION 5
TIER 2: COUNTRY OR BASIN SPECIFIC METHOD POST-MINING ACTIVITIES

a) Underground CH4   =   In-Situ Gas Content
   Emissions (tonnes)   (m3 CH4/tonne)

   x Fraction of Gas Released During Post-Mining
Activities (%)

   x Underground Coal Production (tonnes)
   x Conversion Factor

<u>When Necessary:</u>

b) Surface CH_4 = In-Situ Gas Content
   Emissions (tonnes)   (m^3 CH_4/tonne)

   x Fraction of Gas Released During Post-Mining
Activities (%)

   x Surface Coal Production (tonnes)
   x Conversion Factor

Where:

- In-Situ Gas Content and Fraction of Gas Released During Mining are described in the text

- Conversion Factor converts the volume of CH_4 to a weight measure based on the density of methane at 20C and 1 atm, which is:
    1.49×10^9 m^3 per 1 million metric tons

<u>In-Situ Gas Content</u> represents the methane actually contained in the coal being mined, as determined by measuring gas contents in coal samples. Average values for a coal mine, coal basin or country could be developed, depending on the level of detail in the estimate.

<u>Fraction of Gas Released During Post-Mining Activities</u> represents the percentage of the in-situ gas content that is assumed to be emitted during post-mining activities. There are three key issues related to the development of this fraction:

- For Surface Mined Coal: In most cases, if the Tier 2 approach is used to estimate methane emissions from surface mines, post-mining emissions from surface mined coals are assumed to be zero. In these cases, the use of Equation 5(b) is unnecessary and countries should be careful to avoid double-counting. If a country has not assumed that all of the methane contained in surface mined coal is released during mining, however, Equation 5(b) should be used to estimate post-mining emissions and the value selected for "Fraction of Gas Released During Post-Mining Activities" should be consistent with the previous assumption used.

- For Underground Mined Coal: The assumed fractions for underground mining will be based on information about coal permeability, desorption rates, mining methods and other factors. Recent studies have assumed that 25 to 40 percent of the in-situ CH_4 content of underground mined coal is emitted during post-mining activities (USEPA, 1993b; BCTSRE, 1992).

- Potential Fraction of Methane Not Emitted: It is currently assumed that all of the CH_4 contained in mined coal will be emitted to the atmosphere, although it is possible that a fraction could remain in the coal until the point of combustion and be burned instead of emitted. At this time, estimates of the extent to which this may be the case have not been developed. If countries have such information, however, they could further incorporate this factor into Equation 5.

Total Emissions from Coal Mining Activities

Total methane releases as a result of coal mining activities will be the summation of emissions from underground mining (ventilation and degasification systems), surface mining, and post mining activities. The IPCC recommends that emissions be estimated for each of these categories, in tonnes of CH_4, then aggregated to determine total national methane releases. To the extent that methane is recovered and used that would otherwise have been released to the atmosphere during coal mining, the recovered quantity should be subtracted from the emission total.

Availability and Quality of Activity Data

Data are readily available to develop general emissions estimates using the Tier 1 approach--the Global Average Methods for underground, surface and post-mining activities. For these estimates, the only required data are country statistics on underground and surface coal production, which are available from domestic sources, such as energy ministries, or from the OECD/IEA, which publishes Coal Information (e.g., 1990a) and Coal Statistics (e.g., 1990b). These data are thought to be reliable.

The IPCC recommends that countries involve their coal mining personnel in the development of emissions estimates as much as possible, because of the improved accuracy of emissions estimates prepared with more detailed coal and mining data. The availability and quality of data collected by mining personnel for mine safety purposes should be assessed on a case-by-case basis, however, to ensure that it can be appropriately used for preparing emissions estimates.

The IPCC further recommends that future efforts attempt to better characterize the factors affecting methane emissions from coal mining for those countries and emission sources with limited data, so as to develop more refined emission factors. Specific activities should include:

- Obtaining more data on coal and geologic characteristics in selected coal-producing countries;

- Monitoring emissions from surface mines and post-mining activities; and,

- Monitoring emissions from closed or inactive mining operations, and some other potential methane sources, such as mine water.

1.8.3 CO$_2$ Emissions From Burning Coal Deposits And Waste Piles

Marland and Rotty (1984) estimated that burning of coal in coal deposits is less than 0.3% of total coal produced and that burning of all coal in waste banks in the U.S. over a ten year period would represent less than 1% of U.S. coal consumption. Subsequently, they chose to ignore these emissions.

If these sources are estimated, the amount of coal burned in waste piles and coal deposits must be specified along with an emission coefficient that represents the percentage of coal that is carbon times the percentage of carbon oxidized. We suggest an arbitrary value of 50% of the carbon present in the coal to represent this emission coefficient; this value would be highly variable from one country to another and one site to another. This assumption of 50% for an emission coefficient should be evaluated to determine its validity. The formula for calculating these emissions would be:

> Emissions from Coal Burning (10^3 mt C) = (Quantity of Coal Burning; 10^3 mt)
> X Emission Coefficient
> (i.e., Percentage of Carbon in Coal X Percentage of Carbon Oxidized; default value is 50%)

Note that other GHG's such as N_2O, CO, NO_x, etc. are also emitted from combustion of coal wastes

1.8.4 CO$_2$ Emissions From SO$_2$ Scrubbing

When SO_2 scrubbing (or flue gas desulfuization) technology is used in conjunction with combustion of coal, the process which removes sulfur dioxide from the flue gas also releases CO_2 from the chemical interactions during the process. This can be considered a fugitive emission resulting from coal utilization, since the emissions are emitted only as a result of the combustion process. Typically calcium carbonate reacts with sulfur oxides in flue gas to produce calcium sulfate and release carbon dioxide. Marland and Rotty (1984) suggest that CO_2 emissions from SO_2 scrubbing are small enough to be ignored in global calculations. However, for completeness, some national experts may wish to included this subcategory.

To estimate carbon emissions from SO_2 scrubbing, the approach is derived from Grubb (1989) with slight modifications. In Grubb's approach, carbon emissions would equal the total amount of coal scrubbed times the fraction of sulfur by weight in the coal, adjusted for the differences in molecular weight between carbon and sulfur (12/32). Since this procedure assumes that all of the sulfur is removed, it should be adjusted by the sulfur removal efficiency of the desulfurization process (an average removal efficiency of 90% is suggested). The formula for calculating these emissions would be:

> Emissions from SO$_2$ Scrubbing (10^3 mt C) = (Total Coal Consumption; 10^3 mt)
> X Fraction Scrubbed (%)
> X Average Sulfur Content of Coal Scrubbed (%)
> X Sulfur Removal Efficiency (default value is 90%)
> X 12/32 (i.e., the Carbon/Sulfur Ratio)

1.9 Fugitive Emissions From Oil And Natural Gas Systems

1.9.1 Overview

This section covers "fugitive" emissions of greenhouse gases (GHGs) from oil and natural gas systems. This category includes all emissions from production, processing handling and transport of oil and natural gas, and their derivative products, which are not the result of combustion of these oil, gas or other products as fuel. It excludes use of oil and gas or derived fuel products to provide energy for internal use in energy production processing and transport. The latter are considered fuel combustion and treated in earlier section of this chapter.

By far the most important components of this sub-category are methane emissions from oil and gas production, and from all aspects of natural gas systems. The bulk of this section identifies and describes different methane emission sources from oil and gas systems and presents a default methodology to estimate these emissions on a national level. The basis for estimating methane emissions from oil and gas systems is, however, weak for most regions at this time. Only a few detailed studies of emissions rates have been performed. Better emissions data that take into account region- and country-specific factors are needed. Currently available information indicates that gas production and transportation in the former USSR and Eastern Europe are by far the most important sources, accounting for perhaps 50 percent of global CH_4 emissions from oil and gas systems. Because the data are so limited at present, global and regional estimates of CH_4 emissions from this source category, should be considered highly uncertain.

Oil and gas systems are also responsible for significant fugitive emissions of CO_2, NO_x, and especially NMVOC during production from venting and flaring; and from leakages at all stages. No original work has been done on CO_2, NO_x, and NMVOC emission from oil and natural gas systems, within the IPCC/OECD programme, consistent with the programmes priorities for the first phase. Considerable information has been developed in other national and international emissions inventory programmes, however, because of the importance of these gases for local and regional (as well as global) pollution. This is especially the case

for NMVOC as fugitive emissions from production, processing and distribution of oil and oil products is a major source of this gas. References to some of the available sources of emission factor data and other information for calculating emissions from this category are provided in the last sub-section of this section.

1.9.2 Fugitive Methane Emissions

Background

Fugitive emissions from oil and gas systems are an important source of methane, probably accounting for about 30 to 60 Tg per year of emissions. Methane is emitted during oil and gas production, processing, storage, transportation and distribution. "Fugitive" sources of emissions within oil and gas systems include: releases during normal operation, such as emissions associated with venting and flaring during oil and gas production, chronic leaks or discharges from process vents; emissions during routine maintenance, such as pipeline repair; and emissions during system upsets and accidents.

Oil and Natural Gas System Overview: Oil and gas systems are divided into three main parts, for this discussion:

1   **Oil and Gas Production:** Oil and gas are withdrawn from underground formations using on-shore and off-shore wells. Oil and gas are frequently withdrawn simultaneously from the same geologic formation, and then separated. Gathering lines are generally used to bring the crude oil and raw gas streams to one or more collection point(s) within a production field. Because methane is the major component of natural gas, leaks or venting from these systems result in methane emissions. Oil and/or gas are produced in approximately 186 countries worldwide.

2   **Crude Oil Transportation and Refining:** Crude oil is transported by pipelines and tankers to refineries. Often, the crude oil is stored in tanks for a period of time. Methane is usually found in the crude oil stream, and leaks or venting of vapours from these facilities result in methane emissions, particularly from crude oil tankering. Methane emissions from crude oil streams are strongly dependent on the original methane content of the crude oil and its preparation for transport.

Refineries process crude oil into a variety of hydrocarbon products such as gasoline and kerosene. During the refining process, methane and other hydrocarbons are separated and methane may be leaked or vented in some processes. Refinery outputs, referred to as "refined products," generally contain negligible amounts of methane. Consequently, methane emissions are not estimated for transporting and distributing refined products. Refineries are operated in 102 countries.

3   **Natural Gas Processing, Transportation, and Distribution:** Natural gas is processed to recover heavier hydrocarbons, such as ethane, propane and butane, and to prepare the dried gas for transporting to consumers. Most gas is transported through transmission and distribution pipelines. A small amount of gas is shipped by tanker as liquefied natural gas (LNG). Because only a small portion of gas is transported as LNG, emissions from LNG facilities are not included in default emission methods.

The following are the main processing, transportation, and distribution activities:

- <u>Gas processing plant:</u> Natural gas is usually processed in gas plants to produce products with specific characteristics. Depending on the composition of the unprocessed gas, it is dried and a variety of processes may be used to remove most of the heavier hydrocarbons, or condensate, from the gas. The processed gas is then injected into the natural gas transmission system and the heavier hydrocarbons are marketed separately. Unintentional leaks of methane occur during natural gas processing.

- <u>Transmission pipelines:</u> Transmission facilities are high pressure lines that transport gas from production fields, processing plants, storage facilities, and other sources of supply over long distances to distribution centres, or large volume customers. Although transmission lines are usually buried, a variety of above ground facilities support the overall system including metering stations, maintenance facilities, and compressor stations located along the pipeline routes.

Compressor stations, which maintain the pressure in the pipeline, generally include upstream scrubbers where the incoming gas is cleaned of particles and liquids before entering the compressors. Reciprocating engines and turbines are used to drive the compressors. Compressor stations normally use pipeline gas to fuel the compressors. They also use the gas to fuel electric power generators to meet the station's electricity requirements.

- Distribution systems: Distribution pipelines are extensive networks of generally small diameter, low pressure pipelines. Gas enters distribution networks from transmission systems at "gate stations" where the pressure is reduced for distribution within cities or towns.

Sources of Methane Emissions in the Oil and Natural Gas Systems: Emissions from oil and gas systems can be categorized into: (1) emissions during normal operations; (2) routine maintenance; and (3) system upsets and accidents. In Table 1-38 these emission types are linked to the different stages in oil and gas systems. Typically the majority of emissions are from normal operations.

I   **Normal Operations:** Normal operations are the day-to-day operations of a facility absent the occurrence of abnormal conditions. Emissions from normal operations can be divided into two main source categories: (1) venting and flaring and (2) discharges from process vents, chronic leaks, etc.

Venting and Flaring - Venting and flaring refers to the disposal of gas that cannot be contained or otherwise handled. Such venting and flaring activities are associated with combined oil and gas production and take place in production areas where gas pipeline infrastructure is incomplete and the natural gas is not injected into reservoirs (Emissions from process vents are not included here - see next sub-section).

Venting activities release methane because the vented gas typically has a high methane content. If the excess gas is burned in flares the emissions of methane will depend on how efficient the burning processes are. Generally the combustion efficiency for flare sources are assumed to be between 95 and 100%. However a new study based upon measurements carried out by Norwegian Oil Industry Association - OLF (Forthcoming) indicates very small amounts of unburned methane from flares, less than 0.1% of the gas burned. To estimate the methane emissions from venting and flaring activities satisfactorily it is required to know the flare efficiency rates and the distributed quantity of gas vented and gas flared.

The *combined* quantity of gas vented and flared is reported by countries that produce oil and gas (Barns et al., 1990). A few countries also are able to report the distribution between gas vented and gas flared. The reliability of the data is questionable in many cases because vented and flared amounts normally are not metered and are often an "accounting balance" whereby withdrawal totals are set equal to disposition totals by putting any discrepancies in the estimates in the category of vented and flared.

Discharges from Process Vents, Chronic Leaks etc. - Methane emissions will also occur when gas pipelines infrastructure is available and the market for natural gas is well developed. Oil and gas production, gas processing, oil and gas transportation and gas distribution facilities emit methane due to a wide variety of operating practices and factors, including:

- Emissions from pneumatic devices (gas-operated controls such as valves and actuators). These emissions depend on the size, type, and age of the devices, the frequency of their operation, and the quality of their maintenance.
- Leaks from system components. These emissions are unintentional and usually continuous releases associated with leaks from the failure of a seal or the development of a flaw, crack or hole in a component designed to contain or convey oil or gas. Connections, valves, flanges, instruments, and compressor shafts can develop leaks from flawed or worn seals, while pipelines and storage tanks can develop leaks from cracks or from corrosion.
- Emissions from process vents, such as vents on glycol dehydrators and vents on crude oil tankers and storage tanks. Vapours, including methane, are emitted

from the vents as part of the normal operation of the facilities. However such process vents are minor methane sources in most gas production facilities.

- Emissions from starting and stopping reciprocating engines and turbines.
- Emission during drilling activities, e.g., gas migration from reservoirs through wells.

2   Routine Maintenance: Routine maintenance includes regular and periodic activities performed in the operation of the facility. These activities may be conducted frequently, such as launching and receiving scrapers (pigs) in a pipeline, or infrequently, such as evacuation of pipes ("blowdown") for periodic testing or repair. In each case, the required procedures release gas from the affected equipment. Releases also occur during maintenance of wells ("well workovers") and during replacement or maintenance of fittings.

3   System Upsets and Accidents: System upsets are unplanned events in the system, the most common of which is a sudden pressure surge resulting from the failure of a pressure regulator. The potential for unplanned pressure surges is considered during facility design, and facilities are provided with pressure relief systems to protect the equipment from damage due to the increased pressure.

Relief systems vary in design. In some cases, gases released through relief valves may be collected and transported to a flare for combustion or re-compressed and re-injected into the system. In these cases, methane emissions associated with pressure relief events will be small. In older facilities, relief systems may vent gases directly into the atmosphere or may send gases to flare systems where complete combustion may not be achieved.

The frequency of system upsets varies with the facility design and operating practices. In particular, facilities operating well below capacity are less likely to experience system upsets and related emissions. Emissions associated with accidents are also included under the category of upsets. Occasionally, gas transmission and distribution pipelines are accidentally ruptured by construction equipment or other activities. These ruptures not only result in methane emissions, but they can be extremely hazardous as well.

Table 1-38 lists those emissions types that are the most important sources within each segment of the oil and gas industry. Based on available information, the sources listed as "major" account for the majority of emissions from each segment. Because ·data are limited and there is considerable diversity among oil and gas systems throughout the world, other potential sources are also listed which may, in some cases, be important contributors to emissions.

Available Emissions Data: Only very limited data are available that describe methane emissions from natural gas and oil systems. Estimating the types of emissions defined above is complicated by the fact that emissions rates from similar systems in various regions and countries are influenced by differences in the industry's supporting infrastructure, operating and maintenance practices, and level of technology used. Because natural gas and oil systems are comprised of a complex set of facilities, simple relationships between emissions and gross descriptors of the systems are not easily defined.

TABLE I-38 EMISSIONS FROM OIL AND NATURAL GAS SYSTEMS		
Segment	**Major Emission Sources**	**Other Potential Emission Sources**
Oil and Gas Production Oil and Gas Wells Gathering lines Treatment facilities	Venting Normal operations: fugitive emissions; deliberate releases from pneumatic devices and process vents	Flare and combustion in e.g. gas turbines, IC engines. Routine maintenance System upsets and Accidents
Crude oil transportation and Refining Pipelines Tankers Storage tanks Refineries	Normal operations: fugitive emissions; deliberate releases from process vents at refineries, during loading and unloading of tankers and storage tanks	Combustion in e.g. gas turbines, IC engines. Routine maintenance System upsets and Accidents
Natural Gas Processing, Transportation, and Distribution Gas Plants Underground storage reservoirs Transmission Pipelines Distribution Pipelines	Normal operations: fugitive emissions; deliberate releases from pneumatic devices and process vents	Combustion in e.g. gas turbines, IC engines Routine maintenance System upsets and Accidents

To estimate emissions, the available published data were reviewed to identify emissions estimates that include: a detailed consideration of the physical attributes of oil and gas systems; theoperation and maintenance characteristics of key facilities; and country- or region-specific factors that may influence emissions rates. The following data were identified:

- Surveys: Several studies have surveyed system operators to estimate emissions as a portion of production or throughput. These studies include Alphatania (1989), AGA (1989), and INGAA (1989). While these studies provide a basis for identifying the portions of the systems that operators believe are likely to be major sources of emissions, they are not based on detailed assessments of emissions rates. Consequently, these studies do not provide a quantitative basis for making estimates of methane emissions from oil and natural gas systems.

- Estimates Based on Reported Unaccounted For Gas: Several studies, such as Hitchcock and Wechsler (1972), Abrahamson (1989) and Cicerone and Oremland (1988), have assumed that emissions can be approximated by reported amounts of "unaccounted for" gas. Unaccounted for gas is defined as the difference between gas production and gas consumption on an annual basis. Like estimates of venting and flaring, unaccounted for gas often is used as an accounting convenience to balance company or national production and consumption estimates.

  - The applicability of unaccounted for gas estimates is very limited because factors other than emissions account for the majority of the gas listed as unaccounted for, including: meter inaccuracies, use of gas within the system itself, theft of gas (PG&E, 1990), variations in temperature and pressure and differences in billing cycles and accounting procedures between companies receiving and delivering the gas (INGAA, 1989). Furthermore, because known releases of gas are not

reflected in unaccounted for gas estimates, such as emissions from compressor exhaust, the unaccounted for gas estimates cannot unambiguously be considered an upper or lower bound on emissions.

- <u>Engineering Studies and Measurements</u>: A small number of studies are based on detailed engineering and/or field measurement analyses. Several engineering analyses have considered the manner in which actual or model facilities are built and operated, andextrapolate facility emissions to a system-wide basis. Several measurement studies have measured emissions from operating facilities or identified actual leaks and extrapolated these measurements to estimate system-wide emissions.

TABLE 1-39. SUMMARY OF EMISSION FACTORS			
Data source2	**Study methodology**	**Emission factors**	**Applicability**
EPA (1992) All emissions have been scaled down to 1988 energy consumption or production levels	Compilation of estimates from detailed engineering analyses and field measurement studies	**Oil and Gas Production:**	
		290 - 4670 kg/PJ of oil produced	Emissions from non-gas producing oil wells including fugitive emissions and routine maintenance emissions in the U.S.
		39590 - 104220 kg/PJ of gas produced	Emissions from gas production, including fugitive emissions, dehydrator venting, bleeding from pneumatic devices, routine maintenance, and systems upsets in the U.S.
		2870 - 13920 kg/PJ of total oil and gas produced	Venting and flaring emissions from oil and gas production and fugitive emissions from gas producing oil wells in the U.S.
		Crude Oil Transportation and Refining:	
		110 - 1666 kg/PJ of oil refined	Emissions from oil refining and related oil storage tanks in the U.S.
		Natural Gas Processing, Transmission and Distribution:	
		59660 - 116610 kg/PJ of gas consumed	Emissions from gas processing, transmission and distribution including fugitive emissions, dehydrator venting, bleeding from pneumatic devices, routine maintenance, and system upsets in the U.S.

Generally, data from engineering studies and measurements are the preferred basis for making estimates. Unfortunately, only several of these types of studies have been performed, which limits the ability to estimate emissions nationally, regionally and globally from oil and gas systems. Table 1-39 lists the studies identified and the information they contain. The emissions estimates from the

studies in the table have been converted to common units of kilograms of emissions per petajoule of energy (kg/PJ). A total of 5 studies are listed, with emissions estimates for portions of North America (EPA, 1992), Eastern Europe (Rabchuk et al., 1991), and Western Europe (Schneider-Fresenius et al., 1989,

TABLE I-39 CONTINUED): SUMMARY OF EMISSION FACTORS			
Data source	**Study Methodology**	**Emission Factors**	**Applicability**
Rabchuk et al. (1991)	Compilation of estimates from previous measurement studies and from official data for 1989	**Oil and Gas Production:**	
		218000 - 567600 kg/PJ of gas produced	Emissions from leakages at gas wells including routine equipment venting in the former USSR
		Natural Gas Processing, Transmission and Distribution:	
		340000 - 715800 kg/PJ of gas consumed	Emissions from leakages at underground storage facilities, compressor stations, linear part of main pipelines and distribution networks in the former USSR
Schneider-Fresenius et al. (1989)	Compilation of results from the Batelle study's 1988 literature survey	**Oil and Gas Production:**	
		14800 - 27000 kg/PJ of gas produced	Emissions from gas production and treatment facilities in Germany
		Natural Gas Processing, Transmission and Distribution:	
		58000 - 111000 kg/PJ of gas consumed	Emissions from transportation, distribution and storage of gas in Germany
Barns et al. (1990)	Compilation of official reports and projections on international emissions	**Oil and Gas Production:**	
		96000 kg/PJ of natural gas production	Emissions from gas production and separation facilities in the world
		6300 - 1019000 kg/PJ of gas production	Emissions from venting and flaring activity by region of the world

Norwegian SPCA, 1992 and Norwegian Oil Industry Association, 1993 in prep.). Additionally, Barns et al. (1990) present estimates based on a global assessment. Additional studies of this type are needed to improve the basis for making emissions estimates.

1.9.3 Methodology For Estimating Emissions

A three tiered approach is presented for estimating CH_4 emissions from oil and gas systems. The specific tiers are listed below in the order of increasing sophistication, data requirements, and accuracy:

- Tier 1 - Production Based Average Emissions Factors,

- Tier 2 - Mass Balance, and

- Tier 3 - Rigorous Source-specific Evaluations

	TABLE 1-39 (CONTINUED) SUMMARY OF EMISSION FACTORS		
Data Source	**Study Methodology**	**Emission Factors**	**Applicability**
Norwegian SPCA (1992)	Summary of emissions estimates for 1989 based on information and measurements collected from oil companies and industry associations	**Oil and Gas Production:**	
		12800 kg/PJ of gas produced	Emissions from cold vents and fugitive emissions
		3200 kg/PJ of gas produced	Flare and gas turbines
		200 kg/PJ of gas produced	Pre-production emissions (Well testing)
		Crude oil transportation:	
		2500 kg/PJ oil tankered	Emissions from offshore loading of crude oil
		Natural gas processing:	
		1800 kg/PJ of gas processed	Emissions from one Norwegian gas processing terminal
Norwegian Oil Industry Association (OLF), 1993 (in prep.)	Summary of emission estimates based on information and measurements collected from oil associations	**Oil and Gas Production:**	
		3000 - 7500 kg/PJ of gas produced	Emissions from cold vents and fugitive emissions
		100 - 400 kg/PJ of gas produced	Pre-production emissions

The intent is to allow countries to select an approach or combination of approaches that may be most suited to their circumstances. Some important considerations may include the relative contribution of oil and gas systems to total CH_4 emissions for the country, the available information and resources, and the complexity of the local oil and gas industry.

Regardless of the method that is used, the results must be aggregated back to a Tier 1 format to provide a consistent basis for comparison. Moreover, CH_4 emissions due to incomplete combustion by flares and other process combustion equipment are excluded from these calculations; they are accounted for separately in the section on CH_4 emissions from combustion and industry.

Tier 1 - Production Based Average Emission Factors

This is the simplest approach for estimating CH_4 emission from oil and gas systems, and is the only one that does not require any direct interaction with the oil and gas industry and associated regulatory agencies. Accordingly, it is the least reliable of the methods.

The required activity data may be easily referenced from a published documents of the IEA or the United Nations Statistical Division, and the necessary emission factors are provided in this document. The production based average emission factors approach can be used as a starting point for any country, and may be all that is needed where the emissions from a country's oil and gas industry are comparatively small and/or where data or resources are not available to pursue a more rigorous approach.

Production Base: To estimate emissions, the following steps are recommended as a default estimation procedure:

1   Global oil and gas systems have been divided into regions with the objective of each region having relatively homogeneous oil and gas system characteristics. Each country should decide which system characterisation best fits its own oil and gas system(s).

2   For each region, representative emissions factors for each emissions type within each segment have been selected with the objective of taking into account the various system designs and operating practices found in each region.

3   For each country, country-specific activity levels must be obtained and multiplied by the appropriate emissions factor. Emissions factor for countries should be selected from those corresponding to the appropriate region.

As more data become available for oil and gas producing activities within different countries, the default methodology described above (including activity data and emission factors) should be refined. Each step is discussed below in more detail.

Regional Definitions: Regions have been defined considering the limitations in data on emissions factors and activity levels, but also recognizing the key differences in oil and gas systems that are found globally. The following 5 regions are recommended at this time:

- <u>U.S. and Canada</u>: The U.S is a large producer and importer of oil and is a large producer of gas. Detailed emissions estimates are available for the U.S.

- <u>Former USSR and Eastern Europe</u>: Indications are that emissions rates from this region are much higher than emissions rates from other regions, in particular for the gas system. This region includes the former USSR (which is by far the largest oil and gas producer in the region), Albania, Bulgaria, Czech & Slovak Republics, Hungary, Poland, Romania, and the former Yugoslavia.

- <u>Western Europe</u>: This region is a net importer of oil and gas, and mainly produces oil and gas off shore. This region includes: Austria, Belgium, Denmark, Faroe Islands, Finland, France, Germany, Gibraltar, Greece, Iceland, Ireland, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and UK.

- <u>Other Oil Exporting Countries</u>: This region includes the world's other major oil producing countries: the 13 OPEC members (Algeria, Gabon, Libya, Nigeria, Ecuador, Venezuela, Indonesia, Iran, Iraq, Kuwait, Qatar, Saudi Arabia and the United Arab Emirates) and Mexico. Generally, these countries produce large quantities of oil and have limited markets for gas.

- <u>Rest of the World</u>: This region includes the remaining countries of Asia, Africa, Middle East, Oceania and Latin America.

In defining these regions, countries were aggregated with relatively similar oil and gas systems. Additional investigation would likely improve the definition of the regions.

Emissions Factors: As discussed above, the basis for selecting emissions factors is weak because very few detailed studies of emissions have been performed. Using the information summarized in Table 1-39, emissions factors should be selected by industry segment and emissions type for each of the regions. In some cases data from the U.S. were used when region-specific information was not available.

Tables 2-42 through 2-46 list suggested emissions factors for each region. Emissions factors from EPA (1992) were used for the U.S. Key emissions factors for Eastern Europe and the Former USSR were taken from Rabchuk et al. and Barns et al. Estimates were used for emissions factors for venting and flaring for the several regions, including Eastern Europe.

Studies by Schneider-Fresenius et al. and Norwegian SPCA were adopted as representative of emissions factors for Western European gas production and venting and flaring. No region-specific data were available for the Other Oil Exporting countries and the Rest of the World. Emissions factors in these regions are expected to fall between the relatively low rates found in North America and Western Europe and the relatively high rates found in Eastern Europe. Consequently, a range of emissions factors is suggested for these regions unless more information can be obtained.

Activity Levels: Data on the quantity of oil and gas produced, refined, and consumed can be obtained from the IEA or the U.N. Statistical Division. Sources are described in the introduction to this chapter. Data on oil refining capacity can be used to approximate oil refined. Data on oil tankered were not available by region. It is important for national experts to ensure that production figures used in calculation of apparent consumption for CO_2 emissions estimates (described in section B of this Chapter) are consistent with those used in this section.

Tier 2 - Mass Balance

The mass balance approach employs standard, generally easy-to-obtain, oil and gas data (i.e., production volumes, gas-to oil ratios (GORs), and gas compositions) to estimate the maximum amount of methane that could potentially be available for emissions to the atmosphere by different sectors of the oil and gas industry. These amounts are then adjusted to reflect actual emissions by applying appropriate system adjustment and loss factors. The system adjustment factors account for the amount of gas that is disposed by control devices, consumed by combustion equipment, conserved, or reinjected. Loss factors account for specific losses from these control/utilization systems.

A particular advantage of conducting a mass balance analysis is that it helps avoid any double counting of emissions. This may be most important in the crude oil transportation and refining sector where the methane fraction is difficult to track.

The basic procedures for performing the mass balance calculations are delineated below by sector of the oil and gas industry. Total CH_4 emissions is the sum of emissions for each of these sectors. Default data and factors are provided where possible.

Oil and Associated Gas Production: Emissions from oil and associated gas production may be estimated using the relation,

$$E_{oil_p} = Q_{oil}.GOR.Y_{AG_{CH_4}}.\frac{M_{CH_4}}{V_{STP}}.K_{oil_p}.g_c$$

where
E_{oil} = mass (Tg) of CH_4 emitted to the atmosphere due to oil and associated gas production,
Q_{oil} = volume of oil produced (m^3 /y),
GOR = gas to oil ratio (m^3 /m^3),
Y_{AGCH4}= average mole fraction of CH_4 in the associated gas (dimensionless),
M_{CH4} = molecular weight of CH_4
    = 16,043,
V_{STP} = volume (m^3) of 1 kmole of gas at reference temperature and pressure of the GOR factor (e.g., 23.645 m^3 at 15 C and 101.325 kPa),
K_{oil} = system adjustment factor which accounts for any gas utilization, conservation and disposal schemes and their effectiveness (dimensionless).
g_c = constant of proportionality,
    = 10^{-7}.

The value of the system adjustment factor is determined using the equation presented below.

$$K_{oil_p} = Q_{AG_{fuel}} \cdot L_{fuel} + Q_{AG_{flared}} \cdot L_{flared} + Q_{AG_{injected}} \cdot L_{injected} + Q_{AG_{injected}} + Q_{AG_{sales}} \cdot L_{sales} \overline{GOR.Q_{oil}}$$

where,

Q_{AG_-} = volume of associated gas disposed by control devices (e.g., flare systems), consumed (burned as fuel) or conserved (reinjected or sold) and therefore unavailable for emission to the atmosphere (m^3), and

L_- = loss factors that account for emissions from the gas control and utilization systems (e.g., losses due to fugitive equipment leaks, blowdown activities, and use of natural gas as the supply medium for gas-operated devices). (Note: Emissions due to incomplete combustion are accounted for in the section on CH_4 from combustion and industry.)

If none of the associated gas is controlled or utilized (i.e., $L_x = 1$ for all x), then the system adjustment factor (K) is equal to one. This situation occurs when it is not economical to conserve or reinject the gas (e.g., there is no local market for the gas and the volumes are relatively small) and when venting of the gas is preferable to disposal by flaring. It is not necessary to evaluate the different paths by which CH_4 emissions may occur (e.g., fugitive equipment leaks, process venting, system upsets, etc.) in these cases since the end effect is the same: essentially all the CH_4 produced is emitted to the atmosphere.

If all of the associated gas is controlled or utilized (i.e., none is vented), then the value of the system adjustment factor will be nearly equal to zero. The difference from zero is due to fugitive leaks, blowdown activities and other system losses.

Crude Oil Transportation and Refining: The crude oil from production facilities will initially contain a certain amount of gas in solution. This gas, particularly the CH_4 fraction, evaporates quickly as this oil progresses through the storage and transportation systems enroute to the refinery. When the oil reaches the refinery, it is usually fully weathered and essentially free of any CH_4.

Accordingly, the basic mass balance relation for oil transportation and refining activities may be expressed as follows:

$$E_{oil_t} = Q_{oil} \cdot F_{SG} \cdot Y_{SG_{CH_4}} \cdot \frac{M_{CH_4}}{V_{STP}} \cdot K_{oil_t} \cdot g_c$$

where,

F_{SG} = solution gas factor (m^3/m^3),

Y_{SGCH4} = mole fraction of CH_4 in the solution gas (dimensionless),

K_{oilt} = system adjustment factor to account for the amount of vapour collected and subsequently flared, incinerated or recovered, and

g_c = constant of proportionality,

= 10-9.

The value of the solution gas factor and the corresponding mole fraction of methane is determined by the type of crude oil (light, medium, heavy, or crude bitumen), the composition of the associated gas, and the initial vapour pressure of the crude oil when it is placed in the storage tanks or compartments at the production site. Typically, the initial vapour pressure will be equal to the operating pressure of the first vessel upstream of the storage facilities.

Table 1-40 presents some estimated values for these two parameters at onshore and offshore facilities. Better estimates may be determined by performing site specific process simulations.

The value of the system adjustment factor is determined using the equation below:

$$K_{oil_t} = 1 - \frac{Q_{CH_{4_{collected}}} / Y_{SG_{CH_4}}}{F_{SG} \cdot Q_{oil}}$$

In the absence of any data regarding the volume of CH_4 collected, the value of system adjustment factor should be set to a default value of one.

Exploration and Drilling Losses

Total CH_4 emissions from the exploration and drilling sector will usually be small compared to the amount emitted by other sectors of the oil and gas industry. Consequently, a simple Tier 1 approach is perhaps most appropriate for use here.

The basic relation is shown below:

$$E_D = N_{wells} \cdot F_D$$

where,

E_D = total CH_4 emissions (Tg) from drilling and testing of oil and gas wells,

N_{wells} = number of wells drilled and tested, and

F_D = average amount of CH_4 emitted per well (Tg/well).

Gas Systems - Production, Processing and Transmission: Methane emissions from gas systems may be estimated by applying appropriate loss factors to the total volume of gas that passes through the different stages of the system, and by adding to this value emissions do to accidental releases (e.g., pipeline ruptures and well blowouts). This latter component can be quite significant for gas systems in developing countries.

Type of Crude Oil	Onshore Facilities		Offshore Facilities	
	F_{SG}	Y_{CH4}	F_{SG}	Y_{CH4}
Light	3.3 to 5.0	0.5642	n.a.	n.a.
Medium	3.2 to 5.0	0.1001	n.a.	n.a.
Heavy (Primary)	1.0	0.8723	n.a.	n.a.
Heavy (Thermal)	8.3	0.6666	n.a.	n.a.

TABLE 1-40 SOLUTION GAS FACTORS AND CORRESPONDING CH4 MODE FRACTIONS FOR DIFFERENT TYPES OF CRUDE OIL PRODUCTION AT ON SHORE AND OFFSHORE FACILITIES

The resulting mass balance relation for gas systems is as follows:

$$E_{gas} = [Q_{gas} \cdot (L_{gas_G} + L_{gas_P} + L_{gas_T}) + Q_{accidents}] \cdot Y_{gas_{CH_4}} \cdot M_{CH_4} \overline{V_{STP}} \cdot g_c$$

where,

E_{gas} = total CH_4 emissions (Tg) from gas systems,

Q_{gas} = total volume of natural gas produced into the gas system (possibly including some associated gas) (m3),

$L_{gas\_}$ = loss factors for the gathering/production (G), processing (P) and transmission (T) stages of the system (dimensionless),

$Q_{accidents}$ = total volume of unburned natural gas released into the atmosphere due to major accidents such as pipeline ruptures and well blowouts (m^3), and

Y_{gasCH4} = average mole fraction of CH_4 in the produced gas dimensionless),

g_c = constant of proportionality,

= 10^{-7}.

The loss factor for a given stage "i" of the gas system may be estimated using a relation,

$$L_{gas_i} = \frac{Q_{leaks_i} + Q_{venting_i}}{Q_{gas}}$$

where,

Q_{leaksi} = volume of gas lost to the atmosphere due to fugitive equipment leaks (m^3), and

$Q_{ventingi}$ = volume of gas lost to the atmosphere due to process venting and use of natural gas as the supply medium for gas operated devices (m^3).

Table 1-41 presents some default values for the different loss factors.

TABLE 1-41		
DEFAULT LOSS FACTORS FOR DIFFERENT STAGES OF ONSHORE AND OFFSHORE NATURAL GAS SYSTEMS.		
Stage	Onshore	Offshore
Gathering/Production	0.2 to 1.0	n.a.
Processing	0.04 to 0.10	n.a.
Transmission	0,03 to ?	n.a.

Tier 3 - Rigorous Source-specific Evaluations

Rigorous source-specific evaluations will generally involve compiling the following types of information and may require significant interaction with industry and associated regulatory agencies:

- detailed inventories of the amount and types of process infrastructure (e.g., wells, minor field installations, a major production and processing facilities),

- production disposition analyses (e.g., oil and gas production; vented, flared and reinjected volumes of gas; and fuel gas consumption),

- accidental releases (i.e., well blow-outs and pipeline ruptures),

- typical design and operating practices and their impact on the overall level of emission control.

The amount of emissions is then assessed by applying appropriate emission factors, empirical correlations, process simulation results, and field measurements to these data.

Some examples of detailed emission inventories that have been developed in this manner are listed below:

- U.S. Environmental Protection Agency (U.S. EPA). Anthropogenic Methane Emissions in the United States. Estimates for 1990: Report to the Congress. October 1992.

- Picard, D.J., B.D. Ross, and D.W.H. Koon. A Detailed Inventory of CH_4 and VOC Emissions from Upstream Oil and Gas Operations in Alberta. Clearstone Engineerineg Ltd., for the Canadian Petroleum Association, Mars 1992.

- UK Offshore Operators Association Ltd. Methane Emissions From Offshore Oil & Gas Exploration & Production Activities. Submitted to The Watt Committee on Energy. 1993.

- Norwegian Oil Industry Association - OLF. Report from OLF Environmental Programme - Phase 2. Will be available Mars 1993.

1.9.4 Uncertainty

Because relatively few detailed emissions studies have been conducted, the emissions estimates resulting from application of these methodologies must be considered very uncertain. The overall magnitude of the emissions that will be obtained for some countries is driven by two key studies:

- Rabchuk et al. report that emissions from gas production and transportation in the former USSR is very high, about 3 to 7 percent of total gas production. Recent visits to this region indicate that system construction, maintenance, and operations may be consistent with high emissions rates (Craig, 1992). However, a better quantitative evaluation is needed to validate the current emissions estimates.

- Barns et al. report emissions from venting and flaring by region. The emissions estimates for the OPEC countries are relatively high, and account for most of the emissions from this category. The safety concerns associated with venting, and the value of re-injecting gas into oil reservoirs to maintain reservoir pressures, would tend to question the high emissions estimates. Improved data are needed to resolve this question.

The adoption of emissions factor estimates from EPA (1992) for various regions also adds uncertainty to the overall estimates. U.S. oil and gas production facilities and refineries are subject to emission control requirements. The U.S. emissions factors, particularly for refining, may under-estimate emissions in other regions. Nevertheless, this may not be a significant uncertainty since, if the emissions factors for oil production and oil refining were increased by a factor of 10 for the entire world, the estimate of total global emissions would only increase by about 1 to 6 Tg for 1988.

TABLE 1-42 U.S AND CANADA - EMISSIONS FACTORS		
Emissions Type	Emissions Factor kg/Petajoule	Source
Oil and Gas Production		
Oil	290 - 4,670 of Oil Production	EPA (1992)
Gas	39,590 - 104,220 of Gas Production	EPA (1992)
Oil & Gas	2,870 - 13,920 of Oil & Gas Prod.	EPA (1992)
Crude Oil Transportation and Refining		
Transportation	745 of Oil Tankered	API (1987)
Refining	90 - 1,400 of Oil Refined	EPA (1992)
Storage Tanks	20 - 260 of Oil Refined	EPA (1992)
Natural Gas Processing, Transport, and Distribution	59,660 - 116,610 of Gas Consumption	EPA (1992)
Gas Processing	..	..
Gas Pipelines	..	..
Gas Distribution	..	..

TABLE 1-43 EASTERN EUROPE AND FORMER USSR - EMISSIONS FACTORS		
Emissions Type	Emissions Factor kg/Petajoule	Source
Oil and Gas Production		
Oil	290 - 4,670 of Oil Produced	EPA (1992)
Gas	218,000 - 567,600 of Gas Produced	Rabchuk et al. (1991)
Oil & Gas	6,300 - 29,700 of Gas Produced	Barns et al. (1990)
Crude Oil Transportation and Refining		
Transportation	745 of Oil Tankered	API (1987)
Refining	90 - 1,400 of Oil Refined	EPA (1992)
Storage Tanks	20 - 260 of Oil Refined	EPA (1992)
Natural Gas Processing, Transport, and Distribution	340,000 - 715,800 of Gas Consumption	Rabchuk et al. (1991)
Gas Processing	..	..
Gas Pipelines	..	..
Gas Distribution	..	..

TABLE 1-44		
WESTERN EUROPE - EMISSIONS FACTORS		
Emissions Type	Emissions Factor kg/Petajoule	Source
Oil and Gas Production		
Oil	290 - 4,670 of Oil Produced	EPA (1992)
Gas	14,800 - 27,000 of Gas Produced	Schneider-Fresenius
	13,000-16,000 of Gas Produced	et al. (1989)
Oil & Gas	3,000-8,000 of Gas Produced	Norwegian SPCA (1992)
		OLF in prep. (1993)
Crude Oil Transportation and Refining		
Transportation	745 of Oil Tankered	API (1987)
	2,500 of Oil Tankered	Norwegian SPCA (1992)
Refining	90 - 1,400 of Oil Refined	EPA (1992)
Storage Tanks	20 - 260 of Oil Refined	EPA (1992)
Natural Gas Processing, Transport, and Distribution	58,000 - 111,000 of Gas Consumption	Schneider-Fresenius
	1,800 of Gas Processed	et al. (1989)
Gas Processing	..	Norwegian SPCA (1992)
Gas Pipelines	..	..
Gas Distribution		..

TABLE 1-45		
OTHER OIL EXPORTING COUNTRIES - EMISSIONS FACTORS		
Emissions Type	Emissions Factor kg/Petajoule	Source
Oil and Gas Production		
Oil	290 - 4,670 of Oil Produced	EPA (1992)
Gas	39,590 - 96,000 of Gas Produced	EPA (1992) and Barns
	739,470 - 1,019,220 of Gas Produced	et al. (1990)
Oil & Gas		Barns et al. (1990)
Crude Oil Transportation and Refining		
Transportation	745 of Oil Tankered	API (1978)
Refining	90 - 1,400 of Oil Refined	EPA (1992)
Storage Tanks	20 - 260 of Oil Refined	EPA (1992)
Natural Gas Processing, Transport, and Distribution	116,610 - 340,000 of Gas Consumption	EPA (1992 and
	..	Rabchuk et al. (1991)
Gas Processing	..	..
Gas Pipelines	..	..
Gas Distribution		..

TABLE 1-46 REST OF THE WORLD - EMISSIONS FACTORS		
Emissions Type	**Emissions Factor** kg/Petajoule	**Source**
Oil and Gas Production		
Oil	290 - 4,670 of Oil Produced	EPA (1992)
Gas	39,590 - 96,000 of Gas Produced	EPA (1992) and Barns et al. (1990)
	170,000 - 209,000 of Gas Produced	
Oil & Gas		Barns et al. (1990)
Crude Oil Transportation and Refining		
Transportation	745 of Oil Tankered	API (1987)
Refining	90 - 1,400 of Oil Refined	EPA (1992)
Storage Tanks	20 - 260 of Oil Refined	EPA (1992)
Natural Gas Processing, Transport, and Distribution	116,610 - 340,00 of Gas Consumption	EPA (1992 and Rabchuk et al. (1991)
Gas Processing	..	..
Gas Pipelines	..	..
Gas Distribution	..	..

Recent Revisions to Emission Factors

The above methodology and emission factors are based on the report of an expert group convened to advise the IPCC/OECD programme on methods and data in this specific area (Ebert, et al., 1993). Since that group delivered its report in mid 1993, a more recent analysis (U.S. EPA, in press) has provided a somewhat different interpretation of some emission factors. While this very detailed analysis endorses the basic tiered methodology included in this manual, its evaluation of emission factors differs somewhat. This evaluation was based on essentially the same set of measurement data cited herein, but draws somewhat different results from the limited available data. The results of the recent EPA analysis are summarized in Table 1-47. The most significant differences are in natural gas processing, transportation and distribution, where a somewhat more detailed set of emission factor ranges are recommended for non-OECD countries. These factors include some which are based on production of natural gas and some which are based on consumption of natural gas (which is the case for all of the factors provided above). Where emission factors are provided for more than one sub-category, they are intended to be additive, and would result in somewhat higher total emissions estimates. Other differences in this U.S. EPA analysis are that venting and flaring emissions for Western Europe are based on oil rather than gas production, and there are minor revisions to some factors for fugitive and other emissions from gas production.

These differences are significant, even given the overall uncertainty in this category, and should be considered carefully by national experts in regions where emissions from this source category are significant. It is hoped that the differences can be resolved of explained in more detail in the final version of these Guidelines.

1.9.5 Fugitive Emissions Of Other GHGs

Methane is by far the most important greenhouse gas emitted on a "fugitive" basis from oil and gas systems. However, other GHG's are clearly emitted from this source category and should be included in a comprehensive national inventory. There is one type of combustion - flaring of natural gas during production, which is consider a "fugitive" emission.[36] From this combustion, CO_2 and NO_x are certainly produced and other combustion related gases - N_2O, CO, and NMVOC may be emitted at least in small quantities.

However, after methane, the most significant fugitive emissions from oil and gas production, processing transport and distribution are of non-methane volatile organic compounds (NMVOC). Oil and gas are largely composed of organic compounds, and releases through evaporation or leakages are likely at all stages wherever the fuels or their products contact the atmosphere. Fugitive emissions from refining, transport and distribution of oil products is a major component of national NMVOC emissions in many countries.

The IPCC/OECD programme has not yet addressed the indirect GHG's (including NMVOC) in detail. This is consistent with the initial priorities within the programme - which focused on the direct greenhouse gases, CO_2, CH_4, and N_2O. However, because these gases are important contributors to a range of local and regional (as well as global) atmospheric pollution problems, they have been widely studied and reported elsewhere.

National experts interested including the other fugitive emissions of GHG's from oil and natural gas systems should consult the existing literature which provides detailed emissions factors and procedures for calculating emissions. Some key examples are:

- The CORINAIR Inventory: Default Emission Factors Handbook (Bouscaren, 1992);

- Proceedings of the TNO/EURASAP Workshop (TNO Inst. of Environmental Sciences, 1993)

- Emissions Inventory Guidebook (European Environment Agency, forthcoming)

- EMEP and CORINAIR Emission Factors and Species Profiles for Organic Compounds. (Veldt, 1991);

- U.S. EPA's Compilation of Air Pollutant Emissions Factors (AP-42), 4th Edition 1985, (U.S. EPA, 1985), and Supplement F, (U.S. EPA, 1993);

- Criteria Pollutant Emission Factors for the 1985 NAPAP Emissions Inventory (Stockton and Stelling, 1987)

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[36]This is because the combustion is not for energy purposes and takes place before gas produced is included in national energy accounts.

TABLE 1-47 REVISED REGIONAL EMISSION FACTORS FOR METHANE FROM OIL AND GAS SYSTEMS (KG/PJ)						
Source Type	Basis	Western Europe	US & Canada	Former USSR, Central & Eastern Europe	Other Oil Exporting Countries	Rest of the World
OIL & GAS PRODUCTION						
Fugitive and Other Routine Maintenance Emissions from Oil Production	Oil Produced	300 - 5,000	300 - 5,000	300 - 5,000	300 - 5,000	300 - 5,000
Fugitive and Other Routine Maintenance Emissions from Gas Production	Gas Produced	15,000 - 27,000	46,000 - 84,000	140,000 - 314,000	46,000 - 96,000	46,000 - 96,000
Venting & Flaring from Oil and Gas Production	Oil & Gas Produced[1]	-	3,000 - 14,000	-	-	-
	Oil Produced	1,000 - 3,000	-	-	-	-
	Gas Produced	-	-	6,000 - 30,000	758,000 - 1,046,000	175,000 - 209,000
CRUDE OIL TRANSPORTATION, STORAGE AND REFINING						
Transportation	Oil Tankered	745	745	745	745	745
Refining	Oil Refined	90 - 1,400	90 - 1,400	90 - 1,400	90 - 1,400	90 - 1,400
Storage Tanks	Oil Refined	20 - 250	20 - 250	20 - 250	20 - 250	20 - 250
NATURAL GAS PROCESSING, TRANSPORT AND DISTRIBUTION						
Emissions from Processing, Distribution and Transmission	Gas Produced	-	-	288,000 - 628,000	288,000 (high)[2]	288,000 (high)[2]
	Gas Consumed	72,000 - 133,000	57,000 - 118,000	-	118,000 (low)[3]	118,000 (low)[3]
Leakage at industrial plants and power stations	Non-Residential Gas Consumed[4]	-	-	175,000 - 384,000	0 - 175,000	0 - 175,000
Leakage in the residential and commercial sectors	Residential Gas Consumed[5]	-	-	87,000 - 192,000	0 - 87,000	0 - 87,000

1. In the US and Canada, the emissions are based on total production of both oil and gas produced.

2. The emissions factor of 288,000 kg/Pj of gas produced is used only for the high emissions estimate.

3. The emissions factor of 118,000 kg/Pj of gas consumed is used only for the low emissions estimate.

4. Gas consumption by utilities and industries.

5. Gas consumption by the residential and commercial sectors.

1.9.6 References

Introduction

IAEA. 1993. Assessment of Data Bases on Energy Demand and Supply in Terms of their Adequacy for Use in Studies of Greenhouse Gas Emissions: Report of Advisory Group Meeting, IAEA, Vienna, 5-7 April, 1993. International Atomic Energy Agency, Vienna.

OECD/IEA. 1993a. Energy Statistics and Balances for Non-OECD Countries: 1990-1991 International Energy Agency, OECD, Paris.

OECD/IEA. 1993b. Energy Balances of OECD Countries, 1990-1991. International Energy Agency, OECD, Paris.

OECD/IEA. 1993c. Energy Statistics for OECD Countries, 1990-1991. International Energy Agency, OECD, Paris.

OECD/IEA. 1991. Greenhouse Gas Emissions: The Energy Dimension. OECD, Paris.

UN (United Nations). 1993. 1991 Energy Statistics Yearbook. United Nations, New York.

Carbon Dioxide Emissions From Fossil Fuels

Grubb, M.J. 1989. *On Coefficients for Determining Greenhouse Gas Emissions From Fossil Fuel Production and Consumption.* Energy and Environmental Programme, Royal Institute of International Affairs, London, UK. April. Prepared for IEA/OECD Expert Seminar on Energy Technologies for Reducing Emissions of Greenhouse Gases, Paris.

IPCC. 1992. *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment.* The Intergovernmental Panel on Climate Change (World Meteorological Organization/United Nations Environment Programme). Cambridge University Press.

IPCC/OECD. 1993. *IPCC/OECD Workshop on National GHG Inventories: Transparency in Estimation and Reporting, 1 October, 1992, Bracknell, U.K.* IPCC/OECD Joint Programme on National GHG Inventories, Intergovernmental Panel on Climate Change and Organization for Economic Cooperation and Development, Paris, April.

Jaques, A.P. 1992. *Canada's Greenhouse Gas Emissions for 1990.* Report EP5/AP/4. Environment Canada.

Marland, G.,and R.M. Rotty. 1984. Carbon Dioxide Emissions from Fossil Fuels: A Procedure for Estimation and Results for 1950-1982. *Tellus* 36b:232-261.

Marland, G. and A. Pippin. 1990. "United States Emissions of Carbon Dioxide to the Earth's Atmosphere by Economic Activity," *Energy Systems and Policy,* Volume 14, pp. 319-336.

OECD/IEA (Organisation for Economic Cooperation and Development/International Energy Agency). 1989. *Energy Statistics, 1986-1987.* International Energy Agency, OECD, Paris.

OECD/IEA. 1990a. *World Energy Statistics and Balances: 1985-1988.* International Energy Agency, OECD, Paris.

OECD/IEA. 1990b. *Energy Balances of OECD Countries, 1987-1988.* International Energy Agency, OECD, Paris.

OECD/IEA. 1991. *Greenhouse Gas Emissions: The Energy Dimension.* OECD, Paris.

Okken, P.A., and T. Kram. 1990. *Calculation of Actual CO₂ Emissions from Fossil Fuels.* Presented at ETSAP-IV workshop Petten, the Netherlands, 9-12 April 1990 and IPCC Preparatory Workshop, Paris, 22-23 May 1990.

Summers, G. 1993. Personal communication on behalf of the Coal Industry Advisory Board, Global Climate Committee. 22nd July.

UN (United Nations). 1993. *1991 Energy Statistics Yearbook.* United Nations, New York.

USDOE/EIA. 1992. *Analysis of the Relationship Between the Heat and Carbon Content of U.S. Coals.* Energy Information Administration, U.S. Department of Energy, September.

Other GHG Emission From Stationary Combustion

Bakkum, A., and C. Veldt. 1986. *PHOXA: Statistical Data and Emission Factors.* MT-TNO, Department of Environmental Technology, Apeldoorn, Netherlands.

Bakkum, A., H. Bartelds, J.A. Duiser, and C. Veldt. 1987. *Handbook of Emission Factors: Part 3 - Emissions from Stationary Sources.* Ministry of Housing, Physical Planning, and Environment (VROM), Government Publishing Office. The Hague, The Netherlands, November.

Berdowski, J., J. Olivier, and C. Veldt. 1993. *Methane From Fuel Combustion and Industrial Processes.* in A.R. van Amstel, (ed.), Proceedings of an International IPCC Workshop on Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control. RIVM Report no. 481507003, Bilthoven, The Netherlands.

Brieda, F., and K.-O.Pakleppa. 1989. *Development of a Model for the Compiling of National Totals Emission Inventories for the European OECD Member Countries.* Unweltforschungs Plan Des Bundesminister für Unwelt, Naturschutz, und Reaktorsichereit. November.

Bouscaren, R. (1992). CORINAIR Inventory: Default Emission Factor Handbook, 2nd Ed. 12:1-3. Published by CITEPA, Paris, France.

De Soete, G.G. 1993. *Nitrous Oxide from Combustion and Industry: Chemistry, Emissions and Control.* in A.R. van Amstel, (ed.), Proceedings of an International IPCC Workshop on Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control. RIVM Report no. 481507003, Bilthoven, The Netherlands.

Eggleston, H.S., and G. McInnes. 1987. *Method for the Compilation of UK Air Pollutant Emission Inventories.* ISBN-0-85624-493-7. Warren Spring Laboratory, Stevenage, UK.

European Environment Agency. Forthcoming. Emissions Inventory Guidebook for the UNECE and CORINAIR Emissions Inventories.

Fritsche, U. 1989. *Zusammenstellung von klimarelevanten Emissionsdaten fuer Energiesysteme in der BRD, Endbericht.*

Fritsche, U., L. Rausch, and K.H. Simon. 1989. *Umweltwirkungsanalvse von Energiesystemen: Gesamt-Emissions-Modell Integrierter Systeme (GEMIS)* Endbericht. OEKO-Institut, Darmstadt/Kassel, Germany. August.

Garret, C. 1990. Personal communication. Office of Research and Development, U.S. EPA, Research Triangle Park, North Carolina. December 7.

Hao, W.M., S.C. Wofsy, M.B. McElroy, J.M. Beer, and M.A. Toqan. 1987. Sources of atmospheric nitrous oxide from combustion. *Journal of Geophysical Research* 92:3098-3104.

IPCC/OECD Programme on National GHG Inventories. 1991. *Proceedings of a Workshop on National GHG Emission Methods, Geneva, 3-7 December, 1991.* Intergovernmental Panel on Climate Change, Working Group I, Bracknell, U.K. and Organization for Economic Cooperation and Development, Environment Directorate, Paris.

JAERI (Japanese Atomic Energy Research Institute). 1988. Data provided through personal communicaton with Mr. Doug Hill, Operating Agent for the IEA Energy Technology Systems Analysis Project (ETSAP), Annex III.

Linak, W.P., J.A. McSorley, R.E. Hall, J.V. Ryan, R.K. Srivastava, J.O.L. Wendt, and J.B. Mereb. 1990. Nitrous oxide emissions from fossil fuel combustion. *Journal of Geophysical Research* 95:7533-7541.

Montgomery, T.A., G.S. Samuelsen, and L.J. Muzio. 1989. Continuous infrared analysis of N_2O in combustion products. *Journal of the American Chemical Society* 39:721-726.

Muzio, L.J., and J.C. Kramlich. 1988. An artifact in the measurement of N_2O from combustion sources. *Geophysical Research Letters* 15:1369-1372.

Muzio, L.J., M.E. Teague, J.C. Kramlich, J.A. Cole, J.M. McCarthy, and R.K.Lyon. 1989. Errors in grab sample measurements of N_2O from combustion sources. *Journal of the American Chemical Society* 39:287-293.

OECD/IEA (Organisation for Economic Cooperation and Development/International Energy Agency). 1989. *Energy Statistics, 1986-1987.* International Energy Agency, OECD, Paris.

OECD/IEA. 1990a. *World Energy Statistics and Balances: 1985-1988* (OECD/IEA, 1990b). International Energy Agency, OECD, Paris.

OECD/IEA. 1990b. *Energy Balances of OECD Countries, 1987-1988.* International Energy Agency, OECD, Paris.

OECD/IEA. 1991. *Greenhouse Gas Emissions: The Energy Dimension.* OECD/IEA, Paris.

OFPE (L'Office Federal de la Protection de l'Environnement). 1988. *Emissions Polluantes en Suisse Dues a l'Activite Hunaime (de 1950 a 2010, et Complement).* Les Cahiers de l'Environnement, No. 76, Berne, Switzerland, decembre 1987 et septembre 1988.

Okken, P.A. 1989. Impact of NO_x and CO_2 constraints on the Netherlands energy system. in Proceedings of the 8th World Clean Air Congress, The Hague, September.

Olivier, J.G.J. 1993. *Working Group Report: Nitrous Oxide Emissions from Fuel Combustion and Industrial Processes.* in A.R. van Amstel, (ed.), Proceedings of an International IPCC Workshop on Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control. RIVM Report no. 481507003, Bilthoven, The Netherlands.

Radian Corporation. 1990. *Emissions and Cost Estimates for Globally Significant Anthropogenic Combustion Sources of NO_x, N_2O, CH_4, CO, and CO_2.* Prepared for the Office of Research and Development, U.S. Environmental Protection Agency, Washington, D.C.

Rentz, O., H.D, Haasis, T. Morgensterm, F. Pewrello-Aracena, J. Remmers, and G. Schons. 1988. *Optimal Control Strategies for Reducing Emissions from Energy Conversion and Energy Use.* Institute for Industrial Production, Karlsruhe, FRG, March.

Statens forurensningstilsyn. 1990. *Klimagass Regnskap for Norge.* Oslo, Norway.

Stockton M.B. and J. Stelling. 1987. *Criteria Pollutant Emission Factors for the 1985 NAPAP Emissions Inventory.* EPA-600/7-87-015. Office of Research and Development, U.S. EPA. May.

TNO (1993). Proceedings of the TNO/EUROSAP Workshop, Delft, June 1993. TNO, Institute of Environmental Sciences, Petten, NL.

UN (United Nations). 1990. *1988 Energy Statistics Yearbook*. United Nations, New York.

U.S. EPA (1985). *Compilation of air pollutant emission factors, Vol. I, Stationary point and area sources, AP-42, 4th Edition 1985*; Suppl. A/1986, Suppl. B/1988, Suppl. C/1990. U.S. Environmental Protection Agency.

U.S. EPA (1993). *Compilation of air pollutant emission factors, Vol. I, Stationary point and area sources, AP-42, Supplement F*. U.S. Environmental Protection Agency.

Veldt, C. (1991). *Development of EMEP and CORINAIR emission factors and species profiles for emissions of organic compounds*. IMET-TNO report 91-299.

Walbeck, M., H.J. Wagner, D. Martinsen, and V. Bundschuh. 1988. *Energie und Umwelt als Optimierungsaufgabe: Das MARNES-Modell/* Springer-Verlag, Berlin.

Zeedijk, H. (1986). *Emissions by combustion of solid fuels in domestic stoves*. Proc. 7th World Clean Air Congress, Sydney (Aus), H.F. Hartmann (ed.)., Vol. IV, 78-85.

Burning Of Traditional Biomass Fuels

Barnard, G.W. 1990. Use of agricultural residues as fuel. In: Pasztor, J., and L.A. Kristoferson (eds.). *Bioenergy and the Environment*. Westview Press, Boulder, Colorado. pp. 85-112.

Crutzen, P.J., M.O. Andreae. 1990. Biomass burning in the Tropics: Impact on atmospheric chemistry and biogeochemical cycles. *Science* 250:1669-1678.

Delmas, R. 1993a. An Overview of Present Knowledge on Methane Emission from Biomass Burning. in A.R, van Amstel (ed.). Proceedings of an International IPCC Workshop: Methane and Nitrous Oxides, Methods in National Emissions Inventories and Options for Control, 3-5 February 1993, Amersfoort, NL. RIVM Report no. 481507003, Bilthoven, NL, July.

Delmas, R. 1993b. Personal communication. Dated October 19, 1993.

Delmas, R.A. and D. Ahuja. 1993. Estimating National Methane Emissions from Anthropogenic Biomass Burning. Working Group Report: Methane Emissions from Biomass Burning. in A.R. van Amstel (ed.), *Proceedings of an International IPCC Workshop: Methane and Nitrous Oxides, Methods in National Emissions Inventories and Options for Control, 3-5 February 1993, Amersfoort, NL*. RIVM Report no. 481507003, Bilthoven, NL, July.

Hall, D.C. 1993. Personal communication. August.

Johansson, T.B., H. Kelly, A.K.N. Reddy, and R.H. Williams. 1992. Renewable Energy: Sources for Fuels and Electricity. Island Press. Washington, DC.

Lacaux, J.P., H. Cachier and R. Delmas. 1993. Biomass Burning in Africa: An Overview of Its Impact on Atmospheric Chemistry. in P.J. Crutzen and J.G. Goldammer (eds.) *Fire in the Environment: The Ecological, Atmospheric and Climatic Importance of Vegetation Fires*. J. Wiley & Sons Ltd.

Levine, J.S. (ed.). 1990. *Global Biomass Burning: Atmospheric, Climatic and Biospheric Implications*. The MIT Press. Cambridge, MA.

Ryan, P., and K. Openshaw. 1991. Assessment of Biomass Energy Resources: A Discussion of its Need and Methodology, World Bank Energy Series Paper No. 48. Washington, DC.

GHG Emissions From Mobile Combustion

Alexandersson, A. (1990). The Swedish investigation - Exhaust emissions from ships. *Proc. EMEP Workshop on Emissions from Ships.* Oslo, Norway, June 7-8, 1990. State Pollution Control Authority, Oslo

Andraeas, A., D. Zafiris, Z. Samaras. (1992). CORINAIR Working Group on Emission Factors for Calculating 1990 Emissions from Road Traffic, Volume 2: COPERT Users Manual. September.

Baas, J. (1991). Study of literature on emission of nitrous oxide by road traffic (in Dutch with English summary). TNO Report No. R91/322. IMW-TNO, Delft, November 1991.

Berdowski, J., J. Olivier, and C. Veldt. 1993. *Methane From Fuel Combustion and Industrial Processes.* in A.R. van Amstel, (ed.), Proceedings of an International IPCC Workshop on Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control. RIVM Report no. 481507003, Bilthoven, The Netherlands.

Berdowski, J., L. Beck, S. Piccot, J. Olivier and C. Veldt (1993). Working Group Report: Methane Emissions from Fuel Combustion and Industrial Sources. in A.R. van Amstel, (ed.), Proceedings of an International IPCC Workshop on Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control. RIVM Report no. 481507003, Bilthoven, The Netherlands.

Bremmes, P.K. 1990. Calculations of exhaust gas emissions from sea transport: Methodology and results. *Proc. EMEP Workshop on Emissions from Ships.* Oslo, Norway, June 7-8, 1990. State Pollution Contro Authority, Oslo.

Dasch, J.M. 1990. Nitrous oxide emissions from vehicles. General Motors Research Publication No. GMR-7236, Warren Michigan.

De Soete, G.G. 1993. *Nitrous Oxide from Combustion and Industry: Chemistry, Emissions and Control.* in A.R. van Amstel, (ed.), Proceedings of an International IPCC Workshop on Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control. RIVM Report no. 481507003, Bilthoven, The Netherlands.

Dietzmann, H.E., M.A. Parness, and R.L. Bradow. 1980. *Emissions from Trucks by Chassis Version of 1983 Transient Procedure.* SAE Paper No. 801371. SAE International, Warrendale, PA.

Eggleston, H.S. et al., (1992). CORINAIR Working Group om Emission Factors for Calculating 1990 Emissions from Road Traffic, Volume 1: Methodology, Final Report, December.

Ford Motor Company. 1989. Annual report to EPA on non-regulated pollutants for calendar year 1988. Dearborn, MI.

Ford Motor Company. 1990. Annual report to EPA on non-regulated pollutants for calendar year 1989. Dearborn, MI.

Ford Motor Company. 1991. Annual report to EPA on non-regulated pollutants for calendar year 1990. Dearborn, MI.

Hadler, C. 1990. Investigation of exhaust gas emission from heavy fuel operated diesel engines on board ships. *Proc. EMEP Workshop on Emissions From Ships.* Oslo, Norway, June 7-8, 1990. State Pollution Control Authority, Oslo.

International Road Federation. 1990. *World Road Statistics 1986-1990.* Edition 1990, Washington, D.C. and Geneva, Switzerland. September.

Iwasaki, Y., S. Tatsuichi, S. Fukuoka, Y. Iida, M. Funeshima, H. Yokota and Y. Takenaga **(1990):** Determination of N_2O from automobiles. Proc. of the *31th Annual meeting of the Japan Society of Air Pollution*, 483, Kanazawa (JP), 1990.

Machiele, P.A. 1988. *Heavy-Duty Vehicle Emission Conversion Factors II: 1962-2000.* EPA Report No. EPA-aa-sdsb-89-1. Ann Arbor, MI.

Melhus, O. 1990. NOx emission factors from marine diesel engines. *Proc. EMEP Workshop on Emissions from Ships.* Oslo, Norway, June 7-8, 1990. State Pollution Control Authority, Oslo.

OECD/IEA. 1991. *Greenhouse Gas Emissions: The Energy Dimension.* OECD/IEA, Paris. 1991.

Olivier, J.G.J. (1991). Inventory of aircraft emissions: a review of recent literature. RIVM Report No. 736 301 008. RIVM, Bilthoven, November 1991.

Olivier, J.G.J. 1993. *Working Group Report: Nitrous Oxide Emissions from Fuel Combustion and Industrial Processes.* in A.R. van Amstel, (ed.), Proceedings of an International IPCC Workshop on Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control. RIVM Report no. 481507003, Bilthoven, The Netherlands.

Otto, K., M. Shelef, and J.T. Kummer. 1970. Studies of surface reations of nitric oxide by nitrogen-15 isotope labeling; I. The reaction between nitric oxide and ammonia over supported platinum at 200-250. *Journal of Physical Chemistry* 74, 2690-2698.

Prigent, M. and G. De Soete. 1989. *Nitrous Oxide N_2O in Engines Exhaust Gases- A First Appraisal of Catalyst Impact.* SAE Paper No. 890492. SAE International, Warrendale, PA.

Radian Corporation. 1990. *Emissions and Cost Estimates for Globally Significant Anthropogenic Combustion Sources of NO_x, N_2O, CH_4, CO and CO_2.* Prepared for the Office of Research and Development, U.S. EPA, Research Triangle Park (NC), May 1990. EPA-600/7-90-010.

Susuki, M., M. Nakazawa, T. Hidaka and M. Kaneko **(1992):** Study on N_2O emission from motor vehicles. Proc. of the *33th Annual meeting of the Japan Society of Air Pollution*, 347, Osaka (JP), 1992.

UN (United Nations). 1989. *Annual Bulletin of Transport Statistics for Europe: Volume XXXIX.* UN, New York.

U.S. EPA (U.S. Environmental Protection Agency). 1985. *Compilation of Air Pollution Emission Factors: Highway Molile Sources.* AP-42, Fourth Edition, Ann Arbor, Michigan. Secptember.

U.S. EPA (U.S. Environmental Protection Agency). 1989. *User's Guide to Mobile4 (Mobile Source Emission Model).* Emission Control Technology Division, Ann Arbor, MI.

U.S. National Technical Information Service. 1991. MOBILE4 Model and *User's Guide.* U.S. NTIS, U.S. Department of Commerce, Springfield, Virginia.

Veldt, C. (1991). Development of EMEP and CORINAIR emission factors and species profiles for emissions of organic compounds. IMET-TNO report 91-299.

Warner-Selph, M.A. and L.R. Smith. 1991. *Assessment of Unregulated Emissions from Gasoline Oxygenated Blends.* EPA 460/3-91-002. Report under EPA Contract No. 68-C9-0004. Southwest Research Institute, San Antonio, TX.

Weaver, C.S. 1988. *Feasibility and Cost-Effectiveness of Controlling Emissions from Diesel Engines Used in Rail, Marine, Construction, Farm, and Other Mobile Off-Highway Equipment.* Report under EPA Contract No. 68-01-7288, Radian Corporation, Sacramento, CA.

Weaver, C.S and S.H. Turner. 1991. Memorandum to Jane Leggett U.S. EPA and Craig Ebert, ICF, Incorporated, June 3, 1991.

Emissions From Coal Mining, Handling And Utilization

Airuni, A.T. and V.E. Zeidenvarg (1992), "The Role of Coal Production in the Global Contamination of the Biosphere by Methane," Russian Institute of Comprehensive Mineral Resources Exploitation, Moscow, Russia

Barns, D.W. and J.A. Edmonds (1990), An Evaluation of the Relationship between the Production and Use of Energy and Atmospheric Methane Emissions, TR047, USDOE/NBB0088P, U.S. Department of Energy, Washington, D.C.

BCTSRE (1992), Quantification of Methane Emissions from British Coal Mine Sources, prepared by British Coal Technical Services and Research Executive for the Working Group on Methane Emissions, The Watt Committee on Energy, United Kingdom.

Bibler, C.J., et al. (1992), Assessment of the Potential for Economic Development and Utilization of Coalbed Methane in Czechoslovakia. EPA/430/R-92/1008, U.S. Environmental Protection Agency, Office of Air and Radiation, Washington, D.C.

Boyer, C.M., et. al (1990) Methane Emissions from Coal Mining: Issues and Opportunities for Reduction, EPA-400/9-90/008, U.S. Environmental Protection Agency, Office of Air and Radiation, Washington, D.C.

CIAB (1992), Global Methane Emissions from the Coal Industry, prepared by the Coal Industry Advisory Board, Glboal Climate Committee/International Energy Agency, Paris, France.

CMRC (1990), Methane Emissions from Canadian Coal Operations: A Quantitative Estimate, prepared by B. Hollingshead, Coal Mining Research Company, CI 8936, Devon, Alberta.

Creedy, D.P. (1991), "An Introduction to Geological Aspects of Methane Occurrence and Control in British Deep Coal Mines," Quarterly Journal of Engineering Geology, No. 24, pp. 209-220.

Crutzen, P.J. (1987), "Role of the Tropics in Atmospheric Chemistry," in Geophysiology of Amazonia, R. Dickenson, ed., New York: John Wiley, pp. 107-132.

Hargraves, A.J. (1990), "Coal Seam Gas and the Atmosphere," in Greenhouse and Energy, North Ryde, NSW, Australia.

Hitchcock, D.R. and A.E. Wechsler (1972), Biological Cycling of Atmospheric Trace Gases, Final Report, NASW-2128, pp. 117-154.

KfA (1993), personal communication from W. Katscher.

Kirchgessner, D.A., S.D. Piccot and J.D. Winkler (1992), "Estimate of Global Methane Emissions from Coal Mines," Chemosphere (in press)

Koyama, T. (1963), "Gaseous Metabolism in Lake Sediment and Paddy Soils and the Production of Atmospheric Methane and Hydrogen," Journal of Geophysical Research, 68 (13): 3971.

Lama, R.D. (1992), "Methane Gas Emissions from Coal Mining in Australia: Estimates and Control Strategies," in Proceedings of the IEA/OECD Conference on Coal, the Environment and Development: Technologies to Reduce Greenhouse Gas Emissions, IEA/OECD, Paris, France, pp. 255-266.

Marland, G.,and R.M. Rotty. 1984. Carbon Dioxide Emissions from Fossil Fuels: A Procedure for Estimation and Results for 1950-1982. Tellus 36b:232-261.

OECD/IEA (1990a), Coal Information, Paris, France.

OECD/IEA (1990b), Coal Statistics, Paris, France.

OECD (1991), Estimation of Greenhouse Gas Emissions and Sinks, Final Report from the OECD Experts Meeting, Paris, France, 18-21 February 1991.

Okken, P.A. and T. Kram (1989), "CH$_4$/CO - Emission from Fossil Fuels Global Warming Potential," paper presented at the IEA/ETSAP - Workshop, Paris, France, June 1989, ESC-WR-89-12, Petten, The Netherlands, Energy Study Centre: Netherlands Energy Research Foundation.

Pilcher, R.C., et al. (1991), Assessment of the Potential for Economic Development and Utilization of Coalbed Methane in Poland. EPA/400/1-91/032, U.S. Environmental Protection Agency, Washington, D.C.

Polish Central Mining Institute (1990), Official Polish Methane Emissions Data for 1989, provided to Raven Ridge Resources, November 1990.

Seiler, W. (1984), "Contribution of Biological Processes to the Global Budget of CH$_4$ in the Atmosphere," in Current Perspectives in Microbial Ecology, American Society for Microbiology, Washington, D.C.

Seltzer, H. and W. Zittel (1990), Emissions of Methane Gas Affecting the Climate: an Investigation of Global Methane Emissions from the Use of Fossil Fuels, Waste Incineration, Agriculture, and the Earth, LBST-Report No. 10/90, Ottobrunn, Germany.

Smith, I.M. and L.L. Sloss (1992), Methane Emissions from Coal: IEA Perspectives. IEAPER/04, London, United Kingdom, November 1992.

USEPA (1993a), Global Anthropogenic Methane Emissions: Estimates for 1990, Report to the U.S. Congress, U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, Washington, D.C. (in preparation).

USEPA (1993b), Anthropogenic Methane Emissions in the United States: Estimates for 1990, Report to the U.S. Congress, U.S. Environmental Protection Agency, Office of Air and Radiation, Washington, D.C. (in press)

USGS (1993), personal communication.

Williams, A. and C. Mitchell (1992), "Methane Emissions from Coal Mining," Department of Fuel and Energy, The University of Leeds, Leeds, United Kingdom (in preparation).

Zimmermeyer, G. (1989), "Methane Emissions and Hard Coal Mining," Glueckaufhaus, Essen, Germany, Gesamtverband des deutschen Steinkohlenbergbaus, personal communication.

Emissions From Oil And Gas Systems

Abrahamson D. 1989. "Relative Greenhouse Effect of Fossil Fuels and the Critical Contribution of Methane," presented to The Oil Heat Task Force

AGA. 1989. "Natural Gas Transmission and Distribution Methane Emissions," AGA, Engineering Technical Note, Arlington, VA.

Alphatania. 1989. Methane Leakage from Natural Gas Operations. The Alphatania Group.

API (American Petroleum Institute). 1987. "Atmospheric Hydrocarbon Emissions from Marine Vessel Transfer Operations," API publication 2514A, Washington, DC.

Bouscaren, R. (1992). CORINAIR Inventory: Default Emission Factor Handbook, 2nd Ed. 12:1-3. Published by CITEPA, Paris, France.

BP Statistical Review of World Energy. 1992. Published by BP. London.

Barns, D.W. and J.A. Edmonds. 1990. "An Evaluation of the Relationship Between the Production and Use of Energy and Atmospheric Methane Emissions," prepared for the Office of Energy Research, U.S. Department of Energy, Washington, D.C.

Cicerone, R.J. and R.S. Oremland. 1988. "Biogeochemical Aspects of Atmospheric Methane," Global Biogeochemical Cycles, Vol. 2, No. 4, Dec.1988, pp. 299 - 327.

Craig, Bruce. 1991. Personal communication. U.S. Environmental Protection Agency, Global Change Division, Washington, D.C.

Ebert, C., D. Picard, P. Pope, and A. Roslund. 1993. Methane Emissions from Oil and Natural Gas Systems: a Methodology to Estimate national Emissions. in A.R, van Amstel (ed.). Proceedings of an International IPCC Workshop: Methane and Nitrous Oxides, Methods in National Emissions Inventories and Options for Control, 3-5 February 1993, Amersfoort, NL. RIVM Report no. 481507003, Bilthoven, NL, July.

European Environment Agency. Forthcoming. Emissions Inventory Guidebook for the UNECE and CORINAIR Emissions Inventories.

Hitchcock D.R. and A.E. Wechsler. 1972. "Biological Cycling of Atmospheric Trace Gases prepared for the National Aeronautics and Space Administration, Washington, D.C., March 1972.

INGAA (Interstate Natural Gas Association of America). 1989. "Global Warming and Methane Loss from Interstate Natural Gas Pipeline," Rate and Policy Analysis Department, Washington, D.C.

International Petroleum Encyclopedia. 1990. Vol 23, PennWell Publishing Co., Tulsa, Oklahoma.

Norwegian SPCA (State Pollution Control Authority). 1992. Emissions of Greenhouse Gases in Norway - 1989. National versus IPCC estimation method (Transparency study). Rapport 92:29.

Norwegian SPCA (State Pollution Control Authority). 1992. Letter on "Methane Emissions from Oil Activities" from Audun Rosland, SPCA to Craig D. Ebert, ICF Incorporated.

Norwegian Oil Industry Association - OLF, 1993 in prep. Report from OLF Environmental Programme - Phase 2. Will be available Mars 1993.

OECD-IEA. 1989. World Energy Statistics and Balances, 1985 - 1988.

OECD-IEA. 1989. World Energy Balances of OECD Countries, 1980 -1989.

OECD. 1991. "Estimation of Greenhouse Gas Emissions and Sinks," from the OECD Experts Meeting, 18-21 February 1991 prepared for Intergovernmental Panel on Climate Change

PG&E (Pacific Gas & Electric Company). 1990. Unaccounted for Gas Project Summary Volume PG&E Research & Development; San Ramon, CA; GRI-90/0067.1.

Pepper W. et al. 1992. Emissions Scenarios for the IPCC: An Update. Prepared for the Intergovernmental Panel on Climate Change Work Group 1. May 1992.

Rabchuk, V.I, N.I. Ilkevich, and Y.D. Kononov. 1991. "A Study of Methane Leakage in the Soviet Natural Gas Supply System," prepared for the Battelle Pacific Northwest Laboratory, Siberian Energy Institute, Irktsk, USSR.

Radian Corporation. 1992. "Venting and Flaring Emissions from Production, Processing, and Storage in the U.S. Natural Gas Industry," Updated Draft Report prepared for the U.S. EPA and the Gas Research Institute.

Schneider-Fresenius, W. R.A. Hintz, U. Hoffmann-Meienbrock, W. Klopffer, and J. Wittekind. 1989. "Determination of Methane Emission into the Atmosphere due to Losses in the Natural Gas Supply System of the Federal Republic of Germany - Contribution of Methane to the Global Greenhouse Effect." Battelle-Institut, Frankfurt, Germany.

Southern California Gas Company (SOCAL). 1992. *Unaccounted for Gas Project Summary Volume* (in preparation) SOCAL Research & Development; Los Angeles, CA.

Stockton M.B. and J. Stelling. 1987. *Criteria Pollutant Emission Factors for the 1985 NAPAP Emissions Inventory.* EPA-600/7-87-015. Office of Research and Development, U.S. EPA. May.

TNO (1993). Proceedings of the TNO/EUROSAP Workshop, Delft, June 1993. TNO, Institute of Environmental Sciences, Petten, NL.

UK Offshore Operators Association Ltd, 1993. Methane Emissions From Offshore Oil & Gas Exploration & Production Activities. Submitted to The Watt Committee on Energy.

UN (United Nations). 1992. *UN Energy Statistics Yearbook 1990*, UN, New York.

U.S. EPA (1985). Compilation of air pollutant emission factors, Vol. I, Stationary point and area sources, AP-42, 4th Edition 1985; Suppl. A/1986, Suppl. B/1988, Suppl. C/1990. U.S. Environmental Protection Agency.

U.S. EPA (Environmental Protection Agency). 1992. "Anthropogenic Methane Emissions in the United States - Report to Congress," prepared by Global Change Division, Office of Air and Radiation, US EPA, Washington, DC.

U.S. EPA (1993). Compilation of air pollutant emission factors, Vol. I, Stationary point and area sources, AP-42, Supplement F. U.S. Environmental Protection Agency.

U.S. EPA (in Press). International Anthropogenic Methane Emissions, Estimates for 1990: Report to Congress. Office of Policy Planning and Evaluation, U.S. Environmental Protection Agency, Washington, D.C.
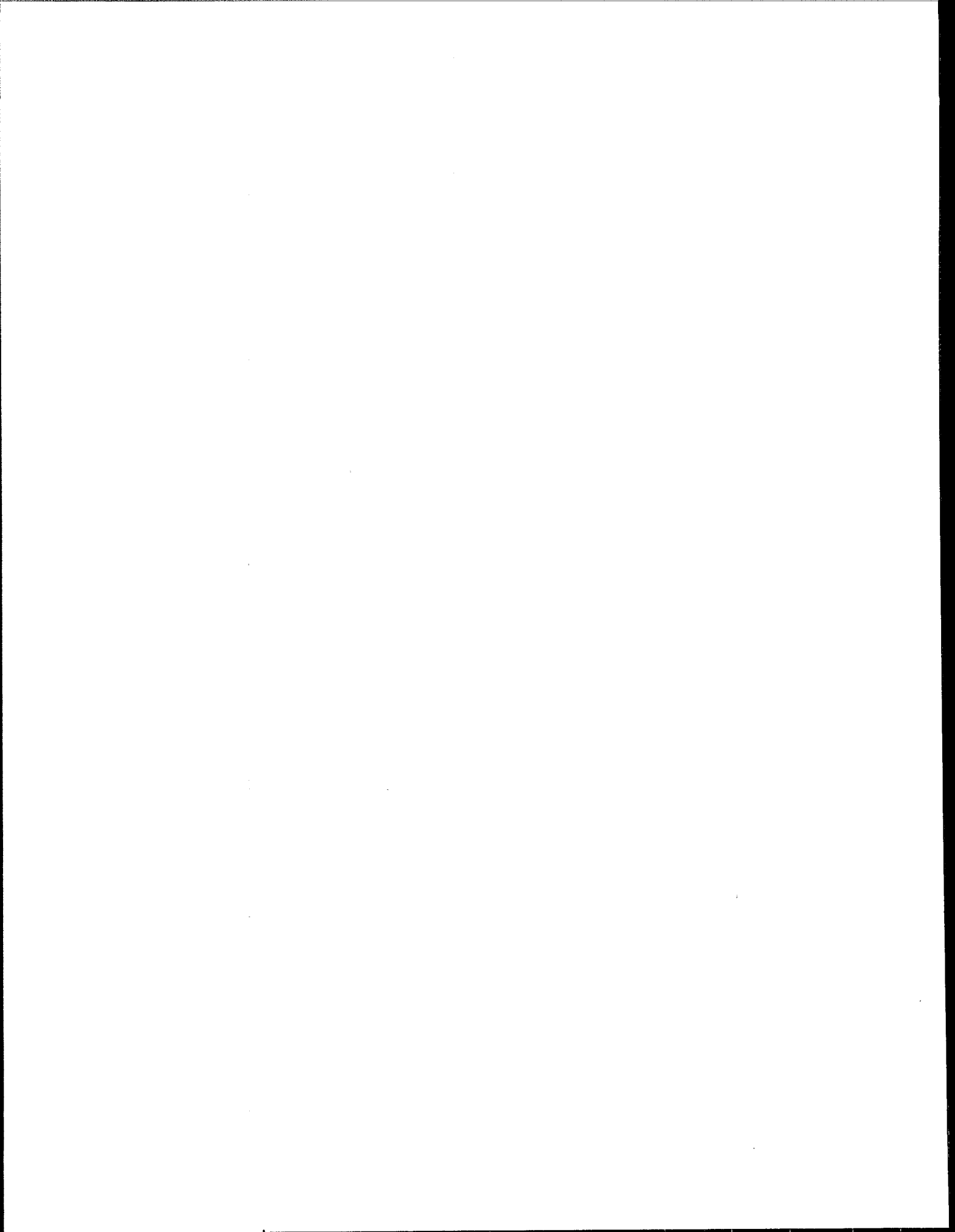
Veldt, C. (1991). Development of EMEP and CORINAIR emission factors and species profiles for emissions of organic compounds. IMET-TNO report 91-299.
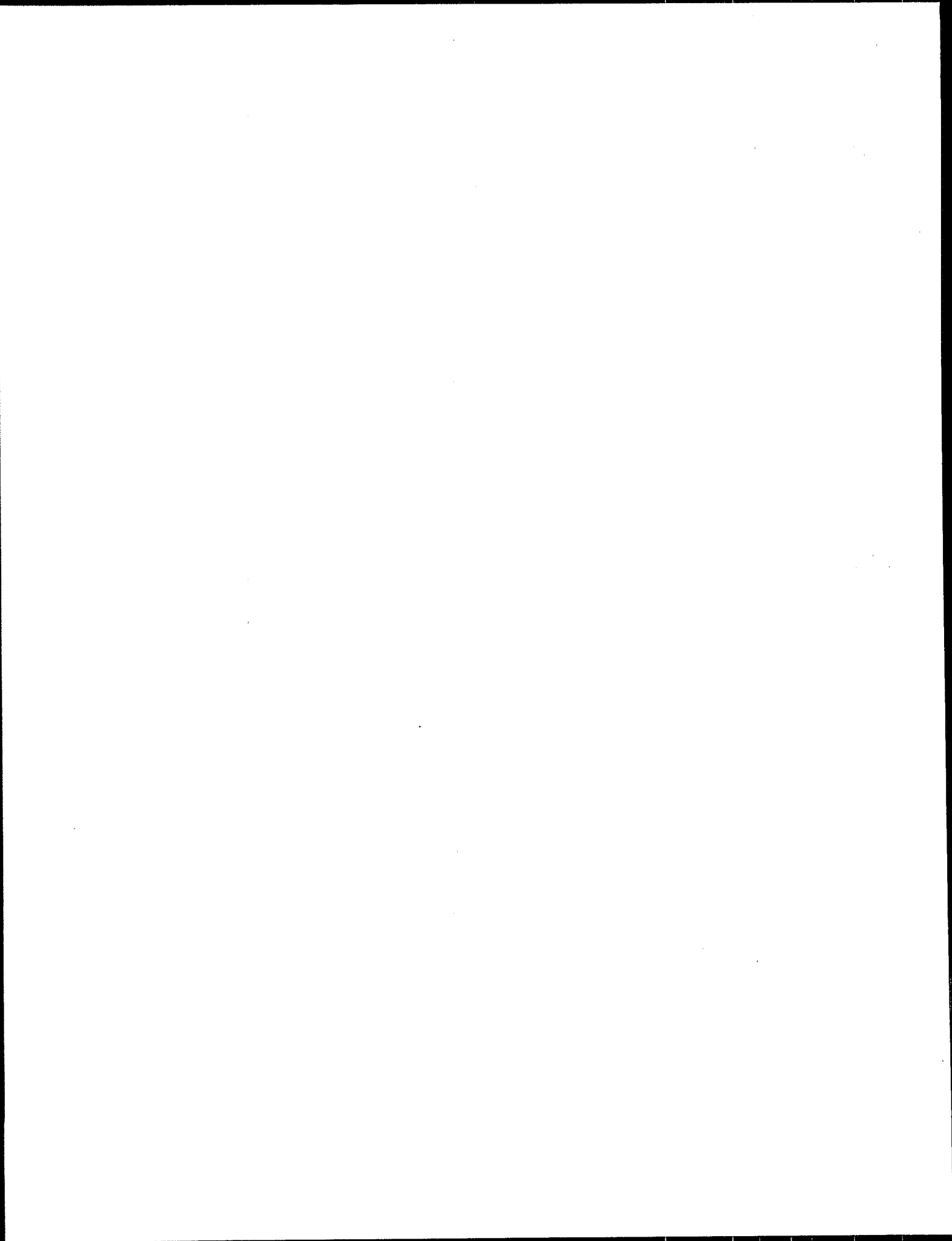
CHAPTER 2
INDUSTRIAL PROCESSES

2   INDUSTRIAL PROCESSES

2.1   Overview

Greenhouse gas emissions are produced from a variety of non-energy related industrial activities. The main emission sources are industrial production processes which chemically or physically transform materials from one state to another. During these production processes, many different greenhouse gases (CO_2, CH_4, N_2O, CO) can be released. Cement production is perhaps the most notable example of such an industrial (transformation) process that releases a significant amount of CO_2.

In some instances industrial process emissions are produced in combination with energy combustion emissions. To the extent that these emissions are the direct result of the fuel combustion, they are included as energy emissions not industrial process emissions. This will avoid double-counting since these emissions should be estimated as a result of energy consumption activities (see the Energy Chapter). Also, all emissions, including evaporative emissions which occur in energy transformation activities (e.g., petroleum refining) are discussed in the Energy Chapter. Other evaporative emissions, primarily of NMVOC, are not included in the Industrial Processes Chapter. These sources, also referred to as "area sources" are now treated separately in the Solvent Use Chapter. Refer to *Volume 1, Greenhouse Gas Inventory Reporting Instructions* for further discussion of source category definitions and reporting issues.

At this time, cement production is the only process for which a detailed methodology is proposed for emissions estimation. However, it has been recommended that all processes generating emissions be identified, the level of emissions from these processes evaluated, and appropriate emission estimation methodologies developed. Some preliminary information is provided for CO_2, CH_4 and N_2O emissions estimation from industrial processes. Experts have suggested general additions to the range of source activities to be addressed in this *Guidelines* document. Some of these are listed in Table 2-1 of this chapter. This is not intended to be a definitive list, but rather to be a working list which will evolve over time as methods improve.

2.1.1 Chapter Organization

The remainder of the chapter is organized by gases of concern. The next section discusses CO_2 emissions from industrial processes including cement manufacturing. The next two sections summarize available preliminary information on industrial process sources of CH_4 and N_2O respectively. The final section discusses sources of other GHGs from industrial processes. The IPCC/OECD programme has not yet addressed these gases in detail. Instead, this section identifies some of the major information sources already available from other international and national emissions inventory programs. The sections in this chapter dealing with industrial process emissions give background information on the sources and uncertainties associated with estimating emissions for the most important gases and source categories. This is consistent with the initial priorities under the IPCC/OECD programme. National experts are encouraged to report any other relevant data, along with documentation of methods and assumptions used. This will greatly assist in the development of more complete methods for future editions of the IPCC *Guidelines*.

2.2 Carbon Dioxide Emissions From Industrial Processes

2.2.1 Cement Manufacturing

Carbon dioxide emitted during the cement production process represents the most important non-energy industrial process source of global carbon dioxide emissions. Cement production accounts for about 2.4 percent of total global industrial and energy CO_2 emissions (Marland et al., 1989). Carbon dioxide is produced during the production of clinker, an intermediate product from which cement is made. High temperatures in cement kilns chemically change raw materials into cement clinker (grayish-black pellets about the size of ½-inch-diameter marbles). Specifically, calcium carbonate ($CaCO_3$) from limestone, chalk, or other calcium-rich materials is heated, forming lime (calcium oxide or CaO) and carbon dioxide in a process called calcination or calcining:

$$CaCO_3 + Heat \rightarrow CaO + CO_2$$
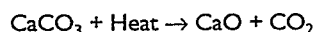
This lime combines with silica-containing materials, provided to the kiln as clays or shales, to form dicalcium or tricalcium silicates, two of the four major compounds in cement clinker (Griffin, 1987). The clinker is then removed from the kiln, cooled, and pulverized into an extremely fine gray powder. During this operation a small amount of gypsum is added to regulate the setting time of the cement. The finished product is called "portland" cement.

Most of the cement currently produced in the world is portland cement type, which contains 60 to 67 percent lime by weight. Other speciality cements are lower in lime, but are typically used in small quantities. Research is underway on cement formulations that have similar structural properties to portland cement, but require less lime (Tresouthick and Mishulovich, 1990). Carbon dioxide emissions from cement production are essentially directly proportional to lime content, so production of cements lower in lime yield less CO_2.

Because carbon dioxide is emitted during clinker production (rather than cement production itself), emission estimates should be based on the lime content and production of clinker. Estimating emissions based on the lime content and production of *finished cement* ignores the consideration that some domestic cement may be made from imported clinker, or that some finished cement may use additional lime that is not accounted for in the cement calculations. Clinker statistics, however, may not be readily available in some countries. If this is the case, cement statistics can be used. The differences between the lime content and production of clinker and cement, *in most countries*, are not significant enough to affect the emission estimates.

Estimating CO_2 Emissions from Cement

Estimation of CO_2 emissions from cement production is accomplished by applying an emission factor, in tonnes of CO_2 released per tonne of clinker produced, to the annual clinker output.[1] The emission factor is the product of the fraction of lime used in the cement clinker and a constant reflecting the mass of CO_2 released per unit lime:

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[1] Note that the estimation of CO_2 from energy use during cement production is explained in the energy chapter; these emissions should be reported under Energy-fuel combustion activities.

$$EF_{clinker} = \text{Fraction CaO} \times (44 \text{ g/mole } CO_2 / 56.08 \text{ g/mole CaO})$$

or

$$EF_{clinker} = \text{Fraction CaO} \times 0.785$$

There are two methods for calculating this emission factor. The first is to assume an average CaO fraction in clinker. Since clinker is mixed with gypsum, which contains less lime per unit, to make cement, clinker has a higher lime percentage than finished cement. The average clinker lime percentage was found to be 64.6%[2]. This number was multiplied by the molecular weight ratio of CO_2/CaO (0.785) to achieve a clinker emissions factor of 0.5071 tonnes of CO_2/tonne of clinker produced.

$$EF_{clinker} = 0.646 * 0.785 = 0.5071$$

A second method is to assemble country or regional data on clinker production by type and clinker CaO content by type, then calculate a weighted average for cement lime content in the country. In most countries, the difference in the results of these two methods is likely to be small; any error in the lime content assumption is likely to be smaller than the uncertainty in clinker and cement production figures (Griffin, 1987).

If information on clinker production is not readily available, an emissions factor in tonnes of CO_2 released per tonne of cement produced can be applied to annual cement production instead. This approach has been followed by Marland et al. (1989), who took the average CaO content of cement to be 63.5%, yielding an emission factor of 0.4985 CO_2/cement (0.136 te CO_2 as C/te cement).

$$EF_{cement} = 0.635 * 0.785$$
$$=$$
$$0.4985$$

Additional research indicates that "masonry cement", as opposed to "portland cement" requires additional lime, over and above the lime used in its clinker. The following formula can be used to account for this activity:

$$a \times (\text{All Cement Production}) \times ((1-(1/1+b) \times c) \times 0.785 = \text{tonnes } CO_2 \text{ from CaO added to masonry cement}$$

where:

    a = fraction of all cement produced that is masonry cement (e.g. 0.1, 0.2)

    b = fraction of weight added to masonry cement by non-plasticizer additives such as lime, slag, and shale (e.g. .03, .05)

    c = fraction of weight of non-plasticizer additives that is lime (e.g. 0.6, 0.8)

    a × (All Cement Production) = Masonry Cement Production

    ((1-1/1+b) × c) = fraction of lime in masonry cement not attributable to clinker

    ((1-1/1+b) × c) × 0.785 = an emissions factor of CO_2 from masonry cement additives

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[2] - Gregg Marland, ORNL, Personal communication.

Data Sources

International cement production data are available from the United Nations (1988) and from the U.S. Bureau of Mines (1988). In some countries, national data may be available from appropriate government ministries. There is substantial overlap between the U.S. Bureau of Mines and the UN data sets, but the former is more complete. Published information is also available from the European Cement Association (CEMBUREAU, 1990).

Recommended Method

The recommended method for estimating CO_2 emissions from cement production is to multiply the most reliable figures available for tonnes of clinker produced by an emission factor of 0.5071 CO_2/clinker. Alternatively, cement production can be multiplied by an emission factor of 0.4985 CO_2/cement.

2.2.2 Other Industrial Processes

There are many other processes which may be significant sources of CO_2 for some countries. In the national inventories collected by the IPCC/OECD joint programme, CO_2 emissions from the following processes have been reported:

Production: coke, iron, steel, aluminum, ferro alloys, carbon carbide, fertilizers, limestone, lime, dolomite, bricks, glass, paper, pulp, and print.

Consumption: limestone

In estimating emissions from these sources, it is expected that most categories will use the following simple method:

> Physical units of production (e.g. tonnes) × Emission Factor = Emissions
> (e.g. tonnes CO_2/tonne
>   product)

As more national data is collected and evaluated in this area, we expect to be able to develop and provide formulae and default emissions for additional categories (IPCC, 1993).

Methane Emissions From Industrial Processes

Most global methane budget estimates do not included a large and diverse group of minor industrial sources which emit methane into the atmosphere. This source class deals with non-combustion processes in industry, which excludes methane emitted from fuel combustion in the production process. Individually, these sources emit minor quantities of methane, but collectively their contribution to the global budget may be significant.

Non-combustion processes include the following:

- primary metals production and associated processes (coke, sinter, pig iron, steel);

- chemical manufacturing processes; production of a variety of chemicals like carbon black, ethylene, dichloro-ethylene, styrene and methanol.

Table 2.2 summarizes estimated global methane emissions from some specific non-combustion industrial processes. These processes include: production of iron/steel (coke included); oil refining; production of carbon black, ethylene, dichloroethylene, styrene and methanol.
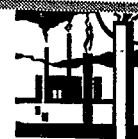
Iron & steel production, appearing as the major source in this category, may be further subdivided in coke, sinter and pig iron production as sources of process emissions. The other processes that have been analyzed for process emissions of methane are of minor importance due to low estimated production level and/or emission. (Berdowski et al., 1993b)

Uncertainties

Further study and clarification of the sources included in this category and their global average emission factors are required in order to arrive at final conclusions with respect to the importance of this source category in total global methane emissions. Table 2.3 presents the estimated global total methane emissions from non-combustion industrial processes along with estimated ranges. The estimated range presented in the table illustrates the uncertainty of point estimates. Wide ranges, such as those presented, imply the need for further examination of the data used, particularly for iron and steel industries and oil refineries.

Methane from industrial processes is estimated to be only 3% of all fossil fuel related CH_4 emissions, and hence seems negligible on a global scale. However, it is recommended that national experts make a critical review of all possible sources in this category because their inclusion may be quite relevant in some national inventories.

N_2O Emissions From Industrial Processes

Non-combustion industry processes resulting in N_2O emissions are recognized as important anthropogenic contributors to global nitrous oxide emissions. It is estimated that this source category represents 10 to 50% of anthropogenic N_2O emissions and 3 to 20% of all global emissions of N_2O emissions. (IPCC, 1992) Three sources of N_2O emissions have been identified within this category: adipic acid production, nitric acid production, and other chemicals production.

Adipic acid

Adipic acid is a raw material primarily used for the manufacturing of 6,6 nylon and is generally produced from cyclohexane. Cyclohexane is used to produce so-called "KA", which is subsequently oxidized with nitric acid to produce adipic acid. This oxidation step unavoidably produces nitrous oxide as a side-product with an associated emission factor (for unabated emissions) of 300 g N_2O/kg adipic acid produced. (Thiemens and Trogler, 1991)

Figures for global adipic acid production are estimated to be 1.8 Tg, with associated emissions of 0.37 Tg N_2O or 0.24 Tg N_2O-N. This emissions estimate assumes a total of 0.55 Tg of N_2O initially produced during the adipic acid production process with an average abatement of about 32%. (Reimer et al., 1992) The abatement of N_2O results from the treatment of the off-gases in a reductive furnace. A number of adipic acid producers treat the off-gases with the aim of reducing NO_x emissions, but the treatment also coincidentally destroys nitrous oxide. (Reimer et al., 1992, and McCulloch, 1993).

Nitric acid

Nitric acid (HNO_3)is a raw material used mainly as a feedstock in fertilizer production. As mentioned above, nitric acid is also a component in the production process of adipic acid. Of the 50 to 65 Tg nitric acid globally produced annually, about 1.6 Tg is used by the adipic acid industry. (Reimer et al., 1992) Off-gas measurements at DuPont showed emission factors ranging from 2-9 g N_2O/kg HNO_3 or 7-27 g N_2O-N/kg HNO_3-N. (Reimer et al., 1992, and McCulloch, 1993) Using this range, global N_2O emissions from nitric acid production are estimated at 0.1-0.45 Tg N_2O or 0.06-0.3 Tg N_2O-N.

Although no abatement techniques are specifically directed at removing nitrous oxide, the emission factors presented include any effect of other abatement systems that may be applied. (McCulloch, 1993) The generation of N_2O in this production process is likely to be accidental, not unavoidable. The representativity of the DuPont nitric acid production process or of the derived emission factor for N_2O for the global production of nitric acid is not known. (Olivier,1993a)

Emissions calculation methodology

Estimation of N_2O emissions from adipic acid and nitric acid production requires four distinct assumptions or type of data: 1) production data on adipic acid and nitric acid, respectively; 2) default emission factors (without specific N_2O abatement); 3) applicable abatement factors for N_2O; and 4) the part of the activity level for which a specific abatement factor applies.

The recommended calculation scheme is described by the following basic formula:

$$N_2O \text{ Emissions} = \Sigma \, (\text{Activity}_{ij} \times EF_{ij})$$

where:

Activity	= production level (tonne of product annually produced)
EF_{ij}	= Effective Emission Factor (kg/tonne product)
	= Emission Factor EF_i x abatement factor$_i$
i	= Total Activity of type i
j	= Part of activities of type i with a specific applicable abatement factor

Abatement factor = 1 - percentage abated / 100

Total emissions for a country is the sum across activities and sub-activities with distinct abatement levels. In the absence of information on the abatement factor one may either chose to disregard it or instead use a range for this factor. When production figures are not available, instead production capacity figures of national production facilities can be used to estimate associated emissions. (Olivier,1993b) Table 2.4 lists the emission factors and level of abatement discussed in the adipic acid and nitric acid sections.

In general, emission abatement also needs to be considered when estimating emissions from industrial sources. Technical options for reducing the N_2O emissions have been developed. Table 2.5 lists some of these options. Some of the options may not be technically or economically feasible at the current time, but further research should improve the possibilities.

Other chemicals production

The industrial production of other chemical compounds has been identified as a source of nitrous oxide. There has not been enough study to determine whether this represents a significant global source of N_2O. Emissions reported in the Netherlands in the chemical industry showed an emission of about 1.7 Gg N_2O in 1990 from the production of chemicals other than adipic acid or nitric acid. (Project Emission Registration, 1990)

The precise nature and location of the processes that produce these emissions are not known. Suggested sources are related to either a process using a N-compound or a catalytic reduction step. Although global N_2O emissions from this source category will probably be small as compared to emissions associated with adipic acid and nitric acid production, further investigation is recommended. It is possible that other industrial sources make significant contributions at a national level. The Netherlands reports about

25% of the total energy related emissions of national N_2O in 1988-1990, or about 6.6 kton N_2O/yr. (Van den Born et al., 1991) The study suggests that any process in which a nitrogen compound is used or catalytic reduction is applied can be a source of N_2O emissions. (Olivier,1993a)

Emissions calculation methodology

It is recommended that national inventories include the adipic acid and nitric acid production processes at this time. adipic acid and nitric acid manufacture should be included as source categories in national inventories. Other industrial processes can be included if the national experts have data on relevant processes. It is likely that these figures will be highly country specific, since both process conditions and application of abatement technology of some kind may be very different for different countries.

It is recommended that further research on industrial processes focus on N_2O emissions in measurements of the off-gases and other emissions. A more comprehensive study of industrial processes and N_2O emission measurements at production sites may reveal more processes in which nitrous oxide is released. More representative measurements will further reduce the uncertainty in the current estimate of global emissions from this source category. (Olivier,1993b)

Other GHGs From Industrial Processes

Although the major GHG emissions have been dealt with above, there are other GHG emissions from these processes. These may be significant sources for some countries. The following simple method can be used to estimate these GHGs:

Physical units of production   x   Emission Factor   =   Emissions

(e.g. tonnes)   (e.g. tonnes CO_2/

                                                  tonne product)

The IPCC/OECD documents do not provide specific examples of emissions factors for other GHGs. For information on emissions factors and estimation procedures for GHGs which are currently not provided in this chapter, experts should consult extensive existing literature developed by other emissions inventory programmes. Some key examples are:

- CORINAIR Default Emissions Handbook (Bouscaren, 1992);

- U.S. EPA's Compilation of Air Pollutant Emissions Factors (AP-42) (US EPA, 1985) and Supplement F (AP-42) (US EPA, 1993);

- Criteria Pollutant Emission Factors for the 1985 NAPAP Emissions Inventory (Stockton and Stelling, 1985).

- Proceedings of the TNO/EURASAP Workshop (TNO Inst. of Environmental Sciences, 1993).

- Emission Inventory Guidebook (European Environmental Agency, 1994).

2.2.3 Conclusion

There is not much information available on national emission factors and levels of abatement for emissions of GHG from industrial processes. This chapter describes basic methods and global mean values for emission factors for the following GHG sources:

- CO_2 from cement production;

- N_2O from adipic acid production;

- N_2O nitric acid production.

In addition, the chapter discusses possible sources and basic approaches to estimate CO_2, CH_4, and N_2O from other industrial processes. National experts are encouraged to report any relevant emissions for which data are available, along with documentation of methods used. This will greatly assist in the development of more complete methods for future editions of IPCC guidelines.

TABLE 2.1 EMISSIONS FROM PRODUCTION PROCESSES						
PROCESS	POLLUTANTS					
	NO_x	NMVOC	CH_4	CO	CO_2	N_2O
Cement Production					X	
Limestone Production					X	
Agricultural Liming					X	
Aluminum Production				X	X	
Ferro-alloy Production	X				X	
Silisium Carbide Production				X	X	
Coke Production		X	X	X	X	
Nitric Acid Production	X					X
Nitrogen Fertilizer Production	X					
Steel Plant (electric, BOF, etc.)	X		X	X	X	
Ammonia Production		X	X		X	X
Sodium Carbonate					X	
Urea Production						X
Carbon Black		X				
Titanium Dioxide						
Ethylene Production	X				X	
Propylene Production		X				
1,2 Dichlorothane Production		X				
Vinylchloride Production		X				
Polyethylene Low Density Production		X				
Polyethylene High Density Production		X				
Polyvinylchloride Production		X				
Polypropylene Production		X				
Styrene Butadiene		X				
ABS Resins		X				
Ethylene Oxide		X				
Formaldehyde Production		X				
Ethylbenzene Production		X				
Styrene Butadiene Latex		X				
Styrene Butadiene Rubber		X				
Phtalic Anhydride Production		X				
Acrylonitrile Production		X			X	
Chipboard Production		X				
Paper Pulp Production		X				
Bread Production		X			X	
Wine Production		X			X	
Beer Production		X			X	
Spirits Production		X			X	
Nitrate Production					X	

TABLE 2.2
GLOBAL EMISSION FACTORS AND EMISSIONS OF METHANE FROM INDUSTRIAL MANUFACTURING PROCESSES EXCLUDING COMBUSTION EMISSIONS MENTIONED IN TABLE 4.

Manufacturing process	Production *) (Tg)	Emission factor (g/kg)	Emission (Tg)	References emission factor
Integrated iron & steel plant	750	< 3	< 2	[1-6]
of which: Coke production	400	0.5	0.2	[1, 5, 6]
Sinter production	650	0.5	0.3	[3, 4, 6]
Pig iron production	550	0.9	0.5	[2]
Carbon black	5	11	0.06	[3], [7]
Ethylene	40	1	0.04	[3], [7]
Dichloroethylene	20	0.4	0.01	[3], [7]
Styrene	15	4	0.06	[3], [7]
Methanol	15	2	0.03	[3], [7]

Note:

*) Production data are estimated from various data sources (UN a.o.).

Source: Berdowski et al., 1993b

[1] Schade, H. (1980)

[2] Stallings, R.L. (1984)

[3] Shareef, G.S., W.A. Butler, L.A. Bravo and M.B. Stockton (1988)

[4] Stoehr, R.A. (1982)

[5] Project Emission registration.

[6] Barnard, W.R. (1990)

[7] Stockton, M.B. and J.H.E. Stelling (1987)

TABLE 2.3
ESTIMATED GLOBAL METHANE EMISSIONS FROM INDUSTRIAL PROCESSES (Tg CH_4 PER YEAR)

Source category	Emission estimate	Estimate range
Industrial processes		
• Iron & steel	2	0.4 - 4
• Chemical manufacturing	0.2	0.1 - 2
• Miscellaneous	0.6	0.6
Total	3.3	1.6 - 9.5

Source: Berdowski et al.,1993a

TABLE 2.4
ESTIMATED EMISSION FACTORS AND ABATEMENT FACTORS FOR INDUSTRIAL SOURCES OF N_2O

Activity	Emission factor (g N_2O/kg)	Emission factor range (g N_2O/kg)	Percentage abated (%)
Adipic acid production	300	-	32 [*]
Nitric acid production [***]	NA	2-9 [**]	0

[*]   Global average value for total AA industry; global value for Du Pont: 53%; national uncertainty range not available.

[**]   (7-27 g N_2O-N/HNO_3-N)

[***]   At present no specific N_2O abatement techniques are in use.

Source: (Olivier, 1993b) and references therein (Thiemens and Trogler, 1991); (McCulloch, 1993).

TABLE 2.5
OVERVIEW OF TECHNICAL OPTIONS FOR N_2O REDUCTION

Source	Global strength (Tg N_2O-N/yr)	Options
Industry		
1. adipic acid	0.4-0.6	Incineration (technically and economically feasible); research programme On long term: • alternative production process for adipic acid • alternatives for applications of 6,6-nylon
2. nitric acid	0.1-0.3	On long term: • alternative production process for nitric acid • alternatives for applications of 6-nylon • modify/optimize production processes

Source: (Olivier, 1993b)

2.3   References

Barnard, W.R. (1990). Emission factors for iron and steel sources - criteria and toxic pollutants. EPA-600/2-90-024 (PB 90-242314).

Berdowski, J., J. Olivier, C. Veldt. (1993)a. Methane from Fuel Combustion and Industrial Processes. In A.R. van Amstel (ed.), Proceeding of an International IPCC Workshop on Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control. RIVM Report no. 481507003, Bilthoven, The Netherlands.

Berdowski, J.J.M., L. Beck, S. Piccot, J.G.J. Olivier, & C. Veldt. (1993)b. Working Group Report: Methane Emissions from Fuel Combustion and Industrial Processes. In A.R. van Amstel (ed.), Proceeding of an International IPCC Workshop on Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control. RIVM Report no. 481507003, Bilthoven, The Netherlands.

Bouscaren R. (1992). CORINAIR Inventory, Default Emissions Handbook, 2nd ed., 12: 1-3. Published by CITEPA.

CEMBUREAU. 1990. *World Cement Market in Figures* and *World Statistics Review.*

European Environmental Agency. 1994. Emissions Inventory Guidebook.

Griffin, R.C. 1987. CO_2 release from cement production, 1950-1985. In Marland, G., T.A. Boden, R.C. Griffin, S.F. Huang, P. Kanciruk, and T.R. Nelson. *Estimates of CO_2 Emissions from Fossil Fuel Burning and Cement Manufacturing, Based on the United Nations Energy Statistics and the U.S. Bureau of Mines Cement Manufacturing Data.* Report #ORNL/CDIAC-25, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee. May 1989. 643-680.

IPCC, 1992. Climate Change 1992. The Supplementary Report to the IPCC Scientific Assessment. Published for The Intergovernmental Panel on Climate Change (IPCC), World Meteorological Organization/United Nations Environment Programme. Cambridge University Press. Edited by J.T. Houghton, G.J. Jenkins, and J.J. Ephraums.

IPCC parts I & II, 1993. National GHG Inventories: Transparency in Estimation and Reporting, p. 11. Prepared by The Intergovernmental Panel on Climate Change (IPCC) and Organization for Economic Co-operation and Development, World Meteorological Organization/United Nations Environment Programme.

Marland, G., T.A. Boden, R.C. Griffin, S.F. Huang, P. Kanciruk, and T.R. Nelson. 1989. *Estimates of CO_2 Emissions from Fossil Fuel Burning and Cement Manufacturing, Based on the United Nations Energy Statistics and the U.S. Bureau of Mines Cement Manufacturing Data.* Report #ORNL/CDIAC-25, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee. May.

McCulloch, A. [ICI] (1993). Personal communication 21-1-93.

Olivier, J. (1993)a. Nitrous Oxide Emissions from Industrial Processes. In A.R. van Amstel (ed.), Proceeding of an International IPCC Workshop on Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control. RIVM Report no. 481507003, Bilthoven, The Netherlands.

Olivier, J. (1993)b. Working Group Report: Nitrous Oxide Emissions from Fuel Combustion and Industrial Processes. In A.R. van Amstel (ed.), Proceeding of an International IPCC Workshop on Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control. RIVM Report no. 481507003, Bilthoven, The Netherlands.

Project Emission registration. Ministry of Housing, Physical Planning and the Environment (Mln. VROM), The Hague, The Netherlands.

Reimer, R.A., R.A. Parrett and C.S. Slaten (1992). Abatement of N_2O emission produced in adipic acid. Proc. of 5th Int. Workshop on Nitrous Oxide emissions, Tsukuba (JP), July 1-3, 1992.

Schade, H. (1980). Die Schadstoffemissionen der Eisen- und Stahlindustrie in den Belastungsgebieten Ruhrgebiet-West und Ruhrgebiet-Ost. *Schriftenr. d. Landesanstalt für Immissionsschutz des Landes N.W.* **52** 55-62.

Selzer, H. (1989). Energiebedingte Methanemissionen. Ludwig-Bölkow-Systemtechnik GmbH, quoting Frische, Emissions-Matrix 1989 (without further reference).

Shareef, G.S., W.A. Butler, L.A. Bravo and M.B. Stockton (1988). Air emissions species manual Vol. I, Volatile organic Compounds (VOC) Species profiles. EPA-450/2-88-003a (PB 88-215792); Addendum (1989), EPA-450/2-88-003c (PB 90-146416).
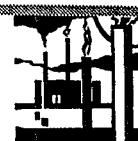
Stallings, R.L. (1984). Metallurgical industries: compilation of emission factors and control technologies. EPA-600/2-84-003 (PB 84-141548).

Stockton M.B., and J.H.E. Stelling. 1987. Criteria Pollutant Emission Factors for the 1985 NAPAP Emissions Inventory. U.S. EPA Washington, Ouverage, EPA-600/7-87-015 XV-211.

Stoehr, R.A. (1982). Organic emissions from iron ore sintering plants. EPA-600/2-82-091 (PB 83-116897).

Thiemens, M.H. and W.C. Trogler (1991). Nylon production: an unknown source of atmospheric nitrous oxide. *Science* **251** 932-934.

TNO Institute of Environmental Sciences. 1993. Proceedings of the TNO/EURASAP Workshop on the Reliability of VOC Emission Databases. Edited by H.P. Baars, P.J.H. Builtjes, M.P.J. Pulles, C. Veldt. IMW-TNO Publication P 93/040. Delft, The Netherlands.

Tresouthick, S.W., and A. Mishulovich. 1990. Energy and environment considerations for the cement industry. In conference proceedings *Energy and Environment in the 21st Century.* Massachusetts Institute of Technology, Cambridge, Massachusetts. March 26-28, 1990. B-110 to B-123

United Nations, 1988. *United Nations Statistical Yearbook.* United Nations, New York.

U.S. Bureau of the Mines. 1988. *Cement Minerals Yearbook,* authored by Wilton Johnson. U.S. Bureau of the Mines, U.S. Department of the Interior, Washington, D.C.

U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. 1985. Compilation of Air Pollutant Emission Factors (Fourth Edition), Volume I: Stationary Point and Area Sources. EPA-AP-42 (GPO 055-000-00251-7), Research Triangle Park.

U.S. Environmental Protection Agency. 1993. Office of Air Quality Planning and Standards. 1985. Compilation of Air Pollutant Emission Factors, Volume I: Stationary Point and Area Sources. EPA-AP-42, Supplement F.

Van den Born, G.J., A.F. Bouwman, J.G.J. Olivier and R.J. Swart (1991). The emission of greenhouse gases in the Netherlands. RIVM, Bilthoven, July 1991. RIVM report 222 901 003.
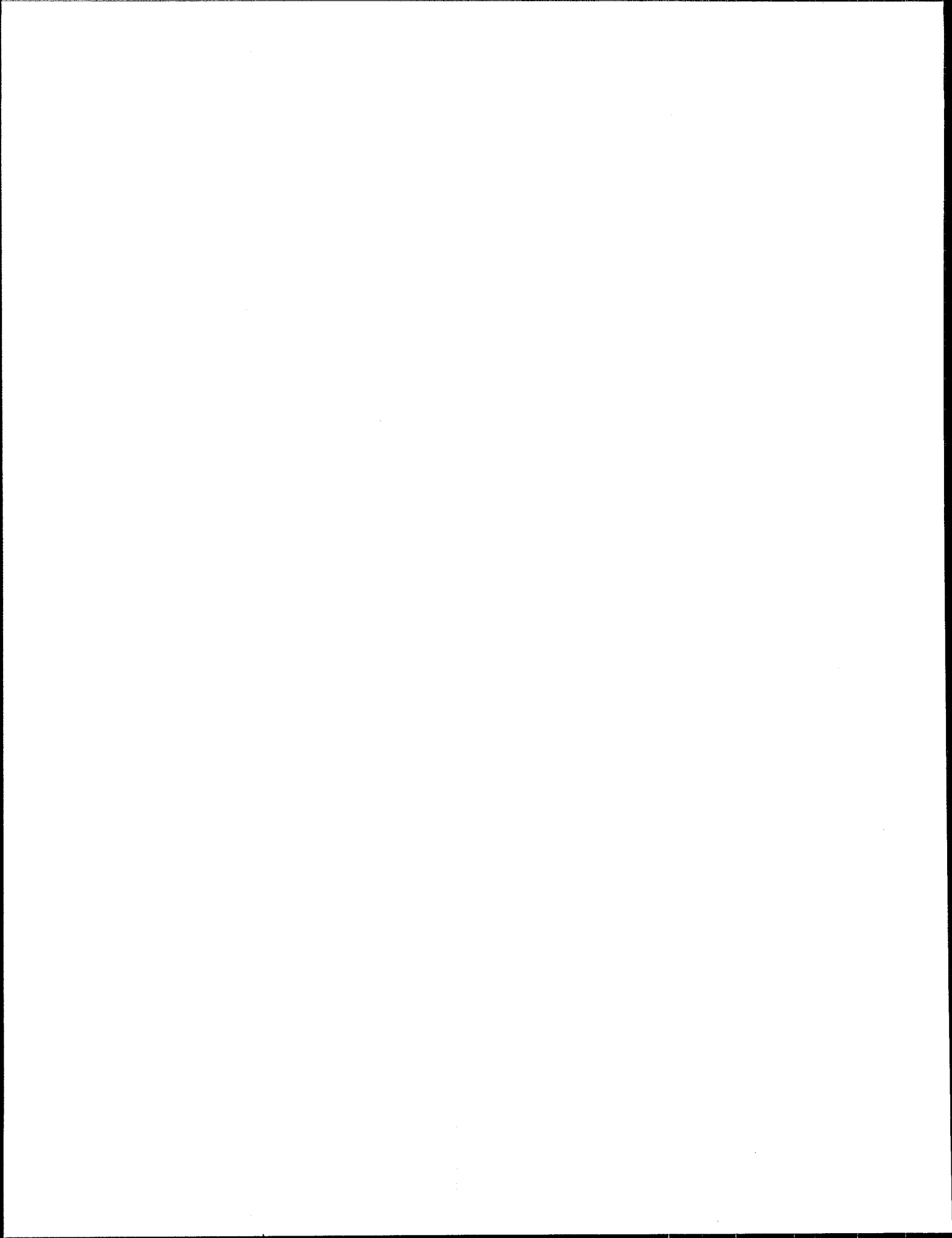
CHAPTER 3
SOLVENT USE

3   SOLVENT USE

3.1   Overview

Solvents and related compounds are important for greenhouse gas (GHG) and other emission inventories because they are a significant source of emissions of non-methane volatile organic compounds (NMVOC). No other GHGs are emitted in significant amounts from this category, which includes chemical cleaning substances used in dry cleaning, printing, metal degreasing, and a variety of industrial applications as well as household use. Also included in this category are paints, lacquers, thinners and related materials used in coatings in a variety of industrial, commercial and household applications. Table 3.1 lists some of the potentially important subcategories included under this source category.

All of the substances included here contain significant amounts of NMVOC. Emissions are produced through evaporation of the volatile chemicals when these products are exposed to air. Non-methane volatile organic compounds (NMVOC) are often emitted in significant quantities from evaporation during the variety of dispersed activities discussed above. These emissions are sometimes referred to as "area" sources because they occur in large numbers of small dispersed applications, rather than from large centralized industrial processes (or "point sources").

Solvent use is treated as a separate category in detailed inventory procedures (e.g., CORINAIR) because the nature of this area source requires a somewhat different approach to emissions estimation than that used for calculating other emissions categories. The draft IPCC *Guidelines* treats the category separately for this reason.

3.2   NMVOC Emissions from Solvent Use

NMVOC emissions estimates are characterized by high uncertainty. This is especially true for the solvent use source category on a global scale. The contribution of this source category is believed to be quite significant. A preliminary analysis estimated total global NMVOC release from solvent use to be about 11 percent of total NMVOC emissions. (Watson, et al., 1991)

Based on national GHG emissions inventories, NMVOC emissions from solvent use can represent a much larger share of the total NMVOC emissions for some countries. NMVOC from solvent use represents 31% of the total NMVOC emissions for both Italy and Denmark. (ENEA, 1991, Fenger et al., 1990) The Netherlands estimates solvent use to account for 25%, and both Finland and the United States estimate emissions to be 24% of their total NMVOC emissions. (van den Born et al., 1991, Boström et al., 1992, US EPA, 1991) By contrast, emissions from solvent use in Nigeria were only 3% of the total NMVOC. (Obioh et al., 1992)

3.2.1 Estimating Emissions

The wide variations in national emissions from solvent use highlight the differences in solvent use in countries and some of the difficulties associated with accurately estimating emissions from this source category.

There are two basic approaches to estimation of emissions from Solvent Use, which depend of the availability of data on the activities producing emissions and the emission factors.

1   **Production based** - In some cases, solvent or coating use is associated with centralized industrial production activities, such as automobile and ship production, textile manufacture, paper coating, chemical products manufacture, etc. In these cases it is generally possible to develop NMVOC emission factors based on unit of product output. These are based on the amount of paint, solvents, or other chemically volatile products consumed per unit of production of the final products. Once reasonable factors are developed it is straightforward to estimate annual emissions based on production data which is generally available on an annual basis for most countries. Industrial production data is also compiled and published by international organizations (e.g., United Nations, 1992) and these data can be used to supplement locally available data.

2   **Consumption based** - In many applications of paints, solvents and similar products, the end uses are too small-scale, diverse, and dispersed to be tracked directly. Therefore emissions estimates are generally based on total consumption (i.e., sales) of the solvents, paints, etc. used in these applications. The assumption is that once these products are sold to end users, they are applied and emissions produced relatively rapidly. For most surface coating and general solvent use, this approach is used. Emission factors are developed based on the likely ultimate release of NMVOC to the atmosphere per unit of product consumed. These emission factors can then be applied to sales data for the specific solvent or paint products.

The IPCC/OECD joint programme has not produced any original work on estimation of NMVOC from solvent use. This is for two reasons. First, NMVOC is a greenhouse gas (actually a class of gases) covered under the programme, but it has been assigned a lower priority for national experts just initiating greenhouse gas inventory work. Most methods development work within the IPCC/OECD programme has focused on providing methods and default information for the first priority gases - CO_2, CH_4, and N_2O, which are direct greenhouse gases. Second, NMVOC is one of the gases already under heavy scrutiny in national and international inventory programmes because of its role as a local and regional air pollutant. Hence there is a large and growing body of literature containing guidance on estimation procedures and emission factors for NMVOC from solvent use and other source categories. National experts who are already familiar with these procedures and have emissions data available or under development, should report these data to the IPCC/OECD programme, as discussed in *Volume 1: Reporting Instructions*. Other experts needing information should consult the existing major references such as:

■   CORINAIR Default Emissions Handbook (Bouscaren, 1992);

■   U.S. EPA's Compilation of Air Pollutant Emissions Factors (AP-42) (US EPA, 1985) and Supplement F (AP-42) (US EPA, 1993);

■   Criteria Pollutant Emission Factors for the 1985 NAPAP Emissions Inventory (Stockton and Stelling, 1985).

■   Proceedings of the TNO/EURASAP Workshop (TNO Inst. of Environmental Sciences, 1993).

■   Emission Inventory Guidebook (European Environmental Agency, 1994).

3.2.2 Uncertainties

Because NMVOC emission controls vary widely throughout the world, it is important for national experts to account for the level of emission control application in their country. Also, there may be significant differences among countries regarding the processes and equipment used. These differences can affect the level of NMVOC emissions. Finally, because estimates based on commodities data provide only an approximation of the activities associated with the manufacture of all products within a particular subcategory, there is a degree of uncertainty in the estimates. (Watson, et al., 1991)

TABLE 3.1 POTENTIALLY IMPORTANT SUBCATEGORIES INCLUDED UNDER SOLVENT USE	
Surface coating (e.g., painting) operations	Applications of paints, lacquer, enamel and primer to cans, wood products, metal parts, buildings, etc. Use of thinning solvents.
Paper coating operations	Coating operations, mixing and use of thinning solvents.
Printing and Publishing	Press operations, lithography, use of thinning solvents.
General Solvent Use	Vapor degreasing, dry cleaning, textile manufacture, household solvent use.
Production of Automobiles and Trucks	Surface coating, cleaning/degreasing operations.
Ship building -	Surface coating, cleaning/degreasing operations.
Chemical Products Manufacture and Processing	Solvents are used in a variety of applications in the manufacturing of chemicals and chemical products.

3.3   References

Boström, S., R. Backman, M. Hupa. 1992. Greenhouse Gas Emissions in Finland 1988 and 1990, Energy, Industrial, and Transport Activities. Published by Innsinööritoimisto Prosessikemia.

Bouscaren R. 1992. CORINAIR Inventory, Default Emissions Handbook, 2nd ed., 12: 1-3. Published by CITEPA.

ENEA. 1991. National Emission Inventories of SO_x, NO_x, NMVOCs, CO, TSP, NH_3, CH_4, CO_2, N_2O in Italy, 1985-1989.

European Environmental Agency. 1994. Emissions Inventory Guidebook.

Fenger, J., J. Fenhann, N. Kilde. 1990. Danish Budget for Greenhouse Gases. Nordic Council of Ministers, Copenhagen. Nord 1990:97.

Obioh, I.B., A.F. Oluwole, F.A. Akeredolu. 1992. The Methodology and Status of Greenhouse Gases (GHG) Inventory In Nigeria: 1988 Inventory Results. Paper presented at the IPCC/OECD Workshop on National Inventories of GHGs, Hadley Centre, Bracknell, UK.

Stockton M.B., and J.H.E. Stelling. 1987. Criteria Pollutant Emission Factors for the 1985 NAPAP Emissions Inventory. U.S. EPA Washington, Ouverage, EPA-600/7-87-015 XV-211.

TNO Institute of Environmental Sciences. 1993. Proceedings of the TNO/EURASAP Workshop on the Reliability of VOC Emission Databases. Edited by H.P. Baars, P.J.H. Builtjes, M.P.J. Pulles, C. Veldt. IMW-TNO Publication P 93/040. Delft, The Netherlands.

United Nations. 1992. United Nations Statistical Yearbook. United Nations Statistical Office, New York.

U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. 1985. Compilation of Air Pollutant Emission Factors (Fourth Edition), Volume I: Stationary Point and Area Sources. EPA-AP-42 (GPO 055-000-00251-7), Research Triangle Park.

U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. 1991. National Air Pollutant Emission Estimates 1940-1989. EPA-450/4-91-004, Research Triangle Park.

U.S. Environmental Protection Agency. 1993. Office of Air Quality Planning and Standards. 1985. Compilation of Air Pollutant Emission Factors, Volume I: Stationary Point and Area Sources. EPA-AP-42, Supplement F.

van den Born, G.J., A.F. Bouwman, J.G.J. Olivier, and R.J. Swart. 1991. The Emission of Greeenhouse Gases in the Netherlands (Report no. 222901003). National Institute of Public Health and Environmental Protection, The Netherland.

Watson, J.J., J.A. Probert and S.D. Picot. 1991. *Global Inventory of Volatile Organic Compound Emissions from Anthropogenic Sources.* Prepared for the Office of Research and Development, USEPA, Washington, D.C.

CHAPTER 4
EMISSIONS FROM AGRICULTURE
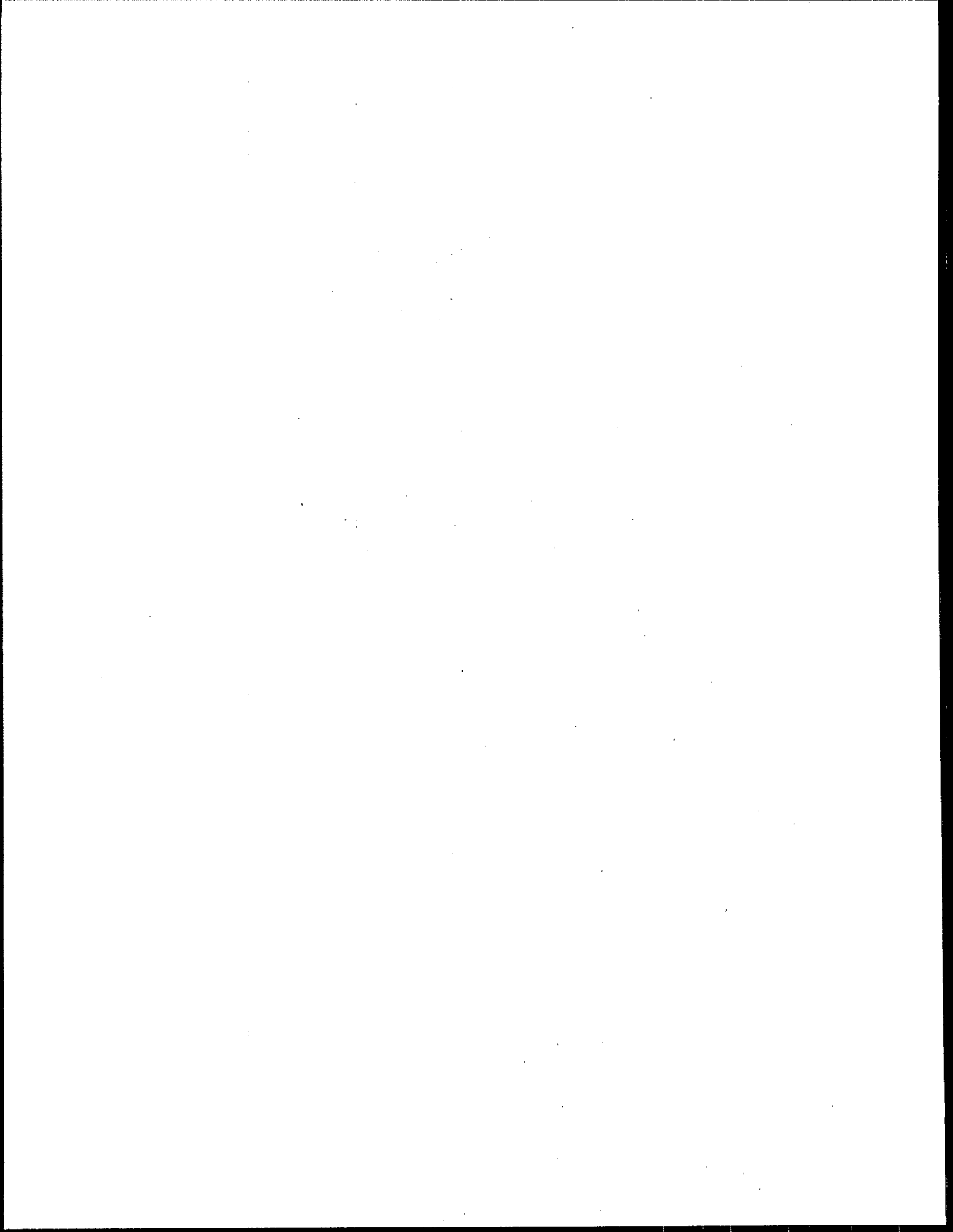
4   EMISSIONS FROM AGRICULTURE

4.1   Overview

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of different processes. This chapter discusses four greenhouse gas-emitting activities:

- **CH_4 emissions from animals and animal wastes**

    - *CH_4 emissions from enteric fermentation in domestic animals*
      Methane is produced in herbivores as a by-product of enteric fermentation, a digestive process by which carbohydrates are broken down by microorganisms into simple molecules for absorption into the bloodstream. Both ruminant animals (e.g., cattle, sheep) and some non-ruminant animals (e.g., pigs, horses) produce CH_4, although ruminants are the largest source since they are able to digest cellulose due to the presence of specific microorganisms in their digestive tracts. The amount of CH_4 that is released depends on the type, age, and weight of the animal, the quality and quantity of the feed, and the energy expenditure of the animal.

    - **CH_4 emissions from anaerobic decomposition of animal wastes**
      CH_4 is produced from the decomposition of manure under anaerobic conditions. These conditions often occur when large numbers of animals are managed in a confined area (e.g., dairy farms, beef feedlots, and swine and poultry farms), where manure is typically stored in large piles or disposed of in lagoons.

- **CH_4 emissions from rice cultivation**
    Anaerobic decomposition of organic material in flooded rice fields produces methane, which escapes to the atmosphere primarily by transport through the rice plants. The amount emitted is believed to be a function of rice species, number and duration of harvests, soil type and temperature, irrigation practices, and fertilizer use.

- **CH_4, CO, N_2O, and NO_X emissions from agricultural burning:**

    - *CH_4, CO, N_2O, and NO_X emissions from the prescribed burning of savannas*
      The burning of savannas -- areas in tropical and sub-tropical formations with continuous grass coverage -- results in the instantaneous emissions of carbon dioxide. But because the vegetation regrows between burning cycles, the carbon dioxide released into the atmosphere is reabsorbed during the next vegetation growth period. CO_2 emissions are therefore assumed to be zero. But savanna burning also releases gases other than CO_2, including methane, carbon monoxide, nitrous oxide and oxides of nitrogen. Unlike CO_2 emissions, these are net emissions.

- *CH₄, CO, N₂O, and NOₓ emissions from the prescribed burning of agricultural wastes*
  Crop residues burning is not thought to be a net source of carbon dioxide because the carbon released to the atmosphere is reabsorbed during the next growing season. However crop residue burning is a significant source of emissions of methane, carbon monoxide, nitrous oxide, and nitrogen oxides. It is important to note that some crop residues are removed from the fields and burned as a source of energy, especially in developing countries. Emissions from this type of burning are dealt with in the *Energy* module of this manual. Crop residue burning must be properly allocated to these two components in order to avoid double counting.

- **N₂O emissions from agricultural soils**
  Emissions of N₂O from agricultural soils are primarily due to the microbial processes of nitrification and denitrification in the soil. Increases in the amount of N added to the soil generally result in higher N₂O emissions (Bouwman, 1990). Increases in the input of N to the soil may result from (1) atmospheric deposition, (2) commercial fertilizer, (3) animal manures and plant residues, (4) biological N fixation, and (5) soil organic matter mineralization.

4.2 Methane Emission From Domestic Livestock Enteric Fermentation And Manure Management

4.2.1 Overview Of Methane Emissions From Livestock

This section covers methane emissions from enteric fermentation and manure of domestic livestock. Cattle are the most important source of methane from enteric fermentation in most countries because of their high numbers, large size, and ruminant digestive system. Methane emissions from manure management are usually smaller than enteric fermentation emissions, and are principally associated with confined animal management facilities where manure is handled as a liquid. This section presents a brief overview of the key factors affecting methane emissions from these sources. The methods for estimating these emissions are then presented.

Enteric Fermentation

Methane is produced during the normal digestive processes of animals. The amount of methane produced and excreted by an individual animal is dependent primarily on the following:

- **Digestive System**
  The type of digestive system has a significant influence on the rate of methane emission. *Ruminant animals* have the highest emissions because a significant amount of methane-producing fermentation occurs within the rumen. The main ruminant animals are cattle, buffalo, goats, sheep, and camels. *Pseudo-ruminant animals* (horses, mules, asses) and *monogastric animals* (swine) have relatively lower methane emissions because much less methane-producing fermentation takes place in their digestive systems.

- **Feed Intake**
  Methane is produced by the fermentation of feed within the animal's digestive system. Generally, the higher the feed intake, the higher the methane emission. Feed intake is positively related to animal size, growth rate, and production (e.g., milk production, wool growth, or pregnancy).

The amount of methane emitted by a population of animals is calculated by multiplying the emission rate per animal by the number of animals. To reflect the variation in emission rates among animal types, the population of animals is divided into subgroups, and an emission rate per animal is estimated for each subgroup. Population subgroups are recommended in the method[1].

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[1]Countries are encouraged to carry out emissions inventory calculations at a finer level of detail if possible. Many countries have available more detailed information than was used in constructing default values here. Countries may wish to calculate emissions estimates at a finer level of detail by sub-category -- further disaggregating recommended activity categories and sub-categories -- or they may choose to subdivide the categories on some other basis which they feel is appropriate to their particular national circumstances. Working at finer levels of disaggregation does not change the basic nature of the

Manure Management

Livestock manure is principally composed of organic material. When this organic material decomposes in an anaerobic environment (i.e., in the absence of oxygen) it produces methane. Methanogenic bacteria produce the methane as part of an interrelated population of microorganisms.

The principal factors affecting methane emission from animal manure are the amount of manure produced and the portion of the manure that decomposes anaerobically. The amount of manure that is produced is dependent on the amount produced per animal and the number of animals. The portion of the manure that decomposes anaerobically depends on how the manure is managed. When manure is stored or treated as a liquid (e.g., in lagoons, ponds, tanks, or pits), it tends to decompose anaerobically and produce a significant quantity of methane. When manure is handled as a solid (e.g., in stacks or pits) or when it is deposited on pastures and rangelands, it tends to decompose aerobically and little or no methane is produced.

To estimate methane emission, the animal population must be divided into subgroups to reflect the varying amounts of manure produced per animal, and the manner in which the manure is handled. Population subgroups are recommended in the method.

4.2.2 Inventory Method

Overview

The method for estimating methane emission from enteric fermentation and manure management requires three basic steps:

Step 1: Divide the livestock population into subgroups and characterize each subgroup.

Step 2: Estimate emission factors for each subgroup in terms of kilograms of methane per animal per year -- separate emission factors are required for enteric fermentation and manure.

Step 3: Multiply the subgroup emission factors by the subgroup populations to estimate subgroup emission, and sum across the subgroups to estimate total emission.

These three steps can be performed at varying levels of detail and complexity. This chapter presents the following two approaches:

- **Tier 1**
  A simplified approach that relies on default emission factors drawn from previous studies. The Tier 1 approach is likely to be sufficient for most animal types in most countries.

- **Tier 2**
  A more complex approach that requires country-specific information on livestock characteristics and manure management practices. The Tier 2 approach is

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calculations. Once emissions have been calculated at whatever is determined by the national experts to be the most appropriate level of detail, results should also be aggregated up to the minimum standard level of information requested in the IPCC proposed methodology. This will allow for comparability of results among all participating countries. The data and assumptions used for finer levels of detail should also be reported to the IPCC to ensure transparency and replicability of methods. *Volume 1: Reporting Instructions* discusses these issues in more detail.

recommended when the data used to develop the default values do not correspond well with the country's livestock and manure management conditions. Because cattle characteristics vary significantly by country, it is recommended that countries with large cattle populations consider using the Tier 2 approach for estimating methane emissions from cattle and cattle manure. Similarly, because buffalo and swine manure management practices vary significantly by country, it is recommended that countries with large buffalo and swine populations consider using the Tier 2 approach for estimating methane emissions from buffalo and swine manure.

Some countries for which livestock emissions are particularly important may wish to go beyond the Tier 2 method and incorporate additional country-specific information in their estimates. Although countries are encouraged to go beyond the Tier 2 approach presented below when data are available, these more complex analyses are only briefly discussed here. Table 4-1 summarizes the recommended approaches for the livestock emissions included in this inventory.

Tier 1 Approach

This Tier 1 method is simplified so that only readily-available animal population data are needed to estimate emissions. Default emission factors are presented for each of the recommended population subgroups. Each step is discussed in turn.

TIER 1: STEP 1 -- LIVESTOCK POPULATIONS

The *average annual population* of animals is required for each of the livestock categories listed in Table 4-1. In some cases the population fluctuates during the year. For example, a census done before calving will give a much smaller number than a census done after calving. A representative average of the population is therefore needed. In the case of poultry and swine, the number of animals *produced* each year exceeds the annual average population because the animals live for less than 12 months. The population data can be obtained from the FAO Production Yearbook (FAO, 1990) or similar country-specific livestock census reports.

The dairy cow population is estimated separately from other cattle (see Table 4-2). Dairy cows are defined in this method as mature cows that are producing milk in commercial quantities for human consumption. This definition corresponds to the dairy cow population reported in the FAO Production Yearbook.

In some countries the dairy cow population is comprised of two well-defined segments: high-producing "improved" breeds in commercial operations; and low-producing cows managed with traditional methods. These two segments can be combined, or can be evaluated separately by defining two dairy cow categories. However, the dairy cow category does not include cows kept principally to produce calves or to provide draft power. Low productivity multi-purpose cows should be considered as other cattle (non-dairy).

Data on the average milk production of dairy cattle is also required. These data are expressed in terms of kilograms of whole fresh milk produced per year per dairy cow, and can be obtained from the FAO Production Yearbook or similar country-specific reports. If two or more dairy cow categories are defined, the average milk production per cow is required for each category.

Finally, the livestock populations must be described in terms of warm, temperate, or cool climates for purposes of estimating emissions from livestock manure. Data on the annual

average temperature of the regions where livestock are managed should be used as follows:

- Areas with annual average temperatures less than 15°C are defined as cool.

- Areas with annual average temperatures greater than 15°C and less than 25°C are defined as temperate.

- Areas with annual average temperatures greater than 25°C are defined as warm.

For each animal population, the fraction in each climate should be estimated. These data can be developed from country-specific climate maps and livestock census reports. To the extent possible, the temperature data should reflect the locations where the livestock are managed. If necessary, data from nearby cities can be used. Table4-2 summarizes the animal population data that must be collected in Step 1.

TIER 1: STEP 2 -- EMISSION FACTORS

The purpose of this step is to select emission factors that are most appropriate for the country's livestock characteristics. Default emission factors for enteric fermentation and manure management have been drawn from previous studies, and are organized by region for ease of use. The basis for the emission factors, described more fully under Tier 2, includes the following:

- *Enteric Fermentation:*

  - *Feed Intake:* Feed intake is estimated based on the energy intake required by the animal for maintenance (the basic metabolic functions needed to stay alive) and production (growth, lactation, work, and gestation). The animal characteristics required to estimate feed intake are taken from regional and country-specific studies and include: population structure (portion of adults and young); weight; rate of weight gain; amount of work performed; portion of cows giving birth each year; and milk production per cow.
  - *Conversion of Feed Energy to Methane:* The rate at which feed energy is converted to methane is estimated based on the quality of the feed consumed -- low quality feed has a slightly higher methane conversion rate. Feed quality is assessed in terms of digestibility on a regional basis.

- *Manure Management:*

  - *Manure Production:* Manure production is estimated based on feed intake and digestibility, both of which are used to develop the enteric fermentation emission factors.
  - *Methane Producing Potential:* Methane producing potential (referred to as B_o) is the maximum amount of methane that can be produced from a given quantity of manure. The methane producing potential varies by animal type and the quality of the feed consumed. Reported measurements for selected animals are used.
  - *Methane Conversion Factor (MCF):* The MCF defines the portion of the methane producing potential (B_o) that is achieved. The MCF varies with the manner in which the manure is managed and the climate, and can theoretically range from 0 to 100 percent. Manure managed as a liquid under hot conditions promotes methane formation and emissions. These manure management conditions have high MCFs, of 65 to 90 percent. Manure managed as dry material in cold climates does not readily produce methane, and consequently has an MCF of about 1 percent. Laboratory measurements were used to estimate MCFs for the major manure management techniques.

- *Manure Management Practices*: Regional assessments of manure management practices are used estimate the portion of the manure that is handled with each manure management technique.

The data used to estimate the default emission factors for enteric fermentation and manure management are presented in Appendix A and Appendix B respectively.

Table 4-3 shows the enteric fermentation emission factors for each of the animal types except cattle. As shown in the table, emission factors for sheep and swine vary for developed and developing countries. The differences in the emission factors are driven by differences in feed intake and feed characteristic assumptions (see Appendix A). Although point estimates are given for the emission factors, an uncertainty of about ±20 percent exists due to variations in animal management and feeding. Deviations from the emission factors can be larger than 20 percent under specialized feeding or management conditions.

Table 4-4 presents the enteric fermentation emission factors for cattle. A range of emission factors is shown for typical regional conditions. As shown in the table, the emission factors vary by over a factor of four on a per head basis.

While the default emission factors shown in Table 4-4 are broadly representative of the emission rates within each of the regions described, emission factors vary among countries within regions. Also, as with the emission factors shown in Table 4-3, an uncertainty of about ±20 percent exists due to variations in animal management and feeding. Animal size and milk production are important determinants of emission rates for dairy cows. Relatively smaller dairy cows with low levels of production are found in Asia, Africa, and the Indian subcontinent. Relatively larger dairy cows with high levels of production are found in North America and Western Europe.

Animal size and population structure are important determinants of emission rates for non-dairy cattle. Relatively smaller non-dairy cattle are found in Asia, Africa, and the Indian subcontinent. Also, many of the non-dairy cattle in these regions are young. Non-dairy cattle in North America, Western Europe and Oceania are larger, and young cattle constitute a smaller portion of the population[2].

Select emission factors from Tables 4-2 and 4-3 by identifying the region most applicable to the country being evaluated. The data collected on the average annual milk production by dairy cows should be used to help select a dairy cow emission factor. If necessary, interpolate between dairy cow emission factors shown in the table using the data collected on average annual milk production per head.

Table 4-5 shows the default manure management emission factors for each animal type except cattle, buffalo, and swine. Separate emission factors are shown for developed and developing countries, reflecting the general differences in feed intake and feed characteristics of the animals in the two regions. These emission factors reflect the fact that virtually all the manure from these animals is managed in dry manure management systems, including pastures and ranges, drylots, and daily spreading on fields (Woodbury and Hashimoto, 1993).

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[2] One method which has been suggested to account for animal growth (increase in weight) over time is to use the mean live weight for a given animal category over the year of the inventory. A weight correction factor (integrator) equal to the ratio of the averaged annual weight and the projected end weight (which is derived from statistics) is multiplied by the number of animals in a category to get the live weight of animals in that category.

The ranges of values shown in Table 4-5 reflect the range of MCF values of 1 to 2 percent. The higher value is appropriate for manure managed in warm climates, while the lower value is appropriate for manure managed in cooler and dryer climates. A middle value is assigned to temperate conditions. The uncertainty in the emission factors remains substantial, however, because field measurements are required to validate the laboratory measurements that form the basis for the MCFs used in the analysis. Appendix B summarizes the data used to estimate the emission factors shown in Table 4-6.

The climate data collected in Step 1 is used to select the emission factors from Table 4-6. A weighted average emission factor for each animal type is computed by multiplying the percentages of the animal populations in each climate region by the emission factor for each climate region. For example, if sheep in a developing country were 25 percent in a temperate region and 75 percent in a warm region, the emission factor for sheep would be estimated at about 0.2 kg/head/yr as follows:

Emission Factor = (25% × 0.16) + (75% × 0.21) = 0.1975 kg/head/yr.

An alternative way of handling these calculations is to sub-divide the category of sheep into two populations: one in warm and one in temperate region. Calculations could then be done separately and summed.

Because the manure from cattle, buffalo, and swine is managed in a variety of ways, including both dry and liquid systems, the variations in manure management practices among regions and countries must be considered to develop emission factors for these animals. Table 4-6 presents emission factors based on regional manure management practices described in Safley et al. (1992).

As shown in the table, the emission factors for dairy cattle range between 81 kg/head/year in warm parts of Western Europe to 0 kg/head/year in cool parts of Latin America. The emission factors for non-dairy cattle range between 38 kg/head/yr in warm parts of Western Europe to 1 kg/head/year in cool parts of North America and Latin America. In addition to climate, the range of emission factors is due to the manure management practices used in each region. For example, the emission factors for North American dairy cattle manure and European dairy and non-dairy cattle manure are relatively high because the manure is often managed using liquid systems that promote methane production. The emission factors for North American non-dairy cattle and for all animals in Africa and the Middle East are relatively low because their manure is generally managed using dry systems that do not promote methane production.

To select emission factors from Table 4-6, first identify the appropriate region, such as Latin America. Within that region, identify the animal type of interest. For that animal type three values are given for the three climate regions. Compute a weighted average emission factor for the animal type by multiplying the percentages of the animal population in each climate region by the emission factor for each climate region. Appendix B summarizes the estimates of manure management system usage and MCFs that underlie the emission factors in Table 4-6.

As with the other manure management emission factors, there is substantial uncertainty in the estimates shown in Table 4-6 because field measurements are required to validate the laboratory measurements that form the basis for the MCFs used in the analysis, and because there is uncertainty and variability in the manner in which manure is managed in each region.

TIER 1: STEP 3 -- TOTAL EMISSION

To estimate total emission the selected emission factors are multiplied by the associated animal population and summed. The emission estimates should be reported in gigagrams (Gg).[3] Because the emission factors are reported in kilograms per head per year, the total emissions in Gg is estimated as follows for each animal category:

$$\text{emission factor (kg/head)} \times \text{population (head)} / 10^6 \text{ kg/Gg} = \text{emissions in Gg.}$$

As a point of reference, in 1990 total annual global methane emissions from domestic livestock enteric fermentation were on the order of .060 to .100 Gg (Gibbs and Johnson, 1993). Enteric fermentation emissions from countries with large populations of livestock may be on the order of .001 to .005 Gg per year. Countries with smaller populations of livestock would likely have emissions of less than .001 Gg per year.

In 1990 total annual global methane emissions from manure management was on the order of .010 to .018 Gg (Woodbury and Hashimoto, 1993). Manure management emissions from countries where manure is managed in liquid-based systems may be on the order of .001 to .002 Gg per year. Countries where manure is not managed in liquid-based systems would likely have emissions of much less than .001 Gg per year.

Tier 2 Approach For Enteric Fermentation Emissions

The Tier 2 approach is recommended for estimating methane emissions from enteric fermentation from cattle for those countries with large cattle populations. As contrasted with the Tier 1 method, this approach requires much more detailed information on the cattle population. Using this detailed information, more precise estimates of the cattle emission factors are developed. When the Tier 2 method is used the default emission factors listed in Tier 1 for cattle are not used.

This Tier 2 approach is similar to the August 1991 OECD method (OECD, 1991), with some modifications:

- The Blaxter and Clapperton (1965) equation is replaced with a recommended set of methane conversion rate "rules of thumb."

- Feed energy intake requirements for pregnancy have been added.

- The energy requirements required for grazing have been reduced based on newly available data from AAC (1990).

- The equations used to relate gross energy intake to net energy used by the animal have been made more general to accommodate a wider variety of feed conditions.

The three steps outlined for Tier 1 are also used here.

ENTERIC FERMENTATION TIER 2: STEP 1 -- LIVESTOCK POPULATION

To develop precise estimates of emissions, cattle should be divided into categories of relatively homogeneous groups. For each category a representative animal is chosen and characterized for purposes of estimating an emission factor. Table 4-7 presents a set of recommended representative animal types for cattle. Three main categories, Mature Dairy

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[3] 1 Tg = 10^{12} grams = 10^9 kilograms = 10^6 metric tons.

Cows, Mature Non-Dairy Cattle, and Young Cattle, are recommended as the minimum set of representative types. The sub-categories listed should be used when data are available. In particular, the sub-population of cows providing milk to calves should be identified among non-dairy cattle because the feed intake necessary to support milk production can be substantial. In some countries the feedlot category is needed so that the implications of the high-grain diets can be incorporated.

For each of the representative animal types defined, the following information is required:

- annual average population (number of head);
- average daily feed intake (megaJoules (MJ) per day and kg per day of dry matter); and
- methane conversion rate (percentage of feed energy converted to methane).

Generally, data on average daily feed intake are not available, particularly for grazing animals. Consequently, the following data should be collected for estimating the feed intake for each representative animal type:

- weight (kg);
- average weight gain per day (kg);[4]
- feeding situation: confined animals; animals grazing good quality pasture; and animals grazing over very large areas;
- milk production per day (kg/day);[5]
- average amount of work performed per day (hours/day);
- percent of cows that give birth in a year;[6] and
- feed digestibility (%).[7]

These data should be obtained from country-specific cattle evaluations. Some data, such as weight, weight gain, and milk production, may be available from production statistics. Care should be taken to use the live cattle weights, as contrasted with slaughter weights. Appendix B lists the data used to develop the default emission factors presented in Tier 1. Individual country data can be compared to the data presented in Appendix A to ensure that the data collected are reasonable.

Data on methane conversion rates are also not generally available. The following rules of thumb are recommended for the methane conversion rates:

- Developed Countries. A 6% conversion rate (±0.5%) is recommended for all cattle in developed countries except feedlot cattle consuming diets with a large quantity of grain. For feedlot cattle on high grain diets a rate of 4% (±0.5%) is recommended. In circumstances where good feed resources are available (i.e., high digestibility and high

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[4] This may be assumed to be zero for mature animals.

[5] Milk production is required for dairy cows and non-dairy cows providing milk to calves.

[6] This is only relevant for mature female cows.

[7] Feed digestibility is defined as the proportion of energy in the feed that is not excreted in the feces. Digestibility is commonly expressed as a percentage (%). Common ranges for feed digestibility for cattle are 50% to 60% for crop by-products and rangelands; 60% to 70% for good pastures, good preserved forages, and grain-supplemented forage-based diets; and 75% to 85% for grain-based diets fed in feedlots.

energy value) the lower bounds of these ranges can be used. When poorer feed resources are available, the higher bounds are more appropriate.

- Developing Countries. Several recommendations are made for different animal management situations in developing countries:
  - All dairy cows and young cattle are recommended to have a conversion rate of 6.0% (±0.5%). These cattle are generally the best-fed cattle in these regions.
  - All non-dairy, non-young stall-fed animals consuming low-quality crop by-products are recommended to have a conversion rate of 7.0% (±0.5%) because feed resources are particularly poor in many cases in these regions.
  - Grazing cattle are recommended to have a conversion rate of 6.0% (±0.5%), except for grazing cattle in Africa, which are recommended to have a rate of 7.0% (±0.5%) because of the forage characteristics found in many portions of tropical Africa.

These rules of thumb are a rough guide based on the general feed characteristics and production practices found in many developed and developing countries. Country-specific exceptions to these general rules of thumb should be taken into consideration as necessary based on detailed data from cattle experts.

ENTERIC FERMENTATION TIER 2: STEP 2 -- EMISSION FACTORS

The emission factors for each category of cattle are estimated based on the feed intake and methane conversion rate for the category. Feed intake is estimated based on the feed energy requirements of the representative animals, subject to feed-intake limitations. The net energy system described in NRC (1984 and 1989) is recommended as the starting point for the estimates. Because the NRC system was developed for feeding conditions in temperate regions, several adjustments were made to avoid potential biases when applied to evaluate feed-energy intakes for tropical cattle (see Appendix C). Comparisons with alternative feeding systems (e.g., ARC, 1980) indicate that the emissions estimates are not sensitive to the feeding system used as the basis for making the estimates.

The net energy system specifies the amount of feed energy required for the physiological functions of cattle, including maintenance, growth, and lactation. Feed energy requirements for work have also been estimated, and are included in this analysis for the draft animals in developing countries. Energy requirements for pregnancy have also been added for the portion of cows that give birth in each year. The following information is required to estimate feed energy intakes:

- *Maintenance*
  Maintenance refers to the apparent feed energy required to keep the animal in energy equilibrium, i.e., there is no gain or loss of energy in the body tissues (Jurgens, 1988). For cattle, net energy for maintenance (NE_m) has been estimated to be a function of the weight of the animal raised to the 0.75 power (NRC, 1984):

> ### EQUATION 1
>
> NE_m (MJ/day) = 0.322 × (weight in kg)$^{0.75}$
>
> NRC (1989) recommends that lactating dairy cows be allowed a slightly higher maintenance allowance:
>
> NE_m (MJ/day) = 0.335 × (weight in kg)$^{0.75}$ {dairy cows}

Additional energy is required for animals to obtain their food. Grazing animals require more energy for this activity than do stall-fed animals. The following energy requirements are added for this activity based on their feeding situation:[8]

- – Confined animals (pens and stalls): no additional NE_m;
- – Animals grazing good quality pasture: 17% of NE_m; and
- – Animals grazing over very large areas: 37% of NE_m.

- *Growth*
  The energy requirements for growth can be estimated as a function of the weight of the animal and the rate of weight gain. NRC (1989) presents formulae for large- and small-frame males and females, the estimates from which vary by about ±25%. The equation for large-frame females is recommended, which is about the average for the four types:

> ### EQUATION 2
>
> NE_g (MJ/day) = 4.18 × (0.035 $W^{0.75}$ × $WG^{1.119}$ + WG)   (2)

where:

W   =   animal weight in kilograms (kg); and

WG   =   weight gain in kg per day.

The relationships for NE_g were developed for temperate agriculture conditions, and may over-estimate energy requirements for tropical conditions, particularly for draft animals that may have a lower fat content in their weight gain (Graham, 1985). However, no data are available for improving the estimates at this time.

- *Lactation*
  Net energy for lactation has been expressed as a function of the amount of milk produced and its fat content (NRC, 1989):

> ### EQUATION 3
>
> NE_l (MJ/day) = kg of milk/day × (1.47 + 0.40 × Fat %)

At 4.0% fat, the NE_l in MJ/day is about 3.1 × kg of milk per day.

- *Draft Power*
  Various authors have summarized the energy intake requirements for providing draft power (e.g., Lawrence, 1985; Bamualim and Kartiarso, 1985; and Ibrahim, 1985). The strenuousness of the work performed by the animal influences the energy requirements, and consequently a wide range of energy requirements have been estimated. The values by Bamualim and Kartiarso show that about 10% of NE_m

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[8] The original OECD method recommended slightly higher energy additions. These revised figures are based on newly-published information in AAC (1990).

requirements are required per hour of typical work for draft animals. This value is used as follows:

EQUATION 4

NE_{draft} (MJ/day) = 0.10 x NE_m x hours of work per day

- *Pregnancy*
  Daily energy requirements for pregnancy are presented in NRC (1984). Integrating these requirements over a 281-day gestation period yields the following equation:

EQUATION 5

$NE_{pregnancy}$ (MJ/281-day period) = 28 x calf birth weight in kg

---

The following equation can be used to estimate the approximate calf birth weight as a function of the cow's weight:[9]

EQUATION 6

Calf birth weight (kg) = 0.266 x (cow weight in kg)$^{0.79}$

Manipulating Equations 5 and 6, in conjunction with Equation 1, shows that the NE required for pregnancy is about 7.5% of NE_m for the range of cow sizes considered in this analysis. Therefore, a factor of 7.5% of NE_m is added to account for the energy required for pregnancy for the portion of cows giving birth each year.

Based on these equations, each of the net energy components for each of the cattle categories can be estimated from the data collected in Step 1: weight in kilograms; feeding situation; weight gain per day in kilograms; milk production in kilograms of 4% fat-corrected milk; number of hours of work performed per day; and portion that give birth.

These net energy requirements must be translated into gross energy intakes. Also, by estimating the gross energy intake, the net energy estimates can be checked for reasonableness against expected ranges of feed intake as a percentage of animal weight. To estimate gross energy intake, the relationship between the net energy values and gross energy values of different feeds must be considered. This relationship can be summarized briefly as follows:

Digestible Energy = Gross Energy - Fecal Losses

Metabolizable Energy = Digestible Energy - Urinary and Combustible Gas Losses

Net Energy = Metabolizable Energy - Heat Increment

Net Energy = Gross Energy - Fecal Losses - Urinary and Combustible Gas Losses - Heat Increment

The quantitative relationship among these energy values varies among feed types. Additionally, the values depend on how the feeds are prepared and fed, and the level at which they are fed. For purposes of this method, simplifying assumptions are used to derive a relationship between net energy and digestible energy that is reasonably

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[9] This species-specific equation from Robbins and Robbins (1979) was adjusted to the mean cow and calf weight of a typical beef breed of cattle. This adjustment increases the coefficient in the equation from 0.214 to 0.266.

representative for the range of diets typically fed to cattle. Gross energy intake is then estimated using this relationship and the digestibility data collected in Step 1.

Given the digestibility of the feed (defined in Step 1), a general relationship between digestible energy and metabolizable energy can be used as follows (NRC, 1984):

EQUATION 7

Metabolizable Energy (ME) = 0.82 × Digestible Energy (DE)

Equation 7 is a simplified relationship; larger (smaller) methane conversion rates would tend to reduce (increase) the coefficient to values below (above) 0.82.

NRC (1984) presents separate quantitative relationships between metabolizable energy and net energy used for growth versus net energy used for other functions. Using Equation 7, the NRC relationships can be re-arranged to quantify the ratio of NE to DE, as follows:

EQUATION 8

$$\text{NE/DE} = 1.123 - 4.092 \times 10^{-3} \times \text{DE\%} + 1.126 \times 10^{-5} \times (\text{DE\%})^2 - 25.4/\text{DE\%}$$

EQUATION 9

$$\text{NE}_g/\text{DE} = 1.164 - 5.160 \times 10^{-3} \times \text{DE\%} + 1.308 \times 10^{-5} \times (\text{DE\%})^2 - 37.4/\text{DE\%}$$

---

where:

NE/DE = the ratio of net energy consumed for maintenance, lactation, work and pregnancy to digestible energy consumed;

NE_g/DE = the ratio of net energy consumed for growth to digestible energy consumed; and

$\text{DE\%}$ = digestible energy as percentage of gross energy, expressed in percent (e.g., 65%).

Because the NRC (1984) relationships were developed based on diets with relatively high digestibilities (generally above 65%), they may not be appropriate for the relatively low digestibility diets that are commonly found in tropical livestock systems. In particular, the non-linear nature of the relationships could bias the estimates of feed intake upward for low-digestibility feeds. An upward bias in feed intake would lead to an upward bias in emissions estimates.

Based on a review of other energy systems (e.g., ARC, 1980), a linear relationship between digestible energy and net energy was derived for digestibilities below 65% as follows (see Appendix C):

EQUATION 10

$$\text{NE/DE} = 0.298 + 0.00335 \times \text{DE\%}$$

EQUATION 11

$$NE_g/DE = -0.036 + 0.00535 \times DE\%$$

Given the estimates for feed digestibility (from Step 1) and equations 8 through 11, the gross energy intake (GE in MJ/day) can be estimated as follows:

EQUATION 12

$$GE = [(NE_m + NE_{feed} + NE_l + NE_w + NE_p) / \{NE/DE\} + (NE_g / \{NE_g/DE\})] / (DE\%/100)$$

where:

$\{NE/DE\}$ is computed from equation 8 for digestibility greater than 65% and from equation 10 for digestibility less than or equal to 65%;

$\{NE_g/DE\}$ is computed from equation 9 for digestibility greater than 65% and from equation 11 for digestibility less than or equal to 65%; and

DE% is digestibility in percent (e.g., 60%).

To check the estimate of daily gross energy intake from equation 12, the estimate can be converted in daily intake in kilograms by dividing by 18.45 MJ/kg. This estimate of intake in kilograms should generally be between 1.5% and 3.0% of the animal's weight.

Using Equation 12 and the cattle data summarized in Appendix A, Gibbs and Johnson (1993) found that the intake estimates are consistent with expected intakes as a percent of body weight and previously published values. For example, the intake estimate for Indian cattle is the equivalent of about 10,000 MJ per year of metabolizable energy (ME). Winrock (1978) estimates the average ME requirements for Indian cattle at 10,600 MJ per year. Similarly, the ME values implied for U.S. dairy and beef cows are 58,000 MJ and 31,000 MJ per year, respectively, which are similar to estimates of 62,000 MJ and 31,700 MJ derived in U.S. EPA (1993). Consequently, for a diverse set of conditions, the intake estimates correspond to reasonably expected ranges from previously published estimates.

To estimate the emission factor for each cattle type, the feed intake is multiplied by the methane conversion rate (from Step 1) as follows:

EQUATION 13

Emissions (kg/yr) = Intake (MJ/day) $\times Y_m \times$ 365 days / 55.65 MJ/kg of methane

where Y_m is the methane conversion rate expressed in decimal form (such as 0.06 for 6%). The result of this step of the method is an emission factor for each cattle type defined in Step 1.

ENTERIC FERMENTATION TIER 2: STEP 3 -- TOTAL EMISSIONS

To estimate total emissions the selected emission factors are multiplied by the associated animal population and summed. As described above under Tier 1, the emissions estimates should be reported in gigagrams (Gg).

Tier 2 Approach For Manure Management Emissions

The Tier 2 approach provides a more detailed method for estimating methane emissions from manure management systems. The Tier 2 approach is recommended for countries with large cattle, buffalo and swine populations managed under confined conditions. Compared to the Tier 1 approach, this method requires additional detailed information on animal characteristics and the manner in which manure is managed. Using this additional detailed information, emission factors are estimated that are specific to the conditions of the country, and the default emission factors from Tier 1 are not used.

The Tier 2 approach is similar to the original OECD method described in OECD (1991). Improvements to the method have been made to incorporate more recent figures on methane conversion factors and to link the method more closely to the animal characteristic data collected for estimating enteric fermentation.

MANURE MANAGEMENT TIER 2: STEP 1 -- LIVESTOCK POPULATIONS

To develop precise estimates of emissions, the animals should be divided into categories of relatively homogeneous groups. For each category a representative animal is chosen and characterized for purposes of estimating an emission factor. Suggested categories for cattle are discussed above under the enteric fermentation Tier 2 method and are summarized in Table 4-7. Similar categories can be used for buffalo. Categories for swine could include sows, boars, and growing animals (farrows to finishers). For each of the representative animal types defined, the following information is required:

- annual average population (number of head) by climate region (cool, temperate, and warm);

- average daily manure volatile solids (VS) excretion (kg per day of dry matter);[10]

- methane producing potential (B_o) of the manure (cubic meters (m^3) of methane per kg of VS);

- manure management system usage (percentage of manure managed with each manure management system).

Population data are generally available from country-specific livestock census reports. As described above under Tier 1, the portion of each animal population in cool, temperate, and warm climate regions is required.

Often, data on average daily VS excretion are not available. Consequently, the VS values may need to be estimated from feed intake levels. The enteric fermentation Tier 2 method should be used to estimate feed intake levels for cattle and buffalo.[11] For swine, country-specific swine production data may be required to estimate feed intake. To develop the default emission factors for swine presented in Tier 1, average feed intake estimates for swine in developed and developing countries were used from Crutzen et al. (1986) (see Appendix B).

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[10] Volatile solids (VS) are the degradable organic material in livestock manure.

[11] By using the enteric fermentation Tier 2 method to estimate feed intake, consistency is assured in the data underlying the emissions estimates for both enteric fermentation and manure management.

Once feed intake is estimated, the VS excretion rate is estimated as:[12]

> **EQUATION 14**
>
> VS (kg/day dry) = Intake (MJ/day) * (1 kg/18.45 MJ) * (1 - DE%/100) * (1- ASH%/100)

where:

VS = VS excretion per day on a dry weight basis;

Intake = the estimated daily average feed intake in MJ/day;

DE% = the digestibility of the feed in percent (e.g., 60%);

ASH% = the ash content of the manure in percent (e.g., 8%).

For cattle, the DE% value used should be the same value used to implement Tier 2 for enteric fermentation. The ash content of cattle and buffalo manure is generally around 8%. For swine, the default emission factors were estimated using 75% and 50% digestibility for developed and developed countries, respectively, and an ash content of 2% and 4% for developed and developed countries, respectively. Appendix B summarizes the data used to estimate the VS excretion rates for cattle, buffalo, and swine.

The maximum methane-producing capacity for the manure (B_o) varies by species and diet. Country specific data should be used where feasible. A range of representative B_o values for cattle, buffalo, and swine populations were used to develop the default emission factors as follows (see Appendix B):

- Dairy Cattle
  - Developed Countries: 0.24 m^3/kg VS
  - Developing Countries: 0.13 m^3/kg VS
- Non-Dairy Cattle
  - Developed Countries: 0.17 m^3/kg VS
  - Developing Countries: 0.10 m^3/kg VS
- Buffalo in all regions: 0.10 m^3/kg VS
- Swine
  - Developed Countries: 0.45 m^3/kg VS
  - Developing Countries: 0.29 m^3/kg VS

The portion of manure managed in each manure management system must also be collected for each representative animal type. Table 4-8 summarizes the main types of manure management systems. The first four types in the table, pasture, daily spread, solid storage, and drylot are all dry manure management systems. These systems produce little or no methane. The wet manure management systems, liquid/slurry, anaerobic lagoon, and pit storage are the primary sources of manure methane emissions. To implement this Tier 2 method, at a minimum the proportion of manure managed in wet and dry systems must be estimated.

The default emission factors presented in Tier 1 are based on manure management system usage data collected by Safley et al. (1992). Appendix B presents these data by region for cattle, buffalo, and swine. Although the data in Appendix B can be used as defaults,

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[12] The energy density of feed is about 18.45 MJ per kg of dry matter. This value is relatively constant across a wide range of forage and grain-based feeds commonly consumed by livestock.

country-specific data, e.g., obtained through a survey, would improve the basis for implementing the Tier 2 method. The resulting estimates must show the portion of manure from each animal type managed within each management system, by climate region.

MANURE MANAGEMENT TIER 2: STEP 2 -- EMISSION FACTORS

Emission factors are estimated for each animal type based using the data collected in Step 1 and the methane conversion factors (MCFs) for each manure management system. The MCF defines the portion of the methane producing potential (B_o) that is achieved. The MCF varies by manure management system and climate and can range between 0 and 100 percent. Table 4-8 presents the latest available MCF estimates for the major manure managements systems that have been developed.

To calculate the emission factor for each animal type, a weighted average methane conversion factor (MCF) is calculated using the estimates of the manure managed by waste system within each climate region. The average MCF is then multiplied by the VS excretion rate and the B_o for the animal type. In equation form, the estimate is as follows:

$$
\boxed{
\begin{array}{c}
\textbf{EQUATION 15} \\[6pt]
EF_i = VS_i \bullet 365\ days/yr \bullet Bo\,i \bullet 0.67 kg/m^3 \bullet \sum_{jk} MCFj\,k \bullet MS\%_{ijk}
\end{array}
}
$$

where:

EF_i	=	annual emission factor (kg) for animal type i (e.g., dairy cows);
VS_i	=	daily VS excreted (kg) for animal type i;
B_{oi}	=	maximum methane producing capacity (m^3/kg of VS) for manure produced by animal type i;
MCF_{jk}	=	methane conversion factors for each manure management system j by climate region k;
and		
$MS\%_{ijk}$	=	fraction of animal type i's manure handled using manure system j in climate region k.

MANURE MANAGEMENT TIER 2: STEP 3 -- TOTAL EMISSIONS

To estimate total emissions the selected emission factors are multiplied by the associated animal population and summed. As described above under Tier 1, the emissions estimates should be reported in gigagrams (Gg).

Beyond Tier 2

The default values used in the Tier 1 and 2 methods were derived from available livestock and manure management data and are generally representative of regional conditions. Because livestock and manure management conditions can vary significantly across and within countries, the default values may not reflect adequately the conditions in a given country. Additionally, the variability of conditions has not been well characterized to date.

The emissions estimates can be improved by going beyond the Tier 2 default data and collecting key country- or region-specific data. Data elements that would benefit from data collection initiatives (such as targeted surveys of major livestock types) include the following:

- *Cattle weight*
  In many regions the weights of cattle are not well quantified.

- *Feed intake*
  Field data on feed intake would be valuable for validating the feed intake estimates made under Tier 2 for cattle.

- *Manure production*
  Field data on manure production by livestock would be valuable for validating the manure production estimates made under Tier 2.

- *Manure management*
  Field data on manure management system usage would improve the basis for making the estimates. Considerations of seasonal management practices could be incorporated into the data.

In addition to these data collection initiatives, measurement programs can be used to improve the basis for making the estimates. In particular, measuring emissions from manure management systems under field conditions is needed. Techniques for making these measurements are described in IAEA (1992). Additionally, measurements of the maximum methane producing ability of manure (B_o) from livestock in tropical regions is needed.

Additionally, new techniques are being deployed to measure emissions from cattle under field conditions (Johnson et al., 1993). Using these techniques, coefficients used in Tier 2 can be verified (such as the methane conversion rate) and the emissions estimates can be validated. Targeted assessments of tropical cattle populations would be most valuable.

4.2.1 References

AAC (Australian Agricultural Council) (1990), *Feed Standards for Australian Livestock. Ruminants*, Commonwealth Scientific and Industrial Research Organization (CSIRO) Publications, East Melbourne, Victoria, Australia.

ARC (Agriculture Research Council) (1980), *The Nutrient Requirements of Ruminant Livestock*, Commonwealth Agricultural Bureaux, The Lavenham Press Ltd., the United Kingdom.

Bamualim, A., and Kartiarso (1985), "Nutrition of draught animals with special reference to Indonesia," in Copland, J.W., ed. *Draught Animal Power for Production*, Australian Centre for International Agricultural Research (ACIAR) Proceedings Series No. 10. ACIAR, Canberra, A.C.T., Australia.

Blaxter, K.L., and J.L. Clapperton (1965), "Prediction of the amount of methane produced by ruminants," *British Journal of Nutrition* 19:511-522.

Crutzen, P.J., I. Aselmann, and W. Seiler (1986), "Methane Production by Domestic Animals, Wild Ruminants, Other Herbivorous Fauna, and Humans," *Tellus* 38B:271-284

FAO (Food and Agriculture Organization) (1990), *Yearbook - Production Vol. 44*, FAO, United Nations, Rome, Italy.

Gibbs, M.J. and D.E. Johnson (1993). "Livestock Emissions," in *International Methane Emissions*, U.S. Environmental Protection Agency, Climate Change Division, Washington, D.C. (in press).

Graham, N.M. (1985), "Relevance of the British metabolisable energy system to the feeding of draught animals," in Copland, J.W., ed. *Draught Animal Power for Production*, ACIAR (Australian Centre for International Agricultural Research) Proceedings Series No. 10. ACIAR, Canberra, A.C.T., Australia.

Hashimoto, A. and J. Steed (1993), *Methane Emissions from Typical U.S. Livestock Manure Management Systems*, Draft report prepared for ICF Incorporated under contract to the Global Change Division of the Office of Air and Radiation, U.S. Environmental Protection Agency, Washington, D.C.

IAEA (International Atomic Energy Agency) (1992), *Manual on measurement of methane and nitrous oxide emissions from agriculture*, International Atomic Energy Agency Publication IAEA-TECDOC-674, Vienna, Austria.

Ibrahim, M.N.M. (1985), "Nutritional status of draught animals in Sri Lanka," in Copland, J.W., ed. *Draught Animal Power for Production*, ACIAR (Australian Centre for International Agricultural Research) Proceedings Series No. 10. ACIAR, Canberra, A.C.T., Australia.

Johnson, K.A., H. Westberg, M. Hyler, and B. Lamb (1993), *Cattle Methane Measurement Techniques Workshop*, August 9-12, 1993, Washington State University, Pullman, WA, sponsored by the Global Change Division, Office of Air and Radiation, U.S. Environmental Protection Agency, Washington, D.C.

Jurgens, M.H. (1988), *Animal Feeding and Nutrition*, Sixth Edition, Kendall/Hunt Publishing Company, Dubuque, Iowa.

Lawrence, P.R. (1985), "A review of nutrient requirements of draught oxen," in Copland, J.W., ed. *Draught Animal Power for Production*, ACIAR (Australian Centre for International Agricultural Research) Proceedings Series No. 10. ACIAR, Canberra, A.C.T., Australia.

Lichtman, R. J. (1983), *Biogas Systems in India*, Volunteers In Technical Assistance (VITA), Arlington, Virginia.

NRC (National Research Council) (1984), *Nutrient Requirements of Beef Cattle*, National Academy Press, Washington, D.C.

NRC (National Research Council) (1989), *Nutrient Requirements of Dairy Cattle*, National Academy Press, Washington, D.C.

OECD (Organization for Economic Cooperation and Development) (1991), *Estimation of Greenhouse Gas Emissions and Sinks: Final Report from the OECD Experts Meeting, 18-21 February 1991*, OECD, Paris, France.

Robbins, C.T., and D.L. Robbins (1979), "Fetal and neonatal growth patterns and maternal reproductive effort in ungulates and sub-ungulates," *Amer. Naturalist* 114:101.

Safley, L.M., M.E. Casada, J.W. Woodbury, and K.F. Roos (1992). *Global Methane Emissions from Livestock and Poultry Manure*. U.S. Environmental Protection Agency, Global Change Division. Washington, D.C., February 1992, EPA/400/1091/048.

Safley, L.M. Jr., and P.W. Westerman, (1992), "Performance of a low temperature lagoon digester," *Bioresource Technology* 41:167-175.

Stuckey, D.C. (1984), "Biogas: a global perspective," in El-Halwagi, M.M., ed. *Biogas Technology, Transfer and Diffusion*, Elsevier, New York, pages 18-44.

U.S. EPA (U.S. Environmental Protection Agency) (1993), *Anthropogenic Methane Emissions in the United States*, Global Change Division, Office of Air and Radiation, Washington, D.C.

Winrock (Winrock International) (1978), *The Role of Ruminants in Support of Man*, Winrock International, Morrilton, Arkansas.

Woodbury, J.W. and A. Hashimoto (1993). "Methane Emissions from Livestock Manure," in *International Methane Emissions*, U.S. Environmental Protection Agency, Climate Change Division, Washington, D.C. (in press).

Yancun, C., H. Cong, and Liang Pusen (1985), "Development of a new energy village - Xinbu, China," in El Mahgary, Y., and A.K. Biswas, eds. *Integrated Rural Energy Planning*, Butterworths Publishing, Guildsford, England, pages 99-108.

TABLE 4-1		
DOMESTIC LIVESTOCK INCLUDED IN THE METHODS		
Livestock	Recommended Emissions Inventory Methods	
	Enteric Fermentation	Manure Management
Dairy Cows	Tier 2[a]	Tier 2[a]
Cattle Other than Dairy Cows	Tier 2[a]	Tier 2[a]
Buffalo	Tier 1	Tier 2[a]
Sheep	Tier 1	Tier 1
Goats	Tier 1	Tier 1
Camels	Tier 1	Tier 1
Horses and Mules	Tier 1	Tier 1
Swine	Tier 1	Tier 2[a]
Poultry	(Not Estimated)	Tier 1

a The Tier 2 approach is recommended for countries with large livestock populations. Implementing the Tier 2 approach for additional livestock subgroups may be desirable when the subgroup emissions are a large portion of total methane emissions for the country.

TABLE 4-2
ANIMAL POPULATION DATA COLLECTED IN TIER I STEP I

Livestock	Data Collected				
	Population (# head)	Milk Production (kg/head/yr)	Population By Climate (%)		
			Cool	Temperate	Warm
Dairy Cows	Average Annual Population	Milk Production per Head	% Cool	% Temp.	% Warm
Cattle Other than Dairy Cows	Average Annual Population	Not Applicable (NA)	% Cool	% Temp.	% Warm
Buffalo	Average Annual Population	(NA)	% Cool	% Temp.	% Warm
Sheep	Average Annual Population	(NA)	% Cool	% Temp.	% Warm
Goats	Average Annual Population	(NA)	% Cool	% Temp.	% Warm
Camels	Average Annual Population	(NA)	% Cool	% Temp.	% Warm
Horses and Mules	Average Annual Population	(NA)	% Cool	% Temp.	% Warm
Swine	Average Annual Population	(NA)	% Cool	% Temp.	% Warm
Poultry	Average Annual Population	(NA)	% Cool	% Temp.	% Warm

Data can be obtained from the FAO Production Yearbook and country-specific livestock census reports. Climates are defined in terms of average annual temperature as follows: Cool = less than 15°C; Temperate = greater than 15°C and less than 25°C; Warm = greater than 25°C.

TABLE 4-3
ENTERIC FERMENTATION EMISSION FACTORS
(kg per head per year)

Livestock	Developed Countries	Developing Countries
Buffalo	55	55
Sheep	8	5
Goats	5	5
Camels	46	46
Horses	18	18
Mules and Asses	10	10
Swine	1.5	1.0
Poultry	Not Estimated	

All estimates are ±20 percent.

Sources: Emission factors for buffalo and camels from Gibbs and Johnson (1993). Emission factors for other livestock from Crutzen et al. (1986).

TABLE 4-4
ENTERIC FERMENTATION EMISSION FACTORS FOR CATTLE

Regional Characteristics	Animal Type	Emission Factor (kg/head/yr)	Comments
North America: Highly productive commercialized dairy sector feeding high quality forage and grain. Separate beef cow herd, primarily grazing with feed supplements seasonally. Fast-growing beef steers/heifers finished in feedlots on grain. Dairy cows are a small part of the population.	Dairy Cows	118	Average milk production of 6,700 kg/yr
	Non-Dairy Cattle	47	Includes beef cows, bulls, calves, growing steers/heifers, and feedlot cattle
Western Europe: Highly productive commercialized dairy sector feeding high quality forage and grain. Dairy cows also used for beef calf production. Very small dedicated beef cow herd. Minor amount of feedlot feeding with grains.	Dairy Cows	100	Average milk production of 4,200 kg/yr
	Non-Dairy Cattle	48	Includes bulls, calves, and growing steers/heifers
Eastern Europe: Commercialized dairy sector feeding mostly forages. Separate beef cow herd, primarily grazing. Minor amount of feedlot feeding with grains.	Dairy Cows	81	Average milk production of 2,550 kg/yr
	Non-Dairy Cattle	56	Includes beef cows, bulls, and young.
Oceania: Commercialized dairy sector based on grazing. Separate beef cow herd, primarily grazing rangelands of widely varying quality. Growing amount of feedlot feeding with grains. Dairy cows are a small part of the population.	Dairy Cows	68	Average milk production of 1,700 kg/yr
	Non-Dairy Cattle	53	Includes beef cows, bulls, and young.
Latin America: Commercialized dairy sector based on grazing. Separate beef cow herd grazing pastures and rangelands. Minor amount of feedlot feeding with grains. Growing beef cattle comprise a large portion of the population.	Dairy Cows	57	Average milk production of 800 kg/yr
	Non-Dairy Cattle	49	Includes beef cows, bulls, and young.
Asia: Small commercialized dairy sector. Most cattle are multi-purpose, providing draft power and some milk within farming regions. Small grazing population. Cattle of all types are smaller than those found in most other regions.	Dairy Cows	56	Average milk production of 1,650 kg/yr
	Non-Dairy Cattle	44	Includes multi-purpose cows, bulls, and young.
Africa and Middle East: Commercialized dairy sector based on grazing with low production per cow. Most cattle are multi-purpose, providing draft power and some milk within farming regions. Some cattle graze over very large areas. Cattle of all types are smaller than those found in most other regions.	Dairy Cows	36	Average milk production of 475 kg/yr
	Non-Dairy Cattle	32	Includes multi-purpose cows, bulls, and young.
Indian Subcontinent: Commercialized dairy sector based on crop byproduct feeding with low production per cow. Most bullocks provide draft power and cows provide some milk in farming regions. Small grazing population. Cattle in this region are the smallest compared to cattle found in all other regions.	Dairy Cows	46	Average milk production of 900 kg/yr
	Non-Dairy Cattle	25	Includes cows, bulls, and young. Young comprise a large portion of the population.

TABLE 4-5
MANURE MANAGEMENT EMISSION FACTORS

(kg per head per year)

Livestock	Developed Countries			Developing Countries		
	Cool	Temp.[a]	Warm	Cool	Temp.[a]	Warm
Sheep	0.19	0.28	0.37	0.10	0.16	0.21
Goats	0.12	0.18	0.23	0.11	0.17	0.22
Camels	1.6	2.4	3.2	1.3	1.9	2.6
Horses	1.4	2.1	2.8	1.1	1.6	2.2
Mules and Asses	0.76	1.14	1.51	0.60	0.90	1.2
Poultry[b]	0.078	0.117	0.157	0.012	0.018	0.023

The range of estimates reflects cool to warm climates. Climate regions are defined in terms of annual average temperature as follows: Cool = less than 15°C; Temperate = 15°C to 25°C; and Warm = greater than 25°C. The Cool, Temperate and Warm regions are estimated using MCFs of 1%, 1.5% and 2%, respectively.

a Temp. = Temperate climate region.

b Chickens, ducks, and turkeys.

All estimates are ±20 percent.

Sources: Emission factors developed from: feed intake values and feed digestibilities used to develop the enteric fermentation emission factors (see Appendix A); MCF, and B_O values reported in Woodbury and Hashimoto (1993). All manure is assumed to be managed in dry systems, which is consistent with the manure management system usage reported in Woodbury and Hashimoto (1993).

TABLE 4-6				
MANURE MANAGEMENT EMISSION FACTORS FOR CATTLE, SWINE AND BUFFALO				
Regional Characteristics	Animal Type	Emission Factor by Climate Region[a] (kg/head/year)		
		Cool	Temperate	Warm
North America: Liquid-based systems are commonly used for dairy and swine manure. Non-dairy manure is usually managed as a solid and deposited on pastures or ranges.	Dairy Cows	36	54	76
	Non-Dairy Cows	1	2	3
	Swine	10	14	18
Western Europe: Liquid/slurry and pit storage systems are commonly used for cattle and swine manure. Limited cropland is available for spreading manure.	Dairy Cows	14	44	81
	Non-Dairy Cows	6	20	38
	Swine	3	11	20
	Buffalo	3	8	17
Eastern Europe: Solid based systems are used for the majority of manure. About one-third of livestock manure is managed in liquid-based systems.	Dairy Cows	6	19	33
	Non-Dairy Cows	4	13	23
	Swine	4	7	11
	Buffalo	3	9	16
Oceania: Virtually all livestock manure is managed as a solid on pastures and ranges. About half of the swine manure is managed in anaerobic lagoons.	Dairy Cows	31	32	33
	Non-Dairy Cows	5	6	7
	Swine	19	19	20
Latin America: Almost all livestock manure is managed as a solid on pastures and ranges. Buffalo manure is deposited on pastures and ranges.	Dairy Cows	0	1	2
	Non-Dairy Cows	1	2	1
	Swine	1	1	3
	Buffalo	1	1	2
Africa: Almost all livestock manure is managed as a solid on pastures and ranges.	Dairy Cows	1	1	1
	Non-Dairy Cows	0	1	1
	Swine	0	1	2
Middle East: Over two-thirds of cattle manure is deposited on pastures and ranges. About one-third of swine manure is managed in liquid-based systems. Buffalo manure is burned for fuel or managed as a solid.	Dairy Cows	1	2	2
	Non-Dairy Cows	1	1	1
	Swine	1	3	6
	Buffalo	4	5	5
Asia: About half of cattle manure is used for fuel with the remainder managed in dry systems. Almost forty percent of swine manure is managed as a liquid. Buffalo manure is managed in drylots and deposited in pastures and ranges.	Dairy Cows	7	16	27
	Non-Dairy Cows	1	1	2
	Swine	1	4	7
	Buffalo	1	2	3
Indian Subcontinent: About half of cattle and buffalo manure is used for fuel with the remainder managed in dry systems. About one-third of swine manure is managed as a liquid.	Dairy Cows	5	5	6
	Non-Dairy Cows	2	2	2
	Swine	3	4	6
	Buffalo	4	5	5

a Cool climates have an average temperature below 15°C; temperate climates have an average temperature between 15°C and 25°C; warm climates have an average temperature above 25°C. All climate categories are not necessarily represented within every region. For example, there are no significant warm areas in Eastern or Western Europe. Similarly, there are no significant cool areas in Africa and the Middle East. See Appendix B for the derivation of these emission factors.

Note: Significant buffalo populations do not exist in North America, Oceania, or Africa.

TABLE 4-7 RECOMMENDED REPRESENTATIVE CATTLE TYPES	
Main Categories	**Sub-Categories**
Mature Dairy Cows	Used principally for commercial milk production
Mature Non-Dairy Cattle	Mature Females: • Beef Cows: used principally for producing beef steers and heifers • Multiple-Use Cows: used for milk production, draft power, and other uses Mature Males: • Breeding Bulls: used principally for breeding purposes • Draft Bullocks: used principally for draft power
Young Cattle	Pre-Weaned Calves Growing Heifers, Steers/Bullocks and Bulls Feedlot-Fed Steers and Heifers on High-Grain Diets

TABLE 4-8 MANURE MANAGEMENT SYSTEMS AND METHANE CONVERSION FACTORS (MCFs)				
System	MCF by Climate[a]			Source
	Cool	Temperate	Warm	
Pasture/Range/Paddock The manure from pasture and range grazing animals is allowed to lie as is, and is not managed.	1%	1.5%	2%	b
Daily Spread Manure is collected in solid form by some means such as scraping. The collected manure is applied to fields regularly (usually daily).	0.1%	0.5%	1.0%	b
Solid Storage: Manure is collected as in the daily spread system, but is stored in bulk for a long period of time (months) before any disposal.	1%	1.5%	2%	b
Drylot In dry climates animals may be kept on unpaved feedlots where the manure is allowed to dry until it is periodically removed. Upon removal the manure may be spread on fields.	1%	1.5%	5%	b
Liquid/Slurry These systems are characterized by large concrete lined tanks built into the ground. Manure is stored in the tank for six or more months until it can be applied to fields. To facilitate handling as a liquid, water may be added to the manure.	10%	35%	65%	b
Anaerobic Lagoon Anaerobic lagoon systems are characterized by flush systems that use water to transport manure to lagoons. The manure resides in the lagoon for periods from 30 days to over 200 days. The water from the lagoon may be recycled as flush water or used to irrigate and fertilize fields.	90%	90%	90%	c
Pit Storage Liquid swine manure may be stored in a pit while awaiting final disposal. The length of storage time varies, and for this analysis is divided into two categories: less than one month or greater than one month. — < 30 Days	5%	18%	33%	b
> 30 Days	10%	35%	65%	b
Anaerobic Digester The manure, in liquid or slurry form, is anae-robically digested to produce methane gas for energy. Emissions are from leakage and vary with the type of digester.	5-15%	5-15%	5-15%	d
Burned for Fuel Manure is collected and dried in cakes and burned for heating or cooking. Emissions occur while the manure is stored before it is burned. Methane emission associated with the combustion of the manure are not considered here. Combustion-related emissions are estimated in the *Traditional Biomass Fuels* section of the *Energy* chapter.	5-10%	5-10%	5-10%	e

a Cool climates have an average temperature below 15°C; temperate climates have an average temperature between 15°C and 25°C; warm climates have an average temperature above 25°C.

b Hashimoto and Steed (1993).

c Safley et al., (1992) and Safley and Westerman (1992).

d Yancun et al. (1985), Stuckey (1984) and Lichtman (1983).

e Safley et al. (1992).

Appendix A
Data Underlying Default Emission Factors for Enteric Fermentation

This appendix presents the data used to develop the default emission factors for methane emissions from enteric fermentation. The detailed information presented for cattle and buffalo was developed in Gibbs and Johnson (1993). The Tier 2 method was implemented with these data to estimate the default emission factors for cattle and buffalo. Also presented are the summary data from Crutzen et al. (1986) that were used to estimate the emission factors for the other species.

TABLE A-I
DATA FOR ESTIMATING ENTERIC FERMENTATION EMISSION FACTORS FOR DAIRY CATTLE

Regions	Weight kg	Weight Gain kg/day	Feeding Situation	Milk kg/day	Work hrs/day	Percent Pregnant	Digestibility of Feed %	CH$_4$ Conversion %
North America[a]	600	0	Stall Fed	18.4	0	90%	65%	6%
Western Europe	550	0	Stall Fed	11.5	0	90%	60%	6%
Eastern Europe[b]	550	0	Stall Fed	7.0	0	80%	60%	6%
Oceania[c]	500	0	Stall Fed	4.7	0	80%	60%	6%
Latin America[d]	400	0	Pasture/Range	2.2	0	80%	60%	6%
Asia[e]	350	0	Stall Fed	4.5	0	80%	60%	6%
Africa & Mid. East	275	0	Stall Fed	1.3	0	67%	60%	6%
Indian Subcontinent[f]	275	0	Stall Fed	2.5	0	50%	55%	6%

a Based on estimates for the U.S.
b Based on estimates for the former U.S.S.R.
c Based on estimates for Australia.
d Based on estimates for Brazil.
e Based on estimates for China.
f Based on estimates for India.
Source: Gibbs and Johnson (1993).

TABLE A-2
DATA FOR ESTIMATING ENTERIC FERMENTATION EMISSION FACTORS FOR NON-DAIRY CATTLE

Type	Weight kg	Weight Gain kg/day	Feeding Situation	Milk kg/day	Work hrs/day	Percent Pregnant	Digesti-bility of Feed %	CH4 Conversion %	Day Weighted Population Mix %	Emission Factors kg/h/yr
North America[a]										
Mature Females	500	0.0	Pasture/Range	3.3	0.0	80%	60%	6.0%	36%	69
Mature Males	800	0.0	Pasture/Range	0.0	0.0	0%	60%	6.0%	2%	75
Calves on milk	100	0.9	Pasture/Range	0.0	0.0	0%	NA	0.0%	16%	0
Calves on forage	185	0.9	Pasture/Range	0.0	0.0	0%	65%	6.0%	8%	42
Growing heifers/steers	265	0.7	Pasture/Range	0.0	0.0	0%	65%	6.0%	17%	47
Replacement/growing	375	0.4	Pasture/Range	0.0	0.0	0%	60%	6.0%	11%	56
Feedlot cattle	415	1.3	Stall Fed	0.0	0.0	0%	75%	3.5%	11%	37
Western Europe										
Mature Males	600	0.0	Pasture/Range	0.0	0.0	0%	60%	6.0%	22%	60
Replacement/growing	400	0.4	Pasture/Range	0.0	0.0	0%	60%	6.0%	54%	84
Calves on milk	230	0.3	Pasture/Range	0.0	0.0	0%	65%	0.0%	15%	0
Calves on forage	230	0.3	Pasture/Range	0.0	0.0	0%	65%	6.0%	8%	33
Eastern Europe[b]										
Mature Females	500	0.0	Pasture/Range	3.3	0.0	67%	60%	6.5%	30%	74
Mature Males	600	0.0	Pasture/Range	0.0	0.0	0%	60%	6.5%	22%	65
Young	230	0.4	Pasture/Range	0.0	0.0	0%	60%	6.0%	48%	40
Oceania[c]										
Mature Females	400	0.0	Pasture/Range	2.4	0.0	67%	55%	6.0%	51%	63
Mature Males	450	0.0	Pasture/Range	0.0	0.0	0%	55%	6.0%	11%	55
Young	200	0.3	Pasture/Range	0.0	0.0	0%	55%	6.0%	38%	39

a Based on estimates for the U.S.
b Based on estimates for the former U.S.S.R.
c Based on estimates for Australia.

TABLE A-2 (CONTINUED)
DATA FOR ESTIMATING ENTERIC FERMENTATION EMISSION FACTORS FOR NON-DAIRY CATTLE

Type	Weight kg	Weight Gain kg/day	Feeding Situation	Milk kg/day	Work hrs/day	Percent Pregnant	Digesti-bility of Feed %	CH₄ Conversion %	Day Weighted Population Mix %	Emission Factors kg/h/yr
Latin America[d]										
Mature Females	400	0.0	Large Areas	1.1	0.0	67%	60%	6.0%	37%	58
Mature Males	450	0.0	Large Areas	0.0	0.0	0%	60%	6.0%	6%	57
Young	230	0.3	Large Areas	0.0	0.0	0%	60%	6.0%	58%	42
Asia[e]										
Mature Females-Farming	325	0.0	Stall Fed	1.1	0.55	33%	55%	6.5%	27%	48
Mature Females-Grazing	300	0.0	Pasture/Range	1.1	0.00	50%	60%	6.0%	9%	41
Mature Males-Farming	450	0.0	Stall Fed	0.0	1.37	0%	55%	6.5%	24%	58
Mature Males-Grazing	400	0.0	Pasture/Range	0.0	0.00	0%	60%	6.0%	8%	44
Young	200	0.2	Pasture/Range	0.0	0.00	0%	60%	6.0%	32%	31
Africa										
Mature Females	200	0.0	Stall Fed	0.3	0.55	33%	55%	6.5%	13%	31
Draft Bullocks	275	0.0	Stall Fed	0.0	1.37	0%	55%	6.5%	13%	40
Mature Females-Grazing	200	0.0	Large Areas	0.3	0.00	33%	55%	7.5%	6%	46
Bulls - Grazing	275	0.0	Large Areas	0.0	0.00	0%	55%	7.5%	25%	55
Young	75	0.1	Pasture/Range	0.0	0.00	0%	60%	6.0%	44%	14
Indian Subcontinent[f]										
Mature Females	125	0.0	Stall Fed	0.6	0.00	33%	50%	7.5%	40%	31
Mature Males	200	0.0	Stall Fed	0.0	2.74	0%	50%	7.5%	10%	41
Young	80	0.1	Stall Fed	0.0	0.00	0%	50%	6.0%	50%	17

d Based on estimates for the Brazil.
e Based on estimates for the China.
f Based on estimates for India.
Source: Gibbs and Johnson (1993).

TABLE A-3
DATA FOR ESTIMATING ENTERIC FERMENTATION EMISSION FACTORS FOR BUFFALO

Type	Weight kg	Weight Gain kg/day	Feeding Situation	Milk kg/day	Work hrs/day	Percent Pregnant	Digesti-bility of Feed %	CH4 Conversion %	Population Mix %	Emissions Factors kg/h/year
Indian Subcontinent[a]										
Adult Males	350 - 550	0.00	Stall Fed	0.00	1.37	0%	55%	7.5	14%	55 - 77
Adult Females	250 - 450	0.00	Stall Fed	2.70	0.55	33%	55%	7.5	40%	57 - 80
Young	100 - 300	0.15	Stall Fed	0.00	0.00	0%	55%	7.5	46%	23 - 50
Other Countries[b]										
Adult Males	350 - 550	0.00	Stall Fed	0.00	1.37	0%	55%	7.5	45%	55 - 77
Adult Females	250 - 450	0.00	Stall Fed	0.00	0.55	25%	55%	7.5	45%	45 - 67
Young	100 - 300	0.15	Stall Fed	0.15	0.00	0%	55%	7.5	10%	23 - 50

a Based on estimates for India.
b Based on estimates for China.
Source: Gibbs and Johnson (1993).

TABLE A-4
DATA FOR ESTIMATING ENTERIC FERMENTATION EMISSION FACTORS FOR OTHER ANIMALS

Animal Type		Feed Intake (MJ/h/day)	Methane Conversion (%)
Sheep	Developed	20	6%
	Developing	13	6%
Goats	Developed	14	5%
	Developing	14	5%
Camels	Developed	100	7%
	Developing	100	7%
Horses	Developed	110	2.5%
	Developing	110	2.5%
Mules/Asses	Developed	60	2.5%
	Developing	60	2.5%
Swine	Developed	38	0.6%
	Developing	13	1.3%
Poultry	Developed	Not Estimated	
	Developing		

Sources: Feed intake and methane conversion for all animals from Crutzen et al (1986). Methane conversion for camels modified as in Gibbs and Johnson (1993).

Appendix B   Data Underlying Default Emission Factors for Manure Management

This appendix presents the data used to develop the default emission factors for methane emissions from manure management. The detailed information presented for cattle and buffalo were developed in Gibbs and Johnson (1993). The swine feed intake data are from Crutzen et al. (1986). The manure management system usage data and B_o estimates are from Safley et al. (1992). The methane conversion factor (MCF) data are from Woodbury and Hashimoto (1993). The Tier 2 method was implemented with these data to estimate the default emission factors for cattle, buffalo, and swine. Also presented are the summary feed intake data from Crutzen et al. (1986) and the manure-related data from Safley et al. (1992) and Woodbury and Hashimoto (1993) that were used to estimate the emission factors for the other species.

TABLE B-1
FEED INTAKE AND MANURE PRODUCTION FOR CATTLE

Region	Animal Category	Sub-Population	Mass (kg)	Feed Digest. (%)	Energy Intake (MJ/day)	Feed Intake (kg/day)	Pct of Category Population	Manure (kg/h/d dry)	VS (kg/h/d)	Bo (m³ CH4/kg VS)
North America	Dairy Cattle	Average	600	65%	299.5	16.2	100%	5.68	5.23	0.24
	Non-Dairy Cattle	Mature Females	500	60%	174.0	9.4	36%	3.77	3.47	0.17
		Mature Males	800	60%	189.3	10.3	2%	4.10	3.78	0.17
		Young on milk	100	NA	NA	NA	15%	negligibl e	negligibl e	0.17
		Young	185	65%	107.2	5.8	8%	2.03	1.87	0.17
		Young	265	65%	120.1	6.5	17%	2.28	2.10	0.17
		Young	375	60%	143.2	7.8	11%	3.10	2.86	0.17
		Feedlot	415	75%	161.8	8.8	11%	2.19	2.02	0.17
		Avg. Non-Dairy Cattle	357	53%	128.0	6.9	100%	2.55	2.35	0.17
Western Europe	Dairy Cattle	Average	550	60%	254.7	13.8	100%	5.52	5.08	0.24
	Non-Dairy Cattle	Mature Males	600	60%	152.5	8.3	22%	3.31	3.04	0.17
		Young Replacements	400	60%	149.8	8.1	55%	3.25	2.99	0.17
		Young Calves	230	65%	83.7	4.5	23%	1.59	1.46	0.17
		Avg. Non-Dairy Cattle	405	61%	135.1	7.3	100%	2.88	2.65	0.17
Eastern Europe	Dairy Cattle	Average	550	60%	207.2	11.2	100%	4.49	4.13	0.24
	Non-Dairy Cattle	Mature Females	500	60%	172.9	9.4	30%	3.75	3.45	0.17
		Mature Males	600	60%	152.5	8.3	21%	3.31	3.04	0.17
		Young	230	60%	102.2	5.5	49%	2.22	2.04	0.17
		Avg. Non-Dairy Cattle	391	60%	134.4	7.3	100%	2.91	2.68	0.17
Oceania	Dairy Cattle	Average	500	60%	174.1	9.4	100%	3.77	3.47	0.24
	Non-Dairy Cattle	Mature Females	400	55%	160.5	8.7	52%	3.91	3.60	0.17
		Mature Males	450	55%	138.8	7.5	10%	3.38	3.11	0.17
		Young	200	55%	98.6	5.3	38%	2.41	2.21	0.17
		Avg. Non-Dairy Cattle	330	55%	134.9	7.3	100%	3.29	3.03	0.17

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Region	Cattle	Category								
Latin America	Dairy Cattle	Average	400	60%	145.9	7.9	100%	3.16	2.91	0.13
	Non-Dairy Cattle	Mature Females	400	60%	148.0	8.0	37%	3.21	2.95	0.10
		Mature Males	450	60%	144.0	7.8	5%	3.12	2.87	0.10
		Young	230	60%	107.5	5.8	58%	2.33	2.14	0.10
		Avg. Non-Dairy Cattle	305	60%	124.4	6.7	100%	2.70	2.48	0.10
Africa & Middle East	Dairy Cattle	Average	275	60%	92.8	5.0	100%	2.01	1.85	0.13
	Non-Dairy Cattle	Mature Females	200	55%	73.2	4.0	13%	1.79	1.64	0.10
		Mature Males Draft	275	55%	93.2	5.1	13%	2.27	2.09	0.10
		Mature Females Grazing	200	55%	93.6	5.1	5%	2.28	2.10	0.10
		Mature Males Grazing	275	55%	112.3	6.1	25%	2.74	2.52	0.10
		Young	75	60%	36.2	2.0	44%	0.78	0.72	0.10
		Avg. Non-Dairy Cattle	173	57%	70.6	3.8	100%	1.68	1.54	0.10
Asia	Dairy Cattle	Average	350	60%	141.6	7.7	100%	3.07	2.82	0.13
	Non-Dairy Cattle	Mature Females Farming	325	55%	113.2	6.1	27%	2.76	2.54	0.10
		Mature Females Grazing	300	60%	105.0	5.7	9%	2.28	2.09	0.10
		Mature Males Farming	450	55%	134.9	7.3	24%	3.29	3.03	0.10
		Mature Males Grazing	400	60%	112.5	6.1	8%	2.44	2.24	0.10
		Young	200	60%	79.3	4.3	32%	1.72	1.58	0.10
		Avg. Non-Dairy Cattle	319	57%	106.8	5.8	100%	2.49	2.29	0.10
Indian Subcontinent	Dairy Cattle	Average Dairy Cow	275	55%	117.7	6.4	100%	2.87	2.64	0.13
	Non-Dairy Cattle	Mature Females	125	50%	63.8	3.5	40%	1.73	1.59	0.10
		Mature Males	200	50%	83.7	4.5	10%	2.27	2.09	0.10
		Young	80	50%	43.2	2.3	50%	1.17	1.08	0.10
		Avg. Non-Dairy Cattle	110	50%	55.5	3.0	100%	1.50	1.38	0.10

Ash content estimated at 8%. Cattle characteristics from Gibbs and Johnson (1993).

TABLE B-2
FEED INTAKE AND MANURE PRODUCTION FOR SWINE AND BUFFALO

Region	Animal Category	Sub-Population	Mass (kg)	Feed Digest. (%)	Energy Intake (MJ/day)	Feed Intake (kg/day)	Pct of Category Population	Manure (kg/h/d dry)	VS (kg/h/d)	Bo (m³ CH₄/kg VS)
					Swine					
Developing Countries	Swine	Average	28	50%	13.0	0.7	100%	0.35	0.34	0.29
Developed Countries	Swine	Average	82	75%	38.0	2.1	100%	0.51	0.50	0.45
					Buffalo					
Indian Subcontinent[a]	Buffalo	Adult Males	450	55%	134.5	7.3	14%	3.28	3.02	0.10
		Adult Females	350	55%	139.0	7.5	40%	3.39	3.12	0.10
		Young	200	55%	74.0	4.0	46%	1.80	1.66	0.10
		Average	295	55%	108.0	5.9	100%	2.65	2.43	0.10
Rest of World[b]	Buffalo	Adult Males	450	55%	134.5	7.3	45%	3.28	3.02	0.10
		Adult Females	350	55%	114.0	6.2	45%	2.78	2.56	0.10
		Young	200	55%	74.0	4.1	10%	1.80	1.66	0.10
		Average	380	55%	119.0	6.5	100%	2.91	2.68	0.10

a Estimates based on data for India.

b Estimates based on data for China.

Ash content taken as 8% for buffalo and 2% and 4% for swine in developed and developing countries, respectively.

Sources: Buffalo characteristics from Gibbs and Johnson (1993). Swine feed intake estimates from Cruzen et al. (1986).

TABLE B-3
MANURE MANAGEMENT EMISSION FACTOR DERIVATION FOR DAIRY CATTLE

Climate	Manure Management System MCFs								
	Lagoon	Liquid/ Slurry	Solid Storage	Drylot	Pasture/ Range	Daily Spread	Digester	Burned for Fuel	Other
Cool	90%	10%	1%	1%	1%	0.1%	10%	10%	1%
Temperate	90%	35%	1.5%	1.5%	1.5%	0.5%	10%	10%	1%
Warm	90%	65%	2%	5%	2%	1%	10%	10%	1%

Region	Dairy Cattle Characteristics			Manure Management System Usage (MS%)									Emission Factors kg CH$_4$/hd/yr		
	Mass[a] kg	Bo m^3 CH4 /kg VS	VS[b] kg/hd/day	Lagoon	Liquid/ Slurry	Solid Storage	Drylot	Pasture/ Range	Daily Spread	Digester	Burned for Fuel	Other	Cool	Temperate	Warm
North America	600	0.24	5.2	10%	23%	18%	5%	0%	37%	0%	0%	7%	36	54	76
Western Europe	550	0.24	5.1	0%	40%	18%	0%	19%	20%	0%	2%	1%	14	44	81
Eastern Europe	550	0.24	4.1	0%	18%	68%	0%	13%	1%	0%	0%	0%	6	19	33
Oceania	500	0.24	3.5	16%	1%	0%	0%	76%	8%	0%	0%	0%	31	32	33
Latin America	400	0.13	2.9	0%	1%	1%	0%	36%	62%	0%	0%	0%	0	1	2
Africa	275	0.13	1.9	0%	0%	1%	0%	83%	5%	0%	6%	4%	1	1	1
Middle East	275	0.13	1.9	0%	1%	2%	0%	60%	2%	0%	17%	0%	1	2	2
Asia	350	0.13	2.8	4%	38%	0%	0%	20%	29%	2%	7%	0%	7	16	27
Indian Subcon.	275	0.13	2.6	0%	1%	0%	0%	27%	19%	1%	51%	0%	5	5	6

a Average dairy cow mass for each region.
b Average VS production for per head per day for the average dairy cow.
Emission Factors (EF) for a climate region k are calculated as follows:

$$EF_k = B_o \cdot VS \cdot 365 \cdot \sum_{j=1} All\ Manure\ Sys MS\%_j \cdot MCF_{j,k}$$

TABLE B-4
MANURE MANAGEMENT EMISSION FACTOR DERIVATION FOR NON-DAIRY CATTLE

Climate	Manure Management System MCFs								
	Lagoon	Liquid / Slurry	Solid Storage	Drylot	Pasture / Range	Daily Spread	Digester	Burned for Fuel	Other
Cool	90%	10%	1%	1%	1%	0.1%	10%	10%	1%
Temperate	90%	35%	1.5%	1.5%	1.5%	0.5%	10%	10%	1%
Warm	90%	65%	2%	5%	2%	1%	10%	10%	1%

Region	Non-Dairy Cattle Characteristics			Manure Management System Usage (MS%)									Emission Factors kg CH$_4$ / hd / yr		
	Mass kg	B$_o$ m^3 CH$_4$ /kg VS	VS kg/hd/day	Lagoon	Liquid / Slurry	Solid Storage	Drylot	Pasture / Range	Daily Spread	Digester	Burned for Fuel	Other	Cool	Temperate	Warm
North America	357	0.17	2.4	0%	1%	0%	14%	84%	0%	0%	0%	1%	1	2	3
Western Europe	405	0.17	2.7	0%	50%	0%	2%	38%	0%	0%	2%	8%	6	20	38
Eastern Europe	391	0.17	2.7	0%	28%	0%	0%	26%	0%	0%	0%	46%	4	13	23
Oceania	330	0.17	3.0	3%	0%	0%	6%	91%	0%	0%	0%	0%	5	6	7
Latin America	305	0.10	2.5	0%	0%	0%	0%	99%	0%	0%	0%	1%	1	1	1
Africa	173	0.10	1.5	0%	0%	0%	1%	95%	1%	0%	3%	0%	0	1	1
Middle East	173	0.10	1.5	0%	0%	0%	1%	79%	2%	0%	17%	2%	1	1	1
Asia	319	0.10	2.3	0%	0%	0%	46%	50%	2%	0%	2%	0%	1	1	2
Indian Subcon.	110	0.10	1.4	0%	1%	0%	4%	22%	20%	1%	53%	0%	2	2	2

a Average non-dairy cow mass for each region.
b Average VS production for per head per day for the average non-dairy animal.
Emission Factors (EF) for a climate region k are calculated as follows:

$$EF_k = B_o \cdot VS \cdot 365 \cdot \sum_{j=1}^{\text{?All Manure Sys}} MS\%_j \cdot MCF_{j,k}$$

Table B-5
Manure Management Emission Factor Derivation for Buffalo

Climate	Manure Management System MCFs						
	Liquid/ Slurry	Drylot	Pasture/ Range	Daily Spread	Digester	Burned for Fuel	Other
Cool	10.0%	1.0%	1.0%	0.1%	10.0%	10.0%	1.0%
Temperate	35.0%	1.5%	1.5%	0.5%	10.0%	10.0%	1.0%
Warm	65.0%	5.0%	2.0%	1.0%	10.0%	10.0%	1.0%

	Emission Factors kg CH4 / hd / yr		
	Cool	Temperate	Warm
North America			
Western Europe	3	8	17
Eastern Europe	3	9	16
Oceania			
Latin America	1	1	2
Africa			
Middle East	4	5	5
Asia	1	2	3
Indian Subcon.	4	5	5

Region	Buffalo Characteristics			Manure Management System Usage (MS%)						
	Mass kg	Bo m³CH4 /kg VS	VS kg/hd/day	Liquid/ Slurry	Drylot	Pasture/ Range	Daily Spread	Digester	Burned for Fuel	Other
North America	(not applicable)									
Western Europe	380	0.10	3.9	20%	79%	0%	0%	0%	0%	0%
Eastern Europe	380	0.10	3.9	24%	0%	29%	0%	0%	0%	47%
Oceania	(not applicable)									
Latin America	380	0.10	3.9	0%	0%	99%	0%	0%	0%	1%
Africa	(not applicable)									
Middle East	380	0.10	3.9	0%	0%	20%	19%	0%	42%	19%
Asia	380	0.10	3.9	0%	41%	50%	4%	0%	5%	0%
Indian Subcon.	295	0.10	3.1	0%	4%	19%	21%	1%	55%	0%

a Average buffalo mass for each region.
b Average VS production for per head per day for the average buffalo.
Emission Factors (EF) for a climate region k are calculated as follows:

$$EF_k = B_o \cdot VS \cdot 365 \cdot \sum_{j=1}^{?All\ Manure\ Sys} MS\%_j \cdot MCF_{j\ k}$$

TABLE B-6
MANURE MANAGEMENT EMISSION FACTOR DERIVATION FOR SWINE

Climate	Manure Management Systems MCFs								
	Lagoon	Liquid/ Slurry	Solid Storage	Drylot	Pit <1 month	Pit >1 month	Daily Spread	Digester	Other
Cool	90%	10%	1%	1%	5%	10%	0.1%	10%	1%
Temperate	90%	35%	1.5%	1.5%	18%	35%	0.5%	10%	1%
Warm	90%	65%	2%	5%	33%	65%	1%	10%	1%

	Emission Factors kg CH4 / hd / yr		
	Cool	Temperate	Warm
North America	10	14	18
Western Europe	3	10	19
Eastern Europe	4	7	11
Oceania	20	20	20
Latin America	0	1	2
Africa	0	1	2
Middle East	1	3	6
Asia	1	4	7
Indian Subcon.	3	4	6

Region	Swine Characteristics			Manure Management System Usage (MS%)								
	Mass kg	B_o m³ CH4 /kg VS	VS kg/hd/day	Lagoon	Liquid/ Slurry	Solid Storage	Drylot	Pit <1 month	Pit >1 month	Daily Spread	Digester	Other
North America	82	0.45	0.5	24%	1%	2%	16%	10%	26%	0%	0%	19%
Western Europe	82	0.45	0.5	0%	0%	21%	2%	3%	73%	0%	0%	1%
Eastern Europe	82	0.45	0.5	8%	0%	39%	14%	19%	19%	0%	0%	1%
Oceania	82	0.45	0.5	54%	0%	3%	15%	0%	0%	0%	0%	28%
Latin America	28	0.29	0.3	0%	8%	10%	41%	0%	0%	2%	0%	40%
Africa	28	0.29	0.3	0%	6%	6%	87%	1%	0%	0%	0%	0%
Middle East	28	0.29	0.3	0%	14%	0%	69%	0%	17%	0%	0%	0%
Asia	28	0.29	0.3	0%	40%	0%	54%	0%	0%	0%	7%	0%
Indian Subcon.	28	0.29	0.3	9%	22%	16%	30%	3%	0%	9%	8%	3%

a Average swine mass for each region.
b Average VS production for per head per day for the average swine.
Emission Factors (EF) for a climate region k are calculated as follows:

$$EF_k = B_o \cdot VS \cdot 365 \cdot \sum_{j=1}^{?} ?\text{All Manure Sys} MS\%_j \cdot MCF_{j,k}$$

TABLE B-7
MANURE MANAGEMENT EMISSION FACTOR DERIVATION FOR OTHER LIVESTOCK

Animal		Animal Characteristics						Manure Management System MCFs[a]			Emission Factors[a] kg CH4 / hd / yr		
		Mass (kg)	Digest (%)	Intake/d (kg Feed)	% Ash (Dry Basis)	VS/d (kg VS)	B_o (m³/kg VS)	MCF Cool	MCF Temperate	MCF Warm	Cool	Temperate	Warm
Sheep	Developed	43	60%	1.08	8.0	0.40	0.19	1%	1.5%	2%	0.19	0.28	0.37
	Developing	28	50%	0.70	8.0	0.32	0.13	1%	1.5%	2%	0.10	0.16	0.21
Goats	Developed	30	60%	0.76	8.0	0.28	0.17	1%	1.5%	2%	0.12	0.18	0.23
	Developing	30	50%	0.76	8.0	0.35	0.13	1%	1.5%	2%	0.11	0.17	0.22
Camels	Developed	217	50%	5.42	8.0	2.49	0.26	1%	1.5%	2%	1.59	2.38	3.17
	Developing	217	50%	5.42	8.0	2.49	0.21	1%	1.5%	2%	1.28	1.92	2.56
Horses	Developed	238	70%	5.96	4.0	1.72	0.33	1%	1.5%	2%	1.39	2.08	2.77
	Developing	238	70%	5.96	4.0	1.72	0.26	1%	1.5%	2%	1.09	1.64	2.18
Mule/Asses	Developed	130	70%	3.25	4.0	0.94	0.33	1%	1.5%	2%	0.76	1.14	1.51
	Developing	130	70%	3.25	4.0	0.94	0.26	1%	1.5%	2%	0.60	0.90	1.19
Poultry[b]	Developed	1.1	NR[c]	NR	NR	0.10	0.32	1%	1.5%	2%	0.078	0.117	0.157
	Developing	NR	NR	NR	NR	0.02	0.24	1%	1.5%	2%	0.012	0.018	0.023

a The range of estimates reflects cool to warm climates. Cool climates have an average annual temperature below 15°C; temperate climates have an average annual temperature between 15°C and 25°C; and warm climates have an average annual temperature above 25°C.

b Poultry include chickens, ducks, and turkeys.

c Not Reported.

Sources: Except for poultry, emission factors were developed from: feed intake values and feed digestibilities used to develop the enteric fermentation emission factors (see Appendix A); MCF, and B_o values reported in Woodbury and Hashimoto (1993). All manure is assumed to be managed in dry systems, which is consistent with the manure management system usage reported in Woodbury and Hashimoto (1993). Emission factors for poultry are based on Safley et al. (1992) and Woodbury and Hashimoto (1993).

Appendix C   Derivation of Tier 2 Enteric Fermentation Equations

This appendix summarizes the derivation of the relationship between net energy (NE) and digestible energy (DE) that is used to estimate total feed-intake requirements for cattle. This derivation is drawn from Gibbs and Johnson (1993).

As described in the main text, the relationship among the energy values of feed consumed by cattle can be summarized as follows:

Digestible Energy	=	Gross Energy - Fecal Losses
Metabolizable Energy = Losses		Digestible Energy - Urinary and Combustible Gas
Net Energy	=	Metabolizable Energy - Heat Increment

Net Energy	=	Gross Energy - Fecal Losses - Urinary and Combustible Gas Losses - Heat Increment

NRC (1984) presents the following quantitative relationships among these energy values:

$$ME = 0.82 \times DE \quad (C.1)$$

$$NE_m = 1.37 \times ME - 0.138 \times ME^2 + 0.0105 \times ME^3 - 1.12 \quad (C.2)$$

$$NE_g = 1.42 \times ME - 0.174 \times ME^2 + 0.0122 \times ME^3 - 1.65 \quad (C.3)$$

where:

DE   = digestible energy in Mcal/kg (dry matter basis);

ME   = metabolizable energy in Mcal/kg (dry matter basis);

NE_m = net energy for maintenance in Mcal/kg (dry matter basis); and

NE_g = net energy for growth in Mcal/kg (dry matter basis).

Using these relationships, the ratio of NE_m and NE_g to ME or DE can be derived as follows:

$$NE/DE = 1.123 - 4.092 \times 10^{-3} \times DE\% + 1.126 \times 10^{-5} \times (DE\%)^2 - 25.4/DE\% \, (C.4)$$

$$NE_g/DE = 1.164 - 5.160 \times 10^{-3} \times DE\% + 1.308 \times 10^{-5} \times (DE\%)^2 - 37.4/DE\% \, (C.5)$$

where:

NE/DE   = the ratio of net energy consumed for maintenance, lactation, work and pregnancy to digestible   energy consumed;

NE_g/DE = the ratio of net energy consumed for growth to digestible energy consumed; and

DE%   = digestible energy as percentage of gross energy, expressed in percent (e.g., 65%).

Graph C-1 shows the relationships in graphical form. As shown in the graph, the ratio of NE to DE is non-linear, with an increasing slope with decreasing DE. These relationships imply that at lower values of DE, cattle are able to recover a decreasing portion of the energy to use for maintenance or growth.

For purposes of estimating methane emissions from cattle, applying these relationships to cattle consuming relatively low-quality feeds (such as cattle in many tropical countries) may be inappropriate because the relationships were developed based on analyses of the higher-quality feeds typically found in the U.S. temperate agriculture system. Consequently, the experimental basis for extrapolating the non-linear relationships to low levels of DE is not very strong.

In examining other energy systems, it is seen that they also indicate that the rate of net energy retention declines at lower values of digestible energy. Unlike the NRC system, however, many imply a *linear* relationship between NE and DE. The U.K. energy system (ARC, 1980), which is typical of the energy systems used in Europe, has a slope for the linear NE_m:DE relationship that is similar to the slope of the non-linear NRC relationship in the range of 65%-70% digestibility. Similarly, the slope of the U.K. NE_g:DE relationship is similar to the slope of the non-linear NRC relationship in the range of 60%-65% digestibility.

To avoid possible biases in estimating feed-intake requirements in this study, the relationships were extrapolated linearly for DE values below 65% using the average slopes of the NRC relationships between 60% and 70% DE. The derived equations are as follows:

$$NE/DE \ = \ 0.298 + 0.00335 \times DE\% \ (C.6)$$

$$NE_g/DE = -0.036 + 0.00535 \times DE\% \ (C.7)$$

Graph C-2 shows the extrapolated linear relationships along with the non-linear estimates. As expected, the linear extrapolations fall *above* the original non-linear estimates.

The implication of making this adjustment to the NRC (1984) relationship for the global emissions estimate is relatively minor. Gibbs and Johnson (1993) report that using the non-linear relationship to estimate global emissions from cattle increases the 1990 emissions estimate by .001 Gg, from .0581 Gg to .0591 Gg. Considering the wide range of factors that contribute to uncertainty in the estimates, including characterization of animal populations, this adjustment has a minor influence on the estimates.

Graph C-1: NRC NE:DE Relationship

NE to DE Ratio by DE
Derived from NRC (1984)
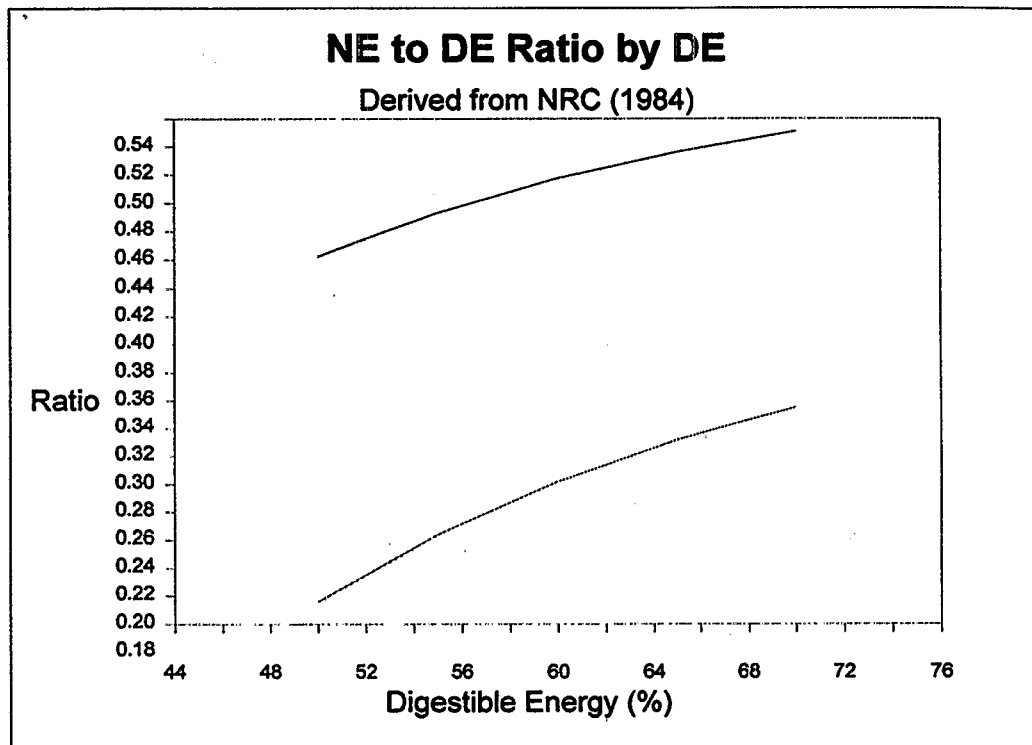
NE$_m$

NE$_g$

Graph C-2: Linear Extrapolation Of The NRC NE:DE Relationship

NE to DE Ratio by DE
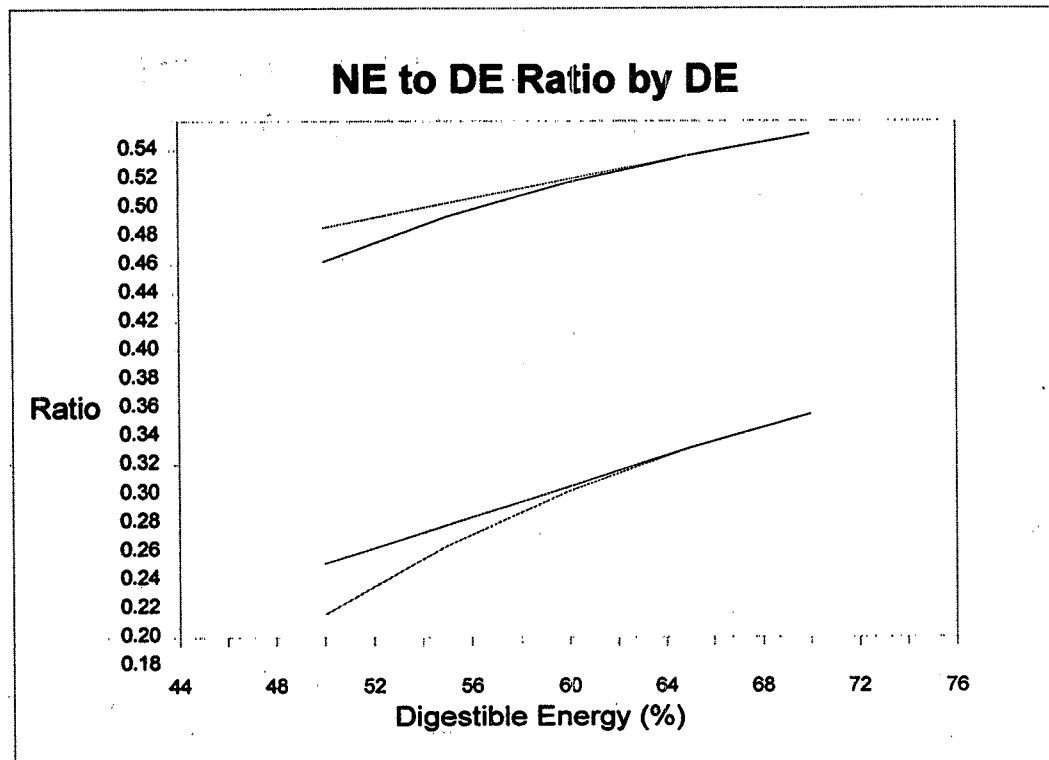
NE$_m$ Linear Extrapolation

NE$_g$ Linear Extrapolation

4.3 Methane Emissions from Flooded Rice Fields

4.3.1 Overview

Anaerobic decomposition of organic material in flooded rice fields produces methane (CH_4), which escapes to the atmosphere primarily by diffusive transport through the rice plants during the growing season. Upland rice fields, which are not flooded and therefore do not produce significant quantities of CH_4, account for approximately 10% of the global rice production and about 15% of the global rice area under cultivation. The remaining area is wetland rice, consisting of irrigated, rainfed, and deepwater rice. The global wetland rice area harvested annually in the early 1980s was about 123.2 million hectares, over 90% of which was in Asia (Neue et al., 1990).[13]

Of the wide variety of sources for the atmospheric CH_4, rice paddy fields are considered one of the most important sources. The Intergovernmental Panel on Climate Change (Watson et al. 1992) estimated the global emission rate from paddy fields to be ranging from 20 to 150 Tg/yr, averaged 60 Tg/yr. This is about 5-30% of the total emission from all sources. This figure is mainly based on field measurements of CH_4 fluxes from paddy fields in the United States, Spain, Italy, China, India, Australia and Japan.

The measurements at various locations of the world show that there are large temporal variations of CH_4 fluxes and that the flux differs markedly with soil type, application of organic matter and mineral fertilizer. The wide variations in CH_4 fluxes also indicate that the flux is critically dependent upon several factors including climate, characteristics of soils and paddy, and agricultural practices. On the other hand, about 90% of the world's harvested area of rice fields is located in Asia. Of the total harvested area in Asia, about 60% is located in India and China.

Methane production processes

The major pathways of CH_4 production in flooded soils are the reduction of CO_2 with H_2, with fatty acids or alcohols as hydrogen donor, and the transmethylation of acetic acid or methyl alcohol by methane producing bacteria (Takai 1970; Conrad 1989). In paddy fields, the kinetics of the reduction processes are strongly affected by the composition and texture of soil and its content of inorganic electron acceptors. The period between flooding of the soil and the onset of methanogenesis can apparently be different for the various soils. However, it is unclear if soil type also affects the rates of methanogenesis and CH_4 emission when steady state conditions have been reached (Conrad 1989).

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[13] The term "harvested area" has a different meaning than "cultivated area" in that the former accounts for double and triple cropping. For example, if a country has 10 million hectares of land under rice cultivation, all of which are double-cropped (i.e., two crops of rice are grown on each hectare each year), then this country has 20 million hectares of rice area harvested annually.

The redox[14] potential is the most important factor for production of CH_4 in soils. The Eh of the soil gradually decreases after flooding. This is due to a decrease in the activity of the oxidized phase and increased activity of the reduced phase. Takai et al. (1956) demonstrated that the redox potential of a soil must be below -200 mv in order to have CH_4 production. Yamane and Sato (1964) also showed that the evolution of CH_4 from flooded paddy soils did not commence until the Eh fell below -200 mv. There is a correlation between the soil redox potential and methane emission (Patrick et al. 1981; Cicerone et al. 1983; Yagi and Minami 1990).

Substrate and nutrient availability is also an important factor. Application of rice straw to paddy fields significantly increase CH_4 emission rate compared with application of compost prepared from rice straw or chemical fertilizer.

Soil temperature is known to be an important factor in affecting the activity of soil microorganisms. This is to a certain extent related to the soil moisture content because both the heat capacity and the heat conductivity are lower for a dry soil than for a wet soil. Yamane and Sato (1961) have already found that CH_4 formation reached a maximum at 40°C in waterlogged alluvial soils. Above 40°C, CH_4 formation decreased and stopped at 60°C. The formation was very small below 20°C.

It is generally recognized that CH_4 formation is only efficient in a very narrow range around neutrality (pH from 6.4 to 7.8). Flooding will have an increasing effect on pH in acid soil, while it will decrease the pH in alkaline soil. The increase of pH in acid soils is mainly due to the reduction of acidic Fe^{3+} to Fe^{2+}.

Growing plants on soils may also affect the emission of gaseous CH_4. At later growth stages of rice, more nitrogen gas and less CH_4 were found in wetlands soils planted to rice than in an unplanted rice field (Yoshida 1978). Yamane and Sato (1963) found that flooded soils planted with rice frequently evolve less CH_4 than the corresponding uncropped sites. The addition of sulfate as chemical fertilizer to flooded soils also influences the production of CH_4 because of its effect on raising the redox potential and of the toxic effect of its reduction product. Also, the addition of sulfate increases the activities of sulfate-reducing bacteria, which outcompete methanogens for the substrate. Sulfate must be reduced before CH_4 is formed in paddy soils (Takai 1980).

The addition of nitrate as chemical fertilizer to flooded soils may also suppress the production of CH_4. Because nitrate acts as a terminal electron acceptor in the absence of molecular oxygen for anaerobic respiration and it poises the redox potential of soils at values such that the activity of strict anaerobes is prevented.

There are three processes of CH_4 release into the atmosphere from rice paddies. Methane loss as bubbles from paddy soils is a common and significant mechanism. Diffusion loss of CH_4 across the water surface is another process. The third, CH_4 transport through rice plants, which has been reported (Seiler et al. 1984; Cicerone et al. 1983; Minami and Yagi 1988; Nouchi et al. 1990), as the most important phenomenon.

Many researchers reported that more than 90% of the total CH_4 released from rice paddies is diffusive transport through the aerenchym system of the rice plants and not through diffusion or escape of bubbles across the air-water interface. Emission through plants may be expected to show great seasonal variations tied to environmental changes in soil conditions and variations in plant growth stage, respiration and photosynthesis rates.

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[14] Redox refers to oxidation-reduction, two processes that take place simultaneously. Oxidation is the loss of an electron by an atom, and reduction is the gain of an electron by an atom.

Although CH_4 flux rates are revealed to be a function of the total amount of CH_4 in the soil, there is a possibility that the gas may be consumed in the thin oxidized layer close to the soil surface and in deep flooding water. It is known that soil methanogenic bacteria can grow with CH_4 as their sole energy source, and other soil bacteria, *Nitrosomonas* species consume CH_4 (Seiler and Conrad 1987). Methane is also leached to ground water as a small part is dissolved in water.

Global emissions from rice paddies

The area harvested of paddy rice has increased from 86×10^6 ha in 1935 to 144×10^6 ha in 1985, which means an annual average increase of 1.05%. The average annual increase has been 1.23% between 1959 and 1985. However, in the last few years, the expansion of the total acreage of paddy is decreasing. (Minami, 1993)

About 90% of the world's harvested area of rice paddies is located in Asia. Of the total harvested area in Asia, about 60% is located in India and China. Although we had no detailed data available for the estimation of CH_4 flux from India and China in 1990, recently some data are published for Asian countries as shown in Table 2.

TABLE 2
METHANE EMISSION FROM RICE PADDY FIELDS IN VARIOUS LOCATIONS OF THE WORLD

Location	Daily average (g/m^2 day)	Flooding period (days)	Season total (g/m^2)	Literature
China (Hangzhou)				Wang et al. (1989)
Early rice	0.19	75-95	14-18	
Late rice	0.69	80-140	55-97	
Single rice	0.44	120-150	53-66	
China (Tuzu)	1.39	120	167	Khalil et al. (1991)
India	0.04-0.46	60	2-28	Parashar et al. (1991)
Italy	0.10-0.68	130	12-77	Schutz et al. (1989)
Japan				Yagi & Minami (1990, 92)
Ryugasaki (Peat soil)	0.39	115	45	
Ryugasaki (Gley soil)	0.07-0.37	110	8-43	
Tsukuba (Andosol)	<0.01-0.10	130	<1-13	
Spain	0.10	120	12	Seiler et al. (1984)
Thailand				Yagi et al. (1992)
Suphan Buri	0.47-0.77	97-109	51-75	
Khlong Luang	0.09	83	7	
Chai Nat	0.04	94	4	
USA				
California	0.25	100	25	Cicerone et al. (1983)
Texas	0.05-0.36	84-85	5-31	Sass et al. (1990, 91)
Louisiana	0.27-0.48	77	21-37	Lindau et al. (1991)

The IPCC (Watson et al. 1990) presented a candidate list of CH_4 sources to the atmosphere as annual release rates. The total annual sources is constrained to be 500×10^{12} g CH_4/yr. Rice paddies are listed as a source of 60×10^{12} g CH_4 with a factor of 7 width in the likely range from 20 to 150×10^{12} g CH_4/yr.

Global emission of CH_4 from rice paddies reported by several researchers are summarized in Table 3. Extrapolation of emission rates to a global scale is very difficult, because the effects of variations in agricultural practices, number of crops per year, soil types and other factors discussed above are uncertain.

More recently, the IPCC (Watson et al., 1992) presented that rice paddies are constrained to be $< 60 \times 10^{12}$ g CH_4/yr with the range of 20 to 100×10^{12} g CH_4/yr. This is the most reasonable data at this moment.

TABLE 3
GLOBAL ANNUAL METHANE EMISSION FROM RICE CULTIVATION AS ESTIMATED BY DIFFERENT AUTHORS

Reference	Estimate (Tg CH$_4$ y^{-1})
Koyama (1964)	190
Ehhalt and Schmidt (1978)	280
Cicerone and Shetter (1981)	59
Khalil and Rasmussen (1983)	95
Seiler et al (1984)	35- 59
Blake (1984)	142-190
Crutzen (1985)	120-200
Holzapfel-Pschorn and Seiler (1986)	70-170
Cicerone and Oremland (1988)	60-170
Schutz et al. (1989)	50-150
Aselman and Crutzen (1989)	30- 75
Schutz and Seiler (1989)	60-140
Wang et al. (1990)	70-170
Neue et al. (1990)	60-120
Bouwman (1990)	25- 60
Yagi and Minami (1990)	53-114
IPCC (1990)	22- 73
IPCC (1992)	25-170
Minami and Yagi (1993)	20-100
	12-113

4.3.2 Methods For Estimating Emissions[15]

Emissions of methane from rice fields can be represented as follows:

$$F_c = \phi_{comp} \times E \quad (1)$$

where F_c is the estimated emission of methane from a country (c) in Tg/yr, ϕ_{comp} is the "composite emission factor" (Tg/hectare/yr) representative of the conditions in a country, and E is the "extrapolant" (hectare-years). The composite emission factor is evaluated from direct field measurements of methane fluxes, and the extrapolant consists of the product of the rice area harvested per year and the fraction of the year the fields are used for growing rice: E = A (hectares) $\times$ T (years). The extrapolant is obtained from geographical and agricultural archives.

In practice it is simpler to calculate the total annual emissions from a country as a sum of the emissions over a number of conditions. The emissions differ under each condition and

$$F_c = \sum_i \sum_j ... \sum \phi_{ijk} ... A_{ijk} ... T_{ijk} ... \quad (2)$$

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[15]From Kalil, 1993, reporting recommendations of the expert group.

represent the effect of the biological, chemical, and physical factors that control methane emissions from rice fields.

where ijk... are categories under which methane emissions from rice fields may vary. For instance, i may represent water levels in the rice fields such as fields inundated for the duration of the growing season (flooded regime) or fields under water only intermittently, either from managed irrigation when water is not readily available or when rains do not maintain flooded conditions throughout the growing season (intermittent regime) or highland rice when the fields are seldom flooded during the growing season (dry regime). j may represent fertilization regimes under each of the conditions represented by the index i, and so on. As more factors are identified, more categories need to be included. Inclusion of additional factors does not, however, lead to an automatic improvement of the total emissions since errors propagate and may create large uncertainties. Similarly, using extremely simplified methods for calculating the representative flux (ϕ_{comp}) also may lead to substantial errors.

From field experiments it is apparent that methane emissions from rice fields are affected by many factors. The working group focused on the factors for which there was sufficient information on both the emission factors and the extrapolants. Including the available information in the present estimates of country-by-country emissions may improve the accuracy, but at present it is not certain which factors have the greatest effect on emissions.

The factors clearly identified by field experiments are 1) water level and its history in the growing season, 2) soil temperature, 3) fertilizer applications, 4) soil type, 5) cultivar, and 6) agricultural practices such as direct seeding or transplanting. Data show that higher temperatures, continuously flooded fields, some types of organic fertilizers and certain cultivars lead to higher emissions compared to rice grown at lower temperatures, with intermittent or managed irrigation in which the fields are not continuously inundated and use of chemical fertilizers.

At present there are insufficient data to incorporate most of these factors. Nonetheless, the estimates can be improved substantially by incorporating the current knowledge on the first two factors, namely water levels and temperature. For some countries the effects of organic and mineral fertilizer can be included. Inclusion of the remaining factors may be feasible within 1-2 years.

Documentation and Accountability

Data on rice agriculture under different water management techniques may be available from most of the important rice producing countries. Therefore, the minimal equation for estimating emissions from each country are to include estimates for the three water regimes namely, flooded, intermittently flooded, and rarely flooded rice agriculture.

There is a consensus that individual countries may use as much detail as can be scientifically justified, based on laboratory and field experiments and theoretical calculations, to arrive at the estimate of emissions from rice agriculture in their country. These details should be incorporated into sub-categories (indices j,k,... in Eqn. 2) under each of the three main water management categories in Eqn. 2 so that they can be compared at that level with data from other countries.

In all cases, the emission inventory must be fully documented. The documentation has two aspects. First, method of calculation must be specified as in Eqn. 2. Matrices of emission factors and extrapolants must be delineated. Second, all data and original sources must be referenced if not included explicitly as part of the inventory report. It is desirable in all cases to rely on published information whether from the country's government, an international organization such as the UN - FAO or the scientific literature.

Default Methodologies

In many cases, especially in the beginning of the process, there will be important rice growing areas for which specific fluxes or details of extrapolants will not be available. In such cases the recommended methodology is to adopt the emission factors from the nearest region where data are available or the most similar climatic zone from which data are available. If data on irrigation practices are not available, it should be taken as the flooded regime.

4.3.3 Summary Of Recommended Method

1 Base years: 1990 as averaged over 1989-1991.

2 Use:

   a Area of rice agriculture under flooded regime = A (flooded) in m^2.
   b Emission factor for flooded conditions, over the three years for emissions from nearby region or similar climatic zone = ϕ ($Tg/m^2/day$).
   c Number of days under cultivation when flooded = T (days/yr)
   d Calculate Flux(flooded) = A(flooded) × ϕ(flooded) × T(flooded) for each of the three base years and take average.
   e Correct flux for temperature effect:

$$multiply\ by\ [Q_{10}]^{(T-T_b)/^{\circ}C}$$

   where Q_{10} is the ratio of the flux at temperature 10°C above the base temperature.
   f Repeat steps a)-e) for intermittently flooded rice agriculture: Flux(intermittent).
   g Repeat steps a)-e) for dryland rice: Flux(dry).
   h Average annual country flux is F(country) = Flux(flooded) + Flux(intermittent) + Flux(dry).

3 Where data are available on fertilizer type, it may be incorporated into the calculations.

   Calculate each of the three factors in h) as follows:
   i Flux(flooded) = Flux(flooded|organic) + Flux(flooded|chemical)
      where Flux(flooded|organic) is calculated according to steps a)-e) using the emission factors, areas, time of flooding, and temperatures applicable to the amount of rice grown under flooded conditions using organic fertilizers. Flux(flooded|chemical) is calculated analogously.
   j Calculate Flux(intermittent) and Flux(dry) analogously to i)

4 Each additional factor may be incorporated in the same manner by further subdividing each category in 3).

The procedure is described by the following general formulae:

$$Base: \quad F = \sum_{i} \phi_i A_i Ti \qquad (3)$$

i represents water management regimes - flooded, intermittent, dry.

Adding fertilizer effect:

$$\phi_i A_i T_i = \sum_j \phi_{ij} A_{ij} T_{ij} \qquad (4)$$

where j represents different fertilizer types. Each component if (3) is calculated by (4).

Additional factors: soil type, for example:

$$\phi_{ij} A_{ij} T_{ij} = \sum_k \phi{ijk} A_{ijk} T_{ijk} \qquad (5)$$

where k represents different soil types. Each component of (4) is calculated from (5) and then each component of (3) is calculated from (4).

The process may be continued for more factors.

Default Data.

Tables 4-6 and 4-7 present regional and country specific information regarding rice production and emissions.
In Table 4-6 the area information is based on statistics from the FAO Yearbook, China Agricultural Yearbook, and World Rice Statistics from IRRI. The crop calendars of Matthews et al. (1991) were modified to reflect the period in which a particular crop was grown, rather than the total possible period in which a crop can be grown. Using the length of the season calculated from the crop calendar leads to an overestimate of the methane emission season. The two exceptions to this are Louisiana, where two crops are being grown, and Italy, which has a longer growing season for rice than the crop calendars suggest. The Matthews et al. tables were the basis for estimating season length and then were reduced by 10 to 45 days depending on the crop calendar season length. In Table 4-6, "Season Length" is the weighted average of all growing seasons after they have been adjusted for the crop calendar length.

Table 4-7 provides default emission factors for intermittently flooded and flooded rice fields. If countries have local measurements data available to develop country-specific emission factors, these should be used and documented. Default values in Table 4-7 can be used for initial calculations where local measurements are not adequate. A "modal" average seasonal flux for Asian countries was estimated to be 20 (+/-5) mg/m^2 hr, Q^{10} = 1.8, with a base temperature of (T_b) = 23 °C. The base temperature is representative of average seasonal temperatures in the areas of Asia where flux measurements are available (20-25 °C). These flux values are representative of flooded rice fields where organic amendments are used, which is common in rice growing countries where measurements are not available. Dryland rice was assigned a flux of 0 and shallow rainfed rice was used as a proxy for *intermittently* flooded rice fields.

Based on the work of Chen et al. (1993) and Sass et al. (1992) intermittently flooded rice was assumed to have a flux rate that is 60% of flooded rice fields. Currently there are no data readily available on intermittently flooded rice. The current estimating procedure probably underestimates the flux of methane from this category, since it assumes that there is one drought episode in every crop of shallow rainfed rice fields worldwide.

TABLE 4-6 DEFAULT ACTIVITY DATA - HARVESTED RICE					
Country	1990 Area 1000s ha	Season Length (days)	Continuously Flooded (%)	Dry (%)	Intermittently Flooded (%)
AMERICAS					
USA	1114	123	100	0	0
Belize	2	139	10	90	0
Costa Rica	53	103	10	90	0
Cuba	150	139	100	0	0
Dominican Rep	93	103	98	2	0
El Salvador	15	123	10	90	0
Guatemala	15	139	10	90	0
Haiti	52	123	40	60	0
Honduras	19	123	10	90	0
Jamaica	0	123	40	60	0
Mexico	123	130	41	59	0
Nicaragua	48	123	10	90	0
Panama	92	103	5	95	0
Puerto Rico	0	123	75	25	0
Trinidad & Tobago	5	103	45	55	0
Argentina	103	121	100	0	0
Bolivia	110	101	25	75	0
Brazil	4450	101	18	76	6
Chile	35	121	79	21	0
Columbia	453	124	53	47	0
Equador	266	100	40	10	50
Guyana	68	123	95	5	0
Paraguay	34	101	50	50	0
Peru	185	167	84	16	0
Surinam	58	123	100	0	0
Uruguay	108	138	100	0	0
Venezuela	119	103	90	10	0

TABLE 4-6 (CONTINUED) DEFAULT ACTIVITY DATA - HARVESTED RICE				
Country	1990 Area 1000s ha	Season Length (days)	Continuously Flooded (%)	Dry (%)	Intermittently Flooded (%)
ASIA					
Brunei	1	82	79	21	0
Hong Kong	0	123	100	0	0
Syria	0	123	100	0	0
Turkey	52	123	100	0	0
India	42321	107	53	15	32
Pakistan	103	103	100	0	0
Bangladesh	10303	132	14	14	72
Burma	4774	139	42	15	43
Nepal	1440	90	29	4	67
Afghanistan	173	103	100	0	0
Bhutan	25	169	21	15	64
China	33265	115	93	2	5
Indonesia	10403	110	78	15	7
Iran	570	103	100	0	0
Iraq	78	123	100	0	0
Japan	2073	123	96	4	0
Malaysia	2073	123	96	4	0
Philippines	3413	98	54	12	34
Sri Lanka	793	122	65	7	28
Taiwan	700	119	97	3	0
Thailand	9878	123	22	12	66
Kampuchea	1800	134	34	27	39
Laos	625	123	11	49	40
Vietnam	6069	119	65	7	28
N Korea	673	103	67	13	20
S Korea	1237	103	91	1	8

TABLE 4-6 (CONTINUED) DEFAULT ACTIVITY DATA - HARVESTED RICE				
Country	1990 Area 1000s ha	Season Length (days)	Continuously Flooded (%)	Dry (%)	Intermittently Flooded (%)
EUROPE					
Albania	2	123	100	0	0
Bulgaria	11	103	100	0	0
France	20	139	100	0	0
Greece	15	103	100	0	0
Hungary	11	123	100	0	0
Italy	208	102	100	0	0
Portugal	33	123	100	0	0
Romania	37	123	100	0	0
Spain	81	103	100	0	0
Former USSR	624	103	100	0	0
Former Yugoslavia	8	123	100	0	0
PACIFIC					
Australia	97	128	100	0	0
Fiji	13	81	50	0	0
Solomon Islands	0	102	38	0	0
Papua/New Guinea	0	102	38	0	0
AFRICA					
Algeria	1	138	100	0	0
Angola	18	121	100	0	0
Benin	7	123	10	90	0
Burkina Faso	19	123	89	11	0
Burundi	12	167	25	75	0
Cameroon	15	103	25	75	0
C African Rep	10	123	25	75	0
Chad	39	123	25	75	0
Comoros	13	100	100	0	0
Congo	4	121	25	75	0
Egypt	427	123	100	0	0
Gabon	0	121	25	75	0
Gambia	14	123	90	10	0
Ghana	85	139	24	76	0
Guinea Bissau	57	123	25	75	0
Guinea	608	123	8	47	45
Ivory Coast	583	123	6	87	7
Kenya	15	139	25	75	0
Liberia	168	123	0	94	6
Madagascar	1135	167	35	19	46

TABLE 4-6 (CONTINUED) DEFAULT ACTIVITY DATA - HARVESTED RICE					
Country	1990 Area 1000s ha	Season Length (days)	Continuously Flooded (%)	Dry (%)	Intermittently Flooded (%)
Malawi	29	137	25	75	0
Mali	222	123	25	75	0
Mauritania	14	123	100	0	0
Morocco	6	138	100	0	0
Mozambique	109	121	25	75	0
Niger	29	102	35	65	0
Nigeria	1567	103	28	55	17
Rwanda	3	167	25	75	0
Senegal	73	103	25	75	0
Sierra Leone	339	139	1	67	32
Somalia	5	103	50	50	0
South Africa	1	167	100	0	0
Sudan	1	103	50	50	0
Swaziland	0	167	25	75	0
Tanzania	375	137	10	26	64
Togo	21	139	4	96	0
Uganda	37	137	25	75	0
Zaire	393	101	5	90	5
Zambia	11	121	25	75	0
Zimbabwe	0	121	25	75	0

Source: Khalil (1993), personal communication.

TABLE 4-7		
SEASONAL AVERAGE EMISSION FACTORS CORRECTEDFOR AVERAGE TEMPERATURE		
Growing Season Average Temperature	**Emission Factor kg/ha/day**	
	Continuously Flooded	Intermittently Flooded
15	2.91	1.75
16	3.09	1.85
17	3.28	1.97
18	3.48	2.09
19	3.68	2.21
20	3.91	2.34
21	4.14	2.94
22	4.39	2.64
23	4.66	2.80
24	4.94	2.97
25	5.24	3.15
26	5.56	3.34
27	5.90	3.54
28	6.25	3.75
29	6.63	3.98
30	7.03	4.22
31	7.46	4.48
32	7.91	4.75
33	8.39	5.03
34	8.90	5.34
35	9.44	5.66

Source: Khalil (1993), personal communication

4.3.4 References

Aselmann, I. and P.J. Crutzen 1989: The global distribution of natural freshwater wetlands and rice paddies, their net primary productivity, seasonality and possible methane emission. J. Atm. Chem., 8, 307-358.

Bingemer, H.G. and P.J. Crutzen 1987: The production of methane from solid wastes. J. Geophys. Res., 92(D), 2181-2187.

Blake, D.R. and F.S. Rowland 1988: Continuing worldwide increase in tropospheric methane, 1978 to 1987. Science, 239, 1129-1131.

Bouwman, A.F. 1990: Exchange of greenhouse gases between terrestrial ecosystems and the atmosphere. Ed. A.F. Bouwman, In Soil and the greenhouse Effect. John Wiley and Sons, 62-127.

Bremner, J.M. and A.M. Blackmer 1982: Composition of soil atmospheres, In Methods of soil analysis, Part 2, Chemical and Microbiological Properties, Agronomy Monograph No. 9, 873-901.

Chen, Z., D. Li, K. Shao, and B. Wang 1983: Features of CH4 emission from rice paddy fields in Beijing and Nanjing, China. Chemosphere, 26(1-4):239-246.

China Agricultural Yearbook, 1990. Agribookstore, Hampton, VA.

Cicerone, R.J., J.D. Shetter and C.C. Delwiche 1983: Seasonal variation of methane flux from a California rice paddy. J. Geophys. Res., 88, 7203-7209.

Cicerone, R.J. and R.S. Oremland 1988: Biogeochemical aspects of atmospheric methane. Global Biogeochem. Cycles, 2, 299-327.

Conrad, R. 1989: Control of methane production in terrestrial ecosystems, In Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere, eds. M.O. Andreae and D.S. Schimel, 39-58.

Ehhalt, D.H. and U. Schmidt 1978: Sources and sinks of atmospheric methane. Pure Appl. Geophys., 116, 452-464.

Graedel, T.E. and J.E. McRae 1980: On the possible increase of the atmospheric methane and carbon monoxide concentrations during the last decade. Geophys. Res. Lett., 7, 977-979.

Grist, D.H. 1986: Rice. Longman, Inc., New York, U.S.A. 6th edition.

Holzapfel-Pschorn, A., R. Conrad, and W. Seiler 1985: Production, oxidation, and emission of methane in rice paddies. FEMS Microbiology Ecology, 31, 343-351.

Holzapfel-Pschorn, A., and W. Seiler 1986: Methane emission during a cultivation period from an Italian rice paddy. J. Geophys. Res., 91, 11803-11814.

Huke, R.F. 1982: Rice area by type of culture; south, southeast and east Asia. International Rice Research Inst., IRRI, Los Banos, Los Banos, Philippines.

IRRI, 1991: World Rice Statistics 1990. International Rice Research Inst., Los Banos, Laguna, Philippines.

Khalil, M.A.K. 1993: Working Group Report: Methane Emissions from Rice Fields. In A.R. van Amstel (ed.), Proceeding of an International IPCC Workshop on Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control. RIVM Report no. 481507003, Bilthoven, The Netherlands. pp. 239-244.

Khalil, M.A.K., R.A. Rasmussen, M.X. Wang, and L.Ren 1991: Methane emission from rice fields in China; Environ. Sci. Tech., 25:979-981.

Lal, S., S. Venkataramani, and B.H. Subbaraya 1993: Methane flux measurements from paddy fields in the tropical Indian region; Atmos. Environ., 27A:1691-1694.

Lindau, C.W., and P.K. Bollich 1993: Methane emissions from Louisiana first and ratoon rice crop; Soil Science, 156:42-48.

Matthews, E., I. Fung, and J. Lerner 1991: Methane emission from rice cultivation; Geographic and seasonal distribution of cultivated areas and emissions. Global Biogeochem. Cycles, 5, 3-24.

Minami, K. 1993: Methane Emissions from Rice Production. In A.R. van Amstel (ed.), Proceeding of an International IPCC Workshop on Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control. RIVM Report no. 481507003, Bilthoven, The Netherlands. pp. 143-162.

Minami, K., and K. Yagi 1988: Method for measuring methane flux from rice paddies. Jpn. J. Soil Sci. Plant Nutr., 59, 458-463 (in Japanese).

Minami, K., K. Kumagai, K. Yagi, and H. Tsuruta 1992: unpublished.

Neue, H.U., P. Becker-Heidmann and H.W. Scharpenseel. 1990: Organic matter dynamics, soil properties and cultural practices in rice lands and their relationship to methane production. Ed. A.F. Bouwman, In Soils and the Greenhouse Effect. John Wiley and Sons, 457-466

Nouchi, I., S. Mariko, and K. Aoki 1990: Mechanisms of methane transport from the rhizosphere to the atmosphere through rice plant. Plant physiology, 94, 59-66.

Nozaki, M. 1989: Rice cultivation in Tropical Africa. Trop. Agr. Rec. Center. (In Japanese).

Patrick, W.H. Jr. 1981: The role of inorganic redox systems in controlling reduction in paddy soils. In Proc. Symp. Paddy Soil, 107-117, Science Press, Beijing, Spring Verlag.

Ponnamperuma, F.N. 1972: The chemistry of submerged soils, Adv. Agron., 24, 29-69.

Rasmussen, R.A., and M.A.K. Khalil 1981: Increase in the concentration of atmospheric methane. Atmos. Environ., 15,883-886.

Rasmussen, R.A., and M.A.K. Khalil 1984: Atmospheric methane in the recent and ancient atmospheres: concentrations, trends, and interhemispheric gradient. J. Geophys. Res., 89(D), 11599-11605.

Rowland, F.S. 1991: Stratospheric ozone in the 21st century, The chlorofluorocarbon problem, Environ. Sci. Technol., 25, 622-628.

Sass, R.L., F.M. Fisher, P.A. Harcombe, and F.T. Turner 1991a: Mitigation of methane emissions from rice fields: possible adverse effects of incorporated rice straw. Global Biogeochemical Cycles, 5(3): 275-287.

Sass, R.L., F.M. Fisher, Y.B. Yang, F.T. Turner, and M.F. Jund 1992: Methane emissions from rice fields: the effect of flood water management. Global Biogeochemical Cycles, 6(3): 249-262.

Seiler, W., A. Holzapfel-Pschorn, R. Conrad, and D. Scharffe 1984: Methane emissions from rice paddies. J. Atmos. Chem., 1, 241-268.

Seiler, W., and R. Conrad 1987: Contribution of tropical ecosystems to the global budgets of trace gases, especially CH_4, H_2, CO and N_2O, In R.E. Dickinson (Ed.), Geophysiology of Amazonia. Vegetation and Climate Interactions, 133-160, Wiley and Sons, New York.

Sheppard, J.C., H. Westberg, J.F. Hopper, K. Ganesan, and P. Zimmerman 1982: Inventory of global methane sources and their production rates. J. Geophys. Res., 87(C), 1305-1312.

Schutz, H., A. Holzapfel-Pschorn, R. Conrad, H. Rennenberg, and W. Seiler 1989: A 3-year continuous record on the influence of daytime, season, and fertilizer treatment on methane emission rates from an Italian rice paddy. J. Geophys. Res., 94, 16405-16416.

Steele, L.P., E.J. Dlugokencky, P.M. Lang, P.P. Tans, R.C. Martin, and K.A. Masarie 1992: Slowing down of the global accumulation of atmospheric methane during the 1980s. Nature, 358, 313-316.

Takai, Y., T. Koyama, and T. Kamura 1956: Microbial metabolism in reduction process of paddy soils (Part I), Soil & Plant Food, 2, 63-66.

Takai, Y. 1970: The mechnism of methane fermentation in flooded paddy soil. Soil Sci. Plant Nutr., 16, 238-244.

Takai, Y. 1980: Microbial study on the behavior of the paddy soils. Fert. Sci., 3, 17-55 (in Japanese).

Thompson, A.M., and R.J. Cicerone 1986: Possible perturbations to atmospheric CO, CH_4 and OH. J. Geophys. Res., 91(D), 10858-10864.

United Nations, 1992: FAO Production Yearbook, vol. 46. Food and Agriculture Organization of the United Nations, Rome.

Wang, W.C., Y.L. Yung, A.A. Lacis, J.E. Mo, and J.E. Hansen 1976: Greenhouse effects due to man-made perturbations of trace gases. Science, 194, 685-690.

Wassman, R., H. Schutz, H. Papen, H. Rennenberg, W. Seiler, A. Dai, R. Shen, X. Shangguan, and M. Wang. 1993: Quantification of methane emissions from Chinese rice fields (Zhejiang Province) as influenced by fertilizer treatment. Biogeochemistry, 20:83-101.

Watson, R.T., H. Rodhe, H. Oeschger, and U. Siegenthaler 1990: Greenhouse gases and aerosol, In Climate Change, the IPCC scientific assessment, ed. J.T. Houghton et al., 1-40.

Watson, R.T., L.G. Meira Filho, E. Sanhueza, and A. Janetos 1992: Greenhouse gases: Sources and Sinks, In Climate Change 1992, The Supplementary Reports to The IPCC Scientific Assessment, eds. J.T. Houghton, B.A. Callander, and S.K. Varney, 25-46.

Yagi, K., and K. Minami 1990: Effect of organic matter application on methane emission from some Japanese paddy fields. Soil Sci. Plant Nutr., 36, 599-610.

Yagi, K., and K. Minami 1990: Estimation of global methane emission from paddy fields. Res. Rep. Div. Environ. Planning, NIAES, 6, 131-142 (in Japanese).

Yagi, K., K. Minami, and Y. Ogawa 1990: Effects of water percolation on methane emission from paddy fields, NIAES, Res. Rep. Div. Environ. Planning, 6, 105-112 (1990).

Yagi, K., and K. Minami 1991: Emission and production on methane in the paddy fields of Japan, JARQ, 25, 165-171.

Yagi, K., and K. Minami 1993: Spatial and temporal variations of methane flux from a rice paddy field. In The Biogeochemistry of Global Change; Radiative Trace Gases, R.S. Oremland (ed.), Chapman & Hall, New York, in press.

Yagi, K., H. Tsuruta, and K. Minami 1992: Methane emission from Japanese and Thai paddy fields. CH_4 and N_2O Workshop, Tsukuba, in press.

Yamane, I., and K. Sato 1961: Effect of temperature on the formation of gases and ammonium nitrogen in the water-logged soils. Sci. Rep. Res. Inst. Tohoku Univ. D(Agr.), 12, 31-46.

Yamane, I., and K. Sato 1963: Decomposition of plant constituents and gas formation in flooded soil, Soil Sci. Plant Nutr., 9, 28-31.

Yamane, I., and K. Sato 1964: Decomposition of glucose and gas formation in flooded soil, Soil Sci. Plant Nutr., 10, 127-133.

Yoshida, T. 1978: Microbial metabolism in rice soils. In Soils and Rice, Int. Rice Res. Inst., 445-463.

4.4 Agricultural Burning

4.4.1 Introduction

Where there is open burning associated with agricultural practices, a number of greenhouse gases (GHG) are emitted from combustion. All burning of biomass produces substantial CO_2 emissions. However, in agricultural burning, the CO_2 released is not considered to be **net** emission. The biomass burned is generally replaced by regrowth 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. Therefore the long term net emissions of CO_2 are considered to be zero. Agricultural burning releases other gases in addition to CO_2 which are by-products of incomplete combustion: methane, carbon monoxide, nitrous oxide, and oxides of nitrogen, among others. These non-CO_2 trace gas emissions from biomass burning are <u>net</u> transfers from the biosphere to the atmosphere. It is important to estimate the emissions in national inventories.[1]

There are two major types of agricultural burning addressed in this section -- savanna burning and field burning of crop residues. The approach is essentially the same as that used for non-CO_2 trace gases for all burning of unprocessed biomass, including traditional biomass fuels and open burning of cleared forests. For all these activities, there is a common approach in the proposed methodology, in that crude estimates of non-CO_2 trace gas emissions can be based on ratios to the total carbon released. The carbon trace gas releases (CH_4 and CO) are treated as direct ratios to total carbon released. To handle nitrogen trace gases, nitrogen to carbon ratios are used to derive total nitrogen released and then emissions of N_2O and NO_x are estimated based on ratios of these gases to total nitrogen released. Tables B and C provide suggested default values for non-CO_2 trace gas emission ratios. These are presented with ranges, which emphasize their uncertainty. However, the basic calculation methodology requires that users select a best estimate value.[2]

The calculation of immediate trace gas emissions, based on the default emission ratios provided in Tables B and C, produces relatively crude estimates with substantial uncertainties.[3] Use of specific emission ratios which vary by type of burning, region, etc. may allow for more precise calculations. The calculations described here ignore the contemporary fluxes associated with past burning activities. These delayed releases are known to exist, but are poorly understood at present. This and other possible refinements are discussed at the end of this section.

4.4.2 Prescribed Burning: Savannas

Background

The term savanna refers to tropical and subtropical vegetation formations with a predominantly continuous grass cover, occasionally interrupted by trees and shrubs.[4] These formations exist in Africa, Latin America, Asia, and Australia. The growth of vegetation in savannas is controlled by alternating wet and dry seasons: most of the growth occurs during the wet season; man-made and/or natural fires are frequent and generally occur during the dry season. The global area of savannas is uncertain, in part due to lack of data and in part due to differing ecosystem classifications. Estimates of the areal extent of savannas range from 1300-1900 million hectares worldwide, about 60% of which

are humid savannas (annual rainfall of 700 mm or more) and 40% are arid savannas (annual rainfall of less than 700 mm).[5] Large-scale burning takes place primarily in the humid savannas because the arid savannas lack a sufficient grass cover to sustain fire. Humid savannas are burned every one to four years on average with the highest frequency in the humid savannas of Africa.[6]

Savannas are intentionally burned during the dry season primarily for agricultural purposes such as ridding the grassland of weeds and pests, promoting nutrient cycling, and encouraging growth of new grasses for animal grazing. Savanna burning may be distinguished from other biomass burning activities like open forest clearing because there is little net change in the ecosystem biomass in the savanna after the vegetation regrows during the wet season. Consequently, while savanna burning results in instantaneous gross emissions of CO_2, it is reasonable to assume that the net carbon dioxide released to the atmosphere is essentially zero because the vegetation typically regrows between burning cycles.[7] Savanna burning does release several other important trace gases: methane (CH_4), carbon monoxide (CO), nitrous oxide (N_2O), and oxides of nitrogen (NO_x, i.e., NO + NO_2).

Estimates of global emissions of these gases due to savanna burning have been based on estimates of the annual instantaneous gross release of carbon from this activity and ratios of the other trace gases released from burning to total carbon released by burning. Estimates of the annual instantaneous gross release of carbon from savanna burning are highly uncertain because of lack of data on the aboveground biomass density of different savannas, the savanna area burned annually, the fraction of aboveground biomass which actually burns, and the fractions which oxidizes (i.e., combustion efficiency). The methodology that is proposed in the next section although conceptually quite simple, takes these factors into account. The approach allows for estimation of non-CO_2 trace gases released by savanna burning based on default data sets and assumptions from average literature values for various regions and types of savannas. It also allows for more accurate national estimates if data and assumptions can be developed to reflect national average conditions accurately. Nonetheless, a wide variety of technical details and open scientific issues remain important research topics.

Calculations

There are two basic components to the calculation. First, it is necessary to estimate the total amount of carbon released to the atmosphere from savanna burning. These are not considered net emissions, but are needed to derive non-CO_2 trace gas emissions which are net emissions. What is required is the annual area burned for the various types of savannas, where type is based primarily upon above and below ground biomass, and perhaps climatological conditions and nutrient status. If data are not directly available, estimates can be derived based on total savanna area[8] and average percentages of savanna burned annually, as shown in Table A. Based on the area and type of savanna burned, the amount of carbon released can be calculated (a reflection of biomass densities, fractions burned, carbon contents and combustion efficiencies). The second component of the calculation is the same as for other biomass burning categories -- emission ratios are applied to estimate the amount of trace gas released based on the amount of carbon released (Table B provides default emission ratios).

The approach formally recognizes that countries generally possess more than one savanna type, each with different characteristics, such as vegetative cover, that would affect trace gas emissions from burning. Also, the savanna area within a country may not be burned all at once, but rather in stages over the course of the dry season. Since the amount and nature (e.g., moisture content) of the vegetation changes during the year, factors such as biomass exposed to burning and burning efficiency will vary among the savanna areas

burned at different times. The data requested by this methodology focus upon country-specific types of savannas and the country-specific rate of burning for each type.[9]

It is also recognized that national and regional estimates of the percent of savanna area burned annually are highly uncertain. An example selection of regional estimates is included in Table A. Though regional variability is great, the methodology, by focusing upon a simple classification of savanna type and the burning by type, can be implemented using data that are available to most countries. The methodology is intended to be flexible to allow users to define the savanna types and/or geographic subregions for calculations. National experts are encouraged to carry out the calculations at the finest levels of detail for which credible data can be obtained. Finally, by varying the rate and/or type of savannas burned, national experts can easily test to the sensitivity of the calculated emissions to the uncertainties in the data.

Part I: Total Carbon Released From Savanna Burning

In order to calculate the carbon released to the atmosphere from savanna burning, these data are required:

- Area of savanna;

- Fraction of savanna area burned annually;

- Average aboveground biomass density (tonnes dry matter/hectare) of savannas;

- Fraction of aboveground biomass which actually burns;

- Fraction of aboveground biomass that is living;

- Fraction of living and of dead aboveground biomass oxidized, (i.e., combustion efficiency of living and dead biomass); and

- Fraction of carbon in living and dead biomass.

Not all of these data must be provided by the user. Initially one could pool the living and dead biomass if data are not available. More importantly, Table A provides much of the basic default data that only need to be refined for country-specific relevance. Given the data, the steps to calculate emissions are not overly difficult. One simply calculates from the area burned the total carbon released based upon the factors listed above. In addition to the data in Table A, other recommended default values are included in the step-by-step discussion below.[10]

The following equations summarize the calculations to estimate the total carbon released due to the burning of savannas:

EQUATION I

Area of Savanna Burned Annually (ha)

=

Total Area of Savanna (ha) x Fraction Burned Annually

EQUATION 2

Biomass Burned (t dm)

=

Area of Savanna Burned Annually (ha) x Aboveground Biomass Density (t dm/ha) x Fraction Actually Burned

---

EQUATION 3

Carbon Released from Live Biomass (t C)

=

Biomass Burned (t dm) x Fraction that is Live x Combustion Efficiency x Carbon Content of Live Biomass (t C/t dm)

EQUATION 4

Carbon Released from DeadBiomass (t C)

=

Biomass Burned (t dm) x Fraction that is Dead x Combustion Efficiency x Carbon Content of Dead Biomass (t C/t dm)

EQUATION 5

Total Carbon Released (t C)

=

C Released from Live Material (t C) + C Released from Dead Material (t C)

In the first equation, the savanna area in the country is multiplied by the percentage of the savanna area that is burned annually, if statistics on area burned annually are not directly available. If national experts have data on the area burned annually they should use this and begin with equation 2. In the second, area burned is multiplied by aboveground dry biomass per hectare (ha) on the savanna at the time of burning and the fraction of biomass which actually burns. Regional estimates of rates of savanna burning and biomass densities are presented in Table A. The fraction actually burned accounts for the fact that when savannas are burned, not all of the biomass on each hectare is actually exposed to flame. If detailed information is not available, a general default value in the range of 0.8-0.85 is recommended.[11]

The aboveground biomass density before burning is a function of the type of savanna being burned and the time of year in which burning occurs.[12] The values for West African savannas provided in Table A correspond to mid-season fires, except for those of the Sahel where burning occurs early. If statistics on maximum biomass density and fraction of maximum biomass density present at the time of burning are not available, countries can use an average biomass density instead. According to this analysis, average savanna biomass densities are lowest in tropical Asia, at about 5 tons per hectare (t/ha),[13] average around 6.6 t/ha in tropical Africa and tropical America,[14] and range between 2 and 6 t/ha in Australia.[15] These estimates have an uncertainty of ±30% based on field measurements.[16]

As mentioned, these regional average densities are presented in Table A and can be used as default values if average biomass density for a specific country or savanna type is not known.

In the third and fourth equations, the living and the dead portions of aboveground biomass burned are multiplied by their respective combustion efficiencies and carbon contents. Estimates of the fraction of aboveground biomass that is living for West African savannas range from 20 to 55% (Table A). Data suggest that the live portion burns with a combustion efficiency that ranges between 65 and 95% and the dead portion with essentially 100% efficiency.[17] If combustion efficiencies are not available, 80% and 100% for the living and dead portions, respectively, can be used. If country or ecosystem values are not available, then the values 0.45 t C/t dry biomass and 0.40 t C/t dry biomass can be used as default values for the carbon contents of the living and dead portions, respectively[18].

The total carbon released from savanna burning (Equation 5) is estimated by summing the carbon released from the living and the dead biomass fractions, calculated in Equations 3 and 4.

Part 2: Non-CO_2 Trace Gas Emissions

Once the carbon released from savanna burning has been estimated, the emissions of CH_4, CO, N_2O, and NO_x can be calculated using emission ratios. (Default values are presented in Table B.)[19] The amount of carbon released due to burning is multiplied by the emission ratios of CH_4 and CO relative to total carbon released 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.

To calculate emissions of N_2O and NO_x, first the carbon released is multiplied by the estimated ratio of nitrogen to carbon (N/C ratio) in savanna biomass by weight (0.006 is a general default value for savanna biomass burning[20]). This yields the total amount of nitrogen (N) released from the biomass burned. The total N released is then multiplied by the ratios of emissions of N_2O and NO_x relative to the N released to yield emissions of N_2O and NO_x (expressed in units of N). To convert to full molecular weights, the emissions of N_2O and NO_x are multiplied by 44/28 and 30/14, respectively.[21]

The non-CO_2 trace gas emissions calculations from burning are summarized as follows:

CH_4 Emissions = (carbon released) x (emission ratio) x 16/12

CO Emissions = (carbon released) x (emission ratio) x 28/12

N_2O Emissions = (carbon released) x (N/C ratio) x (emission ratio) x 44/28

NO_x Emissions = (carbon released) x (N/C ratio) x (emission ratio) x 30/14

TABLE A
REGIONAL SAVANNA STATISTICS

Region	Fraction of Area Burnt Annually to Total Savanna	Aboveground Biomass Density (t dm/ha)	Fraction of Biomass Actually Burned	Fraction of Aboveground Biomass that is Living
Tropical America	0.50	6.6 ±1.8		
Tropical Asia	0.50	4.9		
Tropical Africa	0.75	6.6 ±1.6		
Sahel zone	0.05-0.15[a]	0.5-2.5[a]	0.95	0.20
North Sudan zone	0.25-0.50[a]	2-4[a]	0.85	0.45
South Sudan zone	0.25-0.50[a]	3-6[a]	0.85	0.45
Guinea zone	0.60-0.80[a]	4-8[a]	0.9-1.0	0.55
Australia	5-70	2.1-6		

Sources: Hao et al., 1990, except where noted. These figures are growing season average biomass values, considered most appropriate for general default values

[a] Menaut et al. (1991) These figures are maximum biomass values. For these arid sub-regions, maximums are considered the most appropriate default values.

Note: Biomass density is in tonnes of dry matter (dm) per hectare (ha).

TABLE B
EMISSION RATIOS FOR SAVANNA BURNING CALCULATIONS

Compound	Ratios	
CH_4 [1]	0.004	(0.002 - 0.006)
CO [1]	0.06	(0.04 - 0.08)
N_2O [3]	0.007	(0.005 - 0.009)
NO_x [3]	0.121	(0.094 - 0.148)

Sources: [1] Delmas, 1993

[2] Lacaux, et al., 1993

[3] Crutzen and Andreae, 1990

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 emission relative to total nitrogen released from the fuel.

4.4.3 Prescribed Burning: Agricultural Crop Wastes

Background

Large quantities of agricultural wastes are produced, from farming systems worldwide, in the form of crop residue.[22] Burning of crop residues, like the burning of savannas, is not thought to be a net source of carbon dioxide (CO_2) because the carbon released to the atmosphere during burning is reabsorbed during the next growing season. However, crop residue burning is a significant net source of CH_4, CO, NO_x, and N_2O. This section accounts for emissions of these non-CO_2 gases from field burning of agricultural crop residues (Burning of agricultural crop residues as an energy source is covered in the *Energy* chapter, in the section entitled *Traditional Biomass Fuels*).

The amount of agricultural wastes produced varies by country, crop, and management system. Cereal crops produce between 0.6 and 2.5 tonnes of straw per tonne of grain.[23] For example, wetland rice cultivated under a moderate level of management in the Philippines was found to produce between 0.6 and 0.9 tonnes of straw per tonne of grain.[24] Approximately 3.1 billion tonnes of crop residue are produced each year, with about 60% originating in the developing world, and 40% in the developed world.[25]

Burning of agricultural wastes in the fields is a common practice in the developing world. It is used primarily to clear remaining straw and stubble after harvest and to prepare the field for the next cropping cycle. In Southeast Asia, burning is the major disposal method for rice straw,[26] which accounts for about 31% of the agricultural waste in the developing world. Sugar cane residues, which make up about 11% of the world's agricultural waste, are primarily disposed of by burning.[27] It has been estimated that as much as 40% of the residues produced in developing countries may be burned in fields, while the percentage is lower in developed countries.[28] Estimates suggest that approximately 425 Tg dry matter agricultural wastes (~200 Tg C) are burned in the fields in developing countries and that about one-tenth as much is burned in developed countries.[29]

Calculations

The methodology for estimating greenhouse gas emissions from burning of agricultural wastes is based, as in savanna burning, on 1) total carbon released, which is a function of the amount and efficiency of biomass burned, the carbon content of the biomass, and 2) the application of emission ratios of CH_4 and CO to total carbon released, and N_2O and NO_x to total nitrogen released from biomass fires which are available from the scientific literature on biomass burning. Default values are provided in Table C.

Part 1: Total Carbon Released from Burning Agricultural Residues

Data required, for each crop type, to calculate the amount of carbon burned in agricultural wastes are listed below:

- Amount of crops produced with residues that are commonly burned,
- Ratio of residue to crop product
- Fraction of residue burned
- Dry matter content of residue
- Fraction oxidized in burning (combustion efficiency
- Carbon content of the residue

There are standard default or literature values available for many of these data. Table D provides a summary of available default data. The most important data for users to provide are the actual amount of crops produced (by type) with residues that are commonly burned. Annual crop production statistics by country for most of the crops from which residues are burned may be found in the *FAO Production Yearbooks*.[30] Crop-specific data for each country on ratios of residue to crop, fraction of residue burned, dry matter content of residue, and carbon content of residue can be incorporated at any time to replace the default values. The essential data needed from the countries are the actual amount of crops with residues that are commonly burned. A potentially very valuable data source is the recent study the BUN/UNCED study by Professor D. Hall (and others) of Kings College, London.[31]

From production data one can estimate the actual material (in carbon units) that is burned. One simple procedure is shown below:

Total carbon released =

annual production data (tonnes of biomass per year) for each crop,

x the ratio of residue to crop product (fraction),

x the average dry matter fraction (tonnes of dry matter / tonnes of biomass),

x the fraction actually burned in the field,

x the combustion efficiency (fraction),

x the carbon fraction (tonnes of carbon / tonnes dry matter)

It is highly desirable to use country specific data for these values wherever possible. Example estimates of residue/crop product ratios, average dry matter fraction and carbon fraction for certain crops are presented in Table D.[32] If no other data are available, the following assumptions regarding the percentage of crop residue burned in the field can be used as very crude default factors: for developing countries 0.25, and for developed countries a much smaller share possibly 0.10 or less.[33] A default value of 0.90 can be used to account for the approximate 10% of the carbon that remains on the ground (combustion efficiency).[34]

Part 2: Non-CO$_2$ Trace Gas Emissions

Once the carbon released from field burning of agricultural resides has been estimated, the emissions of CH_4, CO, N_2O, and NO_x can be calculated based on emission ratios (default values are provided in Table C).[35] 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.

To calculate emissions of N_2O and 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. Some crop specific values are given in Table D and 0.015 is a general default value for crop residues.[36] The total N released is then multiplied by the ratios of emissions of N_2O and NO_x relative to the N content of the fuel to yield emissions of N_2O and NO_x (expressed in units of N). To convert to full molecular weights, the emissions of N_2O and NO_x are multiplied by 44/28 and 30/14, respectively.[37]

The calculation for trace gas emissions from burning is summarized as follows:

CH_4 Emissions = Carbon Released × (emission ratio) × 16/12

CO Emissions = Carbon Released × (emission ratio) × 28/12

N_2O Emissions = Carbon Released × (N/C ratio) × (emission ratio) × 44/28

NO_x Emissions = Carbon Released × (N/C ratio) × (emission ratio) × 30/14

TABLE C
EMISSION RATIOS FOR AGRICULTURAL RESIDUE BURNING CALCULATIONS

Compound	Ratios
CH_4 [1]	0.005 Range 0.003 - 0.007
CO [2]	0.06 Range 0.04 - 0.08
N_2O [3]	0.007 Range 0.005 - 0.009
NO_x [3]	0.121 Range 0.094 - 0.148

Sources:

[1] Delmas, 1993

[2] Lacaux, et al., 1993

[3] Crutzen and Andreae, 1990

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 emission relative to total nitrogen released from the fuel.

TABLE D
SELECTED CROP RESIDUE STATISTICS

Product	Residue/Crop Product	Dry Matter Content (%)	Carbon Content (% dm)	Nitrogen-Carbon (N/C) Ratio
Wheat	1.3	78-88	48.53	0.012
Barley	1.2	78-88	45.67	
Maize	1	30-50	47.09	0.02
Oats	1.3			
Rye	1.6			
Rice	1.4	78-88	41.44	0.014
Millet	1.4			0.016
Sorghum	1.4			0.02
Pulse				
Pea	1.5			
Bean	2.1			
Soya	2.1			0.05
Potatoes	0.4	30-60	42.26	
Feedbeet	0.3	10-20 [1]	40.72 [1]	
Sugarbeet	0.2	10-20 [1]	40.72 [1]	
Jerusalem artichoke	0.8			
Peanut	1			

Sources: Strehler and Stützle, 1987

Sugarbeet data from Ryan and Openshaw, 1991

Nitrogen content from Barnard and Kristoferson, 1985

Note: [1] These statistics are for beet leaves.

Possible refinements of the basic calculations

The basic calculations presented above address the immediate release of non-CO_2 trace gases when savannas or crops are burned. This is believed to be the most important effect of biomass burning on GHG emissions and the best characterized at present. However, there are other issues not treated in these calculations. The effect of past burning on current emissions is one such issue. The longer-term release or uptake of these gases following burning is an important research issue and may eventually be included in refinements of the calculations. In particular, grassland fires (savanna burning) may perturb the soils sufficiently to release additional N_2O and NO_x. Little is known about the magnitude of this flux so these emissions may not be included in the first application of the methodology. It is less likely that such delayed releases are significant after field burning of agricultural residues, but this may also require further study.

Long term changes in soil carbon are certainly possible as a result of agricultural practices. In the land use change and forestry chapter, there is a general default assumption that soil carbon is gradually lost from agricultural lands over many years after forests are cleared. In fact, depending on the specific agricultural and soil management practices (including burning) which are used, there may be a variety of impacts on soil carbon. For example, repeated burning of savannas and crop residues in fields may create a store of carbon as charcoal which increases over time. This is an area which requires further research and may lead to more detailed emissions estimation methods in the future.

In addition, agricultural practices (e.g. overgrazing) which degrade the productivity of grasslands or other agricultural lands reduce the amount of aboveground biomass which regrows and could be considered a gradual emissions source for carbon dioxide. This situation is not included in the basic calculations, but could be included in more refined calculations. National experts should determine whether or not this is important for their country, and whether or not they are able to provide input data.

4.4.4 References: Agricultural Burning

Andreae, M.O. 1990. Biomass burning in the tropics: *Impact on environmental quality and global climate.* Paper presented at the Chapman Conference on Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications, 19-23 March 1990, Williamsburg, Virginia.

Barnard, G.W. 1990. Use of agricultural residues as fuel. In: Pasztor, J., and L.A. Kristoferson (eds.). *Bioenergy and the Environment.* Westview Press, Boulder, Colorado. pp. 85-112.

Barnard, G.W., and L.A. Kristoferson. 1985. *Agricultural Residues as Fuel in the Third World.* Technical Report No. 5. Earthscan, London.

Bolin, B., E.T. Degens, P. Duvigneaud, and S. Kempe. 1979. The global biogeochemical carbon cycle. In: Bolin, B., E.T. Degens, P. Duvigneaud, and S. Kempe (eds.). *The Global Carbon Cycle.* SCOPE 13. Wiley, Chichester. pp. 1-56.

Bouliere, F., and M. Hadley. 1970. The ecology of tropical savannas. *Annual Review of Ecology Systems* 1:125-152.

Bucher, E.H. 1982. Chaco and Caatinga-South American arid savannas, woodlands and thickets. In: Huntley, B.J., and Walker, B.H. (eds.). *Ecology of Tropical Savannas.* (Ecological Studies 42). Springer-Verlag, Berlin. pp. 48-79.

Coutinho, L.M. 1982. Ecological effects of fire in Brazilian cerrado. In: Huntley, B.J., and B.H. Walker (eds.). *Ecology of Tropical Savannas*. (Ecological Studies 42). Springer-Verlag, Berlin. pp. 273-291.

Crutzen, P.J., M.O. Andreae. 1990. Biomass burning in the Tropics: Impact on atmospheric chemistry and biogeochemical cycles. *Science* 250:1669-1678.

Crutzen, P.J. 1983. Atmospheric interactions -- Homogenous gas reactions of C, N, and S containing compounds. In: Bolin, B., and R.B. Cook (eds.). *The Major Biogeochemical Cycles and Their Interactions*. SCOPE 21. John Wiley, New York. pp. 67-114.

Delmas, R. 1993. An Overview of Present Knowledge on Methane Emission from Biomass Burning. in A.R, van Amstel (ed.). *Proceedings of an International IPCC Workshop: Methane and Nitrous Oxides, Methods in National Emissions Inventories and Options for Control, 3-5 February 1993, Amersfoort, NL.* RIVM Report no. 481507003, Bilthoven, NL, July.

Delmas, R.A. and D. Ahuja. 1993. Estimating National Methane Emissions from Anthropogenic Biomass Burning. Working Group Report: Methane Emissions from Biomass Burning. in A.R. van Amstel (ed.), *Proceedings of an International IPCC Workshop: Methane and Nitrous Oxides, Methods in National Emissions Inventories and Options for Control, 3-5 February 1993, Amersfoort, NL.* RIVM Report no. 481507003, Bilthoven, NL, July.

FAO/UNEP (Food and Agriculture Organization of the United Nations/United Nations Environment Programme). 1981. *Tropical Forest Resources Assessment Project*. FAO, Rome.

FAO. 1993. *Forest Resources Assessment 1990* - Tropical Countries. FAO Forestry Paper No. 112, FAO, Rome.

Galbally, I.E. 1985. The emission of nitrogen to the remote atmosphere: Background paper. In: Galloway, J.N., R.J. Charlson, M.O. Andreae, and H. Rodhe (eds.). *The Biogeochemical Cycling of Sulfur and Nitrogen in the Remote Atmosphere*. D. Reidel, Dordrecht. pp. 27-53.

González-Jiménez, E. 1979. Primary and secondary productivity in flooded savannas. In: UNESCO/UNEP/FAO (ed.). Tropical grazing land ecosystems of Venezuela. *Nat. Resour. Res.* 16:620-625.

Haggar, R.J. 1970. Seasonal production of *Andropogon gayanus*, 1. Seasonal changes in field components and chemical composition. *Journal of Agricultural Science* 74:487-494.

Hao, W.M., M.H. Liu, and P.J. Crutzen. 1990. Estimates of annual and regional releases of CO_2 and other trace gases to the atmosphere from fires in the tropics, based on the FAO statistics for the period 1975-1980. In: Goldammer, J.G. (ed.). *Fire in the Tropical Biota, Ecosystem Processes and Global Challenges*. Springer-Verlag, Berlin. pp. 440-462.

Harris, D.R. 1980. Tropical savanna environments: Definition, distribution, diversity, and development. In: Harris, D.R. (ed.). *Human ecology in savanna environments*. Academic Press, New York. pp. 3-27.

Hopkins, B. 1965. Observations on savanna burning in the Olokemeji Forest Reserve, Nigeria. *Journal of Applied Ecology* 2:367-381.

Howden, S.M., G.M. McKeon, J.C. Scanlan, J.O. Carter, and D.H. White. Methods for Exploring Options to reduce Greenhouse Gas Emissions from Tropical Grazing Systems. *Climatic Change*. In Press.

Huntley, B.J. 1982. South African savannas. In: Huntley, B.J., and B.H. Walker (eds.). *Ecology of Tropical Savannas*. (Ecological Studies 42). Springer-Verlag, Berlin. pp. 101-119.

Huntley B.J., and J.W. Morris. 1982. Structure of Nylsvley savanna. In: Huntley, B.J., and B.H. Walker (eds.) *Ecology of Tropical Savannas.* (Ecological Studies 42). Springer-Verlag, Berlin. pp. 433-455.

Johansson, T.B., H. Kelly, A.K.N. Reddy, and R.H. Williams. 1992. *Renewable Energy: Sources for Fuels and Electricity.* Island Press. Washington, DC.

Lacaux, J.P., H. Cachier and R. Delmas. 1993. Biomass Burning in Africa: An Overview of Its Impact on Atmospheric Chemistry. in P.J. Crutzen and J.G. Goldammer (eds.) *Fire in the Environment: The Ecological, Atmospheric and Climatic Importance of Vegetation Fires.* J. Wiley & Sons Ltd.

Lacey, C.J., J. Walker, and I.R. Nolde. 1982. Fire in Australian tropical savannas. In: Huntley, B.J., and B.H. Walker (eds.). *Ecology of Tropical Savannas.* (Ecological Studies 42). Springer-Verlag, Berlin. pp. 246-272.

Lanly, J.P. 1982. *Tropical Forest Resources.* Food and Agriculture Organization of the United Nations (FAO) Paper 30. FAO, Rome.

Lashof, D.A., and D.A. Tirpak (eds.). 1990. *Policy Options for Stabilizing Global Climate.* Report to Congress, U.S. Environmental Protection Agency, Washington, D.C.

Levine, J.S. (ed.). 1990. *Global Biomass Burning: Atmospheric, Climatic and Biospheric Implications.* The MIT Press. Cambridge, MA.

Lieth, H. 1978. *Patterns of Primary Productivity in the Biosphere.* Hutchinson Ross, Stroudsberg.

Lobert, J.M., D.H. Scharffe, W.M. Hao, and P.J. Crutzen. 1990. Importance of biomass burning in the atmospheric budgets of nitrogen-containing gases. *Nature* 346:552-554.

Menaut, J.C., L. Abbadie, F. Lavenu, Ph. Loudjani, and A. Podaire. 1991. Biomass burning in West African savannas. In: Levine, J. (ed.). *Global Biomass Burning.* MIT Press, Cambridge, in press.

Menaut, J.C., and J. Cesar. 1982. The structure and dynamics of a West African savanna. In: Huntley, B.J., and B.H. Walker (eds.). *Ecology of Tropical Savannas.* (Ecological Studies 42). Springer-Verlag, Berlin. pp. 8-100.

Menaut, J.C. 1990. *Biomass burning in West African savannas.* Presentation given at the Chapman Conference on Global Biomass Burning. Williamsburg, Virginia, March 19-23. Proceedings forthcoming: MIT Press, Cambridge, Massachusetts.

Ponnamperuma, F.N. 1984. Straw as a source of nutrients for wetland rice. In: *Organic Matter and Rice.* International Rice Research Institute, Los Baños. pp. 117-135.

San José, J.J., and E. Medina. 1976. Organic matter production in the Trachypogon savannas in Venezuela. *Tropical Ecology* 17:113-124.

Seiler, W., and P.J. Crutzen. 1980. Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning. *Climatic Change* 2:207-247.

Singh, K.P., and R. Misra. 1978. *Structure and Functioning of Natural, Modified and Silvicultural Ecosystems of Eastern Uttar Pradesh.* Technical Report MAB Research Project, Banaras Hindu University, Varanasi.

Strehler, A., and W. Stützle. 1987. Biomass residues. In: Hall, D.O., and R.P. Overend (eds.). *Biomass: Regenerable Energy.* John Wiley, Chichester. pp. 75-102.

U.S. HEW (U.S. Department of Health, Education, and Welfare). 1970. *Air Quality Criteria for Carbon Monoxide.* U.S. HEW, Washington, D.C.

Whittaker, R.H., and G.E. Likens. 1975. *The biosphere and Man*. In: Lieth, H., and R.H.

4.4.5 Endnotes

1   It is important to note, as discussed in the introduction to this document, that there is an intentional double counting of carbon emitted from combustion. First, CO_2 is calculated based on the assumption that all carbon in fuel is emitted as CO_2. Methods are provided to then estimate portions of total carbon which are emitted as CH_4 and CO. The reasons for this double counting are discussed in the introduction. For biomass combustion, CO_2 emissions are frequently not considered **net** emissions, and this is the cases for agricultural burning. One could argue, in such cases, that this burning could be considered a short term sink of CO_2. That is, a portion of carbon in biomass is being released as **net** emissions of CH_4 and CO, while regrowth is removing the full amount of the original carbon from the atmosphere in the next cycle. Each year plants take up a certain amount of carbon from the atmosphere. When they are burned some of that carbon is converted to CO, and CH_4, so that some amount less than the total CO_2 taken up by the plants is re-emitted as CO_2. See Howden et al. (in press), for a more detailed discussion of this proposal. Treating emissions of CO and CH_4 to the atmosphere, as a sink for atmospheric CO_2, however, is inconsistent with the proposed IPCC emissions methodology, for the same reasons that some of the carbon emissions from fossil fuel are double counted. Most importantly, the other carbon compounds emitted are converted back into CO_2 in the atmosphere over periods of days up to a decade or so. Thus, over the time horizons of interest for CO_2, (i.e. more than 100 years) there is no sink of CO_2.

2   Emissions inventory developers are encouraged to provide estimates of uncertainty along with these best estimate values where possible or to provide some expression of the level of confidence associated with various point estimates provided in the inventory. Procedures for reporting this uncertainty or confidence information are discussed in Volume 1: Reporting Instructions.

3   Emission ratios used in this section are derived from Crutzen and Andreae (1990), Delmas (1993), Delmas and Ahuja (1993) and Lacaux, et al. (1993) as presented in tables. 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. CO_2, N_2O, and NO_x are mainly emitted in the flaming stage, while CH_4 and CO are mainly emitted during the smoldering stage (Lobert et al., 1990). 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.

4   Bouliere and Hadley, 1970

5   Bolin et al. (1979), Whittaker and Likens (1975), Lanly (1982), Lacey et al. (1982), and Hao et al. (1990).

6   Harris, 1980; Bucher, 1982; Huntley, 1982; all as cited in Hao et al., 1990

7   If grazing pressure coupled with burning too often reduces biomass (i.e., degrades the quality of savannas), then this needs to be considered as a carbon dioxide source. This is not assumed in the basic calculations but could be included as a refinement if considered important.

8   Most countries with significant savanna area should have national statistics on the total area, but FAO publications (e.g. FAO, 1993) also provide country specific estimates.

9   If the area of savanna is not readily available, then the area of "open, broadleaved forests," including open, broadleaved, fallow areas, as defined by the U.N. Food and Agriculture Organization in FAO (1993) can be used as an estimate. This land area, corresponds to "mixed broadleaved forest-grassland tree formations with a continuous dense grass layer in which the [woody vegetation covers] more than 10% [of the area]" (Lanly, 1982). FAO (1993) provides 1990 estimates of this area, by country, for tropical America, Asia, and Africa. Hao et al. (1990) provide an estimate of the humid savanna area in Australia, based on work by Lacey et al. (1982).

10   It is hoped that individual countries have this information since it is needed to execute the proposed methodology. Regional estimates of these statistics are provided by Menaut (1990) and Hao et al. (1990) and reproduced in a table. More country-specific research is clearly needed on this issue before accurate inventories can be developed. This research should include data on savanna area burned annually, savanna biomass densities, live fractions of biomass, burning efficiencies, and carbon contents of savanna biomass. In the meantime, default values can be used.

11   Delmas and Ahuja, 1993.

12   Menaut et al. (1991) calculate this number by multiplying the maximum biomass density of the savanna (which generally is reached at the end of the growing season) by a coefficient that declines as the burning occurs later in the dry season.

13   Singh and Misra, 1978.

14   San José and Medina, 1976; González-Jiménez, 1979; Coutinho, 1982; Hopkins, 1965; Haggar, 1970; Menaut and César, 1982; and Huntley and Morris, 1982.

15   Lacey et al., 1982.

16   Hao et al., 1990.

17   Menaut et al., 1991.

18   Menaut et al., 1991.

19   This approach is adapted from Crutzen and Andreae, 1990, with some values updated based on more recent studies by Delmas (1993), Delmas and Ahuja (1993) and Lacaux et al. (1993).

20   from Crutzen and Andreae, 1990.

21   There is an inconsistency in the methodology in the treatment of the full molecular weight of NO_x. In fossil energy and industry discussions NO_x is expressed as though all of the N were in the form of NO_2. In biomass burning literature, (e.g., Crutzen and Andreae, 1990) NO_x is often discussed as though most of the emissions were in the form of NO. Therefore, the biomass burning discussions in these Guidelines convert NO_x-N to full weight using the

conversion factor (30/14) for NO. All other references to NO_x are based on the full weight of NO_2 (i.e., the conversion factor from NO_x-N would be 46/14).

22   Barnard (1990) outlines several broad categories of crop residue: woody crop residues (coconut shells, jute sticks, etc.), cereal residues (rice and wheat straw, maize stalks, etc.), green crop residues (groundnut straw, soybean tops, etc.), and crop processing residues (bagasse, rice husks, etc.).

23   Barnard, 1990; Ponnamperuma, 1984.

24   Ponnamperuma, 1984

25   Strehler and Stützle, 1987

26   Ponnamperuma, 1984

27   Crutzen and Andreae, 1990

28   Barnard and Kristoferson, 1985.

29   1 Tg dm = 10^{12} Grams of Dry Matter, estimates are from Crutzen and Andreae (1990)

30   See also *United Nations World Trade Yearbooks*.

31   In this context, one should also note the book *Renewable Energy: Sources for Fuels and Electricity* edited by Johansson et al. (1992).

32   Dry matter (dm), or dry biomass, refers to biomass in a dehydrated state. According to Elgin (1991), the moisture content of crop residue varies depending on the type of crop residue, climatic conditions (i.e., in a humid environment the residue will retain more moisture than in an arid environment), and the length of time between harvesting and burning of the residue. From a simple perspective, one can use the dry matter content values in Table D to convert from total crop residue to dry matter. For example, if 200 tonnes of crop residue with a moisture content of 10%, would have a dry matter content of 90%, equal to 180 tonnes of dry matter. To convert from dry matter to carbon content, an average value of 0.45 t C/t dm can be used in the cases where crop specific data are not available. The terms dry matter and dry biomass are used interchangeably in this text.

33   Crutzen and Andreae, 1990. The estimates are very speculative and should be used with caution. The actual percentage burned varies substantially by country and crop type. This is an area where locally developed, country specific data are highly desirable. As this issue is studied further, it may be possible to incorporate more accurate, country-and crop-specific percentages into future editions of the *Guidelines*.

34   To account for charcoal formation and other aspects of incomplete combustion. See Seiler and Crutzen (1980) and Crutzen and Andreae (1990).

35   This approach is adapted from Crutzen and Andreae, 1990, with some values updated based on more recent studies by Delmas (1993), and Delmas and Ahuja (1993).

36   Crop specific values are generally in the range of 0.01-0.02, from Crutzen and Andreae, 1990, so that 0.015 can be used as a generally representative value if no other information is available.

37   There is an inconsistency in the methodology in the treatment of the full molecular weight of NO_x. In fossil energy and industry discussions NO_x is expressed as though all of the N were in the form of NO_2. In biomass burning

literature, (e.g., Crutzen and Andreae, 1990) NO_x is often discussed as though the emissions were in the form of NO. Therefore, the biomass burning discussions in these Guidelines convert NO_x-N to full weight using the conversion factor (30/14) for NO. All other references to NO_x are based on the full weight of NO_2 (i.e., the conversion factor from NO_x-N would be 46/14).

4.5   Nitrous Oxide Emissions from Agricultural Soils

4.5.1 Introduction

This chapter covers emissions of nitrous oxide (N_2O) from agricultural soils. Estimates of N_2O emissions from the biosphere into the atmosphere are highly uncertain, but it is believed that about 70% originate from soils (Bouwman, 1990; Houghton et al., 1992). It seems reasonable then, to assume that changes in N cycling in soil systems have influenced the increases in atmospheric N_2O during the past century and will help dictate future changes in atmospheric N_2O. A direct effect, that can be quantified, is the increase in N input into the soil systems. This increase in N input is derived from atmospheric deposition, which ranges from about 0.5 g N $m^{-2} y^{-1}$ in the central U.S. to 6 g N $m^{-2} y^{-1}$ in western Europe (Andreae and Schimel, 1989), N fertilization with mineral N sources or animal manures and biological N fixation. Nitrogen fertilizer use and biological N-fixation are projected to continue to increase during the next 100 years (Hammond, 1990).

To determine N_2O emissions from agricultural soils for various parts of the earth, we must predict how much N_2O is produced from each unit of fixed N (chemically or biologically) that is added to the soil. To make this prediction we first must understand how and where N_2O is produced in the biosphere, what sinks exist for the gas, and how the gas moves from where it is produced into the atmosphere. Research during the past several decades provides an understanding of how N_2O is produced, factors that control it's production, source/sink relationships, and gas movement processes. However, even with this large amount of knowledge, we are not yet able to reliably predict the fate of a unit of N that is applied or deposited on a specific agricultural field. Studies of emissions of N_2O from presumably "similar" agricultural systems show highly variable results in both time and space. It is the complex interaction of the physical and biological processes involved that must be understood before appropriate predictive capability can be developed.

It is surprising that during the last few years, with the renewed interest in climate change and the role of radiatively active trace gases, little new information concerning emissions of N_2O from agricultural fields has been published. Many recent review papers and inventory assessments have all relied on published gas flux measurements from studies conducted, primarily, during the late 1970's and early 1980's. The number of flux measurements and the variety of soil conditions examined are limited. Therefore, the data from which these reviews and inventories have been drawn are also limited and because of the limitations, inappropriate conclusions may have been drawn.

As noted in the OECD/OCDE (1991) report, we know that N_2O is produced primarily from the microbial processes, nitrification and denitrification in the soil. In well aerated conditions, where soil moisture content is low enough not to limit aeration, N_2O emissions from nitrification of ammonium based fertilizers can be substantial (Bremner and Blackmer, 1978; Duxbury and McConnaughey, 1986). Other work suggests that N_2O release is a byproduct of nitrification (Yoshida and Alexander, 1970) and may occur by denitrification of nitrite by nitrifying organisms under oxygen stress (Poth and Focht, 1985). Recent evidence indicates that in well aerated, porous soils, little N_2O may evolve but much larger amounts of NO may be emitted during nitrification (Williams et al., 1993). In wet soils where aeration is restricted, denitrification is generally the source of N_2O (Smith, 1990). Under these conditions both the rate of denitrification and the $N_2O/(N_2 +$

N_2O) ratio must be known to evaluate N_2O emissions through denitrification. According to Smith (1990), soil structure and water content, affecting the balance between diffusive escape of N_2O and its further reduction to N_2 are important among the factors determining the proportions of the two gases.

Research has also shown us that a number of individual factors are controllers of nitrification and denitrification. Such factors as soil water content, which regulates oxygen supply; temperature, most organisms have a temperature range over which reaction rates are optimal; nitrate or ammonium concentration, substrates may individually regulate reaction rates and in the case of denitrification regulate the N_2O/N_2 ratio; available organic carbon, denitrifiers require a usable organic carbon source and microbial respiration of organic carbon may also regulate oxygen supply; and pH, is a controller of both nitrification and denitrification and the N_2O/N_2 ratio in denitrification.

Increases in the amount of N added to the soil generally increases N_2O emissions from the soil (Bouwman, 1990). The temporal pattern of N_2O emissions following fertilization is generally that of a large efflux of N_2O occurring for a short time (about six weeks). After this time, emission rates are reduced to fluctuate around a low base-line level independent of the amount of fertilizer applied (Mosier et al., 1983). Some studies indicate that N_2O emission rates are higher for ammonium-based fertilizers than for nitrate (Eichner, 1990). For example, Bremner et al. (1981) found a much higher proportion of N_2O released from anhydrous ammonia than from urea or ammonium sulfate. Bouwman's (1990) review, however, suggested no particular trend in N_2O emissions related to fertilizer type. Byrnes et al. (1990) suggest that N_2O emissions from the nitrification of fertilizers may be more closely related to soil properties than to the N source that is supplied. Mineral N applications along with organic matter amendments generally increase total denitrification and N_2O production.

As discussed in more detail by Mosier (1989), N_2O emissions from the soil can vary by orders of magnitude from a location both spatially and temporally. These heterogeneities in both space and time in measured gas fluxes and in the microbial activity which produces the gases make predictions highly uncertain.

External factors also perturb "normal" soil N cycling and thus increase N_2O emissions. Land use conversion has been a primary factor in the past (Houghton and Scole, 1990), and conversion of forests and grasslands to croplands accelerated C and N cycling and increased N_2O emissions from the soil. Globally, land use conversion is important now only in tropical areas. Most of the conversions of forests and grasslands in the northern hemisphere occurred 50 to 200 years ago (Hammond, 1990). Global changes may impart changes in soil temperature and moisture which will directly influence N cycling.

4.5.2 1991 OECD N_2O Emission Methodology

The first OECD/OCDE (1991) methodology for calculating N_2O emissions from nitrogen fertilizers was based on the amount of each type of commercial fertilizer nitrogen consumed (in mass units of N), an emission coefficient for the fraction of applied N that is released as N_2O-N for each fertilizer type, and a factor used to convert the emission from N_2O-N to N_2O. Emissions of N_2O-N are estimated from each fertilizer type, summed over all types, and then converted to units of N_2O:

(1) N_2O-N Emissions (tonnes N_2O-N) $= \Sigma(F_f \times E_f)$

where:

F = Fertilizer Consumption (tonnes N)

E = Emission Coefficient (Tonnes N_2O-N released/tonne N applied)

f = Fertilizer type

N_2O Emissions (tonnes N_2O) = N_2O-N Emissions (tonnes N_2O-N) x 44/28.

The Working Group suggested dropping the attempt to calculate N_2O emissions based on the type of commercial fertilizer N applied. Considering the number of agricultural systems that exist world wide and the number of sources of N available for use, the data set available for these analyses are quite small. As a result, single studies at single locations can dominate, and possibly skew the analysis. Another point is that since most of the data cited were from studies conducted only during the cropping season, or part of the cropping season, little is known about N emissions following crop harvest and before planting in the spring. Recent research (Sommerfeld et al., 1993) indicates that appreciable N_2O emissions can occur from snow covered soils and Goodroad and Keeney (1984) noted large fluxes of N_2O during winter thaw periods. The Expert Group concluded that there is no justification for including fertilizer type in the equation, as existing data shows wide, overlapping ranges of emission factors for each commercial fertilizer type. Many studies show that field variables such as the interaction of soil type, soil water content, and substrate availability regulate N_2O emissions rather than N source.

The second OECD/OCDE (1991) methodology includes the fertilizer source variable discussed in section A and also includes the crop type to which the fertilizer is applied. The approach is the same as section A except that emissions of N_2O-N are summed over all fertilizer and crop types, instead of just over all fertilizer types.

(2) N_2O-N Emissions (tonnes N_2O-N) $= \Sigma_{fc}$ $(F_{fc} \times E_{fc})$

where   F = Fertilizer Consumption (tonnes N)

E = Emission Coefficient (tonnes N_2O-N released/tonne N applied)

f = Fertilizer Type

c = Crop Type

N_2O Emissions (tonnes N_2O) = N_2O-N Emissions (tonnes N_2O-N) x 44/28

Including crop type in the calculation seems reasonable since the type of crop tends to regulate soil water content, the timing of mineral N uptake, and the release of mineralizable carbon into the soil. All of these factors are regulators of N_2O-forming processes. But as noted in OECD/OCDE (1991) there is not enough information to calculate the necessary coefficients for each crop type. This calculation is therefore no longer recommended.

4.5.3 Suggested N_2O emission calculation method

As the data available from which to calculate N_2O emission coefficients from either N fertilizer source or crop type are not adequate to make such calculations, and it is unlikely that within the next few years sufficient studies will be conducted to make adequate coefficient calculations, the following, simplified calculation is recommended for estimating N_2O emission from agricultural soils:

(3) N_2O-N Emission (tonnes N_2O-N) $= \Sigma$ F x 0.01

where   F = Fertilizer Consumption (tonnes N)

where   F = Fertilizer Consumption (tonnes N)

N_2O Emissions (tonnes N_2O) = N_2O-N Emission (tonnes N_2O-N) x 44/28

Because of the limitations of the data available and the scope of the data, a value of 1%/year of fertilizer (both mineral and organic) N direct emission from agricultural fields does not seem unreasonable. The literature on field N_2O flux are adequate to provide the order of magnitude of the multiplication coefficient, greater than 0.001 and less than 0.1 (CAST, 1992).

There is certainly room for arguing the validity of this suggestion. For example in a flooded rice field, when fertilizer N is added immediately before flooding, little N_2O is emitted (Freney et al., 1981). We do not know, however, how much N_2O evolves from the field when the water is drained for harvest or during the intercrop dry period. Some evidence indicates that appreciable N_2O is evolved from a rice field during the first few days after the field is flooded (Byrnes et al., 1993). A simple equation relating soil mineral N content and soil % water-filled pore space to N_2O emissions integrated through the entire year may represent N_2O emissions reasonably well. There is, unfortunately, no possibility to link this to national inventory calculations.

The second major point discussed by the Expert Group was that the OECD (1991) method only addressed direct N_2O emissions from cultivated agricultural soils that had been fertilized with commercial fertilizer N. The consensus of the group was that this narrow concept is not appropriate since N from (1) atmospheric deposition, (2) commercial fertilizer, (3) animal manures and plant residues, (4) biological N fixation, and (5) soil organic matter mineralization should all be considered in the equation. World-wide, the amount of N input into agricultural systems from animal manures and biological N fixation is roughly the same as the input from commercial fertilizer N (about 80 Tg in 1990). Nitrogen input from atmospheric deposition varies globally from about 1 to 50 kg N ha^{-1} y^{-1} while N from mineralization of soil organic matter may vary from 10 to 200 kg N ha^{-1} y^{-1}, both are site dependent.

Based upon information that is considered to be available in most countries, the following N_2O emission calculation method is suggested:

a) Low Estimate

N_2O Emission = Σ (F_{mn} + F_{on} + F_{bnf}) * $C_{0.0005}$

b. High Estimate

N_2O Emission = Σ (F_{mn} + F_{on} + F_{bnf}) * $C_{0.039}$

c. Median Estimate

N_2O Emission = Σ (F_{mn} + F_{on} + F_{bnf}) * $C_{0.0036}$

Where F_{mn} = amount of mineral N applied

F_{on} = amount of organic N applied (animal manure or crop residue)

F_{bnf} = amount of biological N fixation

$C_{0.0005}$ = low end of emission coefficient range

$C_{0.039}$ = high end of emission coefficient range

$C_{0.0036}$ = median emission coefficient

Units are in Tg of N for input and Tg N_2O-N x 44/28 for total N_2O emission. The emission coefficients are those used by OECD (1991) on page 5-51 based on total commercial fertilizer N consumed and N_2O emission based on these low, high, and median

emission factors. These numbers should span the range of most measured N_2O emissions. It was felt that because the range of measured N_2O emissions from different agricultural systems is so large, the whole range must be considered to convey the uncertainty in using these estimates.

Most of the information to calculate N_2O emissions are available for many countries, but part may not be readily available for others:

a) N from commercial fertilizer. Total N consumption as well as mean N-application level (in kg/ha of arable land) is available for all countries in the FAO Fertilizer Yearbooks (e.g. FAO, 1990a).

b) N from animal manure. Animal population data is available from the FAO Production Yearbooks (e.g. FAO, 1990b). The amount of N in the excreta and the volatilization of ammonia are well known for most parts of the world. Where such data are not available, estimates can be made based on animal diet. Further data required are: the portion of the year that animals are grazed and confined, and the portion of the manure collected in the stables and the portion applied to the soil.

The working group on NH_3 of the Global Emission Inventories Activity (GEIA), a core project of the International Global Atmospheric Chemistry Program (IGAC) will develop a methodology to estimate the above parameters. For countries having difficulties to obtain the data, these GEIA-estimates could be used as default values.

c) N from biological N-fixation. Data on the areas cropped to leguminous crops, such alfalfa, pulses, soy beans, are readily available from FAO Production Yearbooks (e.g. FAO, 1990b). Commonly, leguminous crops are not fertilized with commercial N, or are fertilized only a small amount of starter N. It is difficult to estimate the amount of N fixed by the crop if we do not know the amount of soil N before sowing and after harvest, as well as the yield and % N in the crop.

4.5.4 For the Future

The OECD Expert Group made the following suggestions for improving the methodology for estimating N_2O emissions from agricultural soils:

1   The assumption that N_2O emissions directly from fertilizers are relatively small should be reviewed. A critical look at the reviews of Eichner (1990), Bouwman (1990) and CAST (1992) indicate that a conservative estimate of direct emission of N_2O from mineral fertilizer over a full year are in the range of 1% of the N applied, currently about 1 Tg, or about 10% of current global emissions. This estimate does not include either organic N fertilizer from human and farm animal excreta or N fixed by biological N fixation. Limited data suggest that N_2O emissions from these N sources are generally greater than from mineral N application (Bouwman, 1990). Assuming that N emissions from all sources are equal, the *direct* emissions from all three N sources could total 3 Tg annually.

2   Although the individual factors that regulate N_2O production are known, we cannot predict how these factors interact under field conditions to produce measured fluxes (OECD/OCDE, 1991). Both nitrification and denitrification and the regulators of N_2O/N_2 ratios from denitrification have their own set of optimum conditions. As a result, one process may be the primary N_2O producer in one set of field conditions, but as soil conditions change, another process may predominate. The complexity of the interactive factors important to the different processes obviously make a simple description of N_2O production difficult (Mosier et al., 1983). Complex models such as that described by Li et al. (1992) may be the only way that N_2O fluxes may be

predicted. Simpler, mechanistic models such as that described by Parton et al. (1988) may, however, play a role in simplifying estimation of N_2O emission. To accurately inventory N_2O emissions from agricultural soils we must be able to predict N_2O emissions based on N application, soil, crop and management.

It is also likely that N_2O production resulting from fertilizer and increased use of biological nitrogen fixation is underestimated because the effect of a nitrogen input is usually only partially traced through the environment. In an example taken from Duxbury et al. (1993), 50 of the 100 kg ha^{-1} of N applied as fertilizer on a typical dairy farm are harvested in the crop, and 50 are lost by the combination of leaching (25), surface run-off (5), and volatilization (20, primarily denitrification). If N_2O comprises 10% of the volatilized N, 2 kg N_2O-N would be generated in the primary cycle. Assessments of fertilizer effects on N_2O emissions usually stop at this point even though only 20 of the 100 kg N have been returned to the atmosphere and it can be reasonably assumed that almost all would be returned within a few years.

Secondary flows include feeding of the 50 kg of harvested N to animals, which generate 45 kg of manure N. The manure is returned to cropland to fertilize a second crop, however about half of this N is volatilized as NH_3 prior to or during manure application. Volatilized NH_3 is aerially dispersed and subsequently returned to and cycled through both natural ecosystems and cropland. Ammonia volatilization from agricultural systems is globally important (Isermann, 1992) but its impact on N_2O emissions have not been explicitly addressed. To provide some perspective, it should be noted that the quantities of fertilizer N used and animal manure N generated by USA agriculture are equal (Bouldin et al., 1984). On a global basis, about 30 of the 80 Tg fertilizer N used each year are volatilized as NH_3.

Similarly, the amount of N_2O arising from leached nitrate, which may average 20-25% of applied N (Meisinger and Randall, 1991), is not known but much may be denitrified in riparian zones or cycled through wetland or aquatic vegetation. A complete accounting of fertilizer N, biologically fixed N, and N mineralized from soil organic matter is difficult to achieve, but needed if we are to accurately assess the impact of increased use of N in agricultural ecosystems on terrestrial N_2O emissions (Duxbury et al., 1993).

3   The Working Group felt that considering only N_2O emissions from cultivated agricultural soils was too narrow a view. The whole picture of anthropogenic effects of N_2O emissions should include the indirect fertilization of grasslands, forests and wetlands from agricultural and industrial sources. Since cultivated lands represent only about 13% of the global land surface it does not seem appropriate to consider only those areas when estimating global N_2O emissions.

Calculations of N additions and N cycling within all of these ecosystems must include N from atmospheric deposition and N from soil organic matter mineralization. The entire calendar year should be considered, not just the cropping season.

Improving methodology for estimating N_2O emissions may evolve in a series of steps, beginning with the above equations and ending with development of process based models which are used to develop regional and larger scale emission models. With these models, if a relatively simple set of input information can be developed, then detailed emission calculations may be made. Because of the inherent spatial and temporal variability associated with N_2O production and emissions from soils, it appears that very simple approaches will not provide realistic emission estimates.

To support the development of the steps for improved methodology for calculating country-wide N_2O emissions, a number of unknowns were identified. Better understanding of these issues should improve methodologies.

a   Research needs specifically for agricultural systems include:

      i   Improve management strategies to optimize N use efficiency and match plant N input needs.

      ii   Facilitate integration of animal and crop production systems within the agricultural industry.

      iii   Develop mitigation strategies at the farm level.

      iv   Perform measurements in important tropical agricultural systems.

      v   Develop strategy to provide farmers with options and knowledge about N use to limit N leakage.

b   General recommendations:

      i   Estimate anthropogenic N input into "natural systems" and amount processed into N_2O.

      ii   Develop process level models, based on field research measurements, refine and test the models and use these models as basis for developing regional and larger scale emission models.

4.5.5 References

Andreae, M.O. and D.S. Schimel (eds.). 1989. Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere. John Wiley & Sons. 346 p.

Bouldin, D.R., S.D. Klausneer and W.S. Reid. 1984. Use of nitrogen from manure. In R.D. Hauck (ed.). Nitrogen in Crop Production. Amer. Soc. Agron. Madison, WI. pp. 221-245.

Bouwman, A.F. 1990. Exchange of greenhouse gases between terrestrial ecosystems and the atmosphere. In A.F. Bouwman (ed.). Soils and the Greenhouse Effect. John Wiley & Sons. New York. pp. 61-127.

Bremner, J.M. and A.M. Blackmer. 1978. Nitrous oxide: emissions from soil during nitrification of fertilizer nitrogen. Science. 199:295-296.

Bremner, J.M., G.A. Breitenbeck and A.M. Blackmer. 1981. Effect of nitrapyrin on emission of nitrous oxide from soil fertilized with anhydrous ammonia. Geophys. Res. Lett. 8:353-356.

Byrnes, B.H., L. S. Holt and E.R. Austin. 1993. The emission of nitrous oxide upon wetting a rice soil following a dry season fallow. J. Geophys. Res. (In Press).

Byrnes, B.H., C.B. Christianson, L.S. Holt and E.R. Austin. 1990. Nitrous oxide emissions from the nitrification of nitrogen fertilizers. In A.F. Bouwman(ed.). Soils and the Greenhouse Effect. Chichester:Wiley. pp. 484-495.

CAST. 1992. Preparing U.S. Agriculture for Global Climate Change. Task Force Report No. 119. P.E. Waggoner, Chair. Council for Agricultural Science and Technology. Ames, IA. 96 pp.

Duxbury, J.M. and P.K. McConnaughey. 1986. Effect of fertilizer source on denitrification and nitrous oxide emission in a maize field. Soil Sci. Soc. Am. J. 50:644-648.

Duxbury, J.M., L.A. Harper and A.R. Mosier. 1993. Contributions of agroecosystems to global climate change. In Agricultural Ecosystem Effects on Trace Gases and Global Climate Change. L.A. Harper, A.R. Mosier, J.M. Duxbury and D.E. Rolston (eds.). ASA Special Pub. No. 55 Amer. Soc. Agron. Madison, WI. pp. 1-18.

Eichner, M.J. 1990. Nitrous oxide emissions from fertilized soils: summary of available data. J. Env. Qual. 19:272-280.

FAO. 1990a. Fertilizer Yearbook. Volume 39, pp. 127. FAO statistics series No. 95. Food and Agricultural Organization of the United Nations. Rome.

FAO. 1990b. Production Yearbook. Volume 43. FAO statistics series No. 94. Food and Agricultural Organization of the United Nations.me.ns. Rome.

Freney, J.R., O.T. Denmead, I. Watanabe and E.T. Craswell. 1981. Ammonia and nitrous oxide losses following applications of ammonium sulfate to flooded rice. Aust. J. Agric. Res. 32:37-44.

Goodroad, L.L. and D.R. Keeney. 1984. Nitrous oxide emissions from soils during thawing. Can. J. Soil Sci. 64:187-194.

Hammond, A.L. 1990. World Resources 1990-91. A report by The World Resources Institute, Oxford University Press. Oxford, UK. 383 pp.

Houghton, R.A. and D.L. Skole. 1990. Changes in the global carbon cycle between 1700 and 1985. In B.L. Turner (ed.). The Earth Transformed by Human Action. Cambridge University Press.

Houghton, J.T., B.A. Callander and S.K. Varney (eds.). 1992. Climate Change 1992. The Supplementary Report to the IPCC Scientific Assessment. Intergovernmental Panel on Climate Change. Cambridge University Press. 200 pp.

Hynes, R.K. and R. Knowles. 1978. Inhibition of acetylene of ammonia oxidation by Nitrosomas europea. FEMS Microbiol. Lett. 4:319-321.

Iserman, K. 1992. Territorial, Continental and Global Aspects of C, N, P and S Emissions from Agricultural Ecosystems. In NATO Advanced Research Workshop (ARW) on Interactions of C, N, P and S Biochemical Cycles. Springer-Verlag, Heidelberg (In Press).

Li, C., S. Frolking and T.A. Frolking. 1992. A model of nitrous oxide evolution from soil driven by rainfall events: I. Model Structure and Sensistivity. J. Geophys. Res. (In Press).

Meisinger, J.J. and G.W. Randall. 1991. Estimating nitrogen budgets for soil-crop systems. In Managing Nitrogen for Ground Water Quality and Ferm Profitability. R.F. Follett, D.R. Keeney and R.M. Cruse (eds.). Soil Sci. Soc. Am. Inc. Madison, WI. pp. 85-124.

Mosier, A.R. 1989. Chamber and isotope techniques. In M.O. Andreae and D.S. Schimel (eds.). Exchange of Trace Gaes between Terrestrial Ecosystems and the Atmosphere. Chichester:Wiley. pp. 175-187.

Mosier, A.R., W.J. Parton and G.L. Hutchinson. 1983. Modelling nitrous oxide evolution from cropped and native soils. R. Hallberg (ed.). Ecol. Bull (Stockholm). 35:229-241.

OECD/OCDE. 1991. Estimation of Greenhouse Gas Emissions and Sinks. Final report from the OECD Experts Meeting, 18-21 February, 1991. Prepared for Intergovernmental Panel on Climate Change. Revised August, 1991.

Parton, W.J., A.R. Mosier and D.S. Schimel. 1988. Rates and pathways of nitrous oxide production in a shortgrass steppe. Biogeochemistry. 6:45-58.

Poth, M. and D.D. Focht. 1985. ^{15}N kinetic analysis of N_2O production by Nitrosomas europea: an examination of nitrifier denitrification. Applied. Env. Microbiol. 49:1134-1141.

Smith, K.A. 1990. Greenhouse gas fluxes between land surfaces and the atmosphere. Progress in Physical Geography. 14:349-372.

Sommerfeld, R.A., A.R. Mosier and R.C. Musselman. 1993. CO_2, CH_4, and N_2O flux through a Wyoming snowpack and implication for global budgets. Nature. 361:140-142.

Williams, E.J., G.L. Hutchinson and F.C. Fehsenfeld. 1993. NO_x and N_2O emissions from soil. Global Biogeochem. Cycles. (In Press).

Yoshida, R. and M. Alexander. 1970. Nitrous oxide formation by Nitrosomas europea and heterotrophic microorganisms. Soil Sci. Soc. Am. Proc. 34:880-882.

CHAPTER 5
LAND USE CHANGE
& FORESTRY

5   EMISSIONS FROM LAND USE CHANGE AND FORESTRY

5.1   Overview

This chapter summarizes methods for calculating greenhouse gas (GHG) emissions from human activities which:

1   change the way land is used (e.g., clearing of forests for agricultural use, including open burning of cleared biomass), or

2   affect the amount of biomass in existing forests (e.g., logging, fuelwood harvesting).

The biosphere is a strong determinant of the chemical composition of the atmosphere. This has been true since the existence of the biosphere, and hence well before the presence of humans. A rich variety of carbon, nitrogen, and sulfur gases are emitted and absorbed by the biosphere. There is, however, strong evidence, that the expanding human use and alteration of the biosphere for essential food, fuel and fiber is contributing to the increasing concentrations of greenhouse gases. The dominant gas of concern in this source category is carbon dioxide (CO_2), and much of the methodology discussion in this chapter is specific to CO_2. Other important direct greenhouse gases[1], including methane (CH_4) and nitrous oxide (N_2O), and indirect greenhouse gases, including carbon monoxide (CO), and oxides of nitrogen (NO_x, i.e., NO + NO_2) are also produced from land use change and forest management activities, particularly where burning is involved.

Estimates of greenhouse gas emissions due to land use change vary considerably. Estimates of emissions resulting from changes in the use of forests and of forest area vary due to uncertainties in annual forest clearing rates, the fate of the land that is cleared, the amounts of biomass (and hence carbon) contained in different ecosystems, the fate of the biomass removed, and the amounts of CH_4, CO, N_2O, and NO_x released when biomass is burned and soils are disturbed. The 1990 IPCC Scientific Assessment estimated the flux in 1980 to be 0.6-2.5 Pg CO_2-C, and estimated the average annual emissions for the decade 1980-1989 to be 1.6±1.0 Pg CO_2-C.[2] Subsequently, the IPCC (1992) reviewed more recent but still inconclusive information, and could find no basis for changing the earlier estimate. Carbon sequestration by tropical tree plantations was not explicitly included in these estimates but is thought to be relatively small: in 1980 these plantations were estimated to absorb only 0.03-0.11 Pg CO_2-C.[3]   At the time of the IPCC 1990 Assessment estimates in the literature indicated the net release or uptake of CO_2 due to land use change in the temperate and boreal regions in the 1980s to be small with CO_2 emissions from deforestation in these regions almost balanced by CO_2 uptake from the regrowth of forests.[4] More recently, several analyses have suggested that growth of existing forests in temperate and boreal regions may be a significant carbon sink, potentially as much as 1.0 Pg-C annually. Analysts have suggested a number of complementary factors which could be causing these sinks, including regrowth of historically cleared forests, CO_2 fertilization, and nitrogen fertilization due to atmospheric deposition.[5] The precise mix of causes and magnitude of these sinks is still a subject of research and debate.

Gross emissions of non-CO_2 trace gases (CH_4, CO, N_2O, and NO_x) due to biomass burning are also net emissions and are generally produced immediately, while gross emissions of CO_2 due to reductions in forest area may or may not be balanced by uptake of CO_2 and may occur over immediate or delayed time frames.[6] Similarly, increases in forest area or in the biomass density of existing forests will result in CO_2 uptake at varying

rates and over delayed time frames. Only about 50-60% of the carbon estimated to have been released in 1980 was a result of deforestation in that year. The remainder was a release due to oxidation of biomass cleared in previous years.[7] Other land use changes, such as land flooding, result in continuous greenhouse gas emissions for as long as the land remains in its altered state.

5.1.1 Background - biomass stocks and carbon fluxes

Vegetation withdraws carbon dioxide from the atmosphere through the process of photosynthesis. Carbon dioxide is returned to the atmosphere by the (autotrophic) respiration of the vegetation and the decay (heterotrophic respiration) of organic matter in soils and litter. The gross fluxes are large; roughly a seventh of the total atmospheric carbon dioxide passes into vegetation each year (on the order of 100 Pg CO_2-C per year), and in the absence of significant human disturbance, this large flux of CO_2 from the atmosphere to the terrestrial biosphere is balanced by the return respiration fluxes. This remarkable balance is clearly expressed by the relative constancy, which can be inferred from the ice core records, of the concentration of atmospheric CO_2 between 10th and 18th century.

Land use change and the use of forests directly alters these fluxes (and their balance) and consequently the amount of carbon stored in living vegetation, litter, and soils. For example, forest clearing for agriculture by burning greatly increases the return (respiration) flux of CO_2 and decreases for a while the photosynthetic flux. Burning is, after all, simply a rapid form of oxidation or decay. Subsequently, the balance on the cleared area will return: the photosynthesis associated with the agricultural production being balanced by the respiration of the vegetation, the decay of on-site organic material, and the oxidation of the agricultural product when it is consumed, perhaps off site. However, the total amount of carbon stored in the terrestrial system will have been reduced because a forest contains more carbon than does a corn field, and the removed carbon (i.e., the forest) was not put into long term storage pools. An obvious consequence is that the activity resulted in a net flux of CO_2 from the biosphere to the atmosphere. A natural first order assumption is that the net reduction in carbon stocks is equal to the <u>net</u> CO_2 flux from the cleared area.

Forest harvest does not necessarily result in a net flux to the atmosphere. It can produce a complex pattern of net fluxes that change direction over time. For instance, suppose that a forest is harvested producing wood products and leaving some slash and debris. Initially, the CO_2 flux from the wood products that decay rapidly plus the increased respiration flux of CO_2 associated with the oxidation of the slash (in effect the litter pool has been increased and hence so has the respiration flux associated with this pool) could be greater than the flux from the atmosphere due to the photosynthesis and the resulting carbon storage in the regrowing forest. Consequently, there is a net flux of CO_2 from the biosphere to the atmosphere. This would also be reflected in a carbon accounting: the amount of carbon in the original living vegetation, the litter, and the soils would be greater than the amount of carbon in the young regrowing forests, litter, soils and forest products pool. However, if some of the forest products are very long-lived, and if the forest regrows to its original level, then the integrated net flux must have been from the atmosphere to the terrestrial biosphere since the resulting total terrestrial carbon stocks (vegetation, litter, soils, and wood products) would be greater than before the forest harvest.

BOX I
ILLUSTRATIVE CALCULATIONS OF CARBON FLUXES

Consider the example of forest clearing for agriculture which results in a net flux to the atmosphere. For descriptive purposes we consider the following assumptions: 1) a 20 year time frame (e.g., 1970 to 1990), 2) one hectare is cleared each year (so that over the 20 year period, 20 hectares are cleared), 3) cleared land is used as pasture, which is established the year following the clearing, 4) after three years cleared land is abandoned and it regrows linearly to 75% its original biomass in 15 years but no further, 5) all of the vegetation is completely burned at the time of clearing and there are essentially no soil or litter pools, 6) there are 200 tonnes of carbon per hectare in the forest biomass and 5 tonnes carbon per hectare in the pasture.

In the first year, there is a 200 tonne *net* flux of carbon as CO_2 to the atmosphere. In the second there is a 195 tonne *net* flux; the clearing of the second hectare is partially balanced by the establishment of the first pasture. In the third, there is a *net* flux again of 195; the clearing of the third hectare is again partially balanced by the establishment of the second pasture; however, the first pasture is now again in a steady state (as a pasture). The fourth year the pattern is again the same, but in the fifth year the net annual flux drops to 185 as the first pasture is now abandoned and begins to recover to a secondary forest. In the sixth year, the flux drops to 175 as two hectares are recovering to a secondary forest. In this example, in 1989 one hectare would be converted to pasture (200 tonne flux of carbon to the atmosphere), one hectare would have become a pasture (5 tonne flux to the terrestrial biosphere), two hectares would be in steady state as pasture, and 15 hectares would be recovering to secondary forest with one hectare in its final year of recovery (150 tonne flux to the terrestrial biosphere). The 1989 gross flux of carbon from land clearing in 1989 would still be 200 tonnes to the atmosphere, but the net flux to the atmosphere in 1989 associated with land clearing would be 45 tonnes of carbon as CO_2. The 1990 flux would be the same since now the original one hectare of pasture would have reached a new steady state as a secondary forest.

Many variations on this example can be devised: e.g., conversion of some vegetation to charcoal, varying deforestation and regrowth rates. For instance, if the land clearing rates declined over the time period, the 1990 net flux could easily be from the atmosphere to the biosphere even though the net integral flux over the time period was to the atmosphere.

There are other complexities such as the variety of land-use practices, varying assumptions about biomass densities, recovery rates, the dynamics of the associated litter and soil pools, and so forth. However, the net flux to or from a particular site will always be reflected in the change of carbon stocks on site and/or in the products pools associated with the site. Thus, a methodology that determines carbon stock changes, also provides estimates of the net fluxes of CO_2.

This characteristic that changes in land use activity today affects both present and future CO_2 fluxes associated with that specific land use activity is one feature of CO_2 emissions analysis that distinguishes land use from fossil fuel consumption. Consequently, when one considers the issue of CO_2 flux associated with land use today or in a base year, one must consider past land use activities and their effects upon current fluxes of CO_2. Box 1 provides some illustrative numerical examples of carbon fluxes associated with land use change over a series of years.

5.1.2 The Proposed Approach

The fundamental basis for the methodology rests upon two linked themes: i) the flux of CO_2 to or from the atmosphere are assumed to be equal to changes in carbon stocks in existing biomass and soils, and ii) changes in carbon stocks can be estimated by first establishing rates of change in land use and then applying simple assumptions about the biological response to a given land use. As noted above, there are large uncertainties in all current methods for estimating fluxes of CO_2 from forestry and land use change. *Direct* measurements of changes in carbon stocks are extremely difficult since one must confront the difficulty of determining small differences in large numbers as well as the inherent heterogeneity of terrestrial systems. A more practical first order approach in many countries is to make simple assumptions about the effects of *land use change* on carbon stocks and the biological response and to use these assumptions to calculate carbon stock changes and hence the CO_2 flux. This observation is at the heart of the proposed approach. It is also central to more complex terrestrial carbon accounting models.[8]

Rates of change of land use are also difficult to establish. However, on a practical basis it is possible since there are a variety of data on which to base land use change estimates. The Technical Appendix to this chapter reviews sources of data on rates of tropical deforestation, the land use change which currently makes the largest contribution to CO_2 flux. Finally, the assumptions regarding the response of vegetation and soils to different land uses and land use change can be expressed in uncomplicated terms which can be altered for particular differences for different countries.

The methodology is designed to allow calculations based on such assumptions,which cover each of the main categories, and which are feasible for all participating countries. It can be implemented at several different levels of complexity and geographic scale, depending on the needs and capabilities of national experts in different countries.

1   A simple, first order approach can be based on very aggregate default data and assumptions, derived from the technical literature, and provided throughout the text. Methods are presented in the context of national level aggregate calculations for a limited set of subcategories which can be supported by these default values.

2   A more accurate level can be achieved simply by substituting country-specific valued for general defaults provided in the methodlogy. If appropriate and possible, locally available data can be used to carry out calculations at a more detailed geographic and/or sub-category level. Alternative levels of detail are discussed more fully in the next section. National experts are strongly encouraged to substitute more appropriate (i.e., country or region-specific) and more detailed input data wherever this is available.

3   Forest inventory data can also be used with this methodlogy. It is important to note that some countries with highly developed forestry industries do in fact keep track of existing commercial forests through periodic detailed surveys. In these countries it is generally the ongoing management of existing forests rather than land use changes which has the greatest impact on GHG emissions or removals. National

experts who have very detailed, inventory based data, can reformat this data to create equivalent average responses (e.g., annual biomass growth rates by ecosystem type) which can be aggregated up to categories matching the simple approach outlined here. This procedure is discussed in more detail in the managed forests section below.

The intent is to provide a calculation and reporting framework which can accommodate users with vastly different levels of data available, yet allow them all to place the results on a comparable basis.

5.1.3 Priority Categories

In estimating the effects of land use and land use changes on the concentration of greenhouse gases, it is reasonable to stage the calculation methods so that the most important components can be addressed first, and complexities and subtleties of the relationship of forestry and land use change to fluxes of CO_2 and other gases can be incorporated in a consistent manner into subsequent calculations as knowledge advances and data improve. The methodology presented in this chapter focuses initially on a simple, practical, and fair procedure for determining the carbon dioxide flux directly attributed to forest management and land use change activities. This procedure must account for the influence of past land use changes upon the contemporary flux.[9] The method also accounts for trace gas emissions from biomass burning where this occurs in conjunction with land use change.

On a global scale, the most important land use changes that result in CO_2 emissions and removals are:

- **forest clearing** - the conversion of forests to non-forests (e.g., to pasture or cropland)[10]

- **grassland conversion** - the conversion of natural grasslands to cultivated (tilled) or pasture lands

- **abandonment of managed lands** which regrow into grasslands or forests

- **managed forests** - the most important effects of human interactions with existing forests are considered in a single broad category , which includes logging for forest products, the harvest of fuel wood, and establihment and operation of forest plantations.

The method also addresses the immediate release of non-CO_2 trace gases (CH_4, CO, N_2O and NO_x) from the open burning of biomass from forest clearing. The approach is essentially the same as that used for non-CO_2 trace gases from all burning of unprocessed biomass, such as burning of traditional biomass fuels (Chapter 1: Energy), and burning of agricultural residues and savanna burning (Chapter 4: Agriculture). These calculations are similar to fossil fuel emission calculations, in that they do not include time lags and all emissions are *net* emissions.

5.1.4 Relationships Among Categories

It is important to recognize some key linkages and interactions among components of the land use change and forestry methods and with other calculations discussed in other chapters. Figure 1 illustrates a number of complicated relationships among these categories and also with biomass fuel combustion which is covered in the energy source category. Key linkages which should be understood are:

1   To estimate CO_2 emissions from *burning or cleared forests*, it is only necessary to know the total amount of biomass which is burned in the inventory year.

2   However, it is necessary to divide this burning into on-site and off-site (fuelwood) portions for other reasons:

First, the type of burning affects the emissions of non-CO_2 trace gases such as methane so that different emission factors may be applied to open burning on-site and to fuelwood use off-site.

Secondly, the amount of fuelwood removed from cleared forests must be deducted from total fuelwood consumed for the nation or region to determine the residual amount of fuelwood which must have been harvested from managed forests (as broadly defined in this chapter). This is only an issue for those countries which must infer some or all of forest harvest from wood consumption surveys. If some of the fuelwood consumed has already been accounted for once in calculations of forest clearing, this amount must be take out of the amount attributed to managed forests.

3   Fuelwood Consumption Information. Countries which have accurate and complete statistics on direct harvesting of all types of wood from managed forests, and all uses of biomass for fuel, should use locally available data. Many countries, however, have significant amounts of wood removed from forests, primarily for domestic fuel use, which is not accounted for in commercial harvest statistics. For these countries, an optional Fuelwood Consumption Accounting approach is provided. This approach is based on household and other fuel consumption surveys, scaled to population to estimate total annual demand for fuelwood and other fuels. This information can then be used instead of, or in combination with, commercial harvest and sales statistics.

Fuelwood consumption information is used in two ways:

－   for estimating trace gas emissions from biomass fuel combustion (in the Energy section of the methodology); and
－   total wood consumption, corrected to deduct any wood which has come from forest clearing (for which CO_2 is already accounted) is also a key input to the calculations of net CO_2 emissions or removals by managed forests.

FIGURE 1: Relationships Among Categories
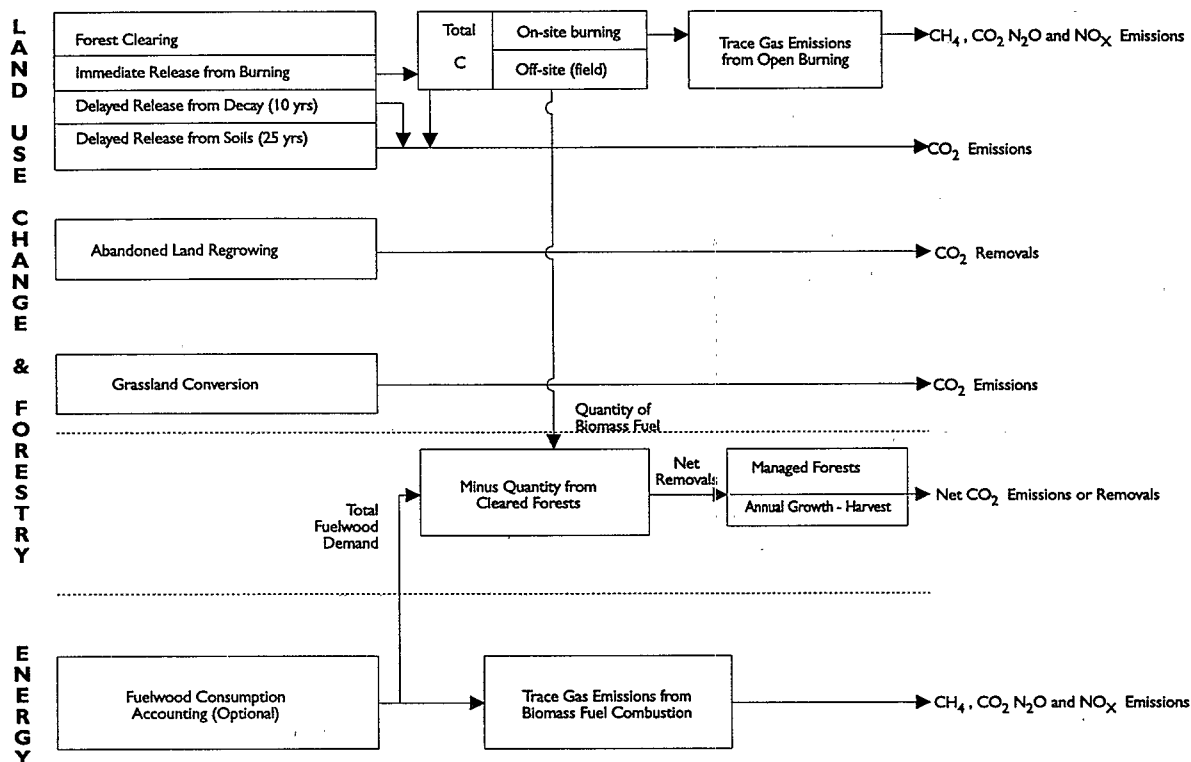
5.1.5 Chapter Organization

The remainder of this chapter presents methods for calculating greenhouse gases from land use change and forestry in two stages. The next section, *Basic Calculations*, presents initial simple calculations for each of the four key land uses and changes in land use identified above. These categories also correspond directly to the subsections of the Land Use Change and Forestry Module of *Volume 2: Workbook*.

The second stage, *Refinements in Calculations*, discusses a range of complexities and refinements which ideally could be included in such calculations, as data and understanding permit, in order to improve accuracy and completeness. These possible refinements include more detailed treatment of some aspects of the basic categories of land uses and land use changes, as well as additional categories, which can affect carbon stocks and are potentially important for other greenhouse gases. Issues discussed include the delayed releases (or uptake) of non-CO_2 trace gases after burning of forests (either as a prescribed forest management tool or as a means of land-clearing), forest degradation, traditional shifting cultivation, and conversion of wetlands to other land uses or the reverse. These activities and other refinements can be incorporated in more detailed versions of the calculations.

A *Technical Appendix*, as mentioned, is also provided, which deals with sources of information on rates of land use change, a critical activity data input for calculating GHG emissions.

5.2 Basic Calculations

5.2.1 Introduction

The basic calculations focus primarily on the flux of CO_2 and the land use changes and land use activities that result in the largest, potential flux of CO_2 to the atmosphere or have the largest potential for sequestering carbon.

Three categories of land use change are considered:

- forest clearing
- conversion of grasslands to agricultural lands
- abandonment of managed lands

In contrast to other aspects of the greenhouse gas emissions methodology, the estimation of CO_2 from land use change requires the consideration of historic time horizons. When forests are cleared or agricultural lands abandoned, the biological responses result in "commitments" of fluxes of carbon to or from the atmosphere for many years after the land use change. This methodology is designed to produce an emissions estimate that is comparable to other elements of the inventory, fossil fuel emissions, for example. That is, it attempts to quantify the flux to or from the atmosphere *in the inventory year*. To do this, it is necessary to obtain estimates of land use change activities for many years prior to the inventory year, and estimate the effects of these activities on the current year fluxes. The three selected categories are considered to be the most important land use changes affecting CO_2 fluxes, but are not a comprehensive set. Many relevant land use changes are excluded from the basic calculations. These are discussed in the last section of this chapter.

Relevant forestry (ongoing land use) activity is combined in one very broad category, **managed forests**, which is defined here to include potentially a wide variety of land use practices. Key examples are establishing and harvesting plantations, commercial forest management and harvesting, and fuelwood gathering. Conceptually, this category is intended to account for all significant human interactions with forests which affect CO_2 fluxes to and from the atmosphere. It is intended to account, at least on a crude level, for all existing forests, with two exceptions.

1   Natural, undisturbed forests, are not considered to be either an anthropogenic source or sink, and are excluded from the calculations entirely.

2   Forests regrowing naturally on abandoned lands are a net carbon sink attributable to past human activities and are accounted for separately. "Abandoned" lands are by definition assumed not to be subject to ongoing human intervention (of significance to carbon stocks) after abandonment.[11]

Several simplifying assumptions are made in the basic calculation methodology. A number of refinements and removals of simplifying assumptions are possible to improve on the basic calculation. One important option is to implement the basic calculations at a more detailed level of subcategories or spatial detail. National experts are strongly encouraged to do so if data are available. Box 2 discusses possibilities for adapting the methodology to various levels of detail, depending on the capabilities and data available to the user, and the relative importance of various components to the individual country.

Other possibilities for improving the accuracy and completeness of the basic calculations are possible. For example, the fate and amount of belowground biomass (roots, etc.) is currently ignored in the calculation. The section titled: Refinements to Calculations, later in this chapter, reviews a number of possible additions and refinements.

BOX 2
ALTERNATIVE LEVELS OF DETAIL

For simplicity and clarity, this chapter discusses calculation of emissions from at a national level and for a relatively few sub-categories within each category of land use changes and forestry. The level of detail in the sub-categories is designed to match the available sources of default input data, carbon contents and other assumptions. It is important, however, for users of these emissions methodology guidelines to understand that they are not only permitted but encouraged to carry out the GHG emissions inventory calculations at a finer level of detail, if possible. Many countries have more detailed information available about land use change, forests and agriculture, than was used in constructing default values here. It may be important in such countries to carry out emissions calculations at finer levels in two ways:

1   **Geographic detail finer than the nation as a whole**

     If data are available, experts may find that GHG estimation for various regions within a country are necessary to capture important geographic variations in ecosystem types, biomass densities, agricultural practices, rates of burning, etc.

2   **Finer detail by sub-category**

     If data are available, experts may subdivide the recommended activity categories and sub-categories to reflect important differences in ecology or species, land use or agricultural practices, bioenergy consumption patterns, etc.

In all cases, working at finer levels of disaggregation, does not change the basic nature of the calculations, although, additional data and assumptions will generally be required beyond the defaults provided in the chapter. Once GHG emissions have been calculated at whatever is determined by the national experts to be the most appropriate level of detail, results should also be aggregated up to the national level and the standard categories requested in the IPCC proposed methodology. This will allow for comparability of results among all participating countries. Generally, the data and assumptions used for finer levels of detail should also be reported to the IPCC to ensure transparency and replicability of methods. *Volume 1: Reporting Instructions* discusses these issues in more detail.

5.2.2 Forest Clearing: CO_2 Release

Background

The calculation of carbon fluxes due to forest clearing is in many ways the most complex of the emissions inventory components. Because of the delayed responses of biological systems, it is necessary to consider forest clearing activity over three different historic time horizons and to sum the results to estimate the total flux in the current year. Also, as with all categories of forest management and land use change activity, it is necessary to determine *net CO_2* flux.

Forests can be cleared to convert land to a wide variety of other uses, including agriculture, highways, urban development, etc.[12] 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 is conversion to pasture and cropland in the tropics. 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. A portion of the biomass remaining on site as slash is not actually combusted and remains on the ground where it decays slowly.[13] Some of the decay of remaining carbon left on the ground is probably accomplished by termites, which produce both CO_2 and CH_4.[14] However, the methane release from cleared, unburned biomass is very difficult to quantify and ignored for purposes of the basic calculation, where all of the carbon in biomass which decays is assumed to be released as CO_2. Of the portion burned on site, a small fraction of the carbon remains as charcoal,[15] which resists decay for well over 100 years or more; the remainder is released instantaneously to the atmosphere.[16] For biomass removed for fuelwood, the fate is very similar. A small fraction of the carbon remains in ash which effectively provides long term storage, while the majority of the carbon is released to the atmosphere.

Forest conversion also results in CO_2 emissions through soil disturbance, particularly when the conversion is to cultivated or tilled lands. When forests are converted to croplands, a fraction[17] of the soil carbon may be released as CO_2, primarily through oxidation of organic matter. This can be a long term process which continues for many years after the land use change occurs. The basic calculations allow for estimation of loss in soil carbon due to forest clearing. Because of the uncertainty in current understanding of this component, and the difficult historic data requirements, the users are encouraged to exercise their own judgement as to whether or not to include this calculation in the basic estimates.

Calculations

Emissions of CO_2 due to forest clearing are calculated through a sequence of easy steps treating:

- the net change in aboveground biomass carbon

- the portion of this change that is burned in the first year versus the amount left to decay over a longer time period

- for the burned portion, loss to the atmosphere versus long term storage in ash

- current emissions from decay of biomass cleared over the previous decade

- if estimated, current releases of carbon from soils due to clearing over the previous 25 years

Net change in aboveground biomass

First, the amount of biomass affected by clearing in the emissions inventory year[18] is calculated by multiplying the annual forest area converted to pasture or cropland or other land uses by the net change in aboveground biomass. This calculation is carried out for each relevant forest type and, if appropriate, by region within a country.[19] The *net change* is the difference between the density (t dm/ha) of aboveground biomass on that forest land prior to conversion, and the density of aboveground living biomass (t dm/ha) remaining as living vegetation, after clearing. The after clearing value includes the biomass that regrows on the land in the year after clearing and any original biomass which was not completely cleared.

Tables 1 and 2 provide a range of values for aboveground biomass in forests prior to clearing, which can be used as default data if more appropriate and accurate data are not available in a given country.[20] For aboveground biomass after clearing, it is necessary to account for any vegetation (i.e., crops or pasture) that replaces the vegetation that was cleared. A reasonable figure for crops or grasslands is 10 tonnes of dry biomass per hectare.[21] The recommended default assumption is that all of the original aboveground biomass is destroyed during clearing. If locally available data indicate that some fraction of the original biomass is left living after clearing, this should be added to the after clearing value.

To arrive at net change, one reduces the gross release from land clearing in a given base year by 10 tonnes dry biomass (or some other value if more accurate information is available) for each hectare cleared. The total affected biomass for a given year can be calculated from the total area cleared (by region and type) and multiplied by the net change in living on site biomass (including regrowth). This provides an estimate of the total affected biomass for the time period in question.

Immediate emissions from burning

The biomass that is cleared has one of three immediate fates:

1   a portion may be burned on site;

2   a portion may be removed from the cleared site and used as fuelwood, or for products;

3   a portion is converted to slash and decays on site to carbon dioxide over a decade or so. Some estimates in the literature suggest that a global average of about 50% of the cleared forests are burned in the first year with the remaining 50% left to decay.[22] This value could be used as a default for first order calculations if the user does not have access to more appropriate local information. It is important to recognize that this average is dominated by practices in Latin America which has the largest current rates of deforestation. There are certainly wide variations in burning practices in different regions. To calculate the gross amount of carbon released in the current year to the atmosphere it is necessary to consider the burned portions and the decaying portion over different time horizons.

To estimate the CO_2 released by the burning of cleared aboveground vegetation, estimate a) the fraction of the affected biomass that is subjected to burning (on and off site - the remaining, disturbed biomass is slash) and b) the fraction of the burned biomass that is oxidized. The fraction of burned biomass which does not oxidize remains as charcoal.[23] The amount of biomass oxidized is converted to carbon units to estimate the carbon dioxide flux from burning.[24] A reasonable average for converting from dry biomass to carbon content is to multiply dry biomass by 0.45.[25] Of the portion of cleared biomass which is burned, some of this may be burned in the field to facilitate clearing, and some

may be removed and used as fuel. The portion which is burned in the field is used subsequently for calculating the trace gas emissions from open burning of cleared forests, in the next section. The amount removed for fuel is important for calculations of fuel wood extracted from managed forests in the last component of these basic calculations.

Emissions from decay

The aboveground biomass which remained on site but was not burned will oxidize in roughly a decade, and this historical release associated with land clearing must be considered. The 10 year period is a recommended default value, as a reasonable historical horizon in light of the twin realities of data availability and biological dynamics.[26] This can be varied if the user has data or a strong rationale to suggest that a longer or shorter average decay time is more representative of local conditions. The "committed" flux calculation simply accounts for the current oxidizing of material left unburned during the specified historic decay period.

The decay phenomenon can be simply characterized for emissions estimation purposes. Each year, some portion of the cleared aboveground biomass is left as slash, and we assume that 10% of this decomposes each year. Therefore, the total carbon being released to the atmosphere in the inventory year is a function of the land clearing rate for each of the past 10 years, and the portion of the aboveground carbon remaining on site but not combusted each year. The current year emissions from decay of biomass cleared in a historic year would be 10% of the total decay. The total current emissions from decay of historically cleared biomass would then be the sum of the current estimated emissions from biomass cleared in each of the ten historic years.

For practical purposes, the methodology recommends working with decadal average values for the land clearing and portion left to decay which can then simplify the calculation. Working with average values, one would in theory divide the total emissions from decay by 10 to get the contribution of one "average" historic year's clearing to current emissions, then multiply by 10 to account for ten historic years' clearing which could be expected to affect current emissions. Obviously the division by 10 and multiplication by 10 cancel each other and can be ignored. Therefore, the flux in the inventory year from historic land clearing of the aboveground vegetation is simply expressed in Equation 5.1.

EQUATION 5.1

average annual land clearing over the period

x the average quantity of aboveground biomass per hectare remaining on site as slash but not burned (either oxidized or converted to charcoal)

x carbon content of dry biomass

=

flux in the inventory year from historic land clearing of the aboveground vegetation

---

Soil carbon release

For calculating the annual CO_2 flux associated with the loss of soil carbon following forest clearing, the methodology is essentially the same as the approach for treating the historic flux from slash. The time horizon suggested is twenty five years. The historic release from soils is simply the average annual land clearing times the change in carbon stock in soil

between the original forest and a twenty five year old pasture or crop land. For simplicity, it is assumed that the soil carbon release is linear over the 25 year period.[27]

The annual rate of soil carbon loss would be total change in soil carbon from before clearing levels to the final level divided by 25. Some evidence exists that roughly 50% of soil carbon is lost over twenty-five years after temperate and boreal forest are converted to cultivated soil.[28] This value, although highly uncertain, could be used as a default for initial calculations, if more accurate information or measurements are not available to users. This would imply that the annual rate of soil carbon los would be 2% (50%/25 years).

The contemporary flux associated with past land use could be calculated by multiplying the number of hectares of land converted in each of the previous 25 years by the annual per hectare loss in soil carbon and summing. Alternatively, the *average* annual historic conversion rate over a twenty-five year period could be multiplied by the annual loss rate times twenty-five. The average rate of conversion is simply the total hectares converted over the period divided by 25 years.

It is an open question if the conversion of tropical forests to pasture results in loss of soil carbon as CO_2.[29] Pending resolution of the scientific debate on this issue, it is left to the judgement of users whether or not to include this component in the calculations, and what values to use for the portion of carbon lost. Tables 3 and 4 provide average values for soil carbon in undisturbed tropical, temperate, and boreal systems.

As with emissions from decay of aboveground biomass, the recommendation is to use average values for the rate of land clearing, soil carbon content and portion of soil carbon lost over time. Again, for the same reason, the theoretical requirement to multiply and divide by 25 cancel. The calculation of current emissions (from soils in forest cleared over 25 years) is expressed in Equation 5.2.

EQUATION 5.2

the average annual clearing rate over the last 25 years

x change in soil carbon between a forest system and a 25 year old pasture
or crop land.

=

current emissions (from soils in forest cleared over 25 years)

The estimate of the total carbon released in the inventory year from current and historic clearing is calculated by summing the current year release of carbon due to burning - on site or as fuelwood, the average long-term annual release of carbon from decay of biomass cleared over the base decade, and, if estimated, the current year release of soil carbon due to land clearing over the previous 25 years.

Burning of Cleared Forests: Non-CO_2 Trace gases

Where there is open burning associated with forest clearing, it is important to estimate the emissions of methane (CH_4), carbon monoxide (CO), nitrous oxide (N_2O), and oxides of nitrogen (NO_x, i.e., NO + NO_2). The approach is essentially the same as that used for non-CO_2 trace gases for all burning of unprocessed biomass, including traditional biomass fuels, savanna burning and field burning of crop residues. For all these activities there is a common approach in the proposed methodology in that crude estimates of trace gas emissions can be based on ratios to the total carbon released by burning. The carbon trace gas releases (CH_4 and CO) are treated as direct ratios to total carbon released. To handle nitrogen trace gases, ratios of nitrogen to carbon in biomass are used to derive

total nitrogen released from burning, and then emissions of N_2O and NO_x are based on ratios to total nitrogen release. Table 7 provides suggested default values for trace gas emission ratios.[30] These are presented with ranges which emphasize their uncertainty. However, the basic calculation methodology requires that users select a best estimate value.[31]

In sum, clearing by burning releases other gases in addition to CO_2 which are by-products of incomplete combustion: methane, carbon monoxide, nitrous oxide, and oxides of nitrogen, among others. Unlike CO_2 emissions from land clearing, which may or may not imply a *net* release of CO_2 to the atmosphere (depending on whether or not the vegetation is allowed to regrow), emissions of these other gases from biomass burning are *net* transfers from the biosphere to the atmosphere. The calculations described here ignore the contemporary releases associated with past burning events. These delayed releases are known to exist, but are sufficiently uncertain that they should be ignored at present. This and other possible refinements to the calculations are discussed in the last section.

All of the crude biomass burning calculations have two components: 1) estimating total carbon released, and 2) applying emission ratios to estimate emissions of the non-CO_2 trace gases. In the case of burning of cleared forests, part 1 has been carried out in the previous section which included the estimation of carbon emissions from the portion of cleared forests which is burned **on site** in inventory year. The total carbon release from this on site burning (not including any carbon released from decay or soils) provides the basis for the inventory year release of non-CO_2 trace gases. To complete the calculations, it is necessary only to add part 2 of the calculation -- the release of non-CO_2 trace gases from current burning.

Once the total carbon released from on site burning of cleared forests has been estimated, the emissions of CH_4, CO, N_2O, and NO_x can be calculated.[32] The total carbon released due to burning is multiplied by the emission ratios of CH_4 and CO relative to emissions of total carbon to yield total 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.

To calculate emissions of N_2O and NO_x, first the total carbon released is multiplied by the estimated N/C ratio of the fuel by weight (0.01 is a general default value for this category of fuel[33]) to yield the total amount of nitrogen (N) released. The total N released is then multiplied by the ratios of emissions of N_2O and NO_x relative to the total N released of the fuel to yield emissions of N_2O and NO_x (expressed in units of N). To convert to full molecular weights, the emissions of N_2O and NO_x are multiplied by 44/28 and 30/14, respectively.[34]

The trace gas emissions from burning calculation are summarized as follows:

- CH_4 Emissions = (carbon released) × (emission ratio) × 16/12

- CO Emissions = (carbon released) × (emission ratio) × 28/12

- N_2O Emissions = (carbon released) × (N/C ratio) × (emission ratio) × 44/28

- NO_x Emissions = (carbon released) × (N/C ratio) × (emission ratio) × 30/14

Conversion of Grasslands to Cultivated or Pasture Lands

Conversion of a grassland to cultivated land could result in net CO_2 emissions to the atmosphere due to soil disturbance and resultant oxidation of soil carbon even if there is no net reduction in standing biomass. The carbon density in the aboveground vegetation in grasslands is approximately the same as the annual average aboveground biomass in crops

or pasture, and therefore any change in this aboveground pool due to the land use change is generally small in comparison to other changes in carbon stocks in terrestrial systems. Consequently, changes in aboveground biomass are ignored in the basic calculation. Thus, this calculation focuses on the change of carbon in soils. The currently available information relates primarily to the temperate zone, where there is evidence that perhaps 50% of the soil carbon in the active layer (roughly the top one meter) has been lost over roughly a 50 year period, with most of this loss occurring in the first 25 years. The loss tends to be exponential. In some agricultural systems, there has been an accumulation of carbon rather than a loss.[35] The actual rate of soil carbon loss in a specific area of agricultural land, is a function of the specific agricultural use and management practices as discussed in the refinements section of this chapter. There is evidence that, in some cases, the conversion of grasslands to cultivated lands has actually increased carbon stocks in certain systems. However, data and scientific understanding are not sufficient to include a simple methodology for characterizing these relationships in the current basic calculations.

Data on changes in soil carbon in tropical systems are sparse. Therefore, no default assumptions can be provided for this region. In the initial application of basic calculations, grassland conversion can be ignored for tropical countries unless the user has access to data on the rate of soil carbon loss (or accumulation) after this land use change. This is an important research issue, as discussed in the refinements section of this chapter. As a result, in the initial application of the basic calculations to the land use change of converting grasslands to cultivated lands, default values are recommended only for changes in the soil carbon pool in temperate grassland systems. The simple calculation structure would be the same for tropical systems but the use of available default assumptions and values (based on temperate systems) is not recommended.

For calculating the carbon flux from this land use change, a twenty-five year time horizon is suggested. The annual rate of soil carbon loss would be total change in soil carbon from before conversion levels to the final level divided by 25. Soil carbon contents of natural grasslands are highly variable and should be evaluated based on locally available data if possible. Very crude general default values are 60 tonnes/ha for tropical systems and 70 tonnes/ha for temperate systems.[36] As noted above, there is some evidence that 50% of soil carbon is lost over twenty-five years after temperate grasslands are converted to cultivated soil.[37] This value could be used as a default for initial calculations, if more accurate information or measurements are not available to users. This would imply that the annual rate of soil carbon loss would be 2% (50%/25 years).

As with soil carbon emissions from forest clearing above, the recommendation is to use average values for the rate of land conversion, soil carbon content and portion of soil carbon lost over time. Again, for the same reason, the theoretical requirement to multiply and divide by 25 cancel. Therefore the calculation is expressed in Equation 5.3.

EQUATION 5.3

average annual land conversion rate over the last 25 years

x change in soil carbon between a grassland system and a 25 year old pasture or crop land.

=

carbon flux from conversion of grasslands to cultivated or pasture Lands

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For emissions from grasslands used for pasture one needs before and after estimates of biomass and soil carbon applied in the above methodology. This category may prove to be important in certain grasslands that are being grazed heavily or burned often.

Abandonment of Managed Lands

If managed lands, e.g., croplands and pastures, are abandoned, carbon may re-accumulate on the land and in the soil. The response of these converted systems to abandonment depends upon a complex suite of issues including soil type, length of time in pasture or cultivation, and the type of original ecosystem. It may be that some of the abandoned agricultural lands are too infertile, saline, or eroded for regrowth to occur. In this case, either the land remains in its current state or it may further degrade and lose additional organic material (i.e., carbon in the biomass and the soils). Therefore, to calculate changes in carbon flux from this activity, the area abandoned should first be split into parts: lands that re-accumulate carbon naturally, and those that do not or perhaps even continue to degrade.

In the basic calculation, only those that begin to return to an approximation of their previous natural state are considered. Those that remain constant with respect to carbon flux can be ignored. Likewise, the CO_2 flux to the atmosphere for those lands that continue to degrade is likely to be small and hence can also be ignored in the initial application of basic calculations. In any event, the issue could be considered in a more refined calculation.

Abandoned lands must be evaluated in the context of the various natural ecosystems originally occupying them. In addition, the effect of previous patterns of abandonment should be considered while recognizing the desire for simplicity and practicality. The process of recovery of aboveground biomass generally is slower than the human-induced oxidation of biomass. With this in mind and in consideration of possible data sources it is recommended that abandoned lands be evaluated in two time horizons. A twenty year historical time horizon is suggested to capture the more rapid growth expected after abandonment. A second time period -- 20 years after abandonment up to roughly 100 years -- may be considered if data are available.

The calculation, by original ecosystem (e.g., closed broadleaf forest, open forest, grassland) is straightforward.

The total area abandoned (total over the previous 20 years including the inventory year) is multiplied by

1   the average annual uptake of carbon in the aboveground biomass, and

2   the average annual uptake of carbon in the soils.

Results of these two calculations are summed to yield the current uptake of carbon due to abandonment over the previous 20 years of managed lands that are naturally regenerating to forests or grasslands.

If land use data are available to support calculations over a longer time horizon, national experts may want to consider adding a pool of forests and grasslands that are regrowing from abandonment that occurred more than 20 years ago. The growth rates of aboveground biomass in these forests would be slower than that of forests regrowing from abandonment that occurred less than 20 years ago. The same calculations can be repeated for lands abandoned more for than 20 years and up to about 100 years prior to the inventory year.

Table 5 presents estimates of average annual aboveground biomass accumulation in vegetation in various regrowing forest ecosystems following abandonment of cultivated land or pasture.[38] These general growth rates, averaged over large regions and many specific ecosystem types, should be considered crude approximations as applied to the particular lands regrowing in a given region or country. If more accurate data on these growth rates are locally available, they should be used. Accumulation of aboveground dry

biomass can be converted to carbon using a general default conversion value for live biomass -- 0.45 t-C/t dm.

If lands are regenerating to grassland, then only the soil pool needs to be considered. Default rates of soil carbon uptake for both forests and grasslands can be derived from the expected soil carbon values for fully restored natural systems and some simple assumptions. In temperate and boreal systems it can be assumed that soil carbon accumulates linearly from some base value (e.g., 50-75% of original stocks) Table 4 provides default soil carbon values for temperate systems. Values for tropical systems are provided in Table 3, and crude defaults for grasslands were provided in the previous section (60 t-C/ha tropical, 70 t-C/has temperate). Soil carbon changes in tropical systems are poorly understood and can be included or ignored in basic calculations at the discretion of national experts.

The base value at the start of the reaccumulation process in soils would depend on the average amount of time that cleared lands had been used for agricultural purposes (and the management practices utilized during the agricultural period) before abandonment. Based on the simple default assumptions for soil carbon losses from forest clearing one could calculate the level to which soil carbon would have fallen during the agricultural use period. The default assumption was that after 25 years, soil carbon would have fallen to 50% of the pre-clearing value (i.e., 2% per year linear average change). For example, if the average agricultural use period was 10 years before abandonment, it could be assumed that the base value in soils would be 80% of original values. It could be assumed that soil carbon is restored at roughly the same rate at which it is lost under cultivation. Available evidence is that the recovery is not this fast in reality. In the forest clearing calculations the default assumption is that soil carbon might be lost at an average rate of 2 percent of the original carbon content per year. If no detailed information is available, a default assumption could be that the soil accumulation occurs linearly[39] roughly one-half this rate after abandonment. This procedure was used to derive the values presented in the *Workbook*. The values given are 1.3 tonnes C/year for temperate evergreen and deciduous forest soils and 2.0 tonnes C/year for boreal forests. These are one percent of the values from table 4 for soil carbon in primary forests. This is an important area for further research.

Managed Forests

The category *managed forests* as used in these basic calculations is very broad, potentially including a wide variety of land use practices. A basic organizing concept in this chapter is that all existing forests can be allocated into one of three categories.

1   Natural, undisturbed forests, where they still exist are in balance and should not be considered either an anthropogenic source or sink. They are therefore excluded form national inventory calculations.

2   Forests regrowing naturally on abandoned lands are a net carbon sink attributable to past human activities and are accounted for as discussed in the previous section. While the current regrowth is considered a response to past anthropogenic activity, "abandoned" lands are by definition assumed not to be subject to ongoing human intervention (of significance to carbon stocks) after abandonment.

3   *Managed Forests* are considered to include all other types of forest. That is any forest which experiences periodic or on-going human interventions that affect carbon stocks would ideally be included here. In the basic calculations, the chapter focuses primarily on a few types of human interactions with forests which are believed to result in the most significant fluxes of carbon. National experts are encouraged, however, to estimate emissions for any activity related to managed forests which is

considered to result in significant carbon emissions or removals, and for which necessary data are available. Any such activities falling within our broad definition of managed forests should be included in this category and reported to the IPCC as discussed in *Volume 1: Reporting Instructions*.

Some of the activities in the managed forests category which can potentially produce significant carbon fluxes are:

- management of commercial forests - including logging, restocking, selective thinning, etc., as practiced by commercial forest products industries

- establishment and management of commercial plantations

- other afforestation, and reforestation programmes

- informal fuelwood gathering

Based on comments from the land use and forestry experts, the managed forests category has been broadened to include sub-categories of trees which may not traditionally have been considered "forests". It can include village and farm trees if these are important for biomass and biofuel accounting in some developing countries. It could also include urban trees, trees planted along highways, aircraft runways, etc., if these are considered significant for a particular country's biomass calculations. These dispersed trees do not contribute greatly to carbon fluxes to or from biomass on a global scale. However, in some countries, they may be important in accounting for the total amount of wood used for fuel. Also, they may be of interest to some countries because of their potential use in response strategies. For these reasons, they have been included in the basic calculation methods so that national experts who feel they are important, and have necessary locally available data, can include them.

As illustrated in the above list, the managed forests category also includes some tree planting activities which, strictly speaking, are land use **changes**. Plantation establishment and other afforestation/reforestation programmes are examples. It is recognized that this is conceptually inconsistent as the category is intended to account for ongoing interactions with existing forest. However, from a pragmatic perspective, including these activities within the category can simplify the calculations. These sub-categories are land-use changes which create new managed forests. As soon as the land use change occurs (i.e., the tree planting), new land use becomes part of the managed forests category which is accounted for on an annual incremental basis. Although it would be possible, it is not necessary to estimate the lagged effects of this change as is done with other land use changes.[41] While including such a range of tree-related activities in one category may introduce some confusion, the calculation procedure is basically the same for all sub-categories, and this allows the simplest possible set of emissions calculations.

As discussed in the *Overview*, the methodology is designed to accommodate users at several levels of detail. This is especially important in the managed forests category. Possible levels include:

1   A simple first order approach, covering the main sub-categories, with calculations based on simple default assumptions and default data provided.

2   Calculations at the same level of detail but substituting more appropriate data and assumptions from local sources.

3   Calculations following the same structure, but broken down to finer levels of detail to improve accuracy and utility of estimates, where locally available data can support this.

4   Estimates derived from much more detailed and precise inventory-based forest accounting methods. These results can be reformatted and **presented** in the form of calculations comparable to those used by the other national experts operating with less detailed data.

It is highly desirable that the methodology be relevant for countries which have access to much more detailed data on managed forests. Some countries with highly developed forestry industries, do in fact keep track of existing commercial forests through periodic detailed surveys. For such countries, it is possible to derive from survey results aggregate values comparable to the data and assumptions used in the simple approach, and present them in this common format. This will assist all interested parties in evaluating various national estimates on a comparable basis, and will thus be necessary to comply with requirements of Volume 1: Reporting Instructions. Box 3 provides some further discussion of these procedures.

BOX 3
ADAPTING DETAILED FOREST INVENTORY DATA TO THE IPCC FORMAT

A number of countries with highly developed commercial forestry industries routinely collect forest biomass data at a detailed inventory level which allows for relatively precise and direct assessment of the changes in biomass stocks, and equivalent carbon fluxes. National experts working with data of this kind, should be able to derive from it values equivalent to those used in calculating emissions with the IPCC methodology.

Regardless of how detailed the data base used, the results will be ultimately presented in units (e.g. Gg) of carbon and CO_2 emitted or removed in a given average responses (e.g., annual biomass growth rates by ecosystem type) which year. Similarly, the number of hectares of forest in various types can be aggregated up to categories matching the simple approach outlined here. The amount of biomass removed as commercial harvest or for other reasons, should also be relatively well established in such inventories. With these data, it should be

possible to, in effect, work backwards to the derive the necessary input assumptions and aggregate values. For example, national experts might start with a change in total biomass for specified forest types (and/or regions) over a specified time period. Then they could add the amounts of biomass removed through commercial harvest or for other reasons (e.g., thinning), to get the total growth of biomass over the period. This could then be divided by the number of kilo-hectares in the category (and the number of years, if a multi-year period) to get average annual growth rates by category. This would then provide all the values needed to reconstruct the calculations in a comparable form to those from countries with minimal data.

The national emission/removal estimates presented in this form would then be easily understood and compared by all other parties involved in the international climate change discussions. The intent is to provide a calculation and reporting framework which can accommodate users with vastly different levels of data available, yet allow them to place the results on a comparable basis.

Managed forests (which are harvested for forest products including fuel wood) may be either a source or a sink for carbon dioxide. The simplest way to determine which is by comparing the annual regrowth versus annual harvest, including the decay of forest products and slash left during harvest. Decay of biomass damaged or killed during logging results in short-term release of CO_2. For the purposes of the basic calculations, the recommended default assumption is that all carbon removed in wood and other biomass from forests is oxidized in the year of removal. This is clearly not strictly accurate in the case of some forest products, but is considered a legitimate, conservative assumption for initial calculations. Box 4 provides some further discussion of this issue.

BOX 4
THE FATE OF HARVESTED WOOD

Harvested wood releases its carbon at rates dependent upon its end-use: waste wood is usually burned immediately or within a couple of years, paper usually decays in up to 5 years (although landfilling of paper can result in longer-term storage of the carbon and eventual release as methane or CO), and lumber decays in up to 100 or more years. Because of this latter fact, forest harvest (with other forms of forest management) could result in a net uptake of carbon if the wood that is harvested is used for long-term products such as building lumber, and the regrowth is relatively rapid. This may in fact become a response strategy.

For the initial calculations of CO_2 emissions from managed forests, however, the recommended default assumption is that all carbon in biomass harvested is oxidized in the removal year. This is based on the perception that stocks of forest products in most countries are not increasing significantly on an annual basis. It is the net change in stocks of forest products which should be the best indicator of a net removal of carbon from the atmosphere, rather than the gross amount of forest products produced in a given year. New products with long lifetimes from current harvests frequently replace existing product stocks, which are in turn discarded and oxidized. The proposed method recommends that storage of carbon in forest products be included in a national inventory only in the case where a country can document that existing stocks of long term forest products are in fact increasing.

If data permits, one could add a pool to Equation 5.4 (1) in the managed forests calculation to account for increases in the pool of forest products. This information would, of course, require careful documentation, including accounting for imports and exports of forest products during the inventory period.

The net regrowth of the forest (and re-accumulation of carbon) depends on the type of forest logged and the intensity of logging or other harvesting. Well managed commercial forests, replacing natural forests, would over the long term be expected to be close to zero net emissions. In many cases, where historically cleared areas are regrowing under commercial management, with limited logging, the forest areas are currently a net sink. If forests (or parts of forests) are logged or harvested at a rate which exceeds regrowth, then there is a net loss of carbon.[42]

Establishment of plantations and other tree planting activities result in absorption of CO_2 from the atmosphere and storage of this carbon until the vegetation is burned or decays. Restocking of managed forests, planting of urban, village and farm trees, and establishing

plantations on unforested lands, therefore, result in an uptake of carbon from the atmosphere, at least until the biomass is harvested and enters a decay pool, or the system reaches maturity. The effect of plantation establishment can be to create a net sink for carbon even if the plantation is harvested for products that are rapidly oxidized (e.g., fuelwood). If the plantations are harvested so that there is no net loss of biomass over time (i.e., harvested in a sustainable fashion), then the rate of carbon accumulation on land is positive (or at least non-negative) and tied directly to changes in the area of plantations and their average biomass.

The conversion of natural forests to plantations may result in an initial loss of biomass carbon due to an initial reduction in standing biomass. If plantations are established by first clearing existing forests, the initial loss should appear under forest clearing above. Reaccumulation of biomass in these plantations in subsequent years would be accounted for here under managed forests. The approach accounts for all plantations in operation in a given year, including both previously planted and newly established plantations.

The method for calculating the affected forest harvest, afforestation, and reforestation on carbon stocks is shown in Equation 5.4.

EQUATION 5.4

1

Hectares of land in a particular category (e.g., plantations)

x Average annual growth per hectare in biomass

=

Gross annual growth increment.

Total biomass increment is the sum of all relevant categories.

2

Total Harvest by category

x Expansion factor to treat slash

=

Gross annual biomass loss.

Total harvest and other biomass loss is the sum of all relevant categories of harvest.

3

Total gross annual growth increment -

Total gross annual biomass loss

=

Net annual biomass change (positive or negative).

The recommended unit of calculation is dry biomass, and it is necessary to convert to carbon for emissions estimation. A general default value of 0.45 tonnes-C/tonne dry biomass is recommended for all biomass calculations. If more accurate conversion values are available for the particular system, these should of course be used.

Growth Increments

Estimates of average annual accumulation of dry matter as biomass per hectare are presented for in forests naturally regrowing by broad category in Table 5. These values can be used as default values for growth rates in similar managed forest categories if no other information is available. Fore forests which are more intensely managed (e.g., with

periodic thinning, restocking, etc.) annual growth increments could be somewhat different. In countries where such practices result in significantly different average growth rates, locally available data should be used instead of Table 5 values. Values for some typical plantation species are presented in Table 6, can be used as default values.

Biomass Loss

Two approaches can be used to estimate biomass harvest and other losses from managed forests.

Commercial Harvest Statistics The first, and obvious, approach is to use statistics on amounts of biomass actually removed from forests. In countries where commercial harvests of various kinds make up a large majority of total biomass losses, and statistics are well maintained, this may be the only approach needed. Country specific estimates of commercial harvest statistics are provided in annual FAO Forests Products Yearbooks (1993b), and periodic Assessments (e.g., FAO, 1993a), and are also generally available from national governments.

In using commercial harvest statistics, users must pay careful attention to the units involved. Commercial harvest statistics are often provided for the commercial portion of biomass only, in cubic meters (m^3) of roundwood. If this is the case, values will need to be converted to tons of dry biomass, and total biomass removed including slash. Some general default values for converting volume data to tons are 0.65 t dm/m_3 for deciduous and 0.45 t dm/m^3 for conifers. To account for the biomass lost beyond the commercial wood portion expansion factors can be applied. Some general default values from the literature are 1.75 for undisturbed forests and 1.90 for logged forests.[43] There is considerable variability in these conversion values and expansion factors, so use of more specific locally available data is highly desirable. Also , some commercial harvest data may be reported as equivalent total biomass (i.e., expansion factors already applied). It is important to check carefully the information in the original harvest data to ensure that expansion factors are used only where appropriate.

Fuelwood Consumption Accounting In many countries, however, commercial statistics will give only a partial account of wood removals and may need to be supplemented with an alternative approach. Significant amounts of biomass may removed from forests on an informal basis (i.e., they are never accounted for in commercial statistics). This is generally true where "traditional" biomass fuels make up a major share of total fuel used in residences and small commercial enterprises.

The alternative approach, Fuelwood Consumption Accounting, first estimates fuelwood consumed based on per capita consumption data and population statistics. This accounting should also consider charcoal consumption, and "back out" an estimate of the wood which must have been consumed in traditional charcoal manufacture. The Fuelwood Consumption Accounting approach is discussed in more detail in the Energy chapter, in the section on emissions from traditional biomass fuels. Results from this type of accounting can be used in managed forest calculations to account for removals of carbon.

Any wood which was extracted from cleared forests and used for fuel, will already have been accounted for in the forest clearing calculations above. This amount should be subtracted from total wood consumed, directly for fuel and for traditional charcoal making, to determine the amount which must have come from remaining managed forests. The result of this calculation can then be combined with any commercial harvest amounts to produce a total amount of biomass lost from managed forests.

There is an implicit assumption that slash is not accumulating. The instantaneous release of CO_2 from the current year's slash that is explicit in Equation 5.4 (2) is a simple mathematical device to treat slash oxidation from previous years under the assumption

that the slash pool is not changing. The expansion factor for slash in Equation 5.4 (2) could be modified to address the destruction of below ground biomass left after harvest.

Finally, although plantation establishment usually results in an accumulation of soil carbon, conversion of natural forests to plantations could cause a net loss of carbon from the soil.[43] Because of the uncertainty about the magnitude and direction of the soil carbon change in plantation systems, this is ignored in the basic calculations. This issue is discussed in the Refinements section.

5.3   Refinements In Calculations

5.3.1 Issues and Possible Methodologies

There are a number of areas in which the basic calculations could be improved at least theoretically. Simplifying assumptions have been made in many places in order to produce methods consistent with data likely to be available in many countries. The basic calculations focus only on the most important categories for emissions of CO_2 within a much larger set of land use and forest management activities having some impact on GHG emission fluxes. Some activities are known to result in GHG fluxes, but cannot be quantified based on the available scientific research results. Many of these issues are summarized below to assist users in considering which, if any, of these possible refinements could be included in national inventories, currently, or in the future as scientific understanding improves.

The first section deals with the subcategories already discussed in the basic calculations, but highlights a number of ways in which these calculations could be augmented. The second section discusses additional categories of land use change or forest management which could be added to the categories in the basic calculations.

5.3.2 Possible Refinements or Additions to Basic Categories

Cleared Forests

Forest clearing is a very complex and diverse set of activities which can have many interactions with biospheric fluxes of greenhouse gases over long periods of time. The components of this set of interactions which are included in the previous section are those on which there is general agreement among experts of their importance and simple estimation procedures. A number of other possible elements have been discussed in the scientific literature, but are controversial or difficult to calculate at present.

- **Emissions from Burning of Cleared Forests**

  A number of aspects of emissions due to burning could be treated in more detail.

  a   *Subsequent burns in years after clearing.* In some cases, where forests are cleared for agricultural purposes, the land may be partially burned in the year of clearing, but may also be burned again in later years. Fearnside (1990b) indicates that pastures in the Brazilian Amazon are typically burned two or three times over about a ten year period. This would cause a larger fraction of carbon in cleared biomass to be released to the atmosphere sooner than the approach now included in the basic calculations, and would certainly increase emissions of non-CO_2 trace gases from biomass burning.

b   *Non-CO$_2$ trace gases released after burning.* Basic calculations address the main issues in trace gas production by burning, however, they do not treat all issues. For instance, the effect of past burning, particularly of forests, on trace gas exchanges must eventually be considered. Specifically, the instantaneous release of non-CO$_2$ trace gases when forests are burned is included in Land Clearing calculations. However, the longer-term release or uptake of these gases following forest burning is an important research issue and should eventually be included in refinements of calculations. The issue of the contemporary release of non-CO$_2$ trace gases associated with past burning is complex. For example, clearing by burning may stimulate soil nutrient loss. Measurements in temperate ecosystems[44] indicate that surface biomass burning enhances emissions of N$_2$O and NO$_x$ from the soils for up to 6 months following the burn; however, in other studies measurements of N$_2$O emissions at a cleared and burned tropical forest site in Brazil, begun five months after the burn and continuing for a year, were not significantly different, however, from those taken from a nearby intact forest site.[45] The "historic" issue is obviously complex and further research is needed before an adequate methodology for emissions calculations can be proposed.

- **Delayed release of non-CO$_2$ trace gases after land disturbance.**

  Even when no burning is involved there may still be a release of trace gases. An experiment in a temperate forest in the northeast United States found that clearcutting resulted in enhanced N$_2$O flux to the atmosphere via dissolution of N$_2$O in the soil water, transport to surface waters, and degassing from solution.[46] An experiment in Brazil found that N$_2$O emissions from newly clearcut tropical forests were about three times greater than those from adjacent undisturbed forests.[47] Conversion of tropical forests to pasture also has been found to result in elevated N$_2$O emissions relative to the intact forest soils.[48] Another example involves the loss of a sink for methane which, in effect, adds to the atmospheric burden of CH$_4$. Specifically, the loss of forest area (tropical or temperate) may also result in increased net CH$_4$ emissions to the atmosphere. Soils are a natural sink of CH$_4$ (i.e., soils absorb atmospheric CH$_4$), and various experiments indicate that conversion of forests to agricultural lands diminishes this absorptive capacity of soils.[49]

- **Methane from termites attributable to biomass left to decay**

  When forests are cleared, a portion of the cleared biomass may be left to decay on the ground. Frequently some of the biomass decay is accomplished by termites which emit both methane and carbon dioxide during this process. Fearnside (1990b) estimates that 75% of the unburned carbon is decomposed by termites, and of this 75%, 99.8% is released as CO$_2$ and 0.2% is released as CH$_4$. Fearnside suggests that forest clearing results in increased termite populations and thereby enhances natural termite CH$_4$ emissions. However, as discussed by Collins and Wood (1984), data from Malaysia, Nigeria, and Japan indicate that clearing and cultivation in some forests reduces termite populations. The only incidence of termite abundance increase following clearing cited by Collins and Wood was entirely due to a fungus-growing termite, a type of termite which is unlikely to produce methane. Because of the uncertainty of the effect of clearing on termite populations and associated CH$_4$ release, no guidance on calculation of this component is included in the methodology.

- **Soil carbon loss in tropical systems**

    The basic calculations allow but do not encourage estimation of soil carbon loss after clearing of tropical forests. There are research results which indicate that conversion of tropical forests to pasture may or may not result in loss of soil carbon.[50] Because of the uncertainty no recommendation is made in the basic method concerning whether and how to estimate this component. Further research appears needed to resolve this issue.

- **Fate of roots in cleared forests**

    The basic calculation ignores the fate of living belowground woody biomass (roots, etc.) after forest clearing. The amount of belowground biomass affected, and its fate, need to be considered as work continues beyond the basic calculations. This belowground biomass could be treated as slash but with perhaps a longer decay time. The issue merits research.

- **Aboveground biomass after conversion**

    In the basic calculation, a single default value (10 tonnes dm/ha) is recommended for aboveground biomass which regrows after forests are cleared for conversion to crops or pastures. This may be somewhat variable depending on the type of crop or other vegetation which regrows. National experts carrying out more detailed assessments may wish to account more precisely for this variability.

Conversion of Grasslands to Cultivated Lands: Non-CO$_2$ Trace Gases

Conversion of natural grasslands to managed grasslands and to cultivated lands may affect not only the net emission of CO$_2$ but CH$_4$, N$_2$O, and CO emissions as well. For instance, the conversion of natural grasslands to cultivated lands has been found in the semi-arid temperate zone to also decrease CH$_4$ uptake by the soils.[51] It is not clear what the effect on N$_2$O would be, unless of course nitrogen fertilization occurs. The effect of conversion of natural grasslands to managed grasslands on trace gas emissions has not been evaluated in the field, except for the effect of associated nitrogen fertilization on N$_2$O emissions. Nitrogen fertilization on managed fields may increase carbon accumulation on land, relative to the unfertilized system, and grazing by domestic animals may also affect trace gas fluxes. CO fluxes may be affected due to changes in soil temperature and moisture. These effects on trace gas fluxes, however, are highly speculative and remain a research issue.

Abandoned Lands

The basic calculations account only for the portion of abandoned lands which regrow toward a natural state. There may be additional releases of carbon from abandoned lands which continue to degrade. Where data are available, analysts doing detailed assessments may wish to account for this phenomenon.

Managed Forests

Prescribed Burning of Forests: Non-CO$_2$ Trace Gases

The issue of prescribed forest burning is complex because of two issues. First, there is the question of the rate of change that humans have induced and second, there is the question of releases of trace gas several years after the burning. Prescribed burning is a method of forest management by which forests are intentionally set on fire in order to reduce the accumulation of combustible plant debris and thereby prevent forest fires, which could possibly be even more destructive. This activity is primarily limited to North America and

Australia.[52] Because carbon is allowed to re-accumulate on the land after burning no net CO_2 emissions occur over time,[53] although emissions of CH_4, CO, N_2O, and NO_x result from the biomass combustion.

Some of the issues associated with prescribed forest burning, particularly in the temperate world, remain important research topics. Some have suggested that prescribed forest burning may be increasing carbon stocks in forests and hence serving as a CO_2 sink, but at the same time adding other radiatively important non-CO_2 trace gases   to the atmosphere. An important issue is the change in burning rate because of human activity. Is prescribed burning, and its consequent emissions, just a man-made replacement for what would have occurred naturally? What is the rate change? If we assume that this question, the rate of change, can be answered, then the issue of trace gas release for prescribed burning is similar to trace gas emissions following forest clearing deforestation.

The second complicating issue which should be considered is the release of non-CO_2 trace gases in years after burning. This is also discussed under "Cleared Forests" above. The same uncertainties apply here, although this may be a less important area for prescribed burning, because the forests will be regrowing quickly, and possibly overcoming the conditions which could cause longer term trace gas emissions.

Soil carbon and establishment of plantations

In the basic calculations, no soil carbon accumulation is assumed plantations are establishing (or other tree planting activities occur) on previously non-forest lands. If plantations are established where natural or managed forests previously existed, then the carbon content of soils may not change significantly. However, it is possible that the establishment of plantations on previously non-forest lands could result in accumulation of soil carbon over time. Further investigation may be useful to determine whether this is a significant enough effect to warrant addition to the calculations.

5.3.3 Other Possible Categories of Activity

Several other land use activities affect the flux of carbon dioxide and other trace gases between the terrestrial biosphere and the atmosphere. Shifting cultivation may now be reducing the storage of carbon in forests, because of shorter fallow periods, and thereby becoming a net source of CO_2 to the atmosphere. The changing areas and distribution of wetlands may be adding to or reducing the methane burden of the atmosphere. These issues are complex; often the sign of the flux is not even known, and simple models may not give reasonable results. In this section, some of the issues and possible methodological approaches are recorded; however, an agreed-upon methodology is not yet at hand.

Shifting Cultivation

Shifting cultivation, or slash-and-burn agriculture, is a common agricultural practice in the tropics in which short periods of cultivation (usually about 3 to 5 years) alternate with longer periods of fallow (about 10 to 50 years). Clearing occurs by initial cutting and felling, followed by a series of burns. When practiced in the traditional manner, shifting cultivation produces essentially no net CO_2 emissions because the forest is allowed to return to its original biomass density during the fallow period.[54] However, increasing population pressure has reduced the lengths of fallow periods so that currently much of the fallow land is not allowed to recover and net CO_2 emissions are believed to result.[55] Loss of soil carbon also may occur during shifting cultivation, although the loss is certainly far less than for permanent cultivation.

Calculation of net emissions due to shifting cultivation requires calculation of average annual emissions due to clearing of forests for cultivation and calculation of average annual uptake due to abandonment of cultivated lands in the fallow period of the shifting cultivation cycle. This involves a rather complex pattern of land cohorts and probably requires a model to do the book keeping.

The basic concepts are not difficult. The carbon calculations would proceed almost exactly like the deforestation and abandonment terms in the basic methodology; however, the difficulty is that the abandonment period may be shorter, and this may only be apparent by using a cohort-based model and a finite stock of forest. In other words the increasing rate of shifting cultivation (the likely data) will force a shorter fallow period and hence less regrowth, and this dynamic may only become apparent when one models the shifting cultivation cycle within a specific area of available forest.

One intermediate simple approach is to split the calculation into the two logical components. The deforestation component which would be treated similarly to the basic calculations; namely, convert the above ground dry biomass[56] to carbon (multiply by 0.45) and assume 90% of this material is released as CO_2 less the amount taken upon by the replacing crops (default value of 5 tonnes of carbon per hectare). In this intermediate step one ignores soil carbon and history since the abandonment period follows so quickly upon deforestation. To calculate the uptake of carbon by the regrowing forest during the fallow cycle, simply estimate the amount of land in abandonment (but not yet in steady-state) and the average rate of carbon accumulation per unit area in these fallow lands. The difference would be the net flux of CO_2 associated with shifting cultivation.

Flooding and Wetland Drainage

Land Flooding

Flooding of lands due to construction of hydroelectric dams, or other activities, results in emissions of CH_4 due to anaerobic decomposition of the vegetation and soil carbon that was present when the land was flooded, as well as of organic material that grows in the floodwater, dies, and accumulates on the bottom. The methane emissions from this source are highly variable and are dependent on the ecosystem "type", and the status of the ecosystem, that is flooded (i.e., above- and below-ground carbon, plant types, whether any pre-flooding clearing occurred, etc.) and on the depth and length of flooding (some regions may only be flooded for part of a year). Rates of methane emissions from freshwater wetlands are also strongly dependent on temperature, and therefore vary seasonally, as well as daily. Net emissions of N_2O and CO also may be affected by this activity, although these fluxes are not well determined.

A straight-forward methane flux calculation can be based on the area of land flooded, due to hydroelectric production or other manmade causes, an average daily CH_4 emission coefficient, and the number of days in the year that the area is flooded. Since measurements of CH_4 emissions from freshwater wetlands are so variable, both spatially and temporally, the area should be divided into groups based on characteristics such as length of flooding, vegetation type, and latitude. Then appropriate emission coefficients can be chosen for each group, rather than choosing one emission coefficient for the entire area of flooding. Table 8 presents average daily CH_4 emission rates for natural wetlands, derived from measured emission rates in field experiments, and average CH_4 production periods based on data on monthly mean temperatures and inundation lengths. These rates and production periods can be used if countries do not have more appropriate estimates.

Wetland Drainage

Freshwater wetlands are a natural source of CH_4, estimated to release 100-200 Tg CH_4 (75-150 Tg CH_4-C) per year due to anaerobic decomposition of organic material in the wetland soils (Note: Tg = teragrams, 1 Tg = 10^{12} grams = 10^6 tonnes).[57] Destruction of freshwater wetlands, through drainage or filling, would result in a reduction of CH_4 emissions, and an increase in CO_2 emissions due to increased oxidation of soil organic material.[58] The magnitude of these effects is largely a function of soil temperature and the extent of drainage (i.e., the water content of the soil). Also, since dryland soils are a sink of CH_4, drainage and drying of a wetland could eventually result in the wetland area changing from a source to a sink of CH_4.[59]

Loss of wetland area could also affect net N_2O and CO fluxes, although both the direction and magnitude of the effect is highly uncertain. Natural dryland soils are a source of N_2O, believed to emit 9-28 Tg N_2O (3-9 Tg N_2O-N) annually as a result of nitrification and denitrification processes.[60] This emission estimate is highly uncertain, however, as emission measurements vary both temporally and spatially by up to an order of magnitude. Moreover, the measurements are not consistently correlated with what are believed to be controlling variables such as soil temperature, moisture, and composition, and vegetation type. Dryland soils both produce and consume CO. Carbon monoxide production, estimated at 2-32 Tg CO (1-14 Tg CO-C) per year, is an abiotic process due to chemical oxidation of humus material.[61] It is strongly dependent on soil temperature, moisture, and pH. Destruction of CO is a biological process believed to be due to microorganisms present in the soil. Carbon monoxide destruction (250-530 Tg CO/yr, or 107-227 Tg CO-C/yr) increases with increasing temperature, although it is independent of soil surface temperature (indicating that the process is more active in deeper soil layers) and requires a minimum soil moisture.[62] Desert soils have always been found to be a net source of CO, as have savanna soils, at least during the hottest parts of the day. CO destruction outweighs production in humid temperate soils; humid tropical soils are believed to also be a net sink of CO because of their higher soil moisture and lower soil temperature than deserts and savannas.

To calculate the reduction of CH_4 emissions due to wetland drainage, the area drained is multiplied by the difference in the average daily CH_4 emission rate before and after draining, and is multiplied by the number of days in a year that the wetland was emitting CH_4 prior to drainage. The number of days of CH_4 emissions prior to drainage can be approximated by using the number of days in the year that the wetland was flooded. To calculate the increase in CO_2 emissions due to this activity, the area drained is multiplied by the difference in the average annual CO_2 emission rate before and after draining. This assumes that the elevation in CO_2 emissions due to drainage continue throughout the year. However, the length of time over which the elevated CO_2 emissions continue is uncertain -- it could be less than a year; it could be greater than a year. The net release would also depend on the degree to which there was regrowing vegetation, a CO_2 sink.

In summary, the difference in CH_4 and CO_2 emissions before and after drainage will vary depending on factors such as soil temperature, extent of drainage, and wetland type. Very little data are available on this subject. A laboratory experiment with materials representing a fen, a bog, and a swamp found that the reduction in CH_4 emissions increased with increasing drainage, although the magnitude of the reduction varied between the three types of materials. CH_4 emissions from the fen decreased from about 21 mg CH_4-C/m^2/day (with the water level about 10 cm above the surface) to about 0.8 CH_4-C/m^2/day (with the water table about 70 cm below the surface); CH_4 emissions from the swamp decreased from about 9 to about 0.6 CH_4-C/m^2/day; and CH_4 emissions from the bog decreased only slightly, from about 0.7 to about 0.6 mg CH_4-C/m^2/day. CO_2 emissions from all three materials were about 0.08 mg CO_2-C/m^2/day (with the water

level about 10 cm above the surface), and increased to about 2 mg CO_2-C/m^2/day (with the water table about 70 cm below the surface.

The direction and magnitude of the effects on these gases are highly uncertain and significant advances in our understanding of the biological processes as well as determination of the areal extent of the activities will be required before these calculations can be adequately accomplished. It may be possible to include methane calculations associated with land flooding in early refinements of the calculations, but the N_2O and CO calculations are more difficult and as yet of uncertain importance.

5.4   Tables

TABLE 5-1
DRY MATTER IN ABOVEGROUND BIOMASS IN TROPICAL FORESTS
(tons dm/hectare)

	Closed Forests						Open Forests	
	Broadleaf			Conifer				
	Undisturbed	Logged	Unproductive	Undisturbed	Logged	Unproductive	Productive	Unproductive
America	230	190	150	150	60	60	60	25
Africa	300	240	185	130	60	110	36	16
Asia	300	150	230	160	135	130	61	20

Sources:
Volume-based estimates derived from a variety of sources. Recent revised estimates for aboveground biomass in undisturbed closed broadleaf forests were taken from Brown and Lugo (1992) for Tropical America, Brown et al. (in press) for Asia and Brown (1993) for Africa. Corresponding values for logged and unproductive forests were derived on the basis of the ratios of these biomass densities to the biomass density for undisturbed forests as reported in Brown et al. (1989). For closed conifer forests, stemwood biomass/hectare was taken from Brown and Lugo (1984) and multiplied by more recent expansion factors for undisturbed, logged and unproductive categories (1.75, 1.90, and 2.0 respectively) from Brown et al. (1989). Values for open forests were taken from Brown and Lugo (1984) and multiplied by 0.77 to obtain the aboveground portion only.

Note:
Estimates based on destructive sampling involve direct measurements (weighing) of biomass harvested from an experimental site. Volume-based estimates are generally somewhat lower than those based on destructive sampling, and are derived from FAO data on commercial wood volumes that are converted to mass units based on average wood densities and ratios of aboveground biomass to commercial biomass (i.e., expansion factors). There is considerable uncertainty in all regional estimates of biomass densities of tropical forests. Researchers agree that there is a great deal of variability from stand to stand and among subregions within large regions. For example, Brown and Lugo (1992) report biomass estimates ranging from 166 to 332 t dm/ha for dense Amazonian forests.

There are also some differences in the way different experts interpret the available data to produce averages. Fearnside (1993) has produced somewhat higher average estimates of aboveground biomass for the Brazilian Amazon than those of Brown and Lugo (1992) His estimates are for :

	Average for Brazilian Amazon (t dm/ha)	Forests Actually Cleared in 1990 in Brazilian Amazon (t dm/ha)
Undisturbed forests	308	291
Logged forests		271

Fearnside (1992) and Brown and Lugo (1992) discuss in detail a number possible explanations for the differences in results.

TABLE 5-2
DRY MATTER IN ABOVEGROUND BIOMASS IN TEMPERATE AND BOREAL FORESTS
(tons dm/hectare)

	Temperate Forests		Boreal Forests
	Evergreen	Deciduous	
Primary	295	250	165
Secondary	220	175	120

Source
Primary forest estimates from Whittaker and Likens (1973); secondary forest estimates from Houghton et al. (1983). Total biomass estimates were converted to aboveground biomass by multiplying by 0.83 (Leith and Whittaker, 1975). Alternate estimates of aboveground biomass per hectare, by country, for coniferous species and non-coniferous species, can be derived using statistics provided in ECE/FAO (1985). Data are provided for 22 countries.

TABLE 5-3
CARBON IN SOILS IN TROPICAL FORESTS

(tons carbon/hectare)

	Moist	Seasonal	Dry
America	115	100	60
Africa	115	100	60
Asia	115	100	60

Source:
Post, W.M., et al., 1982.

Note:
The forest categories presented here are different from those presented in Tables 1 and 2. The average of the values for moist and seasonal forests presented above can be used for both closed forest types (broadleaved and coniferous); the values for dry forests presented above can be used for open forests.

TABLE 5-4
CARBON IN SOILS IN TEMPERATE AND BOREAL FORESTS

(tons carbon/hectare)

	Temperate Forests		Boreal Forests
	Evergreen	Deciduous	
Primary	134	134	206
Secondary	120	120	185

Source: Schlesinger, 1977, as cited in Houghton et al., 1983; and Houghton et al., 1987.

Note: Alternate values for soil carbon in tropical, temperate, and boreal forests, by continent, are available in Zinke et al. (1984). However, care must be taken when choosing appropriate soil carbon values in Zinke et al. (1984). Ecosystem types in this reference may not match the ecosystem types for which clearing data and biomass estimates are available.

TABLE 5-5

ANNUAL AVERAGE ABOVEGROUND BIOMASS UPTAKE BY NATURAL REGENERATION

t dm/ha

Region		Forest Types			
		Closed Forests		Open Forests	
Tropical		0-20 Years	20-100 Years	0-20 Years	20-100 Years
	America	8.0	0.9	4.0	0.25
	Africa	11	1.0	4.0	0.25
	Asia	11	1.0	4.0	0.25
Temperate		0-20 Years	20-100 Years		
	Evergreen	7.5	1.8		
	Deciduous	5.5	1.4		
Boreal		4.0	1.1		

Note: Growth rates are derived by assuming that tropical forests regrow to 70% of undisturbed forest biomass and temperate and boreal forests regrow to 50% of undisturbed forest biomass in the first twenty years. All forests are assumed to regrow to 100% of undisturbed forest biomass in 100 years. Undisturbed forest biomass values are from Tables 1 and 2. For tropical forests, assumptions on the rates of growth in different time periods are derived from Brown and Lugo, 1990. Assumptions for temperate and boreal forests are based on Houghton et al., 1983, and Houghton et al., 1987.

TABLE 5-6

AVERAGE ANNUAL ACCUMULATION OF DRY MATTER AS BIOMASS IN PLANTATIONS

Forest Type	Annual Increment in Biomass (tons dm/hectare/year)
Tropical	
Acacia spp.	15.0
Eucalyptus spp.	14.5
Tectona grandis	8.0
Pinus spp.	11.5
Pinus caribaea	10.0
Mixed Hardwoods	6.8
Mixed Fast-Growing Hardwoods	12.5
Mixed Softwoods	14.5
Temperate	
Douglas fir	6.0
Loblolly pine	4.0

Sources: Derived from Brown et al., 1986.
Farnum et al., 1983

Note:
These are average accumulation rates over expected plantation lifetimes;
actual rates will vary depending on the age of the plantation. The data for
the temperate species are based on measurements in the U.S. Data on
other species, and from other regions, should be supplied by individual
countries (as available). Additional temperate estimates by species and by
country can be derived from data in ECE/FAO (1985), assuming that
country averages of net annual increment for managed and unmanaged
stands are reasonable approximations for plantations.

TABLE 5-7

EMISSION RATIOS FOR OPEN BURNING OF CLEARED FORESTS

Compound	Ratios
CH_4	0.012 (0.009 - 0.015) [1]
CO	0.06 (0.04 - 0.08) [2]
N_2O	0.007 (0.005 - 0.009) [3]
NO_x	0.121 (0.094 - 0.148) [3]

Sources:　　[1] Delmas, 1993

　　　　　　　[2] Lacaux, 1993

　　　　　　　[3] Crutzen and Andreae, 1990

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. Those for the nitrogen compounds are
expressed as the ratios of emission (in units of N) relative to total
nitrogen released from the fuel.

TABLE 5-8
AVERAGE METHANE EMISSIONS AND PODUCTION PERIODS OF NATURAL WETLANDS

Wetland Categories	Emission Rate (mg CH$_4$-C/m^2/day)	Production Period (days)
Bogs	11 (1-38)	178
Fens	60 (21-162)	169
Swamps	63 (43-84)	274
Marshes	189 (103-299)	249
Floodplains	75 (37-150)	122
Lakes	32 (13-67)	365

Source: Aselmann and Crutzen, 1989.

Note: Average daily emission rates are derived from measured emission rates in field experiments (the range in measured emission rates is in parentheses after the average), and average production periods are based on monthly mean temperature data and lengths of inundation.

5.5   References

Anderson, I.C., J.S. Levine, M.A. Poth, and P.J. Riggan. 1988. Enhanced biogenic emissions of nitric oxide and nitrous oxide following surface biomass burning. *Journal of Geophysical Research* 93:3893-3898.

Andreae, M.O. 1990. Biomass burning in the tropics: Impact on environmental quality and global climate. Paper presented at the Chapman Conference on Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications, 19-23 March 1990, Williamsburg, Virginia.

Arbhabhirama, A., D. Phantumvanit, J. Elkington, and P. Ingkasuwan. 1987. Thailand Natural Resources Profile. Bangkok: Thailand Development Research Institute.

Aselmann, I., and P.J. Crutzen. 1989. Global distribution of natural freshwater wetlands and rice paddies, their primary productivity, seasonality and possible methane emissions. *Journal of Atmospheric Chemistry* 8:307-358.

Atjay, G.L., P. Ketner, and P. Duvigneaud. 1979. Terrestrial primary production and phytomass. In: Bolin, B., E.T. Degens, S. Kempe, and P. Ketner (eds.). *The Global Carbon Cycle*. SCOPE 13. Wiley, Chichester. pp. 129-182.

Birdsey, R.A. 1990. Potential changes in carbon storage through conversion of lands to plantation forests. Paper presented at the North American Conference on Forestry Response to Climate Change. 15-17 May 1990, Washington, D.C.

Bolin, B., E.T. Degens, P. Duvigneaud, and S. Kempe. 1979. The global biogeochemical carbon cycle. In: Bolin, B., E.T. Degens, P. Duvigneaud, and S. Kempe (eds.). *The Global Carbon Cycle*. SCOPE 13. Wiley, Chichester. pp. 1-56.

Bowden, W.B., and F.H. Bormann. 1986. Transport and loss of nitrous oxide in soil water after forest clear-cutting. *Science* 233:867-869.

Brown, S., and A.E. Lugo. 1982. The storage and production of organic matter in tropical forests and their role in the global carbon cycle. *Biotropica* 14(3):161-187.

Brown, S., and A.E. Lugo. 1984. Biomass of tropical forests: A new estimate based on forest volumes. *Science* 223:1290-1293.

Brown, S., A.E Lugo, and J. Chapman. 1986. Biomass of tropical tree plantations and its implications for the global carbon budget. *Canadian Journal of Forest Research* 16:390-394.

Brown, S. and A.J.R. Gillespie, and A.E. Lugo. 1989. Biomass estimation methods for tropical forests with applications to forest inventory data. *Forest Science* 35:881-902.

Brown S. and A. E. Lugo. 1990. Tropical Secondary Forests. *Journal of Tropical Ecology.* 6:1-32.

Brown, S and A.E. Lugo. 1992. Aboveground Biomass Estimates for Tropical Moist Forests of the Brazilian Amazon. *Interciencia* 17:8-18.

Brown, S. 1993. Personal communication, based on analysis of inventory data from ongoing research in Africa.

Brown, S., L.R. Iverson, A. Prasad. and D. Liu. In Press. Geographical Distribution of Carbon in Biomass and Soils of Tropical Asian Forests. *Geocarto International.*

Buschbacher, B. 1984. Changes in productivity and nutrient cycling following conversion of Amazon rainforest to pasture. Dissertation, University of Georgia, Athens.

Cerri, C.C., B. Volkoff, and F. Andreux. 1988. Nature and behavior of organic matter in soils under natural forest and after deforestation, burning and cultivation in Amazonia. Paper presented at the 46th International Congress of Americanists, 4-8 July 1988, Amsterdam, Holland.

Cicerone, R.J., and R.S. Oremland. 1988. Biogeochemical aspects of atmospheric methane. *Global Biogeochemical Cycles* 2:299-327.

Collins, N.M., and T.G. Wood. 1984. Termites and atmospheric gas production. *Science* 224:84-86.

Comery, J.A. 1981. Thesis. Department of Forestry, University of Washington, Seattle.

Crutzen, P.J., M.O. Andreae. 1990. Biomass burning in the Tropics: Impact on atmospheric chemistry and biogeochemical cycles. *Science* 250:1669-1678.

da Cunha, R.P. 1989. Deforestation estimates through remote sensing: The state of the art in the Legal Amazonia. In: *Amazonia: Facts, Problems, and Solutions.* University of Saõ Paulo, Saõ Paulo, Brazil. pp. 240-273.

Delmas, R. 1993. An Overview of Present Knowledge on Methane Emission from Biomass Burning. in A.R, van Amstel (ed.). *Proceedings of an International IPCC Workshop: Methane and Nitrous Oxides, Methods in National Emissions Inventories and Options for Control, 3-5 February 1993, Amersfoort, NL.* RIVM Report no. 481507003, Bilthoven, NL, July.

Delmas, R.A. and D. Ahuja. 1993. Estimating National Methane Emissions from Anthropogenic Biomass Burning. Working Group Report: Methane Emissions from Biomass Burning. in A.R. van Amstel (ed.), *Proceedings of an International IPCC Workshop: Methane and Nitrous Oxides, Methods in National Emissions Inventories and Options for Control, 3-5 February 1993, Amersfoort, NL.* RIVM Report no. 481507003, Bilthoven, NL, July.

Delmas, R.A., A. Marenco, J.P. Tathy, B. Cros, and J.G.R. Baudet. 1991a. Sources and sinks of methane in African savanna. Methane emission from biomass burning. *J. Geophys. Res.* 96:7287-7299.

Delmas, R.A., Ph. Loudjani, A. Podaire, and J.C. Menaut. 1991b. Biomass burning in Africa: an assessment of annually burned biomass. In: J.S. Levine (ed.), *Global Biomass Burning*, MIT Press, Cambridge, 126-132.

Delmas, R.A., J. Servant, J.P. Tathy, B. Cros, and M. Labat. 1992a. Sources and sinks of methane and carbon dioxide in mountain forest in equatorial Africa. *J. Geophys. Res.,* 97:6169-6179.

Delmas, R.A., J.P. Tathy, and B. Cros. 1992b. Atmospheric methane budget in Africa. *J. Atmos. Chem.,* 14:395-409.

Detwiler, R.P., and C.A.S. Hall. 1988. Tropical forests and the global carbon cycle. *Science* 239:42-47.

Devol, A.H., J.E. Richey, W.A. Clark, and S.L. King. 1988. Methane emissions to the troposphere from the Amazon floodplain. *Journal of Geophysical Research* 93:1583-1592.

ECE/FAO (United Nations Economic Commission for Europe/Food and Agriculture Organization of the United Nations). 1985. *The Forest Resources of the ECE Region (Europe, the USSR, North America).* The United Nations, Geneva.

Emanuel, W.R., A.W. King, and W.M. Post. In Press. A Dynamic Model of Terrestrial Carbon Cycling. In M. Heimann (ed.) *The Global Carbon Cycle.* Springer-Verlag, Berlin.

FAO/UNEP (Food and Agriculture Organization of the United Nations/United Nations Environment Programme). 1981. *Tropical Forest Resources Assessment Project.* FAO, Rome.

FAO. 1988. *An Interim Report on the State of the Forest Resources in the Developing Countries.* FAO, Rome.

FAO (Food and Agriculture Organization of the United Nations). 1991. *1990 Yearbook of Forest Products 1974-1990.* FAO, Rome.

FAO. 1990. *Interim Report on Forest Resources Assessment 1990 Project.* Committee on Forestry, Tenth Session, FAO. Rome, Italy.

FAO. 1992. The Forest Resources of the Tropical Zone by Main Ecological Regions. Forest Resources Assessment 1990 Project, Food and Agriculture Organization, United Nations.

FAO. 1993a. Forest Resources Assessment 1990 - Tropical Countries. FAO Forestry PaPER No. 112, FAO, Rome.

FAO. 1993b Yearbook of Forest Products (Annual) FAO, Rome.

Farnum, P., R. Timmis, J. Kulp. 1983. Biotechnology of forest yield. *Science* 219:694-702.

Fearnside, P.M. 1980. The effects of cattle pasture on soil fertility in the Brazilian Amazon: Consequences for beef production sustainability. *Tropical Ecology* 21:125-137.

Fearnside, P.M. 1986. Brazil's Amazon forest and the global carbon problem: Reply to Lugo and Brown. *Interciencia* 11:58-64.

Fearnside, P.M., M.M. Keller, N.L. Filho, and F.M. Fernandes. 1990a. Rainforest burning and the global carbon budget: Biomass, combustion efficiency and charcoal formation in the Brazilian Amazon. National Institute for Research in the Amazon, Brazil.

Fearnside, P.M., A.T. Tardin, and L.G.M. Filho. 1990b. Deforestation rate in Brazilian Amazon. National Secretariat of Science and Technology, Brazil.

Fearnside, P.M. 1990c. Deforestation in Brazilian Amazonia as a source of greenhouse gases. Paper presented at the Regional Conference on Global Warming and Sustainable Development: Perspectives from Developing Countries, June 18-20, São Paulo.

Fearnside, P.M. 1990d. Presentation given at the Chapman Conference on Global Biomass Burning. Williamsburg, Virginia, March 19-23. Proceedings forthcoming: MIT Press, Cambridge, Massachusetts.

Fearnside, P.M. 1992. Forest Biomass in Brazilian Amazonia: Comments on the Estimate by Brown and Lugo. *Interciencia*. 17:19-27.

Fearnside, P.M. 1993. Personal Communication. October.

Galbally, I.E. 1985. The emission of nitrogen to the remote atmosphere: Background paper. In: Galloway, J.N., R.J. Charlson, M.O. Andreae, and H. Rodhe (eds.). *The Biogeochemical Cycling of Sulfur and Nitrogen in the Remote Atmosphere*. D. Reidel, Dordrecht. pp. 27-53.

González-Jiménez, E. 1979. Primary and secondary productivity in flooded savannas. In: UNESCO/UNEP/FAO (ed.). Tropical grazing land ecosystems of Venezuela. *Nat. Resour. Res.* 16:620-625.

Green, G.M., and R.W. Sussman. 1990. Deforestation history of the eastern rainforests of Madagascar from satellite images. *Science* 248:212-215.

Hao, W.M., M.H. Liu, and P.J. Crutzen. 1990. Estimates of annual and regional releases of CO_2 and other trace gases to the atmosphere from fires in the tropics, based on the FAO statistics for the period 1975-1980. In: Goldammer, J.G. (ed.). *Fire in the Tropical Biota, Ecosystem Processes and Global Challenges*. Springer-Verlag, Berlin. pp. 440-462.

Harriss, R.C., and D.I. Sebacher. 1981. Methane flux in forested freshwater swamps of the southeastern United States. *Geophysical Research Letters* 8:1002-1004.

Harriss, R.C., D.I. Sebacher, and F.P. Day Jr. 1982. Methane flux in the Great Dismal Swamp. *Nature* 297:673-674.

Hingston, F.J., and R.J. Raison. 1982. Consequences of biogeochemical interactions for adjustment to changing land use practices in forest systems. In: Galbally, I.E., and J.R. Freney (eds.). *The Cycling of Carbon, Nitrogen, Sulfur, and Phosphorus in Terrestrial and Aquatic Ecosystems*. Australian Academy of Science, Canberra.

Holt, J.A., and A.V. Spain. 1986. Some biological and chemical changes in a North Queensland soil following replacement of rainforest with *Araucaria cunninghammii*. (Coniferae: Araucariaceae). *Journal of Applied Ecology* 23:227-237.

Houghton, R.A., J.E. Hobbie, J.M. Melillo, B. Moore, B.J. Peterson, G.R. Shaver, and G.M. Woodwell. 1983. Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: A net release of CO_2 to the atmosphere. *Ecological Monographs* 53(3):235-262.

Houghton, R.A., R.D. Boone, J.R. Fruci, J.E. Hobbie, J.M. Melillo, C.A. Palm, B.J. Peterson, G.R. Shaver, and G.M. Woodwell. 1987. The flux of carbon from terrestrial ecosystems to the atmosphere in 1980 due to changes in land use: geographic distribution of global flux. *Tellus* 39B:122-129.

Houghton, R.A. 1991. Tropical deforestation and atmospheric carbon dioxide. *Climatic Change*.

INPE. 1992. Deforestation in Brazilian Amazonia. Instituto Nacional de Pesquisas Espaciais.

IPCC. 1990. Climate Change: the IPCC Scientific Assessment. J.T. Houghton, G.J. Jenkins and J.J. Ephraums (Eds.) Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

IPCC. 1992. Climate Change 1992: the Supplementary Report to the IPCC Scientific Assessment. Edited by J. T. Houghton, B. A. Callander and S. K. Varney. Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Johansson, T.B., H. Kelly, A.K.N. Reddy, and R.H. Williams. 1992. Renewable Energy: Sources for Fuels and Electricity. Island Press. Washington, DC.

Kartawinata, K., S. Adisoemarto, S. Riswan, and A.P. Vayda. 1981. The impact of man on a tropical forest in Indonesia. *Ambio* 10:115-119.

Kauppi, P.E., K. Mielikainen and K. Kuusela. 1992. Biomass and Carbon Budget of European Forests, 1971 to 1990. *Science*. 256:70-74.

Keller, M., W.A. Kaplan, and S.C. Wofsy. 1986. Emissions of N_2O, CH_4 and CO from tropical forest soils. *Journal of Geophysical Research* 91:11791-11802.

Keller, M., M.E. Mitre, R.F. Stallard. 1990. Consumption of atmospheric methane in soils of Central Panama: Effects of agricultural development. *Global Biogeochemical Cycles*, 4:21-27.

King, G.A., J.K. Winjum, R.K. Dixon, and L.Y. Arnaut. 1990. *Response and Feedbacks of Forest Systems to Global Climate Change.* Environmental Research Laboratory, Corvallis, United States Environmental Protection Agency, EPA/600/3-90/080.

Lacaux, J.P., H. Cachier and R. Delmas. 1993. Biomass Burning in Africa: An Overview of Its Impact on Atmospheric Chemistry. in P.J. Crutzen and J.G. Goldammer (eds.) *Fire in the Environment: The Ecological, Atmospheric and Climatic Importance of Vegetation Fires.* J. Wiley & Sons Ltd.

Lanly, J.P. 1982. *Tropical Forest Resources.* Food and Agriculture Organization of the United Nations (FAO) Paper 30. FAO, Rome.

Lashof, D.A., and D.A. Tirpak (eds.). 1990. *Policy Options for Stabilizing Global Climate.* Report to Congress, U.S. Environmental Protection Agency, Washington, D.C.

Leith, H., and R.H. Whittaker (eds.). 1975. *Primary Productivity of the Biosphere.* Ecological Studies No. 14. Springer-Verlag, New York-Heidelberg-Berlin.

Leith, H. 1978. *Patterns of Primary Productivity in the Biosphere.* Hutchinson Ross, Stroudsberg.

Levine, J.S. (ed.). 1990. *Global Biomass Burning: Atmospheric, Climatic and Biospheric Implications.* The MIT Press. Cambridge, MA.

Levine, J.S., W.R. Cofer III, D.I. Sebacher, E.L. Winstead, S. Sebacher, and P.J. Boston. 1988. The effects of fire on biogenic soil emissions of nitric oxide and nitrous oxide. *Global Biogeochemical Cycles* 2:445-449.

Likens, G.E., F.H. Bormann, N.M. Johnson, D.W. Fisher, and R.S. Pierce. 1970. Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook ecosystem in New Hampshire. *Ecological Monographs* 40:23-47.

Lugo, A.E., M.J. Sanchez, and S. Brown. 1986. Land use and organic carbon content of some subtropical soils. *Plant and Soil* 96:185-186.

Luizão, F., P. Matson, G. Livingston, R. Luizão, and P. Vitousek. 1989. Nitrous oxide flux following tropical land clearing. *Global Biogeochemical Cycles* 3:281-285.

MacKenzie, J.J., and M.T. El-Ashry (eds.). 1989. *Air Pollution's Toll on Forests and Crops*. Yale University Press, New Haven.

Matson, P.A., and P.M. Viotousek. 1981. Nitrogen mineralization and nitrification potentials following clearcutting in the Hoosier National Forest, Indiana. *Forest Science* 27:781-791.

Matson, P.A., P.M. Vitousek, G.P. Livingston and N.A. Swanberg. 1990. Sources of variation in nitrous oxide flux from Amazonian ecosystems. *Journal of Geophysical Research* 95:16789-16798.

Melillo, G., J.R. Fruci, R.A. Houghton, B. Moore, and D.L. Skole. 1988. Land-use change in the Soviet Union between 1850 and 1980: causes of a net release of CO_2 to the atmosphere. *Tellus* 40B:116-128.

Moore, B., R. Boone, J. Hobbie, R. Houghton, J. Melillo, B. Peterson, G. Shaver, C. Vörösmarty, G. Woodwell. 1981. A simple model for analysis of the role of terrestrial ecosystems in the global carbon budget. In B. Bolin (ed.), *Carbon Cycle Modelling*. <u>SCOPE 16</u>. New York: Wiley & Sons.

Moore, T.R., and R. Knowles. 1989. The influence of water table levels on methane and carbon dioxide emissions from peatland soils. *Canadian Journal of Soil Science* 69:33-38.

Mosier, A., D. Schimel, D. Valentine, K. Bronson, and W. Parton. 1991. Methane and nitrous oxide fluxes in native, fertilized and cultivated grasslands. *Nature* 350:330-332.

Myers, N. 1989. *Deforestation Rates in Tropical Forests and their Climatic Implications*. A Friends of the Earth Report, London.

Nicholson, D.I. 1958. An analysis of logging damage in tropical rain forests, North Borneo. *Malaysian Forests* 231:235-245.

Olson, J.S., J.A. Watts, and L.J. Allison. 1983. *Carbon in Live Vegetation of Major World Ecosystems*. ORNL-5862. Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Post, W.M., W.R. Emanuel, P.J. Zinke and A.G. Stangenberger. 1982. Soil Carbon Pools and World Life Zones. *Nature* 298:156-159.

Ranjitsinh, M.K. 1979. Forest destruction in Asia and the South Pacific. *Ambio* 8:192-201.

Scharffe, D., W.M. Hao, L. Donoso, P.J. Crutzen, and E. Sanhueza. 1990. Soil fluxes and atmospheric concentration of CO and CH_4 in the northern part of the Guayana Shield, Venezuela. *Journal of Geophysical Research* 95:22,475-22,480.

Schlesinger, W.H. 1977. Carbon balance in terrestrial detritus. *Annual Review of Ecology and Systematics* 8:51-81.

Schlesinger, W.H. 1982. *The Role of Terrestrial Vegetation in the Global Carbon Cycle: Methods for Appraising Changes*. Wiley, New York.

Schlesinger, W.H. 1984. The world carbon pool in soil organic matter: A source of atmospheric CO_2. In: Woodwell, G.M. (ed.). *The Role of Vegetation in the Global Carbon Cycle: Measurement by Remote Sensing*. Scope 23. John Wiley and Sons, New York. pp. 111-127.

Seiler, W., and P.J. Crutzen. 1980. Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning. *Climatic Change* 2:207-247.

Seiler, W., and R. Conrad. 1987. Contribution of tropical ecosystems to the global budgets of trace gases, especially CH_4, H_2, CO, and N_2O. In: Dickinson, R.E. (ed.). *The Geophysiology of Amazonia*. John Wiley, New York. pp. 133-160.

Singh, K.P., and R. Misra. 1978. *Structure and Functioning of Natural, Modified and Silvicultural Ecosystems of Eastern Uttar Pradesh.* Technical Report MAB Research Project, Banaras Hindu University, Varanasi.

Tans P.P., I.Y. Fung, and P.H. Daum. 1990. Observational Constraints on the Global Atmosphere Carbon Dioxide Budget. *Science* 247:1431-1438.

U.S. HEW (U.S. Department of Health, Education, and Welfare). 1970. *Air Quality Criteria for Carbon Monoxide.* U.S. HEW, Washington, D.C.

Whittaker, R.H., and G.E. Likens. 1973. Carbon in the biota. In: Woodwell, G.M., and E.V. Pecan (eds.). *Carbon and the Biosphere.* U.S. Atomic Energy Commission, Symposium Series 30. National Technical Information Service, Springfield, VA, USA. pp. 281-302.

Whittaker, R.H., and G.E. Likens. 1975. The biosphere and Man. In: Lieth, H., and R.H.

Whittaker (eds.). *Primary Productivity of the Biosphere.* Springer-Verlag, New York. pp. 305-328.

Whittaker, R.H. 1975. *Communities and Ecosystems.* Macmillan, New York.

Zinke, P.J., A.G. Stangenberger, W.M. Post, W.R. Emanuel, and J.S. Olson. 1984. *Worldwide Organic Soil Carbon and Nitrogen Data.* ORNL/TM-8857. Oak Ridge National Laboratory, Oak Ridge, Tennessee.

5.6   Endnotes

1. "Indirect" greenhouse gases here refers to gases which contribute to the chemical formation or destruction of ozone (O_3) in the atmosphere. As O_3 is an important greenhouse gas, the gases which create or destroy it affect the radiative forcing of the atmosphere indirectly.

2. IPCC (1990). Note fluxes of CO_2 are generally expressed in scientific literature as mass of carbon per year. The mass is in 10^{15} grams carbon as CO_2 (pg CO_2-C).

3. Brown et al., 1986

4. Houghton et al., 1987; Melillo et al., 1988

5. See, for example, Tans et al., 1990, IPCC, 1992 and Kauppi et al., 1992.

6. Delayed releases of non-CO_2 trace gases are an important research issue. These releases may be important , but are currently too uncertain to be included in calculations.

7. Houghton, 1991

8. For example, see Moore et al., 1981, Houghton et al., 1983, Houghton et al., 1986, Mellilo et al., 1988, and Emanuel et al., in press.

9. Similarly, current land-use will affect future fluxes of carbon dioxide.

10. This is what the term "deforestation" should mean and it is frequently accompanied by burning.

11. Abandonned lands which are regrowing naturally may be cleared again. In this case, they should shift again to cleared lands, probably with a lower value for preclearing biomass density.

12. Conversion of tropical forests to pasture and cropland accounts for the largest share of global forest clearing and resulting CO_2 emissions. the discussion and default information focus on this case, as it is most important that national inventories account for the largest contributions to emissions first. Forest clearing for other purposes (e.g., urban development) should also be accounted for to the extent possible. as less default information is provided for these cases, this will require national experts to provide input data.

13. For instance, see Houghton, 1991; Crutzen and Andreae, 1990. The decay rates generally depend on several factors including humidity, temperature, and litter quality.

14. This issue is discussed in the section on possible refinements to the methodology.

15. The portion of burned carbon that remains on the ground as charcoal is highly uncertain. Measurements following burning of a forest for conversion to pasture indicate that 2.6% of the pre-burn aboveground carbon, or 8.5% of the burned carbon, is converted to charcoal (Fearnside et al., 1990a). according to Fearnside (1990b), pastures are typically burned two to three times over about a 10-year period. Under such a scenario, the latter burns probably result in combustion of some of the charcoal formed during the first burn and formation of additional charcoal. Fearnside (1990b) estimates that about 4.6% of the pre-burn aboveground carbon, or 10.1% of the burned carbon, is converted to charcoal under this scenario. Based on results of observations in the Brazilian Amazon (Fearnside, 1990a) and in a Florida pine forest (Comery, 1981), Crutzen and Andreae (1990) adopt charcoal values of 5% of the pre-burn aboveground carbon and 10% of the burned carbon for clearing in the tropics.

16. It is important to note, as discussed in the introduction to this document, that there is an intentional double counting of carbon emitted from combustion. CO_2 is calculated based on the assumption that all carbon in fuel is emitted as CO_2. however, methods are also provided to estimate portions of total carbon which are emitted as CH_4 and CO. the reasons for this double counting are discussed in the introduction.

17. On average about 25-50% of the soil carbon, as discussed in Houghton et al., 1983.

18. For simplicity of explanation, the discussion refers to the inventory year as though data for a single year were the desired input. However, as noted in the overview, for land use and forestry emissions estimates, it is recommended that data averaged over three years be used in place of annual data.

19. Defining regions will require balancing data availability, biological and land-use heterogeneity, and practical considerations such as the available time and effort. furthermore, developing adequate land-use and land-use change data is a central issue. In the case of land-clearing, this data would likely be obtained from a combination of departments of land management, agriculture, and forestry. this data will come at a variety of scales in time and space, and producing consistent records will be a challenging task to all countries. in time, new internationally-based remote sensing programs could greatly facilitate this task; this is discussed in the technical appendix.

20. As in the case of land-use data, developing appropriate biomass data is a challenging task. in theory, it can be obtained directly by destructive sampling but this is unrealistic for adequate coverage for even small countries. an alternative approach is to use inventory or production data where one exploits volumetric data on marketable timber and uses a sequence of expansion factors to convert this to total stemwood, total above ground biomass volume, and total biomass volume. see the references to Tables 1 and 2.

21. Houghton et al., 1987.

22. For instance, see Houghton, 1991; Crutzen and Andreae, 1990.

23. Note also that the smoldering that produces charcoal and ash also forms other important greenhouse gases such as CH_4 and N_2O. for instance, see Fearnside et al., 1990a and Crutzen and Andreae, 1990.

24. We are also ignoring the carbon flux associated with CO formation during combustion which accounts for about 8% of the burned carbon.

25. The range most cited is (0.43 - 0.58) hence some suggest that 0.5 as a more appropriate default assumption.

26. See Houghton 1991; Crutzen and Andreae 1990 for discussion of this issue.

27. In temperate systems, in fact, most of the soil carbon is released in the first 5 years after clearing; the rest is released over the next 20 years. see Houghton, 1991.

28. See Houghton et al., 1983.

29. The issue of soil carbon change following land-clearing in the tropics is an important research topic. there is evidence that there is a rapid soil carbon loss follow by soil carbon accumulation depending upon the type of grasses that are used in pasture. (e.g., Fearnside, 1980, 1986; Buschbacher, 1984; Cerri et al., 1988; and Lugo et al., 1986); and clear cutting of tropical forests does not appear to release soil carbon (Keller et al., 1986).The current status of the science, however, may not provide an adequate basis for recommending values for inclusion of this aspect of the carbon cycle in emissions calculations at this time. further research needs to be done.

30. The emission ratios used in this section are derived from Crutzen and Andreae (1990), and Delmas, 1993, as presented in the table. 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. Research will need to be conducted in the future to determine if more specific emission ratios, e.g., specific to forest fires, can be obtained. also, emission ratios vary significantly between the flaming and smoldering phases of a fire. co_2, n_2o, and no_x are mainly emitted in the flaming stage, while CH_4 and CO are mainly emitted during the smoldering stage (lobert et al., 1990). 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.

31. Emissions inventory developers are encouraged to provide estimates of uncertainty along with these best estimate values where possible, or to provide some expression of the level of confidence associated with various point estimates provided in the inventory. procedures for reporting this uncertainty or confidence information are discussed in Volume 1: Reporting Instructions.

32. Crutzen and Andreae, 1990.

33. From Crutzen and Andreae, 1990.

34. There is an inconsistency in the methodology in the treatment of the full molecular weight of NO_x. In fossil energy and industry discussions NO_x is expressed as though all of the N were in the form of NO_2. In biomass burning literature, (e.g., Crutzen and Andreae, 1990) NO_x is often discussed as though the emissions were in the form of NO. Therefore, the biomass burning discussions in these guidelines convert NO_x-N to full weight using the conversion factor (30/14) for no. all other references to NO_x are based on the full weight of NO_2 (i.e., the conversion factor from NO_x-N would be 46/14).

35. See Houghton et al., 1983.

36. Post, et al., 1982.

37. See Houghton et al., 1983.

38. Values given in Table 5 assume linear regrowth of aboveground biomass in each of the two time periods (0-20 years and 21-100 years). In reality, as shown in Brown and Lugo 1990, the regrowth is closer to an exponential function. the calculation could be improved by breaking the 20 year period into finer segments, assuming availability of data, to determine a weighted average.

39. The re-accumulation of carbon in soils is not linear. Generally accumulation occurs quickly in initial stages of regrowth and slows as regrowth slows.

40. Plantations are forest stands that have been established artificially, to produce a forest product "crop". They are either on lands that previously have not supported forests for more than 50 years (afforestation), or on lands that have supported forests within the last 50 years and where the original crop has been replaced with a different one (reforestation) (Brown et al., 1986).

41. There is one omission in this accounting which may be important for some countries. If plantations are established on previously non-forest lands, there may be a long term accumulation of carbon in the soil as a result of the land use change. this would not normally be picked up in the simple managed forest calculations. It could be added if national experts have detailed data on the pre-plantation land uses, The soil carbon contents and rates of accumulation, etc.

42. In addition, logging provides access to previously unaccessible forests, thereby facilitating degradation of forests by activities such as fuelwood collection, habitation, and agricultural activity.

43. Volume to mass conversions and expansion factors are taken from Brown et al., 1989 which reports on tropical forests. however, The values are in the range of those reported by ECE/FAO, 1985, for temperate forests.

43. Holt and Spain, 1986

44. e.g. Anderson et al., 1988 and Levine et al., 1988

45. Luizão et al., 1989

46. Bowden and Bormann, 1986

47. Keller et al., 1986

48. Luizão et al., 1989 and Matson et al., 1990

49. Keller et al., 1990; Scharffe et al., 1990.

50. See, for example, Fearnside, 1980, 1986; Bushbacher, 1984; Cerri et al., 1988; and Lugo et al., 1986. Keller et al. (1986) indicate that clearcutting of tropical forests does not appear to release soil carbon.

51. Mosier et al. 1991

52. Seiler and Crutzen, 1980

53. In fact, prescribed burning may actually result in a net accumulation of carbon when the natural fire that would have occurred (had prescribed burning not taken place) is included in the accounting of emissions.

54. Actually, following the first clearing (i.e., clearing of primary forests), the forest biomass may not recover fully to its original density during the fallow period, but instead reaches a slightly reduced level, referred to as a secondary forest. after this point, however, clearing (of a secondary forest) is balanced by recovery (to a secondary forest), and net CO_2 emissions over time are zero.

55. See Myers (1989) and Houghton (1991)

56. Generally, shifting cultivation is practiced in fallow forests, since the least dense and most accessible forest areas are most susceptible to this form of clearing. Aboveground biomass density estimates for fallow forests are highly uncertain, and vary significantly both within and among countries because of varying ecosystem types as well as varying intervals between clearings. As a rough estimate, 50% the biomass estimates for unproductive forests can be used (see Table 6-1 for regional estimates in units of carbon per hectare). Biomass carbon densities for other forest types, e.g., undisturbed forests, should of course be used if more appropriate in specific cases.

57. Cicerone and Oremland, 1988

58. Moore and Knowles, 1989

59. For example, see Harriss et al., 1982

60. Seiler and Conrad, 1987

61. Seiler and Conrad, 1987

62. Seiler and Conrad, 1987

T5 TECHNICAL APPENDIX: DEFORESTATION DATA

Data on rates of deforestation[1] are essential for calculating the fluxes of carbon dioxide and other trace gases between terrestrial systems and the atmosphere. When arranged on a country-by-country basis, these data provide the forcing function for computation of country-specific emissions from forest clearing. Recognizing that such data sets are not yet available for many countries with the accuracy needed for these computations, this technical appendix provides suggestions for utilizing the available global and national sources of data, while bringing new or better sources of information into the calculations when and where they are available.

T5.1 Food and Agriculture Organization (FAO) Published Data

Currently, the most comprehensive international source of data on rates of deforestation broken down to the country level is maintained by the FAO in the following forms:

1   Source data, preferably in the form of a time series, collected in cooperation with member countries (i.e., without standardization) including data on: forest cover, ecofloristic zone and sub-national boundaries, biomass, plantations and conservation, collected and compiled in the form of a geographic information system.

2   Standardized estimates of forest cover, rate of deforestation, afforestation, and biomass/ha at the country level. Standardization is done by FAO because of variations from country to country in:

  * -the definitions of "forest", "deforestation" and "afforestation"; and

  * -the reference years for forest cover and deforestation measurements.

    The standardization is intended to bring country data to common definitions of forest cover and reference data, and to make the country information useful for regional and global studies. The basis for standardization is adjustment functions by ecological zones based on time-series data on forest cover of countries.

3   Data from a global sample survey of forest cover state and change during 1980 and 1990 based on a limited sample of high résolution satellite images using common definitions and measurement techniques. The main aim of this survey is to calibrate regional and global estimates and provide comprehensive information on various types of on-going forest cover changes, in the form of change matrices (1980 and 1990). It should be noted that the sample survey is not intended to check or replace country estimates, but only to provide reliable estimates (i.e., with standard error) of forests cover and rate of change at regional/global levels. This is being done taking into account the inherent limitations of aggregating heterogeneous country data at regional/global levels.

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[1]   This appendix is limited to discussion of current and future international sources of data on rates of deforestation at the national level. It is understood, however, that other types of input data are also key sources of uncertainty in calculation and are also the subject of a great deal of ongoing activity. This includes other types of land use change and land cover data as well as more detailed information on growth rates and biomass densities for different types of forests and other ecosystems.

The results of these data collection and analysis efforts are provided in a series of publications produced by the FAO. These data can be used to construct national input data for calculating CO_2 from deforestation. This should be useful to many countries at least as a point of comparison with locally available data sources, and may be used to provide a first order estimate of national emissions if desired by national experts.

The FAO Forest Assessment produced in the early 1980s (FAO/UNEP 1981, Lanly 1982) provides a first-order estimate of deforestation rates worldwide. These data produced on a country basis can be used as a baseline land use rate. An interim assessment (FAO 1988) provided deforestation rates by country for the period 1981-85. A 1990 assessment has been recently published (FAO 1993), which provides estimates of deforestation rates by country for the period 1981-1990. Thus, some estimates of current and historic rates of deforestation on a country basis can be obtained from these published reports. More detailed information, including sub-national data, can be obtained by contacting the FAO directly.

It should be noted, however, that there have been controversies and disagreements regarding FAO estimates of national deforestation rates at times. In some cases where national experts have developed significantly more detailed approaches for their own countries, results have been found to be significantly different than the published FAO estimates. (See, for example, Fearnside, et al, 1990b for Brazil). Any internationally provided data should be reviewed carefully by national experts if they are used as a basis for emissions inventory estimates.

Some countries have well-developed estimates of deforestation, based on very good measurements, which provide more detail than is available from the FAO assessments (e.g., Arbhabhirama et al. 1987, INPE 1992). Where detailed national studies exist for the early 1990s they may be a preferred data source for experts preparing national inventories. FAO data may nonetheless be useful for comparison purposes. The choice of input data is always ultimately a decision of the national experts.

Lack of consistent time-series data at national level is considered by FAO staff to be the most critical problem in estimating the deforestation rate. Variation in definitions and measurement techniques from country to country is another problem in making regional and global estimates. FAO has initiated a comprehensive programme for capacity building in forest resources assessment by mobilizing technical and economic cooperation among member countries and among concerned regional and global agencies as follow-up to recommendations of UNCED Agenda 21: Programme Area D.

T5.2 Ongoing Data Efforts

The lack of a comprehensive data set on deforestation rates is a critical problem. The development of such data sets remains one of the priorities for the IPCC process in the coming years (IPCC 1992). Methods using high resolution remote sensing in conjunction with geographic information systems appear most promising. The International Geosphere-Biosphere Programme's Data Information System (IGBP-DIS) is serving as a central focal point to collect and disseminate information about the various ongoing activities and data sets dealing with land use and changes in land cover. The IGBP-DIS is located in Paris, France (Tel: 33-1-4427-6168, Fax: 33-1-4427-6171).

Experts from around the world have begun to build the scientific, technical, and procedural underpinnings of such a system. The World Forest Watch Meeting held in Sao Jose dos Campos, Brazil (June 1992) provided a high-level international forum for the assessment of current approaches to satellite-based forest monitoring. This meeting also

served as a basis for forwarding recommendations from the technical and scientific communities to the policy makers and government leaders at UNCED.

A variety of international participants were represented at the World Forest Watch Conference. The conference concluded that significant technical and methodological advancements have been made in recent years, and they are now sufficient for proceeding with an observation system which could satisfy both scientific and national-level forest management requirements. A priority action now is to establish a fully functional, permanent monitoring system. The system would support national forest management, global change science, and international policy information needs, such as those of the IPCC.

The current research and development being carried out in laboratories and research centers around the world has shown that it is now feasible to acquire repetitive satellite data sets over very large areas, and that the information derived from such data sets can form the core of a global forest monitoring program. The International Space Year World Forest Watch Conference has recently provided illustrations that space observation technology and the community of users are ready for regional and global applications.

Progress made on two forest monitoring projects is worth noting in this respect.

1   The National Institute for Space Research (INPE) of the Secretariat of Science and Technology of the Presidency of the Republic of Brazil has made surveys of the entire Legal Amazon (about 5 million square kilometers) using LandSat images. This survey was first conducted in 1978 (with 1977 and 1979 being used to cover areas covered by clouds in the 1978 imagery. The studies were repeated in 1988, 1989, 1990 and 1991. These space-based surveys mapped the extent of gross deforestation (i.e., without accounting for forest regeneration or the establishment of plantations) in the portion of the Legal Amazon covered by forest. The ecosystems ranged from dense tropical forest to thick savannas (cerradao) with a total surface area between 3.9 and 4 million square kilometers. The 1978 survey used 232 Land Sat MSS black and white images based on channels 5 and 7 at a scale of 1:250,000. The more recent studies used 229 LandSat TM images annually in a color composite of channels 3,4 and 5 at a scale of 1:250,000.

2   In 1990 NASA, in conjunction with the United States Environmental Protection Agency and the U.S. Geological Survey, began a prototype procedure for using large amounts of high resolution satellite imagery to map the rate of tropical deforestation. This activity, the LandSat Pathfinder Project, builds on experience gained during a proof-of-concept exercise as part of NASA's contribution to the International Space Year/World Forest Watch Project. It focused initially on the Brazilian Amazon, and has now been expanded as part of NASA's Earth Observing System activities to cover other regions of the humid tropical forests.

    This project has succeeded in demonstrating how to develop wall-to-wall maps of forest conversion and re-growth. The project is now in the process of extending its initial proof-of-concept to a large-area experiment across Central Africa, Southeast Asia and the entire Amazon Basin. The project is acquiring several thousand LandSat scenes at three points in time -- mid 1970s, mid 1980s, and mid 1990s -- to compile a comprehensive inventory of deforestation and secondary growth (regrowth of forests on land cleared and subsequently abandoned) to support global carbon cycle models. Methodology and procedures have been identified. Although this exercise is being implemented for most of the tropics, it is not an operational global program. In principle it will provide an initial large-scale prototype of an operation program.

The use of geographic information system technology is crucial to the project, as it provides the overall framework upon which the raw satellite data can be synthesized with other cartographic, numerical, and geographical data for scientific research and national forestry management. As its name implies, this project is exploratory, but it could readily be expanded to form the nucleus of a global scale operational program.

These two projects demonstrate the feasibility of developing a global tropical forest information system to support an operational tropical forest monitoring program. High resolution satellite data from LandSat or Spot satellites are being used to provide digital maps of deforestation.

High resolution data from the LandSat series of earth observation satellites can be employed to make regular measurements of deforestation. Large amounts of these data exist in national and foreign archives, dating back approximately 20 years. This satellite data system has been perfected over years of development (5 satellites have been launched) and it is expected to be an operational system into the next century (LandSat 6 is ready for launch, 7 and 8 are being designed). This system is complemented by the French SPOT satellites. Thus, a continuous and consistent source of data is available upon which a high resolution, fine-scale (1:250,000 scale mapping) information system could be developed.

An operational forest monitoring using high resolution data such as that provided by LandSat and SPOT could provide wall-to-wall mapping for the entire tropical zone. The approach would be as follows:

- An initial mapping effort would define where and how much deforestation exists in the tropical forests (a baseline assessment). The stratification of forest types and critical regions could be enhanced by the use of coarse resolution information from AVHRR.

- Acquisition of LandSat and/or SPOT imagery can be coordinated regularly every 3-5 years to obtain cloud-free coverage systematically throughout the tropics. The best way to achieve this is to rely heavily on the foreign ground stations. For example, from the LandSat routine and complete coverage for the Amazon Basin and Southeast Asia is possible from several foreign ground receiving stations in these regions. As a rule these stations regularly collect data from every orbital pass within the line-of-sight radius of their antenna. For regions, such as central Africa where no ground station exits, programmed acquisitions from the satellite are possible.

- The imagery are analyzed for deforestation using a methodology analogous to that developed by the LandSat Pathfinder Project, where a simple delineation of the boundary between intact forest and cleared areas is recorded into a geographic information system. Areas of secondary growth would also be delineated. Subsequent years are compared to the baseline and the increment of new deforestation and secondary growth is recorded. The resulting data set provides a 1:250,000 to 1:500,000 scale map of deforestation at a regular repeat interval, and from this a rate of deforestation is derived.

- These geographically-referenced measurements can directly support the implementation of the IPCC national inventory methodology, which requires a time series of historic forest clearing data, and would require updating at periodic intervals. The proposed accurate and precise deforestation data set would be an important asset to national experts working to implement the IPCC methodology for national emissions and removals from land use change.

- An accuracy assessment effort will need to be put into place to define and track the measurement variance and error. This component will need to determine accuracy with respect to: (a) variance due to positional accuracy (i.e., the mapping precision) and (b) the variance associated with image interpretation.

- An effort focused on establishing in-country cooperation will be necessary. Such cooperation fulfills several ancillary but vital objectives: (a) it builds a process of national acceptance of the methods and results through active involvement, (b) it provides a mechanism for technology transfer and training for eventual implementation of remotely sensed-based national inventories, (c) it facilitates logistical coordination of the field component, (d) it provides direct cooperation at various foreign ground stations, and (e) it enables cooperation with national and regional experts in the interpretation of imagery.

T5.3 Summary

Tropical deforestation and carbon emissions are important components of both science and policy. Yet, in spite of the growing need for precise estimates of deforestation to support both international policy and basic research, an operational program of measurement, monitoring and mapping has yet to be developed. Comprehensive and systematic information on the extent of forest and forest loss is not available on a global basis. The latest IPCC Assessment Report, for example, considers the rate of tropical deforestation to be one of the key unknowns in global climate change assessment. Any lasting and effective implementation of a global system of national emission inventories to support the IPCC and other international processes will require a new, concerted effort to measure and map tropical deforestation, and develop the database necessary for other important components of the calculations. These measurements of deforestation from high resolution satellite remote sensing can also support the UN/FAO Forest Assessment by providing quantitative and spatially comprehensive measures of changes in forest cover for the tropics.

This Technical Appendix summarizes the most comprehensive current data source for tropical deforestation information, and discusses ongoing efforts to improve on this data via analysis of remote sensing images. Ideally, each country would like to have data on their land use changes and associated trace gas emissions and uptake over the past 40 to 50 years so that their estimates of current annual net emissions would include delayed and continuous emissions and uptake due to activities that occurred in prior years. Since this is not the case for many countries, the methodology described has made simplifying assumptions in order to treat the effects of past land use activities on current emissions. This appendix provides some perspective on the available international sources for dealing with one key data gap -- data on rates of forest clearing over time.

In future editions of the *Guidelines*, it may be possible to include more information on data available to assist national experts as a result of some of the ongoing efforts described in this version. It may also be possible and desirable to provide similar discussion of a range of other international data collection efforts which may assist national experts in refining other key data driven uncertainties in the national estimates of emissions and removals from land use change and forestry.

In the meantime, it is recommended that countries continue efforts to collect historical records of land use change and develop systems of tracking land use through time so that as the methodology is further refined, the land use change time series needed to account better for emissions and uptake of carbon dioxide and other trace gases are available.

CHAPTER 6
METHANE EMISSIONS
FROM WASTE
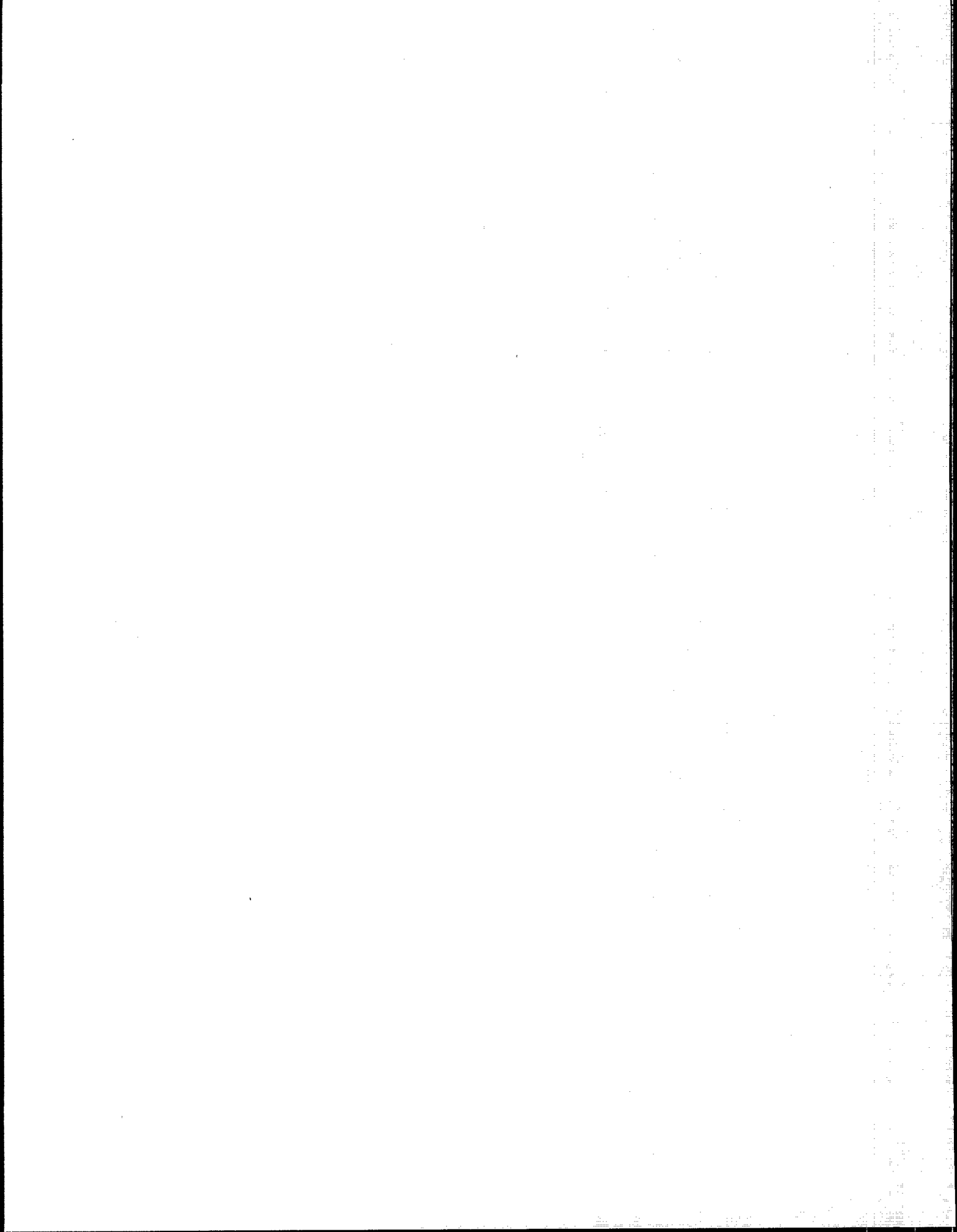
6 METHANE EMISSIONS FROM WASTE

Disposal and treatment of industrial and municipal wastes can produce emissions of most of the important greenhouse gases (GHG). Solid wastes can be disposed of through landfilling, recycling, incineration, or waste to energy. GHG emissions from waste to energy, where waste material is used directly as fuel or converted into a fuel, should be calculated and reported under Energy - Chapter 2. Liquid wastes can be dealt with through various forms of wastewater treatment. In addition, sludge from wastewater can be incinerated. This chapter will deal with emissions resulting from landfilling of solid waste, treatment of liquid wastes, and waste incineration.

The most important gas produced in this source category is methane. Significant amounts of the annual global methane produced and released into the atmosphere are a by-product of the anaerobic decomposition of man-made waste. Two major sources of this type of methane production are landfills and wastewater treatment. In each case, the methanogenic bacteria break down organic matter in the waste to produce methane. These sources are treated in detail in later sections of this chapter.

Landfilling of solid waste represents the major form of solid waste disposal in the industrialized world. (OECD, 1993) In addition to CH_4, landfills also can produce substantial amounts of CO_2 and non-methane volatile organic compounds (NMVOCs). CO_2 is primarily from decomposition of organic material derived from biomass sources (e.g. crops, forests) which are regrown on an annual basis. Hence, these are not treated as **net** emissions from waste in the IPCC methodology. If biomass raw materials are being unsustainably produced, the net CO_2 release should be calculated and reported under the Agriculture or Land Use Change and Forestry sections.

The process of wastewater treatment produces NMVOCs as well as CH_4. (Bouscaren, 1992) Wastewater treatment is also now being studied as a source of N_2O. Norway (IPCC, 1993) and Japan (Kyosai and Mizuochi, 1993) have documented N_2O production from their sewage treatment processes. Future evaluation of ongoing research will give an indication of the importance of this source.

Waste incineration, like all combustion, can produce CO_2, CH_4, CO, NO_x, N_2O and NMVOCs. No detailed methodologies are provided for this source category. Instead, the section on waste incineration later in this chapter provides references to other major methods documents already available for some gases. For CH_4 and N_2O it is only possible to report preliminary estimates and research results at this time. Further studies are needed to give more information about GHG emissions from this source category.

The sections in this chapter dealing with landfills and wastewater treatment give background information on the source, a description of the methodology to estimate methane production only, and uncertainties associated with estimating emissions. This is consistent with the initial priorities under the IPCC methodology programme. National experts are encouraged to report any other relevant emissions for which data are available, along with documentation of methods used. This will greatly assist in the development of more complete methods for future editions of IPCC guidelines. For information on estimation procedures and emissions factors for other GHGs which are currently not provided in this chapter, experts should consult extensive existing literature developed by other emissions inventory programmes. Some key examples are:

- CORINAIR Default Emissions Handbook (Bouscaren, 1992);

- U.S. EPA's Compilation of Air Pollutant Emissions Factors (AP-42) (US EPA, 1985) and Supplement F (AP-42) (US EPA, 1993a);

- Criteria Pollutant Emission Factors for the 1985 NAPAP Emissions Inventory (Stockton and Stelling, 1985);

- Air Emissions from Municipal Solid Waste Landfills - Background Information for Proposed Standards and Guidelines (US EPA, 1991a).

6.1 METHANE EMISSIONS FROM LANDFILLS

6.1.1 Introduction

Since the early 1980s, it has been recognized that the methane component of landfill gas can be a local environmental hazard if precautions are not taken to prevent uncontrolled emissions or migration into surrounding land. Gas can migrate from the landfill either laterally or by venting to atmosphere, and this can cause vegetation damage and unpleasant odours at low concentrations, while at higher concentrations the gas may form explosive mixtures.

More recently, increasing attention has focused on the role of methane in global atmospheric change. Methane from landfills contributes a significant proportion of annual global methane emissions, although the estimation is subject to a great deal of uncertainty. Estimates of global methane emissions from landfills range from 20 to 70 Tg/yr, global anthropogenic sources emit about 360 Tg/yr, which suggests that landfills may account for 6 to 20% of the total. (IPCC, 1992)

This section will describe the processes that result in landfill gas generation and the factors which affect the amount of methane produced within landfills. It will then describe methodologies for estimating methane emissions from landfills. One of these methods is proposed as a default base method with which all countries can comply. Other methods are also described as well as some examples from various countries that have applied them. The section also discusses sources of uncertainty associated with any estimates of methane emissions from landfills, in particular the availability and quality of data required.

6.1.2 Landfill gas generation

Organic waste within landfills is broken down by bacterial action in a series of stages that result in the formation of methane, carbon dioxide and further bacterial biomass. In the initial phase of degradation, organic matter is broken down to small soluble molecules including a variety of sugars. These are then broken down further to hydrogen, carbon dioxide, and a range of acids. These acids are then converted to acetic acid which, together with hydrogen and carbon dioxide, forms the substrate for growth of methanogenic bacteria.

Landfills are by nature heterogeneous, and all microbiological investigations into landfill characteristics have shown that there are considerable differences between different landfills and even different regions within the same landfill (Westlake, 1990). This makes it very difficult to extrapolate from observations on single landfills to predictions of global methane emissions. Nevertheless, there are a number of significant factors which influence the generation of methane and its emission from landfills. A better understanding of these factors can reduce the uncertainty associated with emissions estimates.

6.1.3 Factors influencing methane production in landfills

The factors which influence methane production within landfills have been reviewed comprehensively elsewhere (eg. Peer et al., 1993; US EPA, 1992; US EPA, 1991b; US EPA, 1991c; Lawson and Alston, 1990; Augenstein and Pacey, 1991), therefore this section will only provide a brief summary of the most significant factors relating to methane emissions.

Waste management practices

The two main types of waste management practices of concern for CH_4 emissions are open dumping, which is generally practiced in developing regions, and sanitary landfilling, generally practiced in developed countries and urban areas of developing countries. Both of these types of waste management can result in methane production if the waste contains organic matter.

In **open dumping**, wastes are disposed of in shallow, open piles, generally only loosely compacted, and with no provision for control of any pollutants generated, either gas or leachate. Scavenging by animals and humans can remove much of the biodegradable wastes therefore reducing substrate availability.

Wastes in open dumps generally decompose aerobically, producing carbon dioxide. However, there is anecdotal evidence that some methane production can occur (Thorneloe et al., 1991), but this has not been quantified. Methane from open dumping is therefore not included in any methodology considerations for global inventories. Bhide et al. (1990) reported biogas recovery from two uncontrolled landfills in Nagpur, India. The CH_4 content of the biogas from one site was 30 to 40%. This suggests that open dumps are a source of CH_4.

Thorneloe et al. use the same methodology to calculate CH_4 emissions from open dumping in non-industrialized countries as from sanitary landfills in industrialized regions. However, total CH_4 emissions are reduced by 50% to account for the differences between CH_4 production potential from open dumping and sanitary landfilling. The choice of 50% is arbitrary and should be updated when additional data are available. This procedure can be used by national experts at their discretion. Uncertainty due to this source is discussed later.

Sanitary landfills are designed specifically to receive wastes. Landfill design and management is becoming increasingly sophisticated in many countries, as the serious environmental consequences of uncontrolled landfilling are becoming understood. New landfill design standards in many countries are ensuring that landfills are lined before receiving waste, and also that there are adequate provisions for the safe control, and removal where appropriate, of gas and leachate generated. Good waste management practices ensure that the waste is compacted to minimise use of void space, also that it is covered both with intermediate daily cover and with an effective cap when final restoration takes place. The costs associated with these management practices are encouraging the development of larger landfills to economise on scale, taking in greater quantities of waste. All of these factors can encourage the rapid development and maintenance of anaerobic conditions within the landfill, and hence ensure continued methane production.

Waste composition

The composition of waste is one of the main factors influencing both the amount and the extent of methane production within landfills. Municipal solid waste (MSW) contains significant quantities of degradable organic matter. This can decompose to form acetate and carbon dioxide as intermediate decomposition products, which are the main substrates for methanogenic bacteria. Different countries and regions are known to have MSW with widely differing compositions: wastes from developing countries generally have a high putrescible content, whereas developed countries, especially in North America, have very high paper and card content in their MSW. Thus landfills in developing countries will tend to stabilise within 10-15 years because putrescible material decomposes rapidly, whereas landfills with a high paper and card content will tend to produce methane for 20 years, or more at a lower rate.

Physical factors

The moisture content of the landfill environment is one of the principal physical factors influencing landfill gas production. Moisture is essential for cell growth and metabolism, also for transport of nutrients and bacteria within the landfill. The moisture content of a landfill will depend on the initial moisture content of the waste, the extent of infiltration from surface and groundwater sources, and on the amount of water produced during the decomposition processes.

Temperature will affect the growth rate of the bacteria. Under anaerobic conditions, landfill temperatures are generally between 25-40°C. These temperatures can be maintained within the core of the landfill independent of the external temperatures. Outside of these temperatures, methane production is reduced or can cease altogether.

Optimal pH for methane production is between 6.8 and 7.2. Nutrients that are important for efficient bacterial growth include sulphur, phosphorous, sodium and calcium. CH_4 production rates decrease sharply with pH values below about 6.5 (Zehnder, 1982). When refuse is buried in landfills, there is often a rapid accumulation of carboxylic acids; this results in a pH decrease and a long time lapse between refuse burial and the onset of CH_4 production ranging from months to years.

"The lapsed time preceding the onset of CH_4 production in landfills is an important aspect when considering the management of individual landfills for biogas recovery or emissions mitigation. The age at which landfills and uncontrolled dumps begin to produce CH_4 is of lesser importance when evaluating global CH_4 emissions from MSW management systems. For estimating global emissions, it is the total CH_4 production potential that is more critical." (Thorneloe,1993a)

The importance of these physical factors to methane generation can be demonstrated within controlled laboratory conditions, but the heterogeneity of landfills makes definitive research very hard under field conditions, and there are limited data available. Therefore until better global data become available, none of these factors can be taken into consideration when estimating national or global methane emissions.

6.1.4 Methodologies to estimate methane emissions from landfills

A number of methods have been used to estimate methane emissions from landfills. These methods vary widely, not only in the assumptions that they make, but also in their complexity, and in the amount of data they require for the determinations.

This chapter will deal only with those methods that can be applied to whole regions or countries. There are some very complex models that are concerned with movement of methane and other gases through individual landfills; however these models cannot be applied to landfill populations and therefore will not be considered further here.

Mass balance and theoretical gas yields methodologies

This is the simplest method for calculating methane emissions from landfills. It is based on a mass balance approach, and does not incorporate any time factors into the methodology. The calculation assumes that an instantaneous release of methane takes place from refuse during the same year that the refuse is landfilled.

Using empirical formulae

At its simplest level, an empirical formula for refuse can be used as the starting point for estimating yields from waste. If a complete breakdown to carbon, hydrogen and oxygen is considered, this gives very high and unrealistic levels of methane generation, therefore some adjustments are necessary because complete breakdown is known not to take place. EMCON Associates (1981) modified this by using an extended Buswell equation, which takes other elements into account, and estimated that 53% of the carbon content of refuse is converted to methane. If microbial biomass as an end product is also taken into account, then this further reduces the methane generation potential. Polytechnic of East London (1992) have predicted that this results in the production of 234 m³ of methane per tonne of wet MSW.

Default methodology: using degradable organic carbon content

A more useful approach is to consider the degradable organic carbon (DOC) content of MSW, i.e. the organic carbon that is accessible to biochemical decomposition, and to use this value to calculate the amount of methane released from the MSW. This is the approach taken by Bingemer and Crutzen (1987), who segregated the world into four economic regions, and applied different values of DOC to the waste generated within each of these regions. As a simple and robust method, this is currently the most widely accessible default methodology for calculating country-specific emissions of methane from landfills, since it requires the least amount of data to perform the calculations, and it can be modified and refined as the amount of data available for each country increases.

The four regions derived by Bingemer and Crutzen (1987) were: US, Canada and Australia; other OECD; USSR and Eastern Europe; and developing countries. In their assessment, they determined how much MSW was produced for each region, and how much of that MSW was degradable organic carbon.

The percent degradable organic content (DOC) is based on the composition of waste. The percent of DOC can be calculated from a weighted average of the carbon content of various components of the waste stream. Bingemer and Crutzen (1987) collected data for the various global regions considered in the study. No data were available for the USSR or

Eastern Europe or for some developing countries, so these values had to be approximated. These data were updated by OECD (1991) using more recent data from OECD (1989) where available. The data presented to OECD (1991) are summarized in Table 6-1. It is highly recommended, however, for countries where the composition of the fractions in the waste stream are known, that these be combined with a knowledge of the carbon content of these various fractions to produce a country-specific value for DOC.

The determination of annual methane emissions for each country or region can then be calculated from Equation 6.1

EQUATION 6.1

Total MSW generated (Gg/yr) x Fraction MSW landfilled x Fraction DOC in MSW x Fraction Dissimilated DOC x 0.5 g C as CH_4/g C as biogas x Conversion factor (16/12) - Recovered CH_4 (Gg/yr)

=

Methane emission

Total MSW generated can be calculated from Population (thousand persons) x Annual MSW generation rate (Gg/thousand persons/yr).

In developing countries only urban populations are considered, since the rural populations are assumed to dispose of their waste in very small open dumps, where significant methane generation is assumed not to occur.

Fraction dissimilated carbon: This is the portion of carbon in substrates that is converted to landfill gas. The assimilated fraction is the remainder of carbon that is used to produce new microbial cell material. To date, estimates of how much carbon may be dissimilated have relied on a theoretical model that varies only with the temperature in the anaerobic zone of a landfill: 0.014T + 0.28, where T = temperature (Tabasaran, 1981). The temperature in the anaerobic zone of a landfill is thought to remain constant at about 35°C, regardless of ambient temperature (Bingemer and Crutzen, 1987). Therefore applications of the Bingemer and Crutzen (1987) method use a figure of 0.77 dissimilated DOC.

No allowance was made for any reduction in methane emissions from methane oxidation, also it was assumed that all waste decomposed anaerobically within the landfill rather than aerobically.

Using the data that they had collected, Bingemer and Crutzen (1987) estimated that global emissions of methane from landfills ranged between 30 - 70 Mt per year.

As an example, an estimate for the US can be derived as follows (based on values provided by the US EPA):

Assumptions:

Waste generated:	about 235 Tg/yr to landfills
% waste landfilled:	up to 80
% DOC:	21
% DOC dissimilated:	77
Recovered methane:	1.5 Tg/yr

These assumptions yield an estimate of:

$$((235 \text{ Tg/yr} \times 0.80 \times 0.21 \text{ DOC} \times 0.77 \text{ Dissimilated DOC} \times 0.5 \text{ kg C as} \\ CH_4/\text{kg C as biogas} \times 16/12) - 1.5 \text{ Tg/yr}) = 19 \text{ Tg/yr}$$

OECD (1991) also cites a study by Piccot et al. (1990) who surveyed 31 countries through literature review and personal communication, resulting in country-specific factors of MSW generation rates per capita, waste composition and percentages of waste landfilled. These values are given in Table 4.2 of OECD (1991); however they have been subject to criticism from some countries and some OECD Workshop participants who were concerned that the data may not be very representative of their countries or regions.

It is proposed that the methodology of Bingemer and Crutzen (1987) remains as the methodology that can be used by all countries to calculate methane emissions estimates from their landfills. The Workbook provides a detailed step-by-step version of this methodology as well as default values (as discussed above) for factors to be used where they are not already available from within each country.

Limitations to this methodology

However, there are limitations to this methodology which have resulted in criticism from researchers who have tried to apply it in their own countries. Some of these factors have already been highlighted above. The principal factors which cause these concerns are:

- there is no time factor involved in the calculations; also

- there is a high level of carbon converted to methane because there are no considerations of methane oxidation.

In addition, the assumption that a constant fraction (0.77) of the DOC is dissimilated, under any ambient conditions, is open to discussion. Ranges of values for dissimilated DOC may therefore be more appropriate where local information is available.

Two further factors should be incorporated into the methodology of Bingemer and Crutzen (1987) to account for concerns relating to time factors and to methane oxidation. Both of these factors and suggested modifications to account for them are now discussed further. They may be incorporated into the Workbook calculations in future versions.

Accounting for delayed release of methane: There is a lag time between placement of the waste and the beginning of methanogenesis, after which generation increases until it reaches a plateau. In the later stages of methanogenesis, gas production trails off and eventually ceases. The actual timing of the various stages of methane generation depend on the type of waste and the conditions prevalent in the landfill.

If waste of roughly the same composition were deposited at the same frequency for the number of years that it takes for the majority of carbon in that waste to decay, the assumptions of instantaneous release would not lead to an overestimation of emissions - current emissions from all the waste deposited during those years should equal the eventual emissions from the waste deposited in the current year, as calculated by Bingemer and Crutzen's equation. If however the rate of disposal has increased over time, the uncorrected Bingemer and Crutzen method will overstate the current year's emissions. (US EPA, 1991a)

In most cases, the amount of waste disposed of to landfills is increasing. It should be possible to develop correction factors based on the average annual growth rate of landfill waste disposal, and the average amount of time the waste produces methane. Some initial research in this area has been done recently. (ICF, 1993) Results of this work and other related research will be reviewed and considered for possible updating of the methodology in the future.

Accounting for oxidation: Methane migrating through aerobic soil or waste can be oxidised by microorganisms, whilst sulphate-reducing bacteria may oxidise methane in anaerobic soil or waste. However, very little is known about the extent of methane oxidation that takes place within landfills, or of the factors which influence methane oxidation (Bogner and Spokas, 1993), and there is no widely accepted estimate for the rate at which methane is oxidised after it has been generated within landfills. Factors affecting methane oxidation are known to be related to the microbiological conditions within the site, as well as the depth of the site, its permeability, etc. In addition, site management is likely to be important, including the characteristics of the site cap and any venting or control measures that are installed.

More sophisticated models of methane emissions include a factor related to methane oxidation. However, the factors chosen differ widely: Orlich (1990) chooses 40 - 50%; UK Department of the Environment (1993) use a range between 0 - 40%; van Amstel et al (1993) assume 20%; US EPA (1993) use a factor of 10%. A better understanding of methane oxidation is needed to provide a more reliable factor for inclusion in future models.

Based on these models, it is suggested that the estimate of methane emissions from landfills derived using the Bingemer and Crutzen methodology be reduced by 10% to account for oxidation. Some consideration of the variation associated with this value may also be appropriate.

Thus by incorporating these two modifying factors, the underlying Bingemer and Crutzen approach can be adjusted to reflect more accurately landfill conditions and country-specific data. It has the added advantage that the Bingemer and Crutzen approach is very simple and easy to use, and with these additional modifications, it can provide the best model for estimating emissions in many countries.

Other approaches used

For countries where more comprehensive data are available, different and more sophisticated methods may be applied to arrive at estimates of methane emissions from landfills. There have been various refinements made to Bingemer and Crutzen's approach; these are described in the next section.

Ahuja (1990) used the same approach as Bingemer and Crutzen (1987), but included a further factor in the equation, namely the percentage of MSW that is dry refuse. Methane emissions were calculated according to Equation 6.2.

EQUATION 6.2

Total MSW generated (Gg/yr) x Fraction MSW landfilled x Fraction DOC in MSW x Fraction Dry refuse x Fraction Dissimilated DOC x 0.5 g C as CH_4/g C as biogas x Conversion factor (16/12) - Recovered CH_4 (Gg/yr)

=

Methane emission

Again however, this approach requires application of regional factors which are subject to much uncertainty, also the value for the Fraction Dry refuse can be open to much dispute even within a single country, let alone worldwide.

Another empirical approach was taken by Orlich (1990), who applied factors for waste generation rates per capita and for methane generation rates per tonne of waste for both developed and developing countries. These two factors were 1.0 kg or 0.5 kg per capita per day, and 180 m^3 or 60 m^3 methane per tonne for developed and developing countries

respectively. Orlich (1990) also excluded any waste disposal outside of urban areas in developing countries. This method of calculation gave a global estimate of 32.9 M tonnes of methane emissions from landfills in developed and developing countries in 1990. UN population statistics were also used to estimate future emissions up to 2030.

Richards (1989) used gross domestic product (GDP) as an indicator of waste generation rates, which in turn were used to estimate methane emissions from landfills as an energy resource. Using figures of world GDP, he estimated a world waste generation value of 490 million tonnes per annum, of which about 80% would be landfilled, yielding about 100 m^3 of landfill gas per tonne of refuse over about 10 years. This analysis yielded a value of global methane emissions from landfills of 9.8 - 18.3 Mt/yr.

Theoretical first order kinetics methodologies

More complex methods for estimating methane emissions from landfills acknowledge the fact that methane is emitted over a long period of time rather than instantaneously as in the former methodologies. A kinetic approach therefore needs to take into account the various factors which influence the rate and extent of methane generation and release from landfills. This approach has generally been used to calculate emissions from individual landfills, for example in the estimation of the potential of a site to generate economic quantities of landfill gas, but it can also be applied in a more general way to entire regions or countries.

Early attempts to calculate emissions using a kinetic approach were discussed by EMCON Associates (1981), the most well known and used of which is referred to as the Scholl Canyon Model. This approach modelled the "average" landfill within the region or country, and then scaled the results to take into account the total waste landfilled within the whole region or country.

A number of factors need to be taken into account in any kinetic modelling of landfill methane generation. The main factors to consider are those of waste generation and composition, environmental variables such as moisture content, pH, temperature and available nutrients, as well as information on the age, type and time since closure of the landfill (Thorneloe and Peer, 1990).

The model equation and variables included in the Scholl Canyon model are given as follows:

$$Q_{CH4} = L_0 R \{\exp(-kc) - \exp(-kt)\}$$

where:

Q_{CH4}	=	methane generation rate at year t (m^3/yr)
L_0	=	DOC available for methane generation (m^3/t of refuse)
R	=	quantity of waste landfilled (t)
k	=	methane generation rate constant (yr^{-1})
c	=	time since landfill closure (yr)
t	=	time since initial refuse placement (yr)

Practical applications of kinetic models

A number of countries have applied this or similar modelling approaches to their own situation:

A recent study in the **United Kingdom** (Department of the Environment, 1993) has used the same modelling rationale but with two different approaches to the problem of scaling the modelling to include all wastes within the UK:

(i)   UK landfilled waste was treated as if it were disposed of to a single site. Model parameters were selected to represent nationally weighted average values, and an estimate of methane production from a unit of waste was made. The results were then extrapolated to arisings for the whole of the UK.

(ii)   Data were collated for sites where information was available, the yield of methane was calculated for these sites, and the results were then extrapolated to waste arisings for the whole of the UK. Average parameter values were used as above. It was necessary to assume that the sites covered contained waste types in proportions representative of all UK sites to ensure that the extrapolation was valid.

This study drew on extensive data available on the typical composition of waste arisings from different sources (domestic, civic amenity, commercial, industrial and inert), and used this information to divide the degradable carbon pool into three categories, each with a different decomposition rate constant, representing material that decomposes at different rates. This is a similar approach to that taken by Pacey and Augenstein (1990) and Manley et al (1990). Further modifications to the model predictions included a one year time lag before the start of methane generation, as well as modifications for aerobic decomposition, microbial biomass, leachate generation and methane oxidation. Each of the factors was included in the model as a percentage decrease in methane emissions.

The results from this study provided estimates of the range of methane production per tonne of waste over all time. These were then either compiled with waste arisings statistics, or were incorporated into sites with known data and then extrapolated to national levels, to provide estimates of methane production from MSW in the UK. The results showed a wide range of values for the amount of methane produced from MSW, between 0.6 and 5.3 Mt per year, as well as a best estimate of about 2 Mt per year. These figures have already taken reductions from gas flaring or use into account. The study emphasised that the uncertainty associated with the estimate reflected the lack of confidence in the modelling parameters.

The Netherlands have carried out a national estimate of methane emissions using a first order kinetic model applied to the whole country (Van Amstel et al., 1993). The estimate used detailed information on landfilling that has been collected for the country since 1945, a degradation rate coefficient of 0.1 per year (based on measurements of actual methane emissions at three landfills), and a degradable organic fraction of 18% before 1986, and 17% between 1986 and 1995. After 1995 this fraction is predicted to decrease because of recycling and separation initiatives that are aimed at reducing the organic content of waste to landfills. The calculation also assumed an oxidation percentage in the soil cover of 20% and a methane concentration of 50% of the landfill gas. This approach has provided an estimate of methane emissions from landfills in the Netherlands of 377 kt methane per year (range 178-576), with 25% recovery.

In **Canada**, emissions from landfills have also been calculated using the Scholl Canyon model (Environment Canada, 1992). The approach used population statistics and waste generation rates per capita, as well as collecting as much information as possible on major landfills such as the date opened and closed, waste quantities landfilled, and gas collected. The default value for methane generation used was 232 m^3/t, whilst the rate constant k was determined for specific landfill sites. Using these factors, a value of 1405 kt methane was obtained for methane emissions from Canadian landfills in 1990 (excluding any methane reductions from flaring or use). Environment Canada (1992) estimate that this

value is about 22% lower than one derived using the Bingemer and Crutzen (1987) methodology.

In the **United States,** emission from landfills have been calculated using an adaptation of the Scholl Canyon model (US EPA, 1991b) by EPA's Office of Air Quality Planning and Standards of the Office of Air and Radiation. Data was collected from a stratified sample of 630 U.S. landfills (US EPA, 1988) indicating that 334 teragrams per year of waste are landfilled annually. This data was used to develop inputs for the first-order decomposition model and estimates were generated to consider potential regulations for MSW landfill air emissions. The baseline estimate for the U.S. for active municipal solid waste landfills is 18 teragrams in 2000 and 20 teragrams in 2010. This estimate does not include methane emissions from industrial landfills. Extensive modelling of potential emissions for different regulatory strategies has been conducted. This has been published in a background information document. (U.S. EPA, 1991a)

Other methodologies used

In the **United States,** EPA's Air and Energy Engineering Research Laboratory (AEERL) of the Office of Research and Development has taken a different approach to calculating methane emissions from US landfills. (EPA, 1991b; EPA, 1992; EPA, 1993b) Due to the concern with the inaccuracy of predicting degradable organic content and the occurrence of over-prediction of gas quantities using first-order decomposition rate equations, AEERL gathered data from 112 landfills including landfill gas recovery rates and welled waste (i.e., quantity of waste from which landfill gas is extracted through the recovery wells). The data went through extensive quality assurance including site visits to over 30 facilities and scrutiny by industry and academia exports.

An empirical model was developed relating flow rates to welled waste through statistical and regression analyses. (EPA, 1991b and 1992; Thorneloe, 1992.) The objective was to let statistical criteria dictate the shape and position of the regression curve. A regression model with three different linear segments was the result where each segment applies to a distinct landfill size class. The emission factors that were developed from this approach are believed to represent the actual gas recovery rates as opposed to model predictions based on assumed values for degradable organic content. The results of this research are being published in two EPA reports.

- Estimate of Global Methane Emissions from Landfills and Open Dumps, to be published 1/94.

- Estimate of Methane Emissions from U.S. Landfills, to be published 1/94.

The findings from this modelling approach indicate that U.S. methane emissions account for 11 to 23 tg/yr (with an average of 17) and that global emissions account for 27 to 58 tg/yr (with an average of 43) in 1992. The amount of methane being utilised or flared was excluded from this estimate. Using Bingemer and Crutzen's (1987) approach and similar inputs for these different approaches, an average for U.S. emission was 25 tg/yr and the average for global emissions was 61. This suggests that Bingemer and Crutzen's approach results in an estimate approximately 30% greater than the estimates obtained by AEERL. (Thorneloe, 1993a)

The Global Change Division (GCD) of the Office of Air and Radiation has adopted a similar statistical modelling approach. Data were collected from 85 landfills that were considered to be representative of those US landfills that contain the majority of the waste in place in the US. A statistical model was then developed from the verified database that established the relationship between the quantity of waste in place and the methane

production from the landfill. Their estimate for the US suggests that landfills contribute 8.1 to 12 tg/yr for 1990, with a central estimate of 9.9 tg/yr. The major reason for the difference between the AEERL and GCD model results is believed to be the difference in the waste quantity used. It is recognised that there is uncertainty with estimates available for the quantity of waste being landfilled. In fact, this is considered one of the largest uncertainties with estimating methane emissions from landfills.

A regression approach such as those used by AEERL and GCD may be appropriate to use in other countries outside of the US. However, regression coefficients may vary considerably between different countries because of the many factors that differ between landfills in the US and in other countries. In particular, the landfills included in the US analyses were generally some of the largest landfills in the world. Few other countries have as many landfills as large as this. Other factors which will influence the value of the regression coefficient include the waste composition, site management techniques, and the climate. Other countries are conducting studies to see if similar results are found. The United Kingdom's Department of the Environment is obtaining gas extraction data from landfills and will explore a similar modelling approach.

6.1.5 Sources of uncertainty

Several sources of uncertainty in estimating emissions of CH_4 from landfills exist, these include:

- The quantity of CH_4 that is actually produced from the waste in the landfill;

- The quantity and composition of landfilled waste;

- The quantity of CH_4 that is actually emitted to the atmosphere.

Emissions of methane from open dumps and from older small sites

Most methods of estimating methane emissions from landfills exclude both these categories, on the grounds that emissions from these sources are very insignificant. However, as discussed above, there is anecdotal evidence to indicate that "open" landfills may generate significant quantities of methane, even though they are not managed according to high standards of landfilling techniques. The waste contains high levels of readily degradable organic material, and therefore degrades very rapidly and completely over a period of up to 10 years. National experts may use their own discretion as to whether or not to include these estimates. Obviously this increases the overall range of uncertainty in national estimates.

For old or small landfill sites, US EPA's (1993b) calculations have excluded any consideration of these sites contributing to methane emissions. However, there are thought to be about 30,000 older closed landfills in the US (Thorneloe, 1992), and field measurements of urban methane concentrations indicate that older closed landfills are often significant sources of emissions in the urban environment (Kolb et al. 1992). Omission of older closed landfills from this analysis therefore biases the estimates of methane emissions downwards, contributing to the overall uncertainty in the estimate.

Waste quantities and composition

The most significant factor that determines the accuracy of estimates of methane production from landfills is an accurate knowledge of the quantity and composition of wastes disposed of to landfill. This includes the quantity of waste already in place, plus data relating to annual waste disposal to landfills.

Many developed countries now have effective means for statistical collection of the quantity of waste being disposed of to landfills, and are also improving their understanding of the composition of various waste categories.

Historical knowledge of waste disposal is often less accurate: waste statistics for the UK, for example, are of very limited quality before 1974 - prior to that date, responsibility for waste disposal was at a local level, and was not nationally co-ordinated (Department of the Environment, 1993).

Similarly, many countries have poor records on numbers of landfills, especially of older closed sites. US EPA (1993b) estimates that in the US, approximately 3,000 small landfills closed during the 1980s, additionally that there may be tens of thousands of landfills that closed prior to this. In many countries, the existence of older closed sites may be known but no records of waste types or quantities are available.

For most countries, limitations on funds available will prevent extensive investigations of these older closed sites, except for those that are still causing local environmental concern. It is therefore more cost-effective to concentrate efforts into improving the quality of data being collected on existing landfilling operations, including on the total waste to landfill plus more detailed site-specific landfill data. Detailed site investigations, for example in connection with a gas exploitation scheme, may give additional support to emissions predictions, or can be used to support predictive methodologies as with the US EPA's (1993) method.

Composition of waste is very important in determining the amount of methane generated. The degradable organic content (DOC) of waste is an essential component in all calculations of methane emissions, and small variations in the assumed values for DOC can result in large variations in the overall estimate of methane emissions. As further information becomes available about the composition of a country's waste, so it can be categorised into fractions with varying decomposition half lives, for incorporation into kinetic models.

Different countries have widely differing MSW compositions: developing countries have solid waste that is of a higher putrescible fraction compared with developed countries, where waste has a much higher paper and card content. These factors influence both the rate and the extent of degradation of the various waste fractions, and need to be taken into account where data are available. Future changes in waste management practices will change the composition of waste to landfill considerably, resulting in different methane emissions levels.

The amount of municipal waste landfilled in the U.S. is estimated at approximately 334 Tg (U.S. EPA, Office of Solid Waste [OSW], 1988). This figure represents one of the largest uncertainties in the current estimates. Paper was the largest single component of the degradable organic carbon (DOC) fraction in both the U.S. and Canada. Per capita MSW generation was in the range of 1.7 to 1.8 kg/person/day for both the U.S. and Canada (U.S. EPA, 1990; El Rayes and Edwards, 1991). The average MSW generation rate in other OECD countries is 1.1 kg/person/day. MSW in these countries has a DOC content of approximately 15.3% (Davis et al., 1992). The value used for the U.S. is for MSW only; an additional 15 Tg/yr of biodegradable industrial solid waste is also landfilled, (U.S. EPA,

1987). This industrial solid waste is unaccounted for in the initial estimates of landfill methane.

In most cases, country-specific information does not state specifically whether industrial waste is co-disposed with MSW.

Information on the amount of MSW generated and landfilled in the European countries that are not OECD members and the former Soviet Union is limited. Average MSW generation for Greece, the former Soviet Union, and Eastern Europe is approximately 0.6 kg/person/day (Frantzis, 1988; Papachristou, 1988; Peterson and Perlmutter, 1989 and Bingemer and Crutzen, 1987), and the available data indicate that putrescibles make up a large portion of the MSW (estimates range from 32 to 60%). This MSW contains approximately 15% DOC (Frantzis, 1988; Papachristou, 1988; Peterson and Perlmutter, 1989; Bingemer and Crutzen, 1987; Zsuzsa, 1990).

For most Asian countries, estimates of MSW generation were identified for one or two major cities, but not for the entire country. National per capita MSW generation estimates were identified for Indonesia, Sri Lanka, the Philippines, Singapore, Taiwan, and Pakistan. These estimates range from 0.4 kg/person/day for the Philippines to 1.0 kg/person/day for Singapore. The average per capita MSW generation for these countries is estimated to be 0.6 kg/person/day (Davis et al., 1992).

Few data are available on MSW production and management in Central America, South America, the Caribbean Islands, and Mexico. Most of the available information is only for the larger cities. The average per capita MSW generation rate in Costa Rica, and Mexico and six South American countries (Brazil, Colombia, Chile, Paraguay, Peru, and Venezuela) is estimated to be 0.8 kg/person/day. The components are mainly vegetable and putrescible waste paper and cardboard. The average DOC for the mentioned countries is 17% (Davis et al., 1992).

Information on MSW generation and disposal for African and Middle Eastern countries is very limited. In Africa, it appears that toxic and hazardous industrial and commercial wastes are purposely or inadvertently disposed of with the MSW stream. Some information pertaining to generation rates for African countries was located; but information for only two Middle Eastern countries, Israel and Yemen, was obtained. Based on the very limited information for these two continents, it is estimated that per capita generation rates range from 0.3 to 1.1 kg/person/day, and the DOC content ranges from 3 to 20%. (Thorneloe, 1993a)

Landfill and waste management practices also have significant effects on methane generation, for example the degree and type of landfill cover, the method of landfilling, the water management practices etc.

Flaring and gas recovery schemes

Both of these factors will reduce the amount of uncontrolled methane emissions from landfills. Utilisation and/or flaring of landfill gas as an energy source is one of the most successful methods for reducing uncontrolled methane emissions from landfills (see "Options for controlling methane emissions from landfill sites" for further details).

Gas flaring generally occurs where it is necessary to ensure local site safety, but it is now recognized as a valuable method for reducing the extent of methane emissions to atmosphere.

Any national inventory of methane emissions from landfills therefore needs to take into account the reductions achieved by these two factors. For gas use, numbers of schemes

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are generally well known and documented, therefore an accurate estimate can be made of the amount of methane being used in the schemes. Information on landfill gas schemes around the world is available from a variety of sources, eg. Governmental Advisory Associates (1991) for the US; Landfill Gas TRENDS (1993) for the UK; Gendebien et al. (1992) for the European Community; Lawson (1991) for countries participating in the International Energy Agency's Bioenergy Agreement; Richards (1989) for world statistics, etc. Most of these sources update their information regularly as more schemes are commissioned.

Estimates of the extent of flaring are more difficult to achieve with accuracy, and generally have to be estimated from a knowledge of the state of landfill management within the country. For many countries, new legislation will ensure that most future landfills will be obliged to have gas control equipment installed; therefore in the future this will result in reductions in uncontrolled emissions as well as better quality data on this factor.

6.1.6 Availability and quality of data

Waste management data

The quality of methane emissions estimates are directly related to the quality of the waste management data used to derive these estimates, i.e. data on MSW generation rates, and on quantities of MSW disposed of to landfill. Most developed countries have these data available, and they should be used wherever possible. These data are often lacking however for developing countries and for the former Communist bloc countries.

Some global compilations of data have been made that can be used where local data are not available:

- Thorneloe et al. (In Press) has compiled data on waste management activities;

- World Resources Institute (1990) summarised waste generation rates for some countries, including Eastern European countries;

- Piccot et al. (1990) collected waste generation data;

- Bingemer and Crutzen (1987) compiled regional data;

- Carra and Cossu (1990) compiled data from 15 countries;

- OECD (1989) compiled country-specific data;

- U.S. EPA (forthcoming) compiled data on global waste management activities;

- U.S. EPA (forthcoming 4/94) compiled data on waste management activities;

- U.S. EPA in the forthcoming Report to Congress on Global Anthropogenic Emissions of Methane have compiled a list of over 50 references on global waste generation data.

Historical data on the amount of MSW disposed of to landfill are usually of limited value or quality. Extrapolation to future waste management scenarios is usually easier, especially since many countries are modifying their waste management policies, in particular to promote waste reduction and recycling, and so are required to review and monitor total MSW generation rates and disposal routes to provide current and future waste disposal scenarios (eg. Van Amstel et al. (1993) for the Netherlands, US EPA (1993) for the US).

Waste composition data

The composition of waste directly determines its DOC value. Default factors provided by Bingemer and Crutzen (1987) should be used where no country-specific factors are known.

As with 6.1 above, many countries are improving the quality of data held on waste composition, because of changes to waste management policies that are encouraging reduction and recycling.

Gas flaring and use

Accurate statistics are available in most of the countries where landfill gas use is practiced. However, the extent of gas flaring is often less well documented. Improvements to waste management practices should see an improvement in the collection of regular statistics which monitor the numbers of sites where gas is flared or used.

6.1.7 Conclusion

A methodology is presented here that allows simple calculation of methane emissions from landfills globally, and can be used by all countries. Some of the assumptions used in the method are open to criticism however, therefore countries are encouraged to progress to using a more sophisticated method with more country-specific data when more data become available.

TABLE 6.1
REGIONAL WASTE DISPOSAL, COMPOSITION, AND WASTE GENERATION DATA

Region	% MSW Landfilled	% DOC of MSW	Waste Generation (kg/cap/day)
U.S./Canada/Australia	91	22	1.8
U.S.	62	NA	2.0
Canada	93	NA	1.7
Australia	98	NA	1.9
Other OECD	71	19	0.8
Japan	28	NA	0.9
New Zealand	95	NA	1.8
Austria	57	NA	0.6
Belgium	50	NA	0.9
Denmark	63	NA	1.2
Finland	87	NA	1.1
France	47	NA	0.7
Germany	69	NA	0.9
Greece	100	NA	0.7
Ireland	100	NA	0.9
Italy	35	NA	0.7
Luxembourg	27	NA	1.0
Netherlands	55	NA	1.2
Norway	78	NA	1.3
Portugal	24	NA	0.6
Spain	76	NA	0.8
Sweden	42	NA	0.9
Switzerland	18	NA	1.0
UK	NA	NA	1.0
USSR/E.Europe	85	17.5	0.6
Developing Countries	80	15	0.5

Sources: Bingemer and Crutzen (1987) for regional data and OECD (1989) for individual countries.

6.2 METHANE EMISSIONS FROM WASTEWATER TREATMENT

6.2.1 Introduction

Methane (CH_4) production from wastewater treatment (WWT) under anaerobic conditions is estimated to range from 30 to 40 teragrams per year (Tg/yr). This represents 8 to 11 percent of the total global anthropogenic methane emissions, estimated at 360 Tg/yr (IPCC, 1992). Industrial WWT sources are estimated to be the major contributor to WWT emissions, accounting for 26 to 40 Tg/yr. Municipal WWT is estimated to emit approximately 2 Tg/yr, with Asia accounting for 65 percent. Uncertainty in these estimates result from a lack of data characterizing wastewater management practices, the quantities of wastewater that are anaerobically treated, data on the extent that CH_4 produced is flared or otherwise utilized, and field data on the CH_4 potential of wastewater treatment lagoons. (Thorneloe, 1993b)

Wastewater can produce methane if it is treated anaerobically and if the methane produced is released to the atmosphere. Anaerobic methods are used to treat wastewater from municipal sewage and from food processing and other industrial facilities, particularly in developing countries. In contrast, developed countries typically use aerobic processes for municipal wastewater treatment or anaerobic processes in enclosed systems where methane is recovered and utilized.

This section provides an explanation of the default methodology for estimating CH_4 emissions from WWT. A discussion of the uncertainty involved with these calculations is included.

6.2.2 Background

Highly organic waste streams including municipal wastewater and wastewater from industries such as food processing and pulp and paper plants have a high potential for CH_4 emissions. These waste streams quickly deplete available oxygen as their organic matter decomposes. The organic content or "loading" of wastewater is expressed in terms of biochemical oxygen demand (BOD), which is the principal factor determining methane generation potential of wastewater. BOD represents the amount of oxygen consumed by the organic material in the wastewater during decomposition (expressed in milligrams per liter - mg/l). A standardized measurement of BOD is the "5-day test" denoted as BOD_5. The maximum, or ultimate BOD is denoted as BOD_u. Untreated municipal waste streams typically have a BOD_5 ranging from 110 to 400 mg/l. Food processing facilities, such as fruit, sugar and meat processing plants, creameries, and breweries can produce untreated wastewater with a BOD_5 as high as 10.000 to 100.000 mg/l. (Thorneloe, 1993b) Most other industrial wastewater has a low BOD content.

Under the same conditions, wastewater with higher BOD concentrations will yield more CH_4 than wastewater with relatively lower BOD concentrations. Because of its influence in CH_4, BOD is a commonly measured parameter and data is available on BOD loading rates. Table 6.2 shows BOD values for municipal wastewater by region, while Table 6.5 includes BOD values for the wastewater of key industries.

Five-day BOD can range from 0.023 - 0.091 kg/capita/day for municipal wastewater. Per capita municipal wastewater BOD_5 has been reported from 0.023 - 0.045 kg/day in

developing countries and from 0.024 - 0.059 kg/day in developed countries (the lower value was reported for rural France) (Mara, 1976). The BOD increases when substantial amounts of kitchen wastes are discharged to sewers, for instance as the result of using sink disposals. (Thorneloe, 1993b)

Treatment of wastewater and its residual solids byproduct (sludge) under anaerobic conditions results in CH_4 emissions. Wastewater treatment in developed countries typically occurs aerobically using aerated impoundments. Digesters are also often used and the gas is either flared or utilized. Wastewater in these countries is not expected to be a major source of CH_4. However, facultative and anaerobic lagoons are often used for storage and treatment. EPA estimated in 1987 that there are approximately 5,500 municipal waste stabilization lagoons in the United States which treat 5.2×10^6 m^3/day of wastewater from 8 percent of the population served by municipal treatment systems (Office of Municipal Pollution Control, 1987). The CH_4 potential from these lagoons is not well understood and little field data are available. Industrial and commercial wastewater processes also use lagoons for treatment and storage.

Methane production varies depending upon temperature, retention time, BOD loading, and lagoon maintenance. Facultative lagoons, the most common type, treat wastewater by both anaerobic fermentation and aerobic processes. At the bottom of the lagoon, where an anaerobic environment exists, organic matter is digested to CH_4 and CO_2. As these gases bubble to the surface, much of the CO_2 is adsorbed by algae and is used, along with nutrients liberated during digestion, to produce algal biomass (University of California, 1984). Aerobic conditions, supported by algae growth, are maintained near the surface. Between 20 and 30 percent of the BOD loading to a facultative pond is anaerobically metabolized. As BOD loading increases and natural surface aeration diminishes, facultative lagoons proceed to a more anaerobic state. This results in higher CH_4 production, providing that the temperature is higher than 15°C. Under these conditions, a facultative lagoon may act more as an anaerobic pond, with possibly 95 percent of the lagoon volume functioning anaerobically. Fermentation and thus CH_4 production, is negligible at temperatures below about 15°C, at which point the lagoon serves principally as a sedimentation tank (Gloyna, 1971).

The depth of the lagoon is also an important factor in CH_4 production. Shallow lagoons, one meter or less in depth, are not expected to produce large quantities of CH_4 because the intake of oxygen from the surface, as well as the production of oxygen due to photosynthesis, prevent the formation of a significant anaerobic zone. Facultative lagoons are typically 1.2 to 2.5 meters in depth; lagoons greater than 2.5 meters in depth are typically referred to as anaerobic lagoons. The last important factor influencing the production of CH_4 is the retention time. (Thorneloe, 1993b)

6.2.3 Methodology for Estimating Emissions from Wastewater Treatment

Methane emissions from wastewater treatment should be calculated for two different wastewater types:

1   Municipal wastewater

2   Industrial wastewater

For each category, a simple methodology for calculating methane emissions from wastewater treatment is based on BOD loading and relies on available country-specific data. In each category a more detailed approach is also discussed. The more detailed

approaches would produce more accurate results if input data are available. These data are not readily available now for many countries, but they may be in the future as research continues.

Estimate methane emissions from municipal wastewater treatment

Steps for Method A (simplified approach)[1]

Data needed are:

1   Kg BOD_5 per capita-day (default values are shown in Table 6.2 for different regions.)

2   Country Population (developing countries may choose to estimate wastewatertreatment emissions based only on the urban population of the country if wastes produced in rural areas decompose in an aerobic environment -- see Table 6.3 for list of anaerobic and aerobic treatment methods).

3   Estimate fraction of total wastewater that is treated anaerobically. Wastewater treatment methods that may result in anaerobic decomposition of waste are listed in Table 6.3. Because published data on the fraction of wastewater that is anaerobically treated in different countries are scarce, countries are encouraged to provide their own estimate based on their available data. Table 6.4, however, contains default values for the fraction of total wastewater that is treated anaerobically in certain regions -- these values may be used in the absence of country-specific estimates.

4   Subtract the amount of methane, if any, that is recovered and thus not emitted to the atmosphere. This would include any methane recovered and either flared or used for energy as part of wastewater treatment. If no national data are readily available, the default assumption is that this amount is zero.

Equation 6.3 summarizes the methane emissions calculation.

$$\begin{array}{c} \textbf{EQUATION 6.3} \\ [\text{Population}] \times [\text{kg } BOD_5/\text{capita-day}] \times [365 \text{ days/year}] \times \\ [0.22 \text{ kg } CH_4/\text{kg } BOD_5] \times [\text{Fraction Treated Anaerobically}] \\ - \text{ Methane Recovered} \\ = \\ \text{kg } CH_4/\text{year} \end{array}$$

Steps for Method B (detailed approach)

A more precise estimate of methane emissions from wastewater treatment for a given country is possible if the following additional data are available: 1) The different treatment methods that are used in each country and the total portion of wastewater that is treated using each of these methods; and, 2) the methane conversion factor (MCF) for each of these treatment methods (the MCF represents the extent to which the maximum methane producing capacity of the wastewater is realized for a given wastewater treatment system).

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[1] This method is based on the approach developed for the Wastewater Treatment Chapter of EPA (forthcoming) and is described in Thorneloe (1993b).

Unfortunately, many countries are not likely to have data on the portion of wastewater treated using different methods. This is likely to be the case for many developing countries, which are of particular importance because of their reliance on anaerobic treatment methods. Additionally, at this time, complete information on MCFs for different wastewater treatment systems is not available. Countries which have more detailed information on specific treatment methods and their MCFs are encouraged to use this information in preparing national emissions estimates and to report these results to the IPCC. Through review of such estimates and results of ongoing research, a more comprehensive database of MCFs for specific treatment methods may be developed in the future.

Where these data are available, the following approach would be used to estimate methane emissions from wastewater treatment:

Data Needed are:

1   Country Population

2   Kg BOD_5 per capita-day

3   Fraction of total wastewater treated using different treatment methods. Some common methods are listed in Table 6.3.

4   The MCF (methane conversion factor) of each wastewater treatment method.

Equation 6.4 summarizes the calculation of methane emissions from each wastewater treatment system using the more detailed approach. Total emissions are the sum of emissions from all systems.

EQUATION 6.4

[Population] × [kg BOD_5/capita-day] × [365 days/year] ×

[0.22 kg CH_4/kg BOD_5] × [Fraction Wastewater Treated using Method$_i$]

× Methane Conversion Factor (MCF) for Method$_i$

– Methane Recovered

=

kg CH_4/year

Estimate methane emissions from industrial wastewater treatment

Methane emissions from wastewater produced in a few key industries are estimated to account for a very large portion of total methane emissions from wastewater treatment. (Thorneloe 1993b) Table 6.5 lists industries which are believed to be responsible for most of the emissions. National experts should estimate emissions for these industries, if applicable, and any others which can be estimated to have significant emissions, based on locally available data.

Steps for Method A (Simplified Approach)

1   Determine the relevant industries for a given country. The methane emissions from industrial wastewater treatment are based on wastewater outflow by industry. Table 6.5 lists industries which produce wastewater containing concentrations of organic material likely to produce significant CH_4 emissions.

2   Wastewater outflow by industry must be estimated. If these data are not directly available, they may be estimated based on production by industry, and waste consumed per unit of product. Typical water consumption rates for some key industries are presented in Table 6.6.

3   Then, the BOD content of the wastewater for each product must be estimated. Default BOD values are provided in Table 6.5.

4   Estimate the fraction of wastewater from each industry that is treated anaerobically. Unfortunately, default values are not available by industry. If no information is locally available, the default values shown in Table 6.4 could be used as an initial approximation.

5   If anaerobic treatment with methane recovery is employed, the amount of methane that is recovered should be subtracted from total emissions.

Equation 6.5 summarizes the emissions calculation for industrial wastewater treatment. Emissions should be estimated for each industry; total emissions from industrial wastewater treatment are the sum of emissions from each industry.

EQUATION 6.5

Wastewater outflow by industry (kl) x

[kg BOD_5/l] x [0.22 kg CH_4/kg BOD_5] x [Fraction Wastewater Treated Anaerobically]

- CH_4 Recovered

=

kg CH_4/year

Method B (detailed approach)

As with estimating methane emissions from municipal wastewater treatment, more precise estimates of methane emissions from industrial wastewater treatment can be made if specific methods used to treat wastewater from each industry are known and the MCFs for each method have been estimated.

If this information is available, Equation 6.6 can be used to calculate emissions from industrial wastewater treatment. Total emissions for each industry are the sum of emissions from each wastewater treatment system. Total emissions from industrial wastewater treatment are the sum of emissions from each industry.

EQUATION 6.6

Wastewater outflow by industry (kl) x

[kg BOD_5/l] x [0.22 kg CH_4/kg BOD_5] x [Fraction Wastewater Treated by Method$_i$] x

Methane Conversion Factor (MCF) of Treatment Method$_i$

- CH_4 recovered

=

kg CH_4/year

6.2.4 Global Emissions Estimates

Thorneloe (1993b) provides country-specific CH_4 emission estimates obtained by using the simple methods described above and readily available country and region-specific data and assumptions. Results by country are summarized in Table 6.7 for municipal waste and by industry for industrial waste in Table 6.8. Both calculations assume approximately 10-15 percent of wastewater is anaerobically. See Thorneloe (1993b) for a discussion of regional and country-specific information used to develop these estimates.

6.2.5 Uncertainties

When trying to create wastewater CH_4 emissions estimates, there are several factors which contribute to the uncertainty of these figures.

Wastewater Quantities

Often the specific volumes of municipal and industrial wastewater outflow and the volumes treated under anaerobic conditions in each country are not well known. As a result, data limitations exist for quantifying the fraction of wastewater subject to anaerobic decomposition. The effect of recycling industrial wastewater outflow is also not well understood.

Data are needed for specific volumes of wastewater being processed through anaerobic decomposition. Currently, a large volume of the world's wastewater is emitted to lakes, rivers, and oceans without any kind of treatment, or is deposited in various systems such as pit toilets or merely on the ground and not contained in any way.

Additional Wastewater Treatment Methods

No information is readily available on CH_4 emitted from unsewered wastewater treated in septic systems, pit toilets or cess pools. Emissions from these systems might be considerable if factors such as temperature, retention time, and system configuration are favorable. The CH_4 could be emitted through vent pipes in the systems or through cracks and leaks in the tanks, assuming that CH_4 is not completely oxidized in surrounding soil.

In many warmer regions of the world sewage may be discharged into dry riverbeds, and into rivers that are intermittently dry or have periods of extended low flow such that there is no water to serve as a receiving body for the wastewater (UNEP, 1980; WHO, 1987). Anaerobic conditions can develop in these instances (UNEP, 1988, 1980). No data are available on this topic.

Wastewater Treatment Facility Efficiency and Output

Wastewater supposedly treated aerobically by treatment plants may still be subject to anaerobic conditions, due to poorly functioning facilities. In addition, adjustments should be made for (1) the amount of CH_4 that is controlled through utilization or flaring and (2) the amount of CH_4 that is oxidized prior to atmospheric release. However, the specific data needed are often not available.

Research in Japan has produced data on high levels of methane production resulting from a wastewater treatment process that includes aeration and is essentially operated under aerobic conditions. (Kyosai and Mizuochi, 1993) This is result represents an area that should be studied in more detail in the future.

Current estimates from wastewater treatment lagoons are relatively uncertain due to the limited available data. The US EPA's Office of Research and Development's Global Climate Change Engineering Research Program is conducting field measurements of wastewater treatment lagoons, both anaerobic and facultative, to develop emission factors from these sources.

Physical and Chemical Data

Data on physicochemical wastewater characteristics are limited, especially for country-specific wastewater volumes. For industrial wastewater emission estimates, the BOD values reported for the source categories are averages of BOD values given for several process wastewater streams. The estimate could be improved if data were obtained on the chemical characteristics and volumes of process wastewater streams and the fraction of these wastewater streams anaerobically degraded. Furthermore, the emission methodology does not account for factors, such as temperature, pH and retention time, that influence the rate and extent of anaerobic decomposition, and consequently, the potential for CH_4 production.

6.2.7 Conclusion

The methodology presented in this section gives a simple calculation of methane emissions from wastewater globally, and can be used by all countries. Some of the assumptions used in the method are open to criticism. Therefore countries are encouraged to progress to using a more sophisticated method with more country-specific data, when more data become available.

TABLE 6.2 ESTIMATED BOD5 VALUES IN MUNICIPAL WASTEWATER BY REGION (KG/CAPITA/DAY)	
Region	BOD5 Value
Africa:	0.037
Asia, Middle East, Latin America:	0.04
N. America, Europe, Former USSR, Oceania:	0.05
Source: EPA (forthcoming)	

TABLE 6.3
ANAEROBIC AND AEROBIC METHODS OF WASTEWATER TREATMENT
Treatment Method
Aerobic (low MCF) methods:
Developing Countries
• Open Pits/Latrines
• Aerobic (shallow) ponds
• Ocean Dumping
• River Dumping
Developed Countries
• Sewer systems with aerobic treatment
Anaerobic (high MCF) methods:
Developing Countries
• Anaerobic (deep) ponds
• Sewer systems with aerobic treatment.
Developed and Developing Countries
• Septic Tanks
Anaerobic Methods with Methane Recovery
Primarily Developed Countries

TABLE 6.4	
ESTIMATED TOTAL (URBAN) WASTEWATER FRACTION ANAEROBICALLY TREATED	
Country/Region	Fraction Treated
Africa	N/A
Asia and Oceania	15%
Latin America	7% to 10%
North America and Europe	15%
Latin America	10%

Source: EPA (forthcoming)

Note: For many developing countries, industrial wastewater is often discharged with domestic wastewater.

		TABLE 6.5 BIOCHEMICAL OXYGEN DEMAND (BOD) ESTIMATES FOR VARIOUS INDUSTRIAL WASTEWATERS	
Industry[a]	BOD (kg/l)	References and Notes
Iron and Steel	0.001[b]	No references for BOD were obtained. Used the value for BOD in textile wastewaters, p.67, Carmichael and Strzepek (1987) since it was the lowest value obtained for industrial sources.
Non-ferrous metals	0.001[b]	No references for BOD were obtained. Used the value for BOD in textile wastewaters, p.67, Carmichael and Strzepek (1987) since it was the lowest value obtained for industrial sources.
Fertilizer	0.001[b]	No references for BOD were obtained. Used the value for BOD in textile wastewaters, p.67, Carmichael and Strzepek (1987) since it was the lowest value obtained for industrial sources.
Food & Beverages	0.035	This value is an average of the following categories of the fruit & beverage Industry.
Fruits/vegetables	0.003	Barnes et al. (1984), p. 213
Cereals	0.001[c]	EPA (1974a), p. 39, 40
Meats	0.02[c]	EPA (1975), p. 58, 60; EPA (1974c), p. 39, 41
Butter	0.003[c]	EPA (1974b), p. 59; Barnes et al. (1984), p. 316
Cheese	0.003[c]	EPA (1974b), p. 59; barnes et al. (1984), p. 316
Cane Sugar	0.002[b]	Barnes et al. (1984), p. 20
Beet Sugar	0.01[b]	Barnes et al. (1984), p. 12; EPA (1974d)
Wine	0.135[c]	Barnes et al. (1984), p. 73
Beer	0.085[c]	Barnes et al. (1984), p. 73
Other Beverages	0.083[c]	Barnes et al. (1984), p. 73
Pulp and Paper	0.004[b]	Carmichael and Strzepek (1987), p. 49 and Hall et al. (1988) as cited in Torpy (1988), p. 20
Petroleum Refining (Petrochemical)	0.004[c]	Average of values reported in Carmichael and Strzepek (1987), pp. 33, 36
Textiles	0.001[b]	Carmichael and Strzepek (1987), p. 67
Rubber	0.001[b]	No references for BOD were obtained. Used the value for BOD in textile wastewaters, p.67, Carmichael and Strzepek (1987) since it was the lowest value obtained for industrial sources.
Miscellaneous[d]	0.002	No BOD values obtained. Used BOD reported for the pharmaceutical Industry in Carmichael and Strzepek (1987), p. 85

[a] Industries presented here are taken from table 47, pp 116, 117 in Carmichael and Strzepek (1987).

[b] Reported as BOD. This is assumed to be ultimate BOD.

[c] Reported as BOD5.

[d] Industries in this group were undefined.

Source: Thorneloe, 1993b.

TABLE 6.6 WATER CONSUMPTION PER UNIT OF PRODUCT FOR PAPER AND FOOD PROCESSING FACILITIES	
Process	Water Consumption[a] (liters/metric ton)
Canneries	
- Green beans	80,000
- Peaches and pears	22,000
- Other fruits and vegetables	8,000-40,000
Food and Beverage Industry	
- Beer	60,000
- Wine	20,000 liters/ton live weight
- Meat packing	16,00-20,000
- Dairy products	
- Sugar	
Pulp and Paper	
- Pulp	344,000-966,000
- Paper	200,000 liters
Textiles	
- Bleaching	300,000-400,000 liters/ton cotton
- Dyeing	40,000-80,000 liters/ton cotton

Sources:

a Metcalf and Eddy (1972).

b EPA (forthcoming).

* These were reported as BOD and are assumed to be ultimate BOD, as opposed to BOD_5. These values, however, should still be used as the default assumptions, as other data are not available.

These water consumption factors are approximate, and in some cases, the water used in the process may not all become wastewater.

TABLE 6.7 ESTIMATE OF GLOBAL AND COUNTRY-SPECIFIC METHANE EMISSIONS FROM THE TREATMENT OF DOMESTIC WASTEWATER - 1990 (TG/YR)	
Country	Emissions
Africa[a]	
Egypt	0.02
Kenya	0.01
Morocco	0.01
Nigeria	0.04
South Africa	0.01
Sudan	0.01
Tanzania	0.01
Uganda	0.01
Other Africa	0.09
Total Africa	**0.21**
Asia[b]	
China	0.54
Korea, N.	0.01
Vietnam	0.03
Other Asia	0.92
Total Asia	**1.50**
South America[a]	
Argentina	0.01
Brazil	0.05
Colombia	0.01
Mexico	0.03
Venezuela	0.01
Other So. America	0.02
Total South America	**0.13**
North America[b]	
Canada	0.02
United States	0.15
Other No. America	0.04
Total North America	**0.21**
Europe	
France	0.01
German Democratic Republic	0.01
Italy	0.01
United Kingdom	0.01
Total Europe	**0.04**
Former USSR[b]	**0.18**
Oceania[c]	
Australia	0.01
Total Oceania	**0.01**
World Total	**2.30**
a. Ten percent of BOD5 is assumed to be anaerobically degraded. b. Fifteen percent of BOD5 is assumed to be anaerobically degraded.	

TABLE 6.8 ESTIMATE OF GLOBAL METHANE EMISSIONS FROM INDUSTRIAL WASTE WATER TREATMENT 1990 (TG/YR)											
	Developed Countries				Developing Countries				Worldwide		
Industry	Industrial Waste-water Outflow[b] (Millions m³/yr)	BOD₅ (kg/l)	Percent of BOD₅ Anaerobically Degraded		Industrial Waste-water Outflow[b] (Millions m³/yr)	BOD₅ (kg/l)	Percent of BOD₅ Anaerobically Degraded		Industrial Wastewater Outflow[b] (Millions m³/yr)	BOD₅[c] (kg/l)	
			10%	15%			10%	15%			10%	15%
			Emissions				Emissions				Emissions	
Iron & Steel	168.000	0.001	4	6	56.000	0.001	1	2	224.300	0.001	5	7
Non-Ferrous Metals	26.600	0.001	1	1	8.850	0.001	0	0	35.000	0.001	1	1
Fertilizer	14.300	0.001	0	1	4.500	0.001	0	0	19.000	0.001	0	1
Food & Beverages	7.700	0.035	6	9	2.600	0.035	2	3	10.300	0.035	8	12
Pulp & Paper	33.300	0.004	3	4	11.100	0.004	1	2	44.400	0.004	4	6
Petroleum Refining	54.700	0.004	5	7	18.200	0.004	2	2	73.200	0.004	6	10
Textile	34.600	0.001	1	1	11.450	0.001	0	1	46.100	0.001	1	2
Rubber	6.800	0.001	0	0	2.300	0.001	0	0	9.100	0.001	0	0
Miscellaneous[a]	9.500	0.002	0	1	3.200	0.002	0	0	12.700	0.002	1	1
TOTAL	355.500		20	30	118.200		6	10	474.100		26	40

a. This group was undefined in Carmichael & Strzepec (1987).

b. Carmichael & Strzepec (1987).

c. Sources of BOD values are given in Table 6.5.

6.3   EMISSIONS FROM WASTE INCINERATION

6.3.1 Introduction

Waste incineration like other types of combustion, is a source of many GHGs. Very few data have been compiled on the global emissions from waste incineration. Preliminary indicators are that this source represents a small percentage of the total GHG output from the waste source category.

6.3.2 Emissions

Certainly waste incineration produces CO_2, but it is difficult to identify the portion which should be considered **net** emissions. A large fraction of the carbon in waste combusted (e.g. paper, food waste) is derived from biomass raw materials which are replaced by regrowth on an annual basis. These emissions should not be considered net CO_2 in the IPCC methodology. If the agricultural or forestry sources are not being sustainably managed, net CO_2 emissions (equivalent to reductions in biomass stocks) should be accounted for in those source categories. On the other hand, some carbon in waste is in the form of plastics or other fossil fuel based products. Combustion of these materials, like fossil fuel combustion, releases net CO_2 emissions.

Other relevant gases released from combustion are net GHG emissions. Methane emissions from waste incineration are highly uncertain. An expert working group recognised waste incineration as a source of methane production, but was not able to give global estimates or default emissions factors. Although this source is considered to be relatively small compared to the other CH_4 sources in waste, it was recognised as an area for further research in the future. (Berdowski et al., 1993)

Recent studies have also shown that N_2O may be an important GHG produced from incineration. Table 6-8 provides data from studies of several incineration plants and the N_2O produced from the waste incineration. (de Soete, 1993) Studies in Belgium (IPCC, 1993), Japan (Tanaka et al., 1992) and Norway (Rosland, 1993) have estimated N_2O production from their waste incineration processes. It has also been found that the emission level depends on the nature of the waste burned. Research in Japan has noted that while all types of incineration produce N_2O, sludge incinerators produce the highest emissions rates. (Tanaka et al., 1992)

Traditional air pollutants from combustion - NO_x, CO, NMVOC - are characterized in existing emissions inventory systems. The IPCC does not provide a new methodology for these gases, but recommends that national experts use existing published methods. Some key examples of the current literature providing methods are: CORINAIR Default Emissions Handbook (Bouscaren, 1992), as well as the U.S. EPA's Compilation of Air Pollutant Emissions Factors (AP-42) (US EPA, 1985) and Criteria Pollutant Emission Factors for the 1985 NAPAP Emissions Inventory (Stockton and Stelling, 1985).

					N₂O emission		

TABLE 6.9

NITROUS OXIDE EMISSIONS FROM WASTE INCINERATION

Nature of Waste (reference)	Facility	T⁰C	min.	ppmv aver- age	max	at O₂ (%)	g N₂O ton waste
(65) Municipal refuse	10 furnaces (65-300 tons/day)		1.2	8	18		
(66) Municipal refuse	Stepgrate	780-880	0.8		4.9	10	11-43
	Stepgrate	780-980	4		24	8-14	40-220
	Fluid.bed	830-850	6.7		10.5	13-15	14-123
(67) Municipal solid waste	5 stokers		3	7	12		26-270
	20-400 t/d		5.6	9.8	17.1		97-293
	3 fluid.bed		10.2	11.1	12.1		135-165
	rot.kiln						
	120 t/d						
(65) Sewage- sludge	4 incin. 150-300 t/d		57	87	125		
(66) Sludge	Rotary grate	750		50.7			227
	Fluid.bed	770-812	270		600		580-1528
	"	838-854	135		292		684-1508
	"	834-844	100		320		275-886
	"	853-887	45		145		101-307

Source: de Soete, 1993.

6.4 REFERENCES

Ahuja D. (1990). Estimating regional anthropogenic emissions of greenhouse gases. Indian Geosphere Biosphere Programme. Tata Energy Research Institute, New Delhi, and The Bruce Co., Washingon D.C.

Augenstein D. and Pacey J. (1991). Modelling landfill methane generation. In proceedings of Sardinia 91, Third International Landfill Symposium. Cagliari, Italy.

Barnes, D., C.F. Forster, S.E. Hrudey (eds). 1984. Surveys in Industrial Wastewater Treatment (Vol. 1). Food and Allied Industries. Pitman Publishing Inc., Marshfield, Massachusetts. 376 pp.

Berdowski, J.J.M., L.Beck, S. Piccot, J.G.J. Oliver, C. Veldt. 1993, Working Group Report: Methane Emissions from Fuel Combustion and Industrial Processes, pp. 231-237. From the Methane and Nitrous Oxide Proceedings: Methods in national emissions inventories and options for control, Van Amstel (ed.), RIVM, Amersfoort, The Netherlands.

Bhide, A.D., Gaikwad, S.A., and Alone, B.Z. 1990. CH_4 from Land Disposal Sites in India. Proceedings of the International Workshop on CH_4 Emissions from Natural Gas Systems, Coal Mining and Waste Management Systems. Environment Agency of Japan, the U.S. Agency for International Development, and the U.S. Environmental Protection Agency, Washington, D.C. 04/09-13/90.

Bingemer H.G. and Crutzen P.J. (1987). The production of methane from solid wastes. Journal of Geophysical Research 92 (D2): 2181-2187.

Bogner J and Spokas K. (1993). Landfill methane: rates, fates, and role in global carbon cycle. Chemosphere 26: 369-386.

Bouscaren R. (1992). CORINAIR Inventory, Default Emissions Handbook, 2nd ed., 12: 1-3. Published by CITEPA.

Carmichael, J.B., and K.M. Strzepek. 1987. Industrial Water Use and Treatment Practices. Published for the United Nations Industrial Development Organization (UNIDO). Cassell Tycooly, Philadelphia, PA. 123 pp.

Carra J.S. and Cossu R. (1990). International Perspectives on Municipal Solid Wastes and Sanitary Landfilling. Academic Press.

Davis, L., Huff, L., and Sarsony, C. 1992. Effects of International Municipal Solid Waste Management Trends on Global Greenhouse Gas Emissions, Draft EPA Report. [Cleared peer review, to be published in 10/92]. Prepared for U.S. Environmental Protection Agency, Air and Energy Engineering Research laboratory, Research Triangle Park, N.C.

De Soete G. 1993, Nitrous Oxide from Combustion and Industry: Chemistry, Emissions, and Control, pp. 324-325. Working Group Report: Methane Emissions from Biomass Burning. in A.R. van Amstel (ed.), Proceeding of an International IPCC Workshop on Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control. RIVM Report no. 481507003, Bilthoven, The Netherlands.

Department of the Environment (1993). An assessment of methane emissions from UK landfills. UK DoE report CWM 063/93.

Doorn M.R.J., Stefanski L.A., Peer R.L. and Epperson D.L. (1993). Estimate of methane emissions from US landfills. EPA AEERL Project Report, Research Triangle Park, NC. (In press.)

El Rayes, H. and Edwards. W.C. (B.H. Levelton & Associates, Ltd.) 1991. Inventory of CH_4 Emissions from Landfills in Canada. Prepared for Environment Canada, Hull, Quebec. pp. 25-69.

EMCON Associates (1981). Methane generation and recovery from landfills. Ann Arbor Science: Ann Arbor, Michigan.

Environment Canada. 1979. Biological Treatment of Food Processing Wastewater Design and Operation Manual. Economic and Technical Review. Report EPA, 3-WP-79-7. Water Pollution Control Directorate. 216 pp.

Environment Canada (1992). Canada's greenhouse gas emissions: estimates for 1990. Report EPS 5/AP/4.

Frantzis, I. 1988. Recycling in Greece. BioCycle, 07/88, pp. 30-31.

Gendebien A., Pauwels M., Constant M., Ledrut-Damanet M.-J., Willumsen H.-C., Butson J., Fabry R., Ferrero G.-L. and Nyns E.-J. (1991). "Landfill gas. From environment to energy". Office for Official Publications of the European Communities, Luxembourg.

Gloyna, E.F. 1971. Waste Sabilization Ponds. World Health Organization. Geneva, Switzerland.

Governmental Advisory Associates, Inc. (1991). 1991-2 Methane Recovery from Landfill Yearbook. GAA, Inc. New York.

ICF Incorporated. 1993. Estimating a Correction Factor for the Bingemer and Crutzen Method. Memorandum prepared by ICF Incorporated for the Global Change Division, US EPA, August 9, 1993.

IPCC, 1992. Climate Change 1992. The Supplementary Report to the IPCC Scientific Assessment. Published for The Intergovernmental Panel on Climate Change (IPCC), World Meteorological Organization/United Nations Environment Programme. Cambridge University Press. Edited by J.T. Houghton, G.J. Jenkins, and J.J. Ephraums.

IPCC parts I & II, 1993. National GHG Inventories: Transparency in Estimation and Reporting, p. 11. Prepared by The Intergovernmental Panel on Climate Change (IPCC) and Organization for Economic Co-operation and Development, World Meteorological Organization/United Nations Environment Programme.

IPCC part III, 1993. Preliminary IPCC National GHG Inventories: In-Depth Review, p. 73. Prepared by The Intergovernmental Panel on Climate Change (IPCC) and Organization for Economic Co-operation and Development, World Meteorological Organization/United Nations Environment Programme.

Kolb C.E. et al. (1992). Methane emissions from natural gas distribution systems. Prepared for the Global Change Division Office of Air and Radiation, US Environmental Protection Agency, Washington D.C. (As referenced in US EPA, 1993).

Kyosai S., and M. Mizuochi (1993). Study on release from wastewater treatment plants, pp.110-111. In: Global Environment Research in the FY 1990. Published by Research & Information Office, Global Environment Department, Environment Agency, Government of Japan.

Landfill Gas TRENDS Newssheet Issue 5 (May 1993). UK Department of Trade and Industry and Department of the Environment. Available from ETSU, Harwell, UK.

Lawson, P. (1991). Landfill gas expert working group: summary report 1989-1991. IEA Biomass Conversion Agreement: MSW Conversion Activity, Task VII. Available from ETSU, Harwell, Oxon, UK.

Lawson P. and Alston Y.R. (1990). Landfill microbiology: R&D Workshop. ETSU, Harwell, UK.

Manley B.J.W., Wilson D.C and Tillotson H.S. (1990). National assessment of landfill gas production. Contract report B1192. ETSU, Harwell, UK.

Mara, D. 1976. Sewage Treatment in Hot Climates. John Wiley & Sons, New York. pp. 4-6, 77.

Metcalf & Eddy, Inc. 1979. Wastewater Engineering: Treatment Disposal Reuse, 2nd Edition. McGraw-Hill Book Company, New York. p. 2 to 3, 20, 64, 621.

Mullick, M.A. 1987. Wastewater Treatment Processes in the Middle East. The Book Guild, Sussex, England. 328 pp.

Office of Municipal Pollution Control (OMPC). 1987. Report to Congress, Municipal Wastewater Lagoon Study. PB88-154315. pp. 3-3, 3-7, 3-8.

OECD (1989). Environmental Data Compendium 1989. OECD Paris.

OECD (1991). Estimation of greenhouse gas emissions and sinks. Final report from the OECD Experts meeting, 18-21 February. OECD Paris.

Organization of Economic Cooperation and Development (OECD). 1991. OECD Environmental Data Compendium 1991.

OECD (1993). OECD Environmental Data Compendium 1993. OECD Paris.

Orlich J. (1990). Methane emissions from landfill sites and waste water lagoons. In: Internation workshop on methane emissions from natural gas systems, coal mining and waste management systems. April 9-13, 1990, Washington D.C. Funded by the Environmental Agency of Japan, the US Agency for International Development and the US Environmental Protection Agency.

Pacey J. and Augenstein D. (1990). Modelling landfill methane generation. In: Proceedings of the international conference "Landfill Gas: Energy and Environment '90". Bournemouth, UK.

Papchristou, E. 1988. Solid Wastes Management in Rhodos. In: Proceedings of the 5th International Solid Wastes Conference, International Solid Waste and Public Cleansing Association, Copenhagen, Denmark, September.

Peer, R. L., S. A. Thorneloe, D. L. Epperson, "A Comparison of Methods for Estimating Global Methane Emissions from Landfills", Presented at NATO Conference on Methane Emissions in October, 1991. Published in Chemosphere, Vol. 26 Nos 1-4, p. 387-400, 1993.

Peterson, C., and A. Perlmutter. 1989. Composting in the Soviet Union. BioCycle, July, 74-75.

Piccot S.D., Chadha A., DeWaters J., Lynch T., Marosudiro P., Tax W., Walata S. and Winkler J.D. (1990). Evaluation of significant anthropogenic sources of radiatively important trace gases. Prepared for the Office of Research and Development, US EPA, Washington D.C. (As referenced in OECD, 1991).

Polytechnic of East London (1992). Theoretical estimates of methane yields from refuse. Contract report B1318. ETSU, Harwell, UK.

Richards K.M. (1989). Landfill gas: working with Gaia. Biodeterioration Abstracts: 3, 317-331.

Rosland A. (1993). Greenhouse Gas Emissions in Norway: Inventories and Estimation Methods, p.14. Prepared for the Norwegian Ministry of the Environment, Oslo, Norway.

Schiller, E.J., and R.L. Droste. 1982. Water Supply and Sanitation in Developing Countries. Ann Arbor Science Publishers, Ann Arbor, Michigan.

Stockton M.B., and J.H.E. Stelling. 1987. Criteria Pollutant Emission Factors for the 1985 NAPAP Emissions Inventory. U.S. EPA Washington, Ouverage, EPA-600/7-87-015 XV-211.

Tabasaran O. (1981). Gas production from landfill. In: Household Waste Management in Europe, Economics and Techniques. Ed. Bridgewater A.V. and Lidgren K. Van Nostrand Reinhold Co., New York, 159-175.

Tanaka M., Miyazaki M., Watanabe I. (1992). CH4 and N2O Emission from Waste Disposal Facilities in Japan, pp. 18-19. Presented at the CH4 and N_2O Workshop held by the National Institute of Agro-Envronmental Sciences (NIAES). Tsukuba, Japan, March 25-26, 1992.

Thorneloe S.A. and Peer R.L. (1990). Landfill gas and the greenhouse effect. In: Proceedings of the international conference "Landfill Gas: Energy and Environment '90". Bournemouth, UK.

Thorneloe S.A., R.L. Peer, D.L. Campbell, and K.S. Kepford (1991). Proposed Methodology for Estimating Global Landfill Methane Emissions. January 28. U.S. EPA and Radian Corporation, Research Triangle Park, North Carolina

Thorneloe S.A. (1992). Landfill gas recovery / utilisation - options and economics. Presented at the 16th annual Institute of Gas Technology Conference on Energy from Biomass and Wastes. Orlando, FL.

Thorneloe S.A. (1993)a. Methane Emissions from Landfills and Open Dumps. Proceeding of an International IPCC Workshop on Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control. RIVM Report no. 481507003, Bilthoven, The Netherlands.

Thorneloe S.A. (1993)b. Methane from Wastewater Treatment. Proceeding of an International IPCC Workshop on Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control. RIVM Report no. 481507003, Bilthoven, The Netherlands.

Thorneloe S.A.,M.A. Barlaz, R.L. Peer, L.C. Huff, L. Davis, and J. Mangino, "Global Methane Emissions from Waste Management", Prepared for inclusion in: The Global Methane Cycle: Its Sources, Sinks Distributions and Role in Global Change, In Press.

Torpy, M.F. 1988. Anaerobic Treatment of Industrial Wastewaters. Noyes Data Corporation. Park Ridge, New Jersey.

United Nations Environment Programme (UNEP). 1980. Report of the international Symposium on Wastewater Technology for Developing Countries. UNEP Report No. 4 (1981).

United Nations Environment Programme (UNEP). 1988. Environmental Guidelines for Domestic Wastewater Management. UNEP Environmental Management Guidelines, No. 14.

U.S. Environmental Protection Agency (EPA). 1974a. Development Document for Effluent Limitations Guidelines and New Source Performance Standards for the Animal Feed, Breakfast Cereal, and Wheat Starch Segments of the Grain Mills Points Source Category. EPA 440/1-74/039a. Effluent Guidelines Division, Office of Waste and Hazardous Materials, Washington, D.C. December.

U.S. Environmental Protection Agency. 1974b. Development Document for Effluent Limitations Guidelines and New Source Preformance Standards for the Dairy Product Processing Point Source Category. EPA 440/1-74-021a. Effluent Guidelines Division, Office of Waste and Hazardous materials, Washington, D.C. May.

U.S. Environmental Protection Agency. 1974c. Development Document for Effluent Limitations Guidelines and New Source Performance Standards for the Red Meat Processing Segments of the Meat Products and Rendering Processing Point Source Category. EPA 440/1-74-012A. Effluent Guidelines Division, Office of Waste and Hazardous materials, Washington, D.C. February.

U.S. Environmental Protection Agency. 1974d. Development Document for Effluent Limitations Guidelines and New Source Performance Standards for the Beet Sugar Processing Subcategory of the Sugar Processing Point Source Category. EPA 400/1-74/002b. Effluent Giudelines Division, Office of Waste and Hazardous Materials, Washington, D.C. January.

U.S. Environmental Protection Agency. 1975. Development Document for Effluent Limitations Guidelines and New Source Performance Standards for the Rendering Segment of the Meat Products and Rendering Processing Point Source Category. EPA 400/1-74/031D. Effluent Guidelines Division, Office of Waste and Hazardous Materials, Washington, D.C. January.

U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. 1985. Compilation of Air Pollutant Emission Factors (Fourth Edition), Volume I: Stationary Point and Area Sources. EPA-AP-42 (GPO 055-000-00251-7), Research Triangle Park.

U.S. Environmental Protection Agency. 1987. Report to Congress, Municipal Wastewater Lagoon Study", Office of Municipal Pollution Control, 11/87.

U.S. Environmental Protection Agency. 1988. "Report to Congress, Solid Waste Disposal in the United States", EPA/530-SW-88-011, 10/88.

U.S. Environmental Protection Agency. 1990. Characterization of Municipal Solid Waste in the United States: 1990 Update. PB90-215112.

U.S. Environmental Protection Agency. 1991a. Air Emissions from Municipal Solid Waste Landfills - Background Information for Proposed Standards and Guidelines. EPA-450/3-90-011a, US EPA, Research Triangle Park N.C.

U.S. Environmental Protection Agency. 1991b. Analysis of Factors Affecting Methane Gas Recovery from Six Landfills, Prepared by the Air and Energy Engineering Research Laboratory of EPA's Office of Research and Development. EPA-600/2-91-055, September 1991.

U.S. Environmental Protection Agency/Office of Research and Development. 1991c. Approach for Estimating Global Landfill Methane Emissions, Prepared by the Air and Energy Engineering Research Laboratory of EPA's Office of Research and Development. EPA-600/7-91-002, January 1991.

U.S. Environmental Protection Agency. 1992. Development of an Empirical Model of Methane Emissions from Landfills, Prepared by the Air and Energy Engineering Research Laboratory of EPA's Office of Research and Development. EPA-600/R-92-037, March 1992.

U.S. Environmental Protection Agency. 1993a. Office of Air Quality Planning and Standards. 1985. Compilation of Air Pollutant Emission Factors, Volume I: Stationary Point and Area Sources. EPA-AP-42, Supplement F.

U.S. Environmental Protection Agency. 1993b. Methane emissions from landfills. In: Anthropogenic methane emissions in the United States: Estimates for 1990. Report to Congress. EPA Air and Radiation. EPA 430-R-93-003.

U.S. Environmental Protection Agency. Effects of International Municipal Solid Waste Management Trends on Global Greenhouse Emissions, Prepareed by the Air and Energy Engineering Research Laboratory of EPA's Office of Research and Development. In Press.

U.S. Environmental Protection Agency. (forthcoming). Report to Congress on Global Anthropogenic Emissions of Methane.

U.S. Environmental Protection Agency. Estimate of Methane Emissions from Landfills and Open Dumps, Prepareed by the Air and Energy Engineering Research Laboratory of EPA's Office of Research and Development. (In peer review, to be published in 4/94).

Van Amstel A.R., Swart R.J., Krol M.S., Beck J.P., Bouwman A.F. and Van der Hoek K.W. (1993). Methane, the other greenhouse gas. Research and policy in the Netherlands. RIVM, report no. 481507001.

Westlake K. (1990). Landfill microbiology. In: Proceedings of the international conference "Landfill Gas: Energy and Environment '90". Bournemouth, UK.

World Health Organization (WHO). 1987 Wastewater Stabilization Ponds. Principle of Planning & Practice. WHO EMRO Technical Publication No. 10, Alexandria, Egypt.

World Resources Institute (1990). World Resources 1990-91. WRI, Washington, D.C. (As referenced in OECD, 1991).

Yanez, F. 1980. Evaluation of the San Juan Stabilization ponds final research report of the first phase. Pan American Center for Sanitary Engineering and Environmental Sciences (CEPIS).

Zehnder, A.J.B., et al. 1982 "Microbiology of CH_4 Bacteria," n Anaerobic Digestion, D.E. Hughes, eds., Elsevier Biomedical Press B.V., Amsterdam, p.45.

Zsuzsa, K.P. 1990. Possibilities for Utilization of the Energy Content of the Solid Wastes of Settlements. Resour. Conserva. Recycl., 4:173-180.