MARYLAND DEPARTMENT OF THE ENVIRONMENT
AIR AND RADIATION MANAGEMENT ADMINISTRATION

MARYLAND GREENHOUSE GAS EMMISSIONS INVENTORY
1990

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EXECUTIVE SUMMARY

The purpose of this report is to provide an initial inventory of greenhouse gas emissions for the State of Maryland. This effort was supported by a $25,000 grant from the U.S. Environmental Protection Agency (EPA).

The greenhouse gases included in the inventory are the four primary greenhouse gases emitted as a result of human activity. These are carbon dioxide, methane, nitrous oxide, and ozone depleting compounds (primarily chlorofluorocarbons). Emissions of these gases are estimated for 1990. The emission source categories considered in the study are listed in Table 1 of the Introduction. Emissions were estimated primarily by using the methodologies provided in the *States Workbook: Methodologies for Estimating Greenhouse Gas Emissions* (EPA-230-B-92-002, November 1992) published by the EPA. However, emissions from some EPA source categories (notably landfills) and emissions from some source categories not included in the EPA Workbook, were estimated using alternative methodologies.

The results of this emission inventory are presented in Figures 1 and 2, which summarize greenhouse gas emissions and source category contributions to the total inventory. Table 3 provides a more detailed summary of the results. Approximately 110 million tons (CO_2 -equivalent) of greenhouse gases were emitted as a result of activity in Maryland in 1990.

Carbon dioxide is the major greenhouse gas emitted in Maryland, accounting for 66.3% of the 1990 emissions. Ozone depleting compounds (primarily chlorofluorocarbons) accounted for 29.4% of the 1990 greenhouse gas emissions. Methane and nitrous oxide are both minor contributors and accounted for 2.5% and 1.8% of Maryland's greenhouse gas emissions, respectively.

The consumption of fossil fuels is the major source of greenhouse gas emissions in Maryland, accounting for 65% of the 1990 emissions. The use of coal and petroleum accounted for 56% of the 1990 fossil fuel emissions, while natural gas consumption accounted for 9%. The emission of ozone depleting compounds from various industrial processes is the largest single greenhouse gas emission source category in Maryland, emitting 31% of the 1990 emissions. Transportation is the second largest single source category, emitting 23% of the 1990 emissions. Electric utility coal burning power plants were the third largest category, emitting 19% of the 1990 emissions. These three categories together are responsible for 73% of the 1990 greenhouse gas emissions. The remaining emissions are primarily from fossil fuel consumption by the industrial, residential and commercial sectors, representing 13%, 6% and 3% of the 1990 emissions, respectively. Agriculture, waste disposal, and biomass combustion were all minor emission source categories, accounting for 5 percent of the 1990 emissions. Land use change was the smallest category, contributing 1 percent of the 1990 greenhouse gas emissions.

Figure 1. Maryland 1990 Greenhouse Gas Emissions
(million Tons, CO2 equivalent)

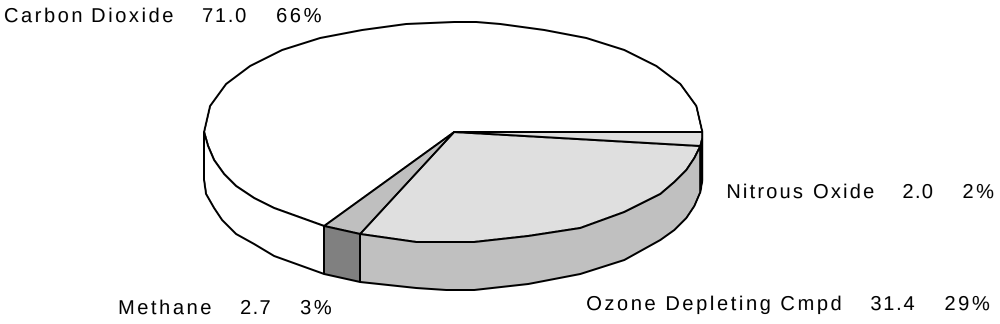
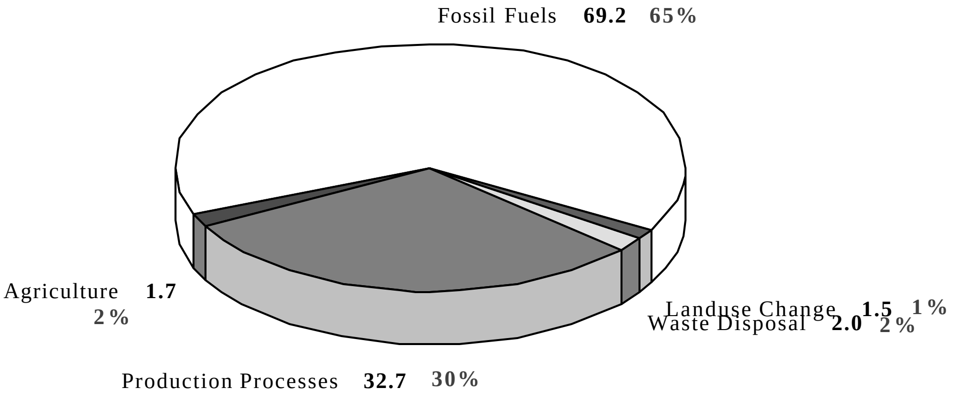


Figure 2. Maryland 1990 Greenhouse Gas Emissions by Source Category
(million Tons, CO2 equivalent)



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INTRODUCTION

1. Greenhouse Gases and Climate Change

The greenhouse effect is a natural phenomenon without which life as we know it on Earth could not exist. The underlying scientific principles are well established. Incoming visible light from the sun is absorbed by the atmosphere and the surface of the Earth. Some of this energy is radiated back toward space as infrared light (i.e., heat). Water vapor and other trace gases in the atmosphere trap much of the re-radiated heat. Without this heat trapping by the trace gases in the atmosphere, the surface of the Earth would be about 59 ^{0}F colder than it is. This effect is similar to a horticultural greenhouse, which uses glass to trap the sun's energy as heat, hence the term greenhouse effect.

Many trace gases in the atmosphere trap the Earth's re-radiated heat and thus act as greenhouse gases. The ones that have the most effect are water vapor (H_2O), carbon dioxide (CO_2), ozone depleting compounds (ODCs, primarily chlorofluorocarbons (CFCs)), methane (CH_4), and nitrous oxide (N_2O). Water is very abundant in the atmosphere (for a trace gas) and occurs naturally in many forms, including clouds, fog, rain, snow, and humidity. Massive amounts of water are naturally cycling through the atmosphere every day. Human activity contributes some water vapor to the atmosphere (primarily from the burning of fossil fuels), but the amount of water vapor from human activity is minuscule compared to the amount of the water cycled through the atmosphere every day. Thus, water vapor is not included in this greenhouse gas emission inventory.

Carbon dioxide is the primary anthropogenic (human-caused) greenhouse gas, although it is also naturally occurring. Scientists estimate that CO_2 is responsible for 68 percent of the U.S. contribution to global warming (USEPA, 1992). By analyzing air bubbles trapped in glacial ice, scientists have determined that carbon dioxide concentrations in the atmosphere have remained relatively stable at about 280 ppm (parts per million) over the several thousand years. But, during the last 200 years or so (i.e., since the beginning of the industrial revolution) CO_2 concentrations have increased by about 25 percent up to about 350 ppm. This increase in CO_2 concentrations is due primarily to the burning of fossil fuels by humans to produce energy. Part of the increase is also due to destruction of forests (which store carbons) to create farmland and urban development.

Chlorofluorocarbons (CFCs) are also significant contributors to global warming. It is estimated that they are responsible for about 24 percent of the U.S. contribution to global warming (USEPA, 1992). CFCs are entirely human-made; there are no biogenic (natural) sources. CFCs are thousands of times more heat absorbing than CO_2, and they remain in the atmosphere for 65 to 400 years before they are finally destroyed by ultraviolet radiation in the stratosphere. They are used by industry for many purposes, including refrigerants, solvents for cleaning metal and electronic parts, and as foam blowing agents. CFCs also destroy ozone in the stratosphere, and, in this capacity, they make up the majority of a group of chemicals known as ozone depleting compounds (ODCs). The ODCs are carbon compounds containing chlorine, fluorine, and/or bromine, and almost all of them are greenhouse gases. The production and use of CFCs and other ODCs is being phased out to protect the ozone layer.

It has also been determined that ozone depletion results in atmospheric cooling, thus diminishing the importance of ODCs as greenhouse gases. The production of the commonly used CFCs is being phased out beginning in 1996 in the U.S., but existing stocks and the CFC replacements being developed will continue to contribute to greenhouse gas emissions for the years to come.

Methane is estimated to be responsible for about 5 percent of the U.S. contribution to global warming (USEPA, 1992). The major sources of methane are livestock, landfills, rice paddies, wetlands, coal mining, and leaks during natural gas production and distribution.

Nitrous oxide is estimated to be responsible for about 3 percent of the U.S. contribution to global warming (USEPA, 1992). It is important to note that nitrous oxide (N_2O) is a completely different gas than nitrogen oxides (NO_x = NO and NO_2). These gases are often confused with one another, but they have different properties and play different roles in the atmosphere. The main sources of N_2O are the breakdowns of nitrogen fertilizers and the combustion of gasoline in automobiles. Some N_2O is also produced by burning of fossil fuels in industrial boilers.

A number of other trace gases also contribute to global warming, but not as much as the gases discussed above. These include nitrogen oxides (NO_x), carbon monoxide (CO), ozone (O_3), carbon tetrachloride (CCl_4), and other chlorinated organics, and a number of volatile organic compounds.

Greenhouse gases (especially carbons) are constantly cycling through the environment and are temporarily stored in various parts of the environment as they are cycling. The major compounds of the environment through which these gases cycle are called reservoirs because they store huge amounts of carbon and other materials. The main carbon reservoirs are the biospheres (including plants, animals, and soils), the oceans, and the atmosphere. Large amounts of carbon move between the reservoirs every year, and these are called carbon fluxes. The carbon fluxes make up the natural carbon cycles which are so important for the life on Earth. These cycles tend to be steady state so that the amount of each gas in each compartment of the environment tends to stay fairly constant while large amounts of material are continuously cycling. Thus, for example, the concentration of carbon dioxide in the atmosphere has been fairly constant for thousands of years. But for the past two hundred years human activities have caused the concentrations of the carbon dioxide in the atmosphere to increase significantly.

The atmosphere is the greenhouse gas reservoir of major interest for global warming. When viewed from this perspective, greenhouse gas sources are activities or processes that increase the amount of greenhouse gases in the atmosphere. One major greenhouse gas source is the burning of fossil fuels, which emits large amounts of carbon dioxide into the atmosphere. Activities or processes that remove greenhouse gases from the atmosphere are called greenhouse gas sinks. An example is photosynthesis, whereby plants remove carbon dioxide from the atmosphere to produce carbohydrates that become plant tissue.

Carbon dioxide concentrations in the atmosphere are expected to double from their pre-industrial levels by the middle of the next century. Scientists are using very large and complex computer models, called global circulation models, to estimate the effect of the increases in carbon dioxide and other greenhouse gases on the global climate. These models predict that a doubling of greenhouse gas concentrations will cause average global temperature to increase by 2^o to 8^o F by the end of the next century (WDNR, 1991).

Increases in global temperature of the magnitude predicted by the global circulation model could cause changes in the climate around the world which may have serious consequences for Maryland and other regions. Some of the potential impacts of climate change include; increasing sea levels and coastal flooding, change in precipitation patterns which could lead to droughts or floods, migration of forests, changes in aquatic ecosystems, disruption of some agricultural practices, more frequent droughts, and higher frequency of storms and severe weather.

There is much uncertainty about the magnitude of potential future global temperature increases. Global circulation models used to predict these future temperature increases attempt to simulate a very complex global climate system. They do not take all factors into account. For example, they do not account for the effect of clouds or ocean circulation on future climate. The models also have not been totally successful at reproducing the temperature changes experienced over the past 100 years using the measured increases in atmospheric CO_2 concentrations. All of the models predict increases in global average temperature, but they differ in the magnitude and timing of their predicted temperature increases. Also, since the models are global in scope, they cannot predict changes in local or a regional climate. Predicted climate changes for Maryland and other small regions must be inferred from the changes in temperature and precipitation predicted by the models for larger areas.

2. Study Objectives

Because climate change could have serious consequences for Maryland, the Maryland Department of the Environment, the Maryland Department of Natural Resources, and other state agencies have begun to address the issue. As U.S., and international policies on global climate change continue to evolve, it is important to continue expanding our information on greenhouse gas emissions and the costs of the various measures available for reducing those emissions.

3. Study Methodology

The primary methodologies used in this study to estimate anthropogenic greenhouse gas emissions are from the U.S. Environmental Protection Agency's *States Workbook: Methodologies for Estimating Greenhouse Gas Emissions* (USEPA, 1992). The EPA workbook is based on the Organization for Economic Cooperation and Development (OECD) guide for estimating greenhouse gas emissions (OECD/OCDE, 1991) which is being used by the U.S. and other countries to estimate greenhouse gas emissions under the United Nations Framework Convention on Climate Change. One of the stipulations in accepting the EPA grant to do this study was that we use and evaluate the methodologies in the workbook. For some emission source categories, other methods were used to estimate emissions when they were expected to yield more accurate results. These other methods were taken from various sources, primarily emission inventory studies done in California, Oregon, Washington, Wisconsin, and Canada, as well as relevant published academic studies or other methodologies previously used by MDE. A comparison of the EPA workbook methodologies and the methodologies used in this study to estimate greenhouse gas emission is included in Section IV of this report. The discussion in section IV includes recommendations on how to improve the EPA workbook methodologies.

This is a comprehensive emission inventory and includes all of the emission source categories we could identify for Maryland. It includes ten of the eleven emission source categories covered by the EPA workbook. The one EPA category omitted does not occur in Maryland. This is flooded rice fields. Also, several other source categories not covered in the EPA workbook were added. These include waste incineration and lime processing. All of the emission source categories considered in this study are listed in Table 1.

This study focuses on anthropogenic (human-caused) emissions of the four main greenhouse gases. These gases are carbon dioxide, methane, nitrous oxide, and ozone depleting compounds (ODCs). This is only one part of much bigger picture that includes anthropogenic and biogenic (natural) sources and sinks of these gases. We have attempted to look at this bigger picture by constructing a rough greenhouse gas budget for Maryland. The greenhouse gas budget focuses primarily on the carbon because carbon dioxide is the major anthropogenic contributor to global warming. Though the carbon budget makes up a minor part of this study, it is included to provide a broader perspective, to examine the cycling of greenhouse gases through the environment, and to provide an understanding of how the anthropogenic emissions are related to the big picture. We are primarily interested in the anthropogenic greenhouse gas emissions because they contribute to the buildup of greenhouse gases in the atmosphere, and they can be managed. Current specific understanding is that biogenic emissions are in a natural balance and do not contribute to this buildup.

Table 1. Greenhouse Gas Emissions and Sources Considered in the Maryland Greenhouse Gas Inventory

CATEGORY	Greenhouse Gases			
	CO_2	CH_4	N_2O	ODC
Biomass and Fossil Fuels				
Stationary Combustion of Fossil Fuels	✓	✓	✓	
Mobile combustion of Fossil Fuels	✓	✓	✓	
Stationary Combustion of Biomass Fuels	✓	✓	✓	
Fuel Production, Refining, Transport	✓	✓	✓	
Power Plant Construction	❍	❍	❍	
Production Processes				
Lime Processing	✓			
Processes/End Use of Ozone Depleter				✓
Other Production Processes				
Furnace Electrode Manfct.	_	_		
Foundries (Iron & Steel)	_	_		
Glass			_	
N-Fertilizer			_	
Bakeries	_			
Cheese	_			
Malt/Yeast	_			
Wine	_			
Beer	_			
Coke Prod./Colliery	_	_		
Primary Metal Prod (misc.)	_			
Secondary Metal Prod (misc.)	_			
Aluminum Production	_		_	_
Calcium Carbide Production	_			
Castable Refractory Production	_			
Nitric Acid			_	
Ammonia		_		
Ethylene		_		
Adipic Acid			_	
Acrylonitrile	_			
Spirits	_			

CATEGORY	Greenhouse Gases			
	CO_2	CH_4	N_2O	ODC
Agriculture and Livestock Production				
Domestic Animals	^	✓		
Animal Manure Management	^	✓		
Fertilizer and Lime Application				
Lime Application	✓			
Fertilizer Application			✓	
Flooded Cultivated Fields		_		
Waste Disposal, Treatment, and Recovery				
Waste Incineration	✓	✓		
On-Site Infectious Waste Incineration	✓	✓		
Open Burning of Rural Waste	✓			
Open Burning of Yard Waste	✓			
Open Burning of Agricultural Crop Residues	_			
Sewage Treatment Plants	_	_	_	
Land-Use Change				
Forest Conversion	✓	^	✓	
Wetland Drainage	✓	✓	^	
Pasture Conversion to Cultivated Land	✓	^	^	
Non-forest Land Development	✓	^	^	
Forests: Fires and Logging	C	C	C	
Cultivated Soils	E	S		

✓ Greenhouse gas emissions produced by this source and accounted for in table 3, *Summary of Maryland 1990 Greenhouse Gas Emissions.*
❍ Greenhouse gas emissions produced by this source and estimated in the text, but not included in Maryland emissions estimates.
_ Greenhouse gas emissions produced by this source and noted in the text but not estimated nor included in the Maryland emissions estimates.
^ Greenhouse gas emissions produced by this source and not addressed nor accounted for in this study, see section III.
C Biogenic cycling, see Section III
E Net emissions, see Section III, no methodology
S Net sinks, see Section III, no methodology

Some anthropogenic sources are not included in this emission inventory because their emissions are cycling through the natural carbon cycle and do not contribute to the buildup of greenhouse gases in the atmosphere. One example of this type of source is sustainable logging, because, for each tree cut down, at least one new tree is planted to replace it. Thus, the carbon released from the logged trees is taken out of the atmosphere by the growing replacement trees in a continual cycle. Another example is forest fires. Burned forest generally becomes forest again after a number of years, so the carbon released by the forest fire is eventually captured by the new forest.

In this study, greenhouse gas emissions were estimated for a 1990 base year, which is the most recent year for which most activity data are readily available. A1990 base year is also used for ozone precursor inventories developed by the states. Using 1990 as the base year for the GHG inventory allows us to evaluate GHG reductions contributed by programs designed to control ozone. The National Energy Policy Act of 1992 provides for voluntary reductions of greenhouse gas emissions using emissions for the period 1987 through 1990 as the basis of emission reductions. For this study, we set out to estimate greenhouse gas emissions for those four years, but it was not feasible to do this for all emission source categories.

4. Global Warming Potential

In this study, we have estimated emissions for several different greenhouse gases: carbon dioxide, methane, nitrous oxide and ozone depleting compounds (ODCs). Each of these gases has different chemical and physical properties and differing contributions to global warming. In other words, one molecule or one ton of methane or nitrous oxide will have a different influence on global temperature than will the same amount of carbon dioxide. In order to be able to compare the effect of the various greenhouse gases on global warming, the concept of global warming potential has been developed.

The concept of global warming potential (GWP) is based on the relative radiative forcing effect of the concurrent emission into the atmosphere of an equal quantity of CO_2 and any other greenhouse gas. Since CO_2 is the major greenhouse gas of concern, it is assigned a GWP of one, GWP for all other greenhouse gases are calculated relative to CO_2. There are various ways to calculate GWP, taking into account various direct and indirect effects of the greenhouse gases. The GWP used in this study are taken from the EPA *States Workbook* (USEPA, 1992) and are based on two main factors: the instantaneous radiative forcing effect, and the atmospheric lifetime of each greenhouse gas. The instantaneous radiative forcing effect refers to the relative amount of the heat captured by a given amount of any greenhouse gas. For example, one CFC molecule can capture several thousand times as much heat as a CO_2 molecule. In general, the other greenhouse gases have a much stronger instantaneous radiative forcing effect than does CO_2, but CO_2 has a longer atmospheric lifetime and a slower decay rate than most other greenhouse gases (USEPA, 1992).

Because of the different atmospheric lifetimes of the various greenhouse gases, the magnitudes of the GWP vary with the length of the time horizon of the analysis. For example, the GWP for methane for a 100-year time horizon is estimated to be 11, while it is estimated to be four for a horizon of 500 years. The difference is due to the relatively shorter atmospheric lifetime of methane compared to carbon dioxide.

Table 2 shows the GWP for methane and nitrous oxide for various time horizons. In this study we used the GWP for the 100-year time horizon, as recommended by EPA in the *States Workbook* (USEPA, 1992). The estimated methane and nitrous oxide emissions were multiplied by the GWP to obtain equivalent CO_2 emissions. The GWP used for the ozone depleting compounds are given in Table 2.2. The ODC GWP were obtained from the EPA *States Workbook* (USEPA, 1992) and from *Emissions of Greenhouse Gases in the United States 1985 - 1990 (USDOE, 1993).*

Table 2. Global Warming Potential of Greenhouse Gases

Greenhouse Gas	Atmospheric Lifetime (years)	GWP Over a 20 Year Time Horizon	GWP Over a 100 Year Time Horizon	GWP Over a 500 Year Time Horizon
Carbon Dioxide	120	1	1	1
Methane	10.5	35	11	4
Nitrous Oxide	132	260	270	170

5. Report Organization and Review

Since the focus of this study is on anthropogenic greenhouse gas emission sources, the majority of the reports present the methodologies and results for the emission estimates for those sources. They are covered in Section I: Anthropogenic Sources. The various anthropogenic sources are grouped into five main source groups, each of which is covered in a different subsection of section I. The five subsections are: 1)Fuel Consumption (fossil and biomass), 2)Production Processes, 3)Agriculture and Livestock Production, 4)Waste Disposal, Treatment, and Recovery, and 5)Land Use Changes. Section II: Maryland Carbon Budget, covers anthropogenic sinks, biogenic sources and sinks, and the Maryland carbon budget summary, which ties together all of the sources and sinks. In other words, Section II presents the big picture in order to put everything into perspective. Section III: Anthropogenic Sources and Sinks Not Included in the Maryland Inventory, discusses the greenhouse gas emission sources which were not included in this inventory. The appendices contain tables of detailed emissions data or emissions estimates for several emission source categories, including landfills, motor vehicles, animal manure, and stationary fossil fuel combustion sources.

References

OECD/OCDE, 1991. *Estimation of Greenhouse Gas Emissions and Sinks, Final Report from the OECD Experts Meeting, 18-21 February 1991,* Prepared for the Intergovernmental Panel on Climate Change.

U.S. Environmental Protection Agency (USEPA), 1992. *States Workbook; Methodologies for Estimating Greenhouse Gas Emissions*, EPA-230-B-92-002. Office of Policy, Planning and Evaluation, November 1992.

U.S. Department of Energy (USDOE), 1993. *Emissions of Greenhouse Gases in the United States, 1985-1990*, DOE/EIA-0573, Energy Information Administration, September 1993.

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RESULTS

1. Summary of Results

Table 3 and Figures 1 through 6 present greenhouse gas emissions for all of the gases and the anthropogenic emission source categories in Maryland. A total of about 107 million tons of greenhouse gases (CO_2 equivalent) were emitted as a result of activity in Maryland in 1990.

Carbon dioxide accounts for the majority of the greenhouse gas emissions in Maryland (66%). Ozone depleting compounds (mainly CFCs) account for 29%, methane accounts for 3% and nitrous oxide accounts for 2% of greenhouse gas emissions (Figure 1).

Fossil fuel combustion is the major source of Maryland's greenhouse gas emissions, accounting for 65% (69 million tons) of total emissions in 1990 (Figure 2). Maryland relies heavily on imported fossil fuels for its energy supply. Liquid petroleum products (gasoline, diesel fuel, oil, kerosene, jet fuel, and liquefied petroleum gas) account for the largest portion of Maryland's greenhouse gas emissions, emitting 42 million tons in 1990 (Figure 4), or 38% of total emissions. Most petroleum used in Maryland is burned in motor vehicles. Thus, the transportation sector is the major source of greenhouse gas emissions from fossil fuel combustion in Maryland, emitting 24.5 million tons in 1990 or 23% of total 1990 emissions. Production processes are another major source of greenhouse gas emissions in Maryland, emitting 33 million tons in 1990, which is 31% of total Maryland greenhouse gas emissions (Figure 3).

Coal is the fossil fuel that is the largest single source category of greenhouse gas emissions in Maryland (20 million tons (Figure 4), at 18% of total emissions in 1990). About 77% of Maryland's electricity is generated by coal burning power plants, and coal is also burned at a number of industrial facilities around the state. This explains why electric utilities are the major source of greenhouse gas emissions in Maryland, emitting 21 million tons in 1990, which is 19% of total Maryland greenhouse gas emissions (Figure 3).

Natural gas is the other major fossil fuel burned in Maryland, primarily in the industrial, residential, and commercial/institutional sectors. In 1990, about 10 million tons of greenhouse gases were emitted from the combustion of natural gas (Figure 4), which represents 9% of total greenhouse gas emissions.

Emissions of ozone depleting compounds (primarily CFCs) by various industrial processes and product end uses is another major source of greenhouse gas emissions in Maryland. This source is estimated to have emitted about 31 million tons of greenhouse gases in 1990, which represents about 29% of total 1990 emissions (Figure 1). This is a very rough estimate, however, since it was done by multiplying the total emissions for the U.S. by the fraction of the U.S. population living in Maryland.

Total Maryland methane emissions in 1990 are estimated to be about 243,000 tons, which translates into about three million tons of CO_2-equivalents. The major source of Maryland's methane emissions is landfills, which accounted for 60% of methane emissions (1.5% of total greenhouse gas emissions). Another major source of Maryland's methane emissions is domestic animals (livestock), which accounted for 25% of methane emissions when emissions from manure are included (Figure 5). The overwhelming majority (99%) of the domestic animal emissions come from cows. When compared with all other greenhouse gas emission sources on a CO_2 equivalent basis, domestic animals (including manure management) contribute about 0.6% of equivalent CO_2 emissions. Fossil fuel consumption accounted for 2% of methane emissions, and coal mining accounted for 13% of methane emissions.

Fossil fuel production and distribution systems account for the majority (87%) of Maryland's fossil fuel methane emissions, while fossil fuel combustion within Maryland produces a very small amount of methane. Most of the methane emissions associated with fossil fuel consumption occur from coal mining.

Maryland's nitrous oxide emissions in 1990 are estimated to be about 7,000 tons, which is equivalent to about two million tons of CO_2. The two main sources of Maryland's nitrous oxide emissions are fertilizer use on farms, which accounted for 54% of N_2O emissions (1% of total greenhouse gas emissions), and fossil fuel combustion for transportation, which accounted for 36% of N_2O emissions, but less than 1% of total greenhouse gas emissions (Figure 6). Stationary fossil fuel combustion contributed another 9% of N_2O emissions, and the one remaining source (land use change) contributed 2%. The N_2O emission estimates are not complete because N_2O emission factors are still not available for some emission source categories.

The accuracy of the anthropogenic greenhouse gas emissions estimates in this study varies greatly from category to category. Estimated carbon dioxide emissions from fossil fuel combustion at power plants and other industrial sources are fairly accurate because detailed and reliable records of the amount of fuel burned are available, and the calculation of CO_2 emissions from fossil fuel combustion is straightforward. The estimate of statewide CO_2 emissions from the transportation sector are probably less accurate since estimates of the amount of transportation fuel consumed in the state are derived from gasoline tax records rather than measured directly. Allocation of transportation sector emissions by vehicle type, age, and county using vehicle miles traveled (VMT) data also affects the accuracy of emission estimates. The accuracy of the emission estimates for such categories as domestic animals, fertilizer use, and land use change is even lower since activity data are sketchy and emission factors are not well established. While the accuracy of the emission estimates varies from category to category, the emission estimates for each category are based on the best available information.

2. Recommendations for Further Research

This study was funded through an EPA grant of $25,000. With additional resources this inventory could be improved through the acquisition or development of better activity data, better emission factors, or improved emission estimation methodologies. In this section, areas where improvements could be made are identified. The following are areas of this study where further research and analysis would improve the results of this greenhouse gas emission inventory.

1. Fuel combustion emission estimates could be improved by calculating fuel combustion emissions for individual emission sources by county.

2. Much more work could be done on the Maryland carbon budget, including:

   a. Quantification of anthropogenic sinks (e.g., carbon stored in structures) and
   b. Quantification of biogenic reservoirs (carbon stored in forests, lakes, soils, etc.).

3. Electric utility methane and nitrous oxide emission factors could be examined to determine the best and most accurate factors. Several different emission factors for these gases have been used by various electric utilities, USEPA, and other greenhouse gas emission studies.

4. Greenhouse gas emissions from land use changes could be updated and improved by using more up-to-date information on land use changes which will be published with the next one to two years. The current emissions were estimated using data for periods before the 1990 base year because more recent data were not available.

5. Emissions could be estimated for additional source categories not included in this emission inventory. These sources are discussed in Section III in this report and include categories such as wastewater treatment plants and septic systems.

6. The contribution of other air pollutants that act as direct or indirect greenhouse gases could be determined. These include carbon monoxide, nitrogen oxides, and volatile organic compounds. These are also discussed in Section III.

7. The accuracy of mobile source emission estimates could be improved if better activity data (fuel use, vehicle miles traveled) could be obtained or developed.

8. Emissions associated with the production and transport of products other than fossil fuels (e.g. rice, adipic acid) could eventually be included.

9. The estimate of ozone depleting compound emissions could be improved by using a bottom-up approach (i.e. surveying production and use in Maryland) to replace the top-down estimate used (apportioning national emissions to Maryland by population fraction).

TABLE 3 SUMMARY OF MARYLAND 1990 GREENHOUSE GAS EMISSIONS (thousands of tons)

Global Warming Potential **(Over 100-year Time Horizon)** **Emission Source Category**	**1** **CO2**	**CH4**	**11** **CH4 as CO2- equiv.**	**N2O**	**270** **N2O as CO2- equiv.**	**ODC as CO2- equiv.**	**Total CO2- equiv.**	**% of CO2- equiv.**
Fossil Fuel Consumption	**68,282**	**5**	**51**	**3.16**	**853**	**-**	**69,187**	**64.58%**
Commercial/Institutional Sector	2,933	0	1	0.49	132		3,066	2.86%
Industrial Manufacturing Sector	14,108	0	2	-	0		14,111	13.17%
Residential Sector	6,728	0	5	-	0		6,733	6.29%
Utilities Sector	20,722	0	1	0.14	38		20,761	19.38%
Transportation Sector	23,791	4	42	2.53	683		24,516	22.89%
			0		0			
			0		0			
Production Processes	**972**	**32**	**353**	**0.00**	**0**	**31,406**	**32,731**	**30.55%**
Lime Processing	972	-	-	-	-	-	972	0.91%
Ozone Depleting Compounds (ODC)	-	-	-	-	-	31,406	31,406	29.32%
Coal Mining	-	32	353	-	-		353	0.33%
Other Processes	-	-	-	-	-	-	0	
Agriculture and Livestock Production	**3**	**60**	**664**	**3.82**	**1,031**	**0**	**1,698**	**1.58%**
Domesticated Animals	-	24	263	-	-	-	263	0.25%
Animal Manure Management	-	36	401	-	-	-	401	0.37%
Fertilizer and Lime Land Application	3	-	-	3.82	1,031	-	1,033	0.96%
Waste Disposal, Treatment, & Recovery	**400**	**146**	**1,602**	**0.00**	**0**	**0**	**2,001**	**1.87%**
Landfills	400	146	1,602	-	-	-	2,001	1.87%
Open Burning of Agricultural Crop Residues	-	-	-	-	-	-	-	
Land Use Changes	**1,475**	**0**	**0**	**0.13**	**35**	**0**	**1,511**	**1.41%**
Forest Conversion	1,339	-	-	0.13	35	-	1,374	1.28%
Drainage of Wetlands	-	-	-	-	-	-	-	
Other	137	-	-	-	-	-	137	0.13%
Total Emissions	**71,132**	**243**	**2,670**	**7.11**	**1,919**	**31,406**	**107,127**	**100**
% Global Warming Potential	66%		2%		2%	29%	(1000 tons)	

Figure 1. Maryland 1990 Greenhouse Gas Emissions
(million Tons, CO2 equivalent)

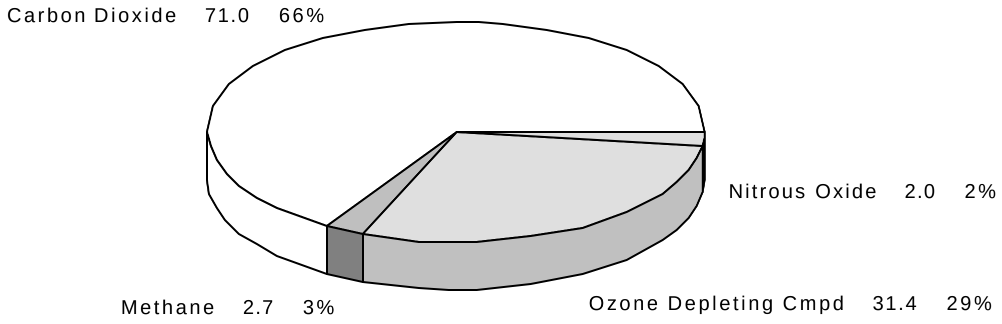


Figure 2. Maryland 1990 Greenhouse Gas Emissions by Source Category
(million Tons, CO2 equivalent)

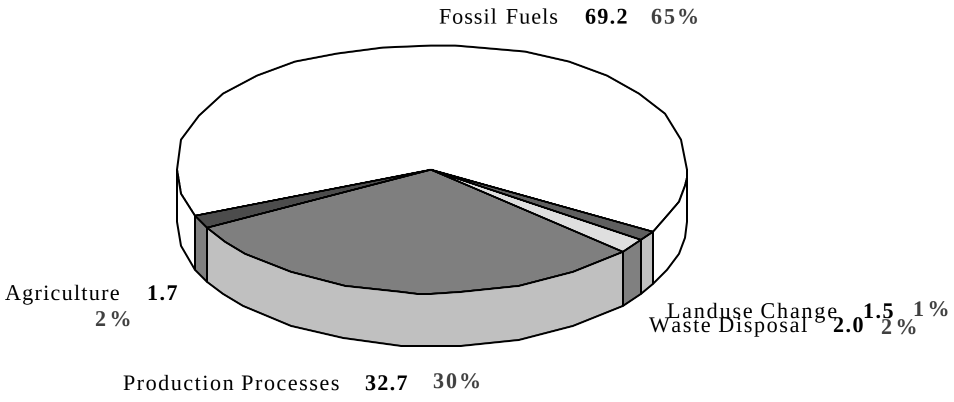


Figure 3. Maryland 1990 Greenhouse Gas Emissions by Source Category and Economic Sector

(million Tons, CO2 equivalent)

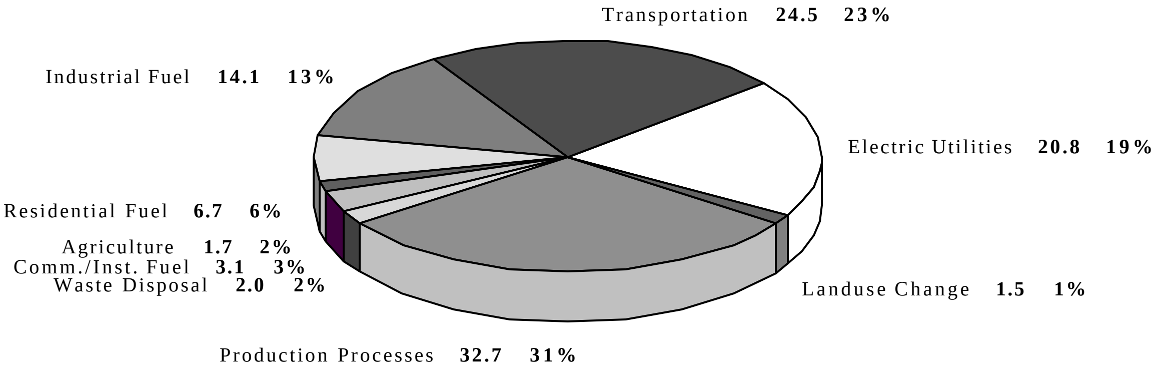


Figure 4. Maryland 1990 Greenhouse Gas Emissions by Source Category and Fuel Type

(Million Tons, CO2 Equivalent)

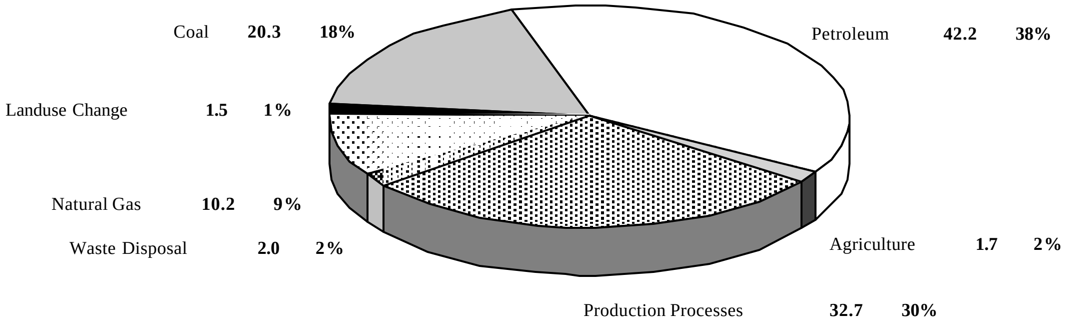


Figure 5. Maryland 1990 Methane Emissions
(Thousand Tons, CH4)

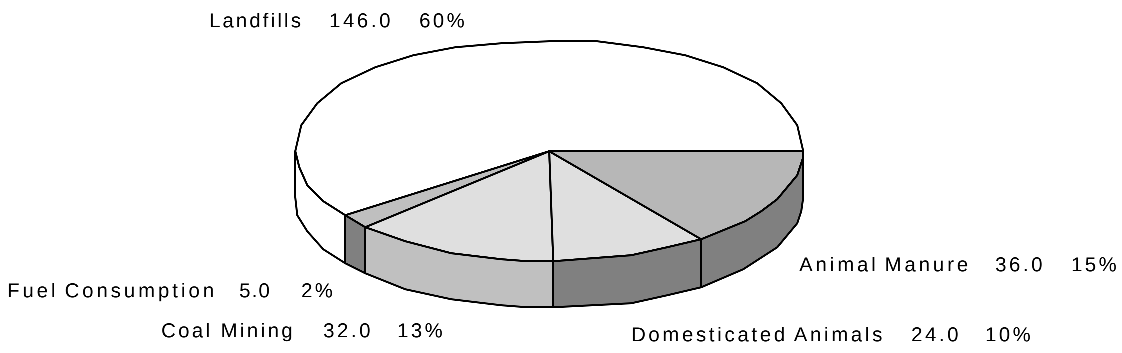
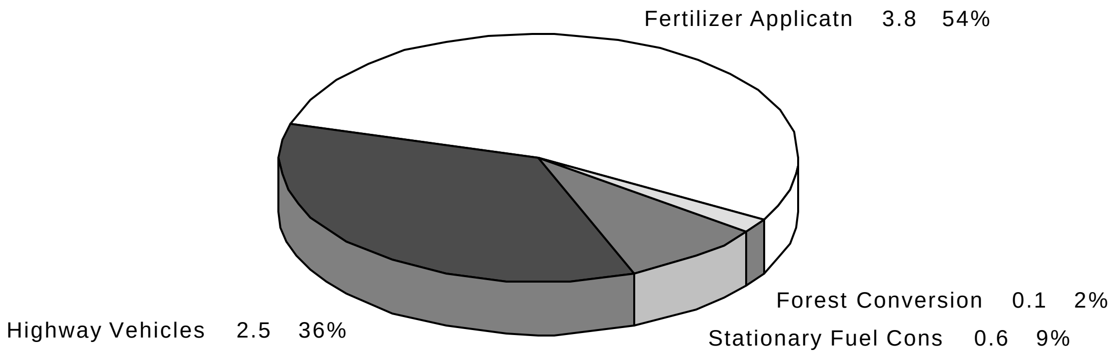


Figure 6. Maryland 1990 Nitrous Oxide Emissions
(Thousand Tons, N2O)



Note:- Due to rounding, percentages do not add up to be 100%

References

U.S., 1993. *Estimation of Greenhouse Gas Emissions and Sinks for the United States 1990,* Review draft, June 21, 1993.

U.S. Environmental Protection Agency (USEPA), 1992. *States Workbook; Methodologies for Estimating Greenhouse Gas Emissions*, EPA-230-B-92-002. Office of Policy, Planning and Evaluation, November 1992.

I. ANTHROPOGENIC SOURCES

1. FUEL CONSUMPTION

To quantify and compare greenhouse gas emissions from activities consuming fossil fuels in Maryland, it is necessary to consider the range of activities that are connected with providing fossil fuel power. Non-energy fossil fuel (i.e., lubricants, motor oil, chemical feedstock, etc.) are considered under Production Processes, Section 2.4.

A fuel cycle includes the extraction, processing, transport, and end use of a fuel, such as natural gas or coal. Emissions are generated during each step of this process, and the steps can be grouped into categories applicable to all fossil fuels:

1. Extraction of the fuel
2. Fuel processing/refining (including transport to processing facilities)
3. Transportation of fuel to end-use facilities
4. Construction of power plant facilities
5. Combustion of fuel

Maryland, like most other states, relies on a variety of fossil fuels to satisfy its energy needs--including several grades of coal, natural gas, and a wide range of petroleum products. All of the fossil fuels consumed in Maryland are not produced in Maryland, some are imported from outside the State. In addition, Maryland generates power not only through conventional fossil fuel power plants, but also through nuclear plants.

For each of these fuel types and corresponding power generation processes, some of the emissions occur within the state of Maryland while other emissions occur in the other states and countries where the fuel is extracted, processed and transported. To enable environmentally-conscious energy planning and policy decisions, it is important to consider all of all these emissions, regardless of where they occur. The purpose of these Section is to facilitate that decision-making process by estimating the emissions associated with Maryland fossil fuel use in 1990.

Sections 1.1 and 1.2 provide estimates of the emissions associated with the combustion of the fuels. This is the traditional way of viewing fuel-related emissions, and is divided between stationary and mobile combustion.

1.1 Stationary Fossil Fuel and Biomass Combustion

The combustion of fossil fuels is the largest single contributor of anthropogenic greenhouse gases, especially carbon dioxide (CO_2). Within the US, 58% of the CO_2 derived from fossil fuel combustion is attributable to stationary sources -- electric utilities, manufacturing, and residential and commercial use (Amann, 1992). In addition to CO_2, stationary fuel combustion also emits methane (CH_4) and nitrous oxide (N_2O), as well as criteria pollutants. Criteria pollutants are air pollutants for which EPA has established health-based ambient air quality standards (SO_2, NO_2, CO, inhalable particulates, and ozone). Estimates of summertime average daily of the ozone precursor emissions in Maryland are included in Section III of this study.

The amount of CO_2 emitted is directly related to the amount of fuel consumed, the fraction of the fuel that is oxidized, and the carbon content of the fuel (USEPA, 1992). Thus, CO_2 emissions depend predominately upon the characteristics of the fuel rather than on the particular combustion process. Emissions of non-CO_2 greenhouse gases (i.e. CH_4 and N_2O) depend on the fuel type, the combustion process technology and efficiency, and the control devices in place (USEPA, 1992).

Thus, non-CO_2 greenhouse gas emissions vary by fuel type and boiler/combustor type. Since activities in the same economic sector (industrial, electric utility, commercial/institutional and residential) use similar boiler/combustor types, emission factors are based on economic sector to account for the variation of boiler/combustor types. For this study, emissions for each greenhouse gas were calculated separately by fuel type and economic sector.

Table 1.1 Fuel Types Used in Each Economic Sector in Maryland

Fuel Type **Economic Sector**	**Coal**	**Distillate Oil**	**Residual Oil**	**Natural Gas**	**Liquefied Petroleum Gas**	**Biomass**	**Kerosene**
Electric Utilities	✓	✓	✓	✓			
Industrial	✓	✓	✓	✓	✓		✓
Commercial/institutional	✓	✓	✓	✓	✓		✓
Residential	✓	✓		✓	✓	✓	✓

Electric utilities are treated as <u>point sources</u>, i.e. all of their emissions are emitted from a relatively small number of smokestacks (emission points). The emissions are calculated "bottom up" based on actual fuel use from the Department's air emissions inventory and emission factors provided in the EPA *States Workbook* (USEPA, 1992). These emissions are calculated for each individual facility.

Industrial, commercial/institutional, and residential sector sources were treated as <u>area sources</u> and emissions were calculated "top downward" for a class of sources in a large area (e.g. state, county, city). Emissions from area source fuel combustion are determined based on quantity of fuel used statewide, summarized by fuel type and economic sector. These emissions are apportioned to the county level based on the county to state ratio of some appropriate measure, such as employment or population.

This section covers only the emissions attributable to stationary fuel combustion. Emissions attributable to transportation, agriculture, and other mobile fuel combustion are contained in Section 1.2, "Mobile Fossil Fuel Combustion".

General Methodology

A. Carbon Dioxide

CO_2 emissions are estimated for each fuel type in a three-step process.

Step 1: Determine the consumption of energy in 1990 (Q_f) by fossil fuel type.

For biomass (wood), consumption is measured in pounds; for all other fuels, it is measured in millions of British Thermal Units (BTU's). All of the fuel consumption data were obtained from the U. S. DOE/EIA State Energy Data Report, Consumption estimates, 1960-1990.

Step 2: Multiply the consumption, Q_f, by the average carbon emission coefficient of the fuel,EF_f. Divide by 2000 to get tons of total carbon emitted per fuel.

The carbon emission coefficients for each fuel are given in Chapter 1 of the EPA *States Workbook* (USEPA, 1992). For biomass (wood), this figure is given as a percent; for all other fuels, it is given as pounds of carbon per million BTU.

Step 3: Multiply by the oxidation factor (OxFac) to calculate total tons of carbon oxidized. Multiply this by 44 tons CO_2/12 ton C to get tons of CO_2 emitted.

Oxidation factors are provided in Chapter 1, of the EPA *States Workbook* (USEPA, 1992). For biomass (wood), the oxidation factor is 0.90; for all other fuels, it is 0.99. The oxidation factor is the fraction of the carbon in the fuel which is oxidized during combustion to form carbon dioxide.

The formula for calculating CO_2 emissions can be written as

$$CO_2 \text{ emissions (tons)} = Q_f * Ef_f * OxFac / 2000(\text{ton/lbs.}) * 44CO_2 / 12C$$

B. Methane and Nitrous Oxide

Methane and nitrous oxide emissions are dependent on the combustion process and emission factors vary for different sectors and for different combustion technologies within the same sector. Chapter D-12 of the EPA *States Workbook* (USEPA, 1992) gives emission factors (where available) for a number of different combustion technologies for each of the sectors. The general formula used to calculate emissions are:

$$CH_4 \text{ or } N_2O \text{ emissions} = Q_f * EF_{fj} * 1 \text{ ton}/2000 \text{ lbs}$$

Where: Q_f = quantity of fuel type f in million BTU
Ef_{fj} = emission factor for fuel type f in combustion process j (lbs/million BTU)

C. Other Factors and Conversions:

Natural gas and wood combustion data require conversion from British Thermal Units (BTU). The heat content of fuels used for calculation of emissions from the residential, commercial/institutional, and industrial sectors are below. Utility emissions are calculated from heat contents reported in the ARMA Air Emissions Inventory.

Natural Gas:	1,021 MMBTU per million cubic feet
wood:	11.3 MMBTU per ton

Commercial/Institutional Sector

Methodology

The SIC code is the Standard Industrial Classification code designating specific manufacturing activities. The commercial/institutional sector is defined as SIC 50-99.

The methodology for calculating greenhouse gas emissions is described under General Methodology in Section 1.1 of this report. The factors used in calculating CH_4 and N_2O emissions were taken from table D12-6 in the EPA *States Workbook* (USEPA, 1992).

Results

Fuel combustion in the commercial/institutional sector generated about three million tons of greenhouse gases in 1990. Two fuels are commonly used in Maryland in the commercial/ institutional sector, natural gas and distillate oil. These fuels generate the majority greenhouse gas emissions from this sector (Table 1.2). Natural gas combustion produced about 49% of emissions, distillate oil produced 33%, and all the rest of the fuels together generated the remaining 18%.

Table 1.2 1990 Maryland Commercial/Institutional Sector Greenhouse Gas Emissions from Fuel Combustion

Fuel	Total Commercial Energy Use MMBTU/Yr..	Oxidized Fraction	Greenhouse Gas Emission Factors (Lbs../MMBTU)			Greenhouse Gas Emissions (Tons)		
			CO_2-C	CH_4	N_2O	CO_2	CH_4	N_2O
Gasoline	1,208,190	0.99	41.8	NE	NE	91,662	NE	NE
Distillate Oil	12,203,375	0.99	44.2	0.0013	0.0350	978,991	8	214
Residual Oil	3,470,424	0.99	46.6	0.0035	0.1030	293,525	6	179
LPG	770,112	0.99	38	NE	NE	53,115	NE	NE
Kerosene	272,160	0.99	43.1	NE	NE	21,290	NE	NE
Bituminous Coal & Lignite	503,005	0.99	59	0.0221	0.1310	53,864	6	33
Anthracite Coal	43,380	0.99	59.2	0.0221	0.1310	4,661	1	3
Natural Gas	24,720,000	0.99	32	0.0025	0.0050	1,435,738	31	62
Total	43,190,646					2,932,846	51	490

NE- Emission Factors are not established for this source.

Industrial/Manufacturing Sector

Methodology

The SIC code is the Standard Industrial Classification code designating specific manufacturing activities. The industrial sector is defined as SIC 20-39.

The methodology for calculating greenhouse gas emissions is described under General Methodology in Section 1.1 of this report. The factors used in calculating CH_4 and N_2O emissions were taken from table D12-3 in the EPA *States Workbook* (USEPA, 1992).

Results

The industrial sector in Maryland emitted a total of about 14 million tons of greenhouse gases in 1990. The major fuels burned by industries in Maryland are bituminous coal and natural gas, so these two fuels contributed the most to greenhouse gas emissions from this sector. Bituminous coal combustion generated 29% of industrial greenhouse gas emissions in Maryland while the combustion of natural gas produced 26% (Table 1.3). All of the other fuels together contributed 45% of greenhouse gas emissions from the industrial sector.

Table 1.3 1990 Maryland Industrial Sector Greenhouse Gas Emissions from Fuel Combustion

Fuel	Total Industrial Energy Use MMBTU/Yr.	Oxidized Fraction	Greenhouse Gas Emission Factors (Lbs./MMBTU)			Greenhouse Gas Emissions (Tons)		
			CO_2-C	CH_4	N_2O	CO_2	CH_4	N_2O
Gasoline	1,549,635	0.99	41.8	NE	NE	117,566	NE	NE
Distillate Oil	10,094,725	0.99	44.2	NE	NE	809,829	NE	NE
Residual Oil	7,751,871	0.99	46.6	0.0064	NE	655,645	25	NE
LPG	2,747,535	0.99	38	NE	NE	189,497	NE	NE
Kerosene	187,110	0.99	43.1	NE	NE	14,637	NE	NE
Asphalt and Road Oil	29,046,400	0.99	44.2	NE	NE	2,330,189	NE	NE
Lubricants	2,459,200	0.99	44.2	NE	NE	197,284	NE	NE
Other Liquids	24,905,200	0.99	44.2	NE	NE	1,997,970	NE	NE
Bituminous Coal & Lignite	38,141,655	0.99	59	0.0053	NE	4,084,399	101	NE
Anthracite Coal	21,690	0.99	59.2	0.0053	NE	2,331	0	NE
Natural Gas	63,860,000	0.99	32	0.0029	NE	3,708,989	93	NE
Total	180,765,021					14,108,337	219	---

NE- Emission Factors are not established for this source.

<u>Residential Sector</u>

Methodology

The methodology for calculating greenhouse gas emissions is described under General Methodology in Section 1.1 of this report. The factors used in calculating CH_4 and N_2O emissions were taken from table D12-5 in the EPA *States Workbook* (USEPA, 1992). The factor used for wood is for wood burning stoves.

Results

The residential sector in Maryland emitted a total of about 6.7 million tons of greenhouse gases in 1990. The major fuels burned by residential sector in Maryland are natural gas and distillate oil, so these two fuels contributed the most to greenhouse gas emissions from this sector. Natural gas combustion generated 59% of residential greenhouse gas emissions in Maryland while the combustion of distillate oil produced 30% (Table 1.4). All of the other fuels together contributed 11% of greenhouse gas emissions from the residential sector.

Table 1.4 1990 Maryland Residential Sector Greenhouse Gas Emissions from Fuel Combustion

Fuel	Total Residential Energy Use MMBTU/Yr. (lbs/yr.)	Oxidized Fraction	Greenhouse Gas Emission Factors (Lbs./MMBTU)			Greenhouse Gas Emissions (Tons)		
			CO_2-C	CH_4	N_2O	CO_2	CH_4	N_2O
Wood	3,464,976 (613,270,000)	0.90	0.27[1]	0.1640	NE	273,212	284	NE
Distillate Oil	24,954,300	0.99	44.2	0.0110	NE	2,001,909	137	NE
LPG	4,363,968	0.99	38	0.0024	NE	300,983	5	NE
Kerosene	2,182,950	0.99	43.1	NE	NE	170,765	NE	NE
Bituminous Coal & Lignite	260,175	0.99	59	NE	NE	27,861	NE	NE
Anthracite Coal	43,380	0.99	59.2	NE	NE	4,661	NE	NE
Natural Gas	67,980,000	0.99	32	0.0021	NE	3,948,278	71	NE
Total	103,249,749					6,727,668	498	---

[1] Represents fraction of carbon content by weight of wood (USEPA, 1992).

NE- Emission Factors are not established for this source.

Electric Utility Sector

Methodology

The methodology for calculating greenhouse gas emissions is described under General Methodology in Section 1.1 of this report. The factors used in calculating CH_4 and N_2O emissions were taken from table D12-2 in the EPA *States Workbook* (USEPA, 1992).

Results

The electric utility sector in Maryland emitted a total of about 20.7 million tons of greenhouse gases in 1990. The major fuel burned by the electric utility sector in Maryland is coal, so this fuel contributed the most to greenhouse gas emissions from this sector. Coal combustion generated 77% of electric utility sector greenhouse gas emissions in Maryland while the combustion of residual oil produced 16% (Table 1.5). All of the other fuels together contributed 7% of greenhouse gas emissions from the electric utility sector.

Table 1.5 1990 Maryland Utility Sector Greenhouse Gas Emissions from Fuel Combustion

Fuel	Total Utility Energy Use MMBTU/Yr.	Oxidized Fraction	Greenhouse Gas Emission Factors (Lbs./MMBTU)			Greenhouse Gas Emissions (Tons)		
			CO_2-C	CH_4	N_2O	CO_2	CH_4	N_2O
Distillate Oil	3,483,350	0.99	44.2	0.00007	NE	279,445	0.12	NE
Residual Oil	39,193,158	0.99	46.6	NE	NE	3,314,918	NE	NE
Bituminous Coal & Lignite	155,151,025	0.99	57	0.0013	0.0018	16,051,149	101	140
Natural Gas	18,540,000	0.99	32	0.0002	NE	1,076,803	2	NE
Total	216,367,533					20,722,315	103	140

1 Represents fraction of carbon content by weight of wood (USEPA, 1992).

NE- Emission Factors are not established for this source.

References

Amann, C.A., 1992. “The Passenger Car and the Greenhouse Effect,” *The International Journal of Environment and Pollution,* Vol. 13, No. 4.

U.S. Environmental Protection Agency (USEPA), 1992. *States Workbook; Methodologies for Estimating Greenhouse Gas Emissions*, EPA-230-B-92-002. Office of Policy, Planning and Evaluation.

U. S. DOE/EIA-0214(90), May 1992. State Energy Data Report, Consumption estimates, 1960-1990. U.S. Department of Energy, Energy Information Administration.

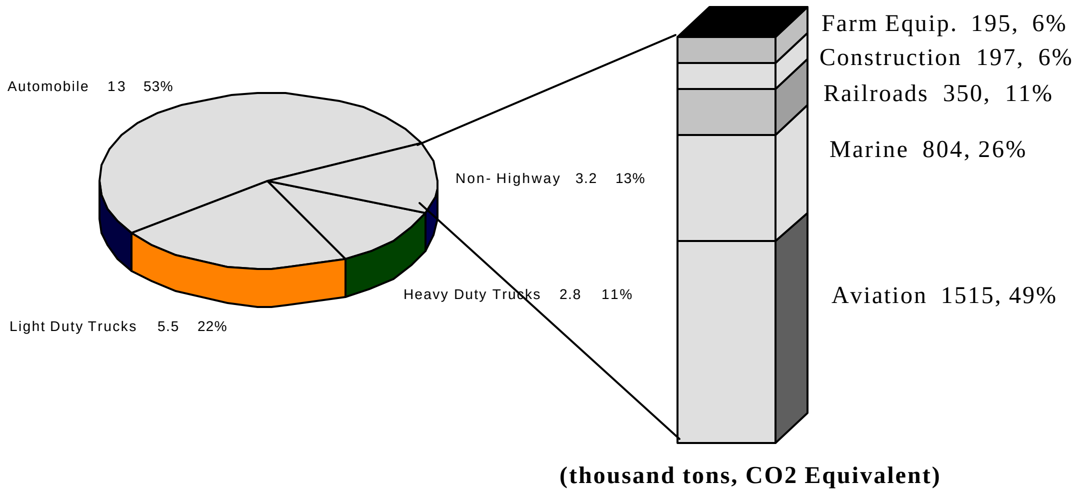
1.2 Mobile Fossil Fuel Combustion

This category includes greenhouse gas emissions from mobile sources (autos, trucks, forklifts, farm equipment, etc). In the summary table (Table 3) this category is referred to as the transportation sector. Emissions occur from the combustion of fossil fuels, where most of the fuel's carbon is emitted as CO_2 . Methane and nitrous oxide are also emitted from these sources. There are many factors that influence methane and nitrous oxide emission rates, including types of fuel consumed, vehicle type, extent of emission control equipment, vintage of vehicle, and operating and maintenance practices (USEPA, 1992).

This category is organized into two major sections, highway and nonhighway fossil fuel use. Nonhighway emissions were estimated for each transport mode (rail, aviation, marine vessels etc.) and highway transportation emissions were estimated for each vehicle type with its emission control technology. Gasoline, diesel and aviation fuel were the primary fuels considered here. The data were mostly readily available for these fuels, but future investigations could include alternative fuels such as ethanol and compressed natural gas. Greenhouse gas emissions from all mobile source categories and percentage gas composition are summarized in Figure 1.1.

Figure 1.1 Maryland 1990 Greenhouse Gas Emissions from Mobile Sources by Source Category

(million tons, CO2 Equivalent)



Highway Fossil Fuel Combustion

Overview

This category includes emissions for all gasoline and diesel powered highway vehicles, including passenger cars, trucks, buses, and motorcycles. Data sources appropriate for estimation of greenhouse gas emissions from the mobile sector are not well developed. The data sources used in this study are the best available; however, they provide only rough estimates.

Fossil fuels are combusted in highway vehicle engines to produce energy. There is a direct relationship between fuel consumption and CO_2 emissions. If the fuel is completely combusted, the only emissions are CO_2 and H_2O. However, under actual conditions, not all of the fuel is combusted, resulting in the formation of other gases in addition to CO_2 and H_2O, including the greenhouse gases CH_4 and N_2O. There are several parameters that determine completeness of combustion, including: air-fuel mix, combustion temperature, pollution control equipment, vehicle care and maintenance, vehicle age, and operating characteristics (USEPA, 1992).

Emissions were estimated using available data on vehicle type, vehicle age, emission control technology, and fuel consumption. The following assumptions were made to handle the data with in the scope of this project:

-- Each vehicle type of a certain age has the same emission control technology, is equally maintained and operates at the same assumed fuel economies.
-- only gasoline, diesel, or jet fuel were consumed.

Highway vehicles were categorized into the following seven vehicle types as described in the EPA methodology (USEPA, 1992).

LDGV - light-duty gasoline vehicles; passenger cars with rated gross vehicle weight less than 8,500 lb designed primarily to carry 12 or fewer passengers (does not include four wheel drive for off-road operation)
LDGT - light-duty gasoline trucks; vehicles with rated gross vehicle weight less than 8,500 lb and which are designed primarily for transportation of cargo, more than 11 passengers, or are equipped with off-road operation
HDGV - heavy-duty gasoline vehicles; vehicles having a manufacturer's gross vehicle weight rating exceeding 8,500 lb, primarily large pickups and vans, along with larger heavy-duty trucks
LDDV - light-duty diesel vehicles; passenger cars as described for LDGV, using diesel fuel
LDDT - light-duty diesel trucks; trucks and vans as described for LDGT, using diesel fuel
HDDV - heavy-duty diesel vehicles; primarily larger heavy-duty trucks and buses with gross weight exceeding 8,500 lb
MCYC - motorcycles

Methodology

Emissions were estimated using the methodology described in the EPA *States Workbook* (USEPA, 1992).

$$Emissions = SUM(EF_{abc} * Activity_{abc})$$

Where EF = emission factor
Activity = amount of energy consumed by a given mobile source activity
a = transport mode (highway)
b = fuel type (gasoline, diesel)
c = vehicle type (e.g., LDGV, LDGT, HDGV, etc.)

Determination of Activity (fuel consumption)

The total amount of highway fuel consumed was provided by State of Maryland, *Comptroller of Treasury - Motor Fuel Tax Unit, Gallonage Report For 1990.* The available emission factors (USEPA, 1992; OECD, 1991) were dependent upon the above vehicle types, which were listed previously and subcategorized by emission control technology in Table 1.2.1. Therefore, total fuel consumption needed to be allocated by vehicle type and then by the percentage of that vehicle type having a certain emission control technology.

To calculate the fuel consumption for each vehicle type, the following steps were performed

1) The total vehicle-miles traveled (VMT) were determined for each vehicle type.

2) The vehicle types were subdivided into emission control categories.

3) The VMT for each emission control category was multiplied by an appropriate fuel economy to yield the fuel consumption of each vehicle type by emission control category.

As noted earlier, data sources appropriate for estimation of greenhouse gas emissions for the mobile sector are not well developed; though they are the best available at this time, there are limitations. The data used to obtain statewide fuel consumption (USDOT, 1990) are based upon fuel tax receipts and may under or overestimate fuel consumption in Maryland. VMT is estimated using data from the Maryland State Highway Administration. This data is based on the Highway Performance Monitoring System (HPMS), a national network used to determine approximate VMT estimates. Maryland has two large metropolitan areas that estimate VMT through travel demand models which are regularly validated. The VMT estimates in this report have been developed based on HPMS with consideration given to VMT estimates developed by modeling methods. Considerable effort has gone into the development of the VMT breakdown by vehicle and road class. Coupled with the assumptions that all vehicles are maintained equally, that all model years have the same emissions control and the lack of accounting speed in the estimate, the greenhouse emissions estimates should be considered a gross estimate, subject to an unknown margin of error. The EPA methodology has stated limitations in the estimation of N_2O emission factors (USEPA, 1992). The error may be compounded when estimated N_2O emissions are multiplied by the GWP of 270 to obtain equivalent CO_2 emissions.

Determination of Emissions by control type

Each activity factor (fuel consumed by vehicle type and emission control category) was multiplied by the appropriate emission factor (OEDC, 1991) and a conversion factor from metric to U.S. measurements to yield emissions of CH_4, N_2O, and CO_2 by each category. The sums of these emissions are shown on Table 1.6. The OEDC emission factors are very general. It is beyond the scope of this project to further breakdown the data to account for many of the elements that affect emissions from fossil fuel consumption by highway vehicles.

Table 1.6 Maryland 1990 Greenhouse Gas Emissions Calculations for Highway Vehicles

*Emissions = Gallons Consumed * Emission Factor * Conversion Factor*

Vehicle Type		Consumed (million	CH4 (g/kg)	N2O (g/kg)	CO2 (g/kg)	(from g/kg to ton/million gal)	CH4 (ton)	N2O (ton)	CO2 (ton)
<1975	Uncontrolled & Non-catalyst contr	81	1.38	0.04	3.172	3.085	345	10	794,016
1975-1980	Oxidation catalyst	210	0.71	0.21	3.172	3.085	461	136	2,057,865
1981-1988	Early three-way catalyst	815	0.50	0.57	3.172	3.085	1,257	1,433	7,974,416
1989-1990	Advanced three-way catalyst	159	0.32	0.30	3.172	3.085	157	147	1,552,984
		1265					**2,220**	**1,726**	**12,379,281**
LDGT1,LDGT	**Light trucks under 8500 lbs**								
<1975	Uncontrolled & Non-catalyst contr	38	1.18	0.04	3.172	3.085	139	5	373,553
1975-1980	Oxidation catalyst	96	0.61	0.21	3.172	3.085	180	62	936,782
1981-1988	Early three-way catalyst	327	0.64	0.57	3.172	3.085	646	575	3,200,806
1989-1990	Advanced three-way catalyst	79	0.50	0.30	3.172	3.085	122	73	775,401
		540					**1,087**	**715**	**5,286,542**
HDGV	**Heavy Duty Gas Trucks 8500+ lbs.**								
<1979	Uncontrolled	30	1.02	0.02	3.172	3.085	93	1.82	289,105
1979-1989	Non-catalyst controls	55	0.65	0.02	3.172	3.085	111	3.42	542,888
1990	Three-way catalyst	4	0.38	0.02	3.172	3.085	5	0.27	43,051
		89					**209**	**6**	**875,043**
MCYC	**Motorcycles**								
<1978	Uncontrolled	1	5.60	0.04	3.172	3.085	9	0.07	5,281
1978-1990	Non-catalyst controls	2	2.98	0.04	3.188	3.085	15	0.20	15,920
		2					**24**	**0**	**21,201**
Total Highway Gasoline Use							**3,540**	**2,447**	**18,562,068**
LDDV	**Diesel Autos**								
<1982	Uncontrolled	7	0.06	0.08	3.188	3.525	1	1.90	75,540
1982-1984	Moderate controls	5	0.08	0.08	3.188	3.525	2	1.53	60,984
1985-1990	Advanced controls	2	0.12	0.08	3.188	3.525	1	0.66	26,159
		14					**4**	**4**	**162,682**
LDDT	**Light Duty Diesel Trucks (<8500 lbs)**								
<1982	Uncontrolled	1	0.10	0.08	3.188	3.525	0	0.33	13,258
1982-1984	Moderate controls	2	0.06	0.08	3.188	3.525	0	0.60	23,962
1985-1990	Advanced controls	2	0.09	0.08	3.188	3.525	1	0.51	20,218
		5					**1**	**1**	**57,437**
HDDV	**Heavy Duty Diesel Trucks & Buses**								
<1979	Uncontrolled	21	0.26	0.08	3.188	3.525	19	5.98	238,485
1979-1984	Moderate controls	52	0.23	0.08	3.188	3.525	42	14.70	585,607
1985-1990	Advanced controls	100	0.19	0.08	3.188	3.525	67	28.25	1,125,756
		174					**129**	**49**	**1,949,847**
Total Highway Diesel Use							**134**	**54**	**2,169,967**
Total (gasoline and diesel)							**3,675**	**2,502**	**20,732,035**

Note: due to spreadsheet rounding, numbers may not add exactly.

(1) See Appendix C for calculations of fuel consumption by vehicle type
(2) OECD Estimation of Greenhouse Gas Emissions & Sinks (August 1991 Revision); (Emission Factors, tables 2-19 thru 2-30)

Results

Tables 1.7 and 1.8 summarize the emissions for the highway mobile sector. Tables C.1 and C.2 in Appendix C show the methodology used to calculate the fuel use activity for the eight different vehicle types. Table 1.6 shows the initial estimate of emissions of CH_4, N_2O and CO_2 generated from the vehicle types by the fuel types.

The great majority (over 99%) of greenhouse gas emissions from highway vehicles is in the form of carbon dioxide. Most of the greenhouse gases emitted from motor vehicles in Maryland are from automobiles (60%). Light duty vehicles (vans and small trucks) contribute 26 % of the highway vehicle emissions, while heavy duty vehicles (buses and trucks) contribute 14% of the emissions.

Maryland's highway vehicles burn more gasoline than diesel fuel. Thus, gasoline combustion accounts for 89% of Maryland's greenhouse gas emissions from highway vehicles.

Table 1.7 1990 Maryland Greenhouse Gas Emissions by Highway Vehicle Type

Vehicle Type	CH_4 (Ton)	N_2O (Ton)	CO_2 (Ton)
Autos	2,224	1,730	12,541,963
Light-Duty Trucks	1,088	716	5,343,979
Heavy-Duty Trucks	338	55	2,824,890
Motorcycles	24	0	21,201
Total Highway Use	3,675	2,502	20,732,035

Table 1.8 1990 Maryland Greenhouse Gas Emissions from Highway Vehicles by Fuel Type

Vehicle Type	CH_4 (Ton)	N_2O (Ton)	CO_2 (Ton)
Highway Gasoline Use	3,540	2,447	18,562,068
Highway Diesel Use	134	54	2,169,967
Total Highway Fuel Emissions	3,675	2,502	20,732,035

Non-Highway Fossil Fuel Combustion

Overview

This section presents non-highway mobile source emissions from railway locomotives, ships and boats, farm equipment such as tractors and harvesters, construction equipment such as bulldozers and cranes, aircrafts, etc. Mobile sources other than road vehicles have received relatively little study compared to passenger cars and heavy-duty trucks (USEPA, 1992). Fuel consumed by small utility engines (i.e. lawnmowers, garden tractors, snowblowers, etc.) was not available as a separate category and is included in miscellaneous gasoline consumed.

Methodology

The emission estimation methodology described in the EPA *States Workbook* (USEPA, 1992) was used.

$$Emissions = SUM(EF_{ab} * Activity_{ab})$$

Where EF = emission factor
Activity = amount of energy consumed by a given mobile source activity
a = transport mode (marine, rail, air, agriculture, etc)
b = fuel type (gasoline, diesel, jet fuel)

Fuel consumption was available for different modes of nonhighway use from the U. S. DOE/EIA State Energy Data Report, Consumption estimates, 1960-1990, U. S. DOE/EIA Fuel Oil and Kerosene Sales 1990, and MDOT. The transport modes used in these sources varied slightly from the EPA's modes and adjustments were made to use the information in the appropriate categories for Maryland's transport modes. Calculations and emissions factors for nonhighway fossil fuel use are shown in Table 1.10.

Results

Non-highway mobile source emissions are summarized in Table 1.9. The aviation category accounts for the largest proportion (1,514,400 tons or 50%) of emissions. The marine category accounts for about 26% and it includes the operation of commercial vessels as well as motorboats used for recreation. The remaining categories account for about 24% of the emissions, with rail (passenger and freight) at 11%, agriculture (farm equipment) at 6% and construction equipment at 6%.

Table 1.9 Summary of 1990 Greenhouse Gas Emissions From Nonhighway Mobile Source Fossil Fuel Combustion in Maryland

Summary Table	**CH_4 (ton)**	**N_2O (ton)**	**CO_2 (ton)**
Marine	0.0	20	803,361
Rail	27.4	8.8	349,860
Agricultural	27.5	4.9	194,654
Aviation	66.3	0.4	1,514,368
Construction	11.1	4.9	197,004
Total Nonhighway	132	28	3,059,247

Table 1.10 1990 Maryland Greenhouse Gas Emissions Calculations for Nonhighway Fossil Fuel Use

Non-Highway Mobile Sources	Fuel Used Thousand Gallons	Emission Factors			Conversion Factor (from g/kg to ton/1000gal)	CH4 (ton)	N2O (ton)	CO2 (ton)
		CH_4 (g/kg)	N_2O (g/kg)	CO_2 (g/kg)				
Pleasure Boats	20,441	n/a	0.08	3,200	0.003085	0	5	201,791
Large Vessels	60,937	n/a	0.08	3,200	0.003085	0	15	601,570
Farm Equipment	19,792	0.45	0.08	3,188	0.003085	27.5	4.9	194,654
Railroads	35,573	0.25	0.08	3,188	0.003085	27.4	8.8	349,860
Aviation: Jet & Turboprop Aircraft	152,754	0.087	n/a	3,149	0.003085	41	0	1,483,954
Aviation: Gasoline (Piston) Aircraft	3,108	2.64	0.04	3,172	0.003085	25.3	0.4	30,414
Construction	20,031	0.18	0.08	3,188	0.003085	11.1	4.9	197,004
Total Nonhighway Emissions	312,635					132	39	3,059,247

Note: due to spreadsheet rounding, numbers may not add exactly

USEPA States Workbook, Methodologies for Estimating Greenhouse Gas Emissions (1992), Section D13

References

OECD/OCDE, 1991, *Estimation of Greenhouse Gas Emissions and Sinks, Final Report from the OECD Experts Meeting, 18-21 February 1991*, Prepared for the Intergovernmental Panel on Climate Change.

U.S. Environmental Protection Agency (USEPA), 1992, *States Workbook; Methodologies for Estimating Greenhouse Gas Emissions*, EPA-230-B-92-002. Office of Policy, Planning and Evaluation, November 1992.

U. S. Department of Transportation (USDOT), *Highway Statistics -1990*.

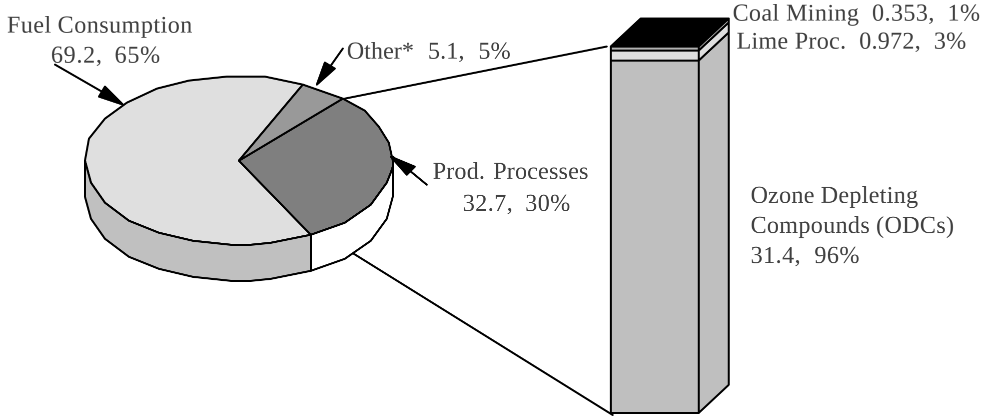
2. PRODUCTION PROCESSES

Non-energy related greenhouse gas emissions are associated with industrial and commercial processes. Emissions in this category result from either the loss of raw material or by-product during production or by the end use of the product. Greenhouse gas emissions covered in this section are divided into four categories: (1) CO_2 emissions from lime processing, (2) emissions from ozone depleting compounds (ODC), (3) emissions from "other processes" and, (4) product end-use emissions. Greenhouse gas emissions from production processes are summarized by source category and gas in Figure 2.1.

Activity data used to estimate lime processing emissions and the data used to identify "other processes" within Maryland were obtained from a computerized search of registered point source facilities in the Maryland Department of the Environment Air Emissions Inventory Database. Appropriate Source Classification Codes (SCC) were used to search for each process type in the emission inventory database. Emissions of ODCs are based on a USEPA estimate of national ODC emissions in their report *Emissions of Greenhouse Gas Emissions and Sinks for the United States 1990* (USEPA, 1993).

Figure 2.1 Maryland 1990 Greenhouse Gas Emissions from Production Processes by Source Category

(million tons, CO2 equivalent)



* Includes Agriculture, Waste Disposal, and Land Use Change

2.1 Lime Processing

Overview

The USEPA has identified cement manufacturing as the only quantifiable source of process CO_2 emissions (USEPA, 1992). The EPA *States Workbook* provides a method for estimating emissions based upon the formation of lime (CaO) during the cement manufacturing process. This method was adapted to estimate emissions from other processes involving the same chemical reaction. All of these processes are addressed in this section as part of a comprehensive lime-processing category.

Lime processing occurs during cement manufacturing (SIC 3241), lime manufacturing (SIC 3274), and use of lime in paper pulp kilns (SIC 2611). The SIC code is the standard industrial classification code designating specific manufacturing activities. Lime processing is the reaction in which a calcium carbonate ($CaCO_3$) is calcined (heated) to form lime (CaO) with the release of carbon dioxide (CO_2) (USEPA, 1992). The chemical equation for the reaction is:

$$CaCO_3 + Heat \text{ ---> } CaO + CO_2$$

This reaction occurs on a large scale in the manufacture of cement during calcining of clinker. In addition to cement manufacturing, this reaction occurs during lime manufacturing and in paper pulp lime kilns. Lime manufacturing is the process by which $CaCO_3$ is mined specifically to be calcined into lime. Some paper mills that use acidic processes neutralize spent pulping liquor with lime (CaO) generated in a kiln from $CaCO_3$. The neutralization reaction yields $CaCO_3$ that is reconverted (with makeup $CaCO_3$ as necessary) to lime in the kiln for reuse (Jaques, 1992).

Methodology

The EPA *States Workbook* (USEPA, 1992) methodology for cement manufacturing calculates CO_2 emissions by multiplying activity data (tons of cement produced) by an emission factor based on lime content in the product.

$$CO_2 \text{ tons} = \text{Emission Factor} * \text{Tons of Cement Produced}$$

This methodology is based on the assumption, as shown by the chemical reaction, that for every mole of $CaCO_3$ calcined, one mole of CaO and CO_2 is generated. It is also assumed that 100% of the $CaCO_3$ undergoes this reaction. Therefore, the amount of CO_2 generated is equal to the mass of CaO produced in the cement multiplied by a molecular conversion factor to give tons of CO_2 (USEPA, 1992).

$$\begin{aligned} EF &= \text{Ton CaO/ Ton Product} * (44 \text{ lb/mole } CO_2)(\text{one mole}/56.08 \text{ lb. CaO}) \\ &= \text{Fraction CaO in product} * 0.785 \end{aligned}$$

This same method is used for lime manufacturing and pulp kiln emissions, with emission factors also based on end-product lime content. The emission factors for each process are developed as follows.

Cement Manufacturing

The fractional lime content varies for different cements and from region to region. It is difficult to obtain data for individual cement plants, so as an average lime content of 63.5% is assumed (USEPA, 1992). Therefore, the emission factor for cement manufacturing is:

$$\begin{aligned} Ef_{\text{cement manfct.}} &= 0.635 \text{ Ton CaO/ Ton Cement} * 0.785 \ CO_2/CaO \\ &= 0.4985 \text{ Ton } CO_2 \text{ / Ton of cement produced} \end{aligned}$$

Lime Manufacturing

Activity data for lime manufacturing is reported in terms of tons of lime produced. Assuming that the lime is 100% pure, the CO_2 emission factor for lime production is:

$$\begin{aligned} Ef_{\text{lime manfct.}} &= 1 \text{ Ton CaO/ Ton Lime} * 0.785 \ CO_2/CaO \\ &= 0.785 \text{ Ton } CO_2 \text{ / Ton of lime produced} \end{aligned}$$

Paper Pulp Kilns

The emission factor for paper pulp lime kiln emissions is based on tons of air-dried paper pulp (ADPP) produced. According to the Washington State greenhouse gas study, a ton of lime is required for neutralization per 4 tons of ADPP produced in the pulping process (Washington State Energy Office, 1993). This assumption is corroborated by a paper pulp facility engineering note for this process in the Maryland Department of Environment Air Emissions Inventory. Assuming the lime requirement is 25% of ADPP for all pulping facilities in Maryland, the emission factor is:

$$\begin{aligned} Ef_{\text{pulp kiln}} &= 0.25 \text{ Tons CaO/ Ton ADPP} * 0.785 \ CO_2/CaO \\ &= 0.1963 \text{ Ton } CO_2 \text{ / Ton of ADPP produced} \end{aligned}$$

Activity Data

Source facilities and activity data for cement manufacturing, lime manufacturing, and paper pulp kilns were obtained by an electronic search of registered point source facilities in the Maryland Department of the Environment Air Emissions Inventory Database by SCC codes:

Cement Manufacturing	3-05-006, 3-05-007
Lime Manufacturing	3-05-016
Paper Pulp Lime Kiln	3-07-001 (-06,08)

Results

There is no operating lime manufacturing facility in Maryland. The majority of CO_2 emissions are from three cement manufacturing facilities and the balance from one pulp mill. A summary of CO_2 emissions by process and facility is presented in Table 2.1.

Table 2.1 Maryland 1990 Carbon Dioxide Emissions From Lime Processing

Plant	Cement Manufacturing		Lime Manufacturing		Paper Pulp Kilns	
	Thru put (tons)	CO2 (tons)	Thru put (tons)	CO2 (tons)	Thru put (tons)	CO2 (tons)
Lehigh Portland Cement	1,016,810	506,880	N/A	N/A	N/A	N/A
ESSROC	361,471	180,193	N/A	N/A	N/A	N/A
Independent Cement	454,200	226,419	N/A	N/A	N/A	N/A
Westvaco	N/A	N/A	N/A	N/A	300,283	58,946
	1,832,481	913,492	N/A	N/A	300,283	58,946

2.2 Ozone Depleting Compounds

Overview

Ozone depleting compounds (ODCs) emitted from industrial processes and product end use have been found to be greenhouse gases. The majority of ODCs are chlorofluorocarbons (CFC), halons, and partially halogenated compounds (USEPA, 1992). Emissions of ODCs are mainly the results of their use in eight categories determined in the *States Workbook:* (1) refrigeration, (2) air conditioning, (3) solvent cleaning, (4) foam production, (5) sterilization, (6) fire extinguishing, (7) chemical intermediates, and (8) miscellaneous uses (e.g., aerosols and other products).

The OECD largely ignores the emissions of ODCs and their warming potential because the Montreal protocol bans the production of CFCs and methyl chloroform by 1995. Also, there is some question of the net ODC warming affect offset by cooling from the destruction of atmospheric ozone. However, because of their relatively large warming potentials and expected continual release to the atmosphere for several decades it is important to make some quantification of ODC emissions. In addition, it is important to examine ODC replacement compounds because they are similar in chemical nature and there is no indication, at this time, that their warming potential will be any less than the ODCs they are replacing.

Two other suspected ozone depleters and greenhouse gases are carbon tetra fluoride (CF_4) and CFC-116 (C_2F_6). Their estimated GWP are greater than either CFC-11 or CFC-12. Emission estimates for these two gases are not included here because the sources and emission mechanisms of these compounds are not well understood at this time, but are addressed further in Section III.

Methodology

The USEPA *States Workbook* describes a method for estimating ozone depleting compound emissions. However, it is most time consuming and relies on data that would be difficult to develop on the state level. For this reason and because of uncertainties involving the present and future effect of ODCs and their replacement compounds, a rough estimate of Maryland emissions was done for this study.

The USEPA estimated 1990 ODC emissions as part of a greenhouse gas emissions inventory for the entire United States (USEPA, 1993). Their method is based on the Atmospherics and Health Effects Framework model using U.S. consumption based on regional shares of ODC consumption. It accounts for emission profiles of each compounds, end use, and release over time (accounting for ODC use in both the current and previous years).

The portion of U.S. emission by compound in Maryland was estimated using the fraction of U.S. population living in Maryland. Where available, the appropriate global warming potential (USEPA, 1992 / USDOE, 1993) was then applied to determine CO_2 warming equivalent. More applicable activity data for disaggregation of ODC emissions to the state level may be developed and used in the future. The equation for this calculation is as follows.

$$\text{Emissions (Tons-}CO_2\text{)} = \text{U.S. Emissions} * \text{Pop. Fraction} * GWP$$

where: Pop. Fraction = Maryland 1990 population/U.S. 1990 population.
= 4,742,500 / 248,709,873 = 0.01907

Results

Results by compounds are given in Table 2.2. Although a rough approximation, this analysis shows ODC emissions of 31.4 million tons CO_2-equivalent. CFC-12 emissions are three times greater than any other ODC emissions. CFC-113, CFC-11, and HCFC-22 are the next highest emitted ODCs, respectively.

Table 2.2 Maryland 1990 Emissions of Ozone Depleting Compounds

Compound	U.S. Emissions (tons)	Fraction Md./U.S. Population	Maryland Emissions (tons)	GWP (100-yr)	Md. CFC GWP (tons CO_2-equiv)
CFC-11	61,343.6	0.01907	1,169.7	3,400	3,977,063
CFC-12	124,229.1	0.01907	2,368.9	7,100	16,818,839
CFC-113	58,039.6	0.01907	1,106.7	4,500	4,980,251
CFC-114	5,176.2	0.01907	98.7	7,000	690,913
CFC-115	3,414.1	0.01907	65.1	7,000	455,710
Carbon Tetrachloride	35,572.7	0.01907	678.3	1,300	881,809
Methyl Chloroform	348,678.4	0.01907	6,648.7	100	664,874
Halon-1211	1,101.3	0.01907	21.0	NA	NA
Halon-1301	1,872.2	0.01907	35.7	4,900	174,929
HCFC-22	90,088.1	0.01907	1,717.8	1,600	2,748,538
HCFC-141b	2,092.5	0.01907	39.9	NA	NA
HCFC-124	2,973.6	0.01907	56.7	NA	NA
HFC-134a	550.7	0.01907	10.5	1,200	12,601
Total	735,132		14,018		31,405,527

1: Source - "Estimation of greenhouse gas emissions and sinks for the United States 1990 (USEPA, 1993).

GWP: global warming potential

CFC: chlorofluorocarbons

NA: GWPs for these compounds were not available.

2.3 Coal Mining

Overview

Methane and coal are formed together during coalification, a process in which vegetation is converted by geological and biological forces into coal. Methane is released when pressure within a coal bed is reduced, either through mining or through natural erosion or faulting.

To estimate state emissions of methane from coal mining, the following steps should be performed: 1) obtain the required data -- annual coal production from surface and underground mines; 2) calculate methane emissions from underground coal mining; 3) calculate methane emissions from surface coal mining; 4) calculate post-mining emissions; and 5) calculate total coal mining emissions.

Methodology

The USEPA States Workbook describes a method for estimating methane emissions from coal mining in the following five steps:

Step (1) Obtain Required Data: the data required to estimate methane emissions from coal mining are annual coal production from surface mines and from underground mines. It is important to distinguish between underground production and surface production because shallow, surface mined coals tend to hold less methane than deeper, underground mined coals. Maryland Department of Natural Resources provided annual coal productions from surface and underground coal mines.

Step (2) Calculate Methane Emissions From Underground Mines: The first step in calculating methane emissions from underground coal mines is to find the annual underground coal production for the state. Next, the methane emissions coefficient for coal produced from underground mines were recorded from USEPA states workbook. Both a low and high emissions coefficients are given so that the potential range of emissions may be calculated. For underground mined coal in Maryland, the low and high methane emissions coefficients are 220 cubic feet/ton (ft^3/ton) and 780 ft^3/ton of coal mined, respectively. Next, calculate methane emissions from underground mines by multiplying the low and high methane emission coefficients by underground coal production.

Step (3) Calculate Methane Emissions From Surface Mines: The first step in calculating methane emissions from surface coal mines is to find the annual surface coal production for the state. For all surface mined coal, the low and high assumed methane emissions coefficients are 15 ft^3/ton and 150 ft^3/ton of coal mined, respectively. Next, calculate methane emissions from surface mines by multiplying the low and high methane emission coefficients by surface coal production.

Step (4) Calculate Post-Mining Methane Emissions: Some methane remains in the coal after it has been mined and can be emitted during transportation and handling of the coal. Post-mining emissions should be calculated for both surface and underground mined coals. To calculate post-mining emissions underground and surface coal production should be multiplied by the appropriate emissions coefficients. For all surface mined coal, the low and high post-mining methane emissions coefficients are 3 ft^3/ton and 30 ft^3/ton of coal mined, respectively. For all underground mined coal, the low and high post-mining methane emissions coefficients are 30 ft^3/ton and 100 ft^3/ton of coal mined, respectively.

Step (5) Calculate Total Methane Emissions from Coal Mining: To find the low and high total emissions from coal mining, add together emissions from underground mines, surface mines, and post-mining emissions. The low and high total emissions represent the potential range of state coal mine methane emissions. Next, calculate the midpoint of the low and high total emission estimates. This value may be used as a single approximation of state coal mining methane emissions. However, it is important to note that there is a large degree of uncertainty associated with using a single emission estimate. The low and high ranges represent the best estimates of state emissions. Finally, total methane emissions should be converted from million cubic feet (mmcf) to tons by multiplying by 20.66 tons/mmcf.

Results

The calculations and results of methane emissions from coal mines are shown in Table 2.3.

Table 2.3 Calculations for Estimating 1990 Maryland Methane Emissions From Coal Mining

	1 Coal Production (Million short tons)	2 Emissions Coefficient (cf/ton)		3 Methane Emitted Column 1 x column 2 (mmcf methane)	
		Low	High	Low	High
1. Underground Mines	2.54236422	220	780	559.3	1,983.0
2. Surface Mines	1.16048412	15	150	17.4	174.1
3. Post-mining(Underground)	2.54236422	30	100	76.3	254.2
4. Post-mining (Surface)	1.16048412	3	30	656.5	34.8
			Total	**656.5**	**2,446.2**
			Average	**1,551.3**	
				- CH_4 Recovered 1,551.3 (mmcf) 32,050.4 (tons)	

2.4 Natural Gas and Oil Systems

Emissions from natural gas and oil systems are primarily methane, although smaller quantities of non-methane VOCs, carbon dioxide, and carbon monoxide can be emitted. Methane emissions occur throughout the total fuel cycle--during field production, processing, storage and injection, transmission, distribution, and from engine exhaust. While emissions occur during all these stages, emission estimates addressed in the EPA *State Workbook* are limited to CO_2 and CH_4 emissions that result from natural gas venting and flaring only. Emissions from other sources associated with natural gas and oil production are not estimated due to a lack of reliable data on the frequency and rate at which emission may occur.

To estimate state emissions of CO_2 and CH_4 from venting and flaring, the following steps should be taken: 1) obtain the required data; 2) calculate CO_2 emissions from flaring and venting; and 3) calculate CH_4 emissions from venting.

At present the percent of vented and flared gas that is vented, is unknown for the State of Maryland, according to the EPA *State Workbook*, the emissions from this category cannot be estimated. However, in future when the required data shall be available, the emissions from this category will be estimated and included in the inventory.

2.5 Other Processes

The number of facilities and employees in the state indicates the extent of potential greenhouse gases emitted from other processes in Maryland. This information was obtained from the MDE Air Emissions Inventory and *County Business Patterns 1990* (USDOC, 1992). The production processes searched for were listed as potential emitters of CO_2, CH_4, or N_2O in the Section D12 of the EPA *States Workbook* (USEPA, 1992). Other processes listed in the *States Workbook* that emit indirect greenhouse gases (CO, NOx and non-methane volatile organic compounds) were not included in this facility search, but statewide estimates of those emissions are included in Section III of this report. The results of the facility search are summarized in Table 2.4.

Table 2.4 Production Processes with Potential Greenhouse Gas Emissions

Process	SCC #	Pollutants			Facilities[1] in Maryland	Number of [2] Employees
		CO_2	CH_4	N_2O		
Coke Production	3-03-003/004	✓			1	
Colliery Coke Production	3-05-010		✓		0	
Aluminum Production	3-03-002	✓		✓	1	
Ferroalloy Production	3-03-006/007	✓			0	
Steel Production	3-03-009	✓			3	
Iron Production	3-03-008	✓			1	
Misc. Primary Metal Production	3-03-005 /010/030	✓			7	
Steel Foundries	3-04-007	✓	✓		1	
Iron Foundries	3-04-003	✓			2	
Furnace Electrode Manufacturers	3-04-020	✓			0	
Calcium Carbide Prod.	3-05-004	✓			0	
Castable Refractory Prod.	3-05-005	✓			1	
Glass Production	3-05-014			✓	2	
Nitric Acid Production	3-01-013			✓	0	
N-Fertilizer Production	3-01-027/030			✓	5	
Ammonia Production	3-01-003		✓		2	
Ethylene Production	3-01-197		✓		unknown	

Adipic Acid	3-01-001			✓	unknown	

Table 2.4(Contd.) Production Processes with Potential Greenhouse Gas Emissions

Process	SCC #	Pollutants			Facilities[1] in Maryland	Number of [2] Employees
		CO_2	CH_4	N_2O		
Bakeries	3-02-032	✓			43	
Cheese Production	3-02-030	✓			3	
Malt/Yeast	unknown	✓			2	
Beer Production	3-02-009	✓			3	
Wine Production	3-02-011	✓			7	
Spirits Production	3-02-010	✓			unknown	

1 MDE 1990 air emissions inventory and registration system.
2 County business patterns 1990 (USBOC, 1990)

2.6 Product End-Use Emissions

A portion of the non-energy fossil fuel carbon sequestered in products such as lubricants, motor oil, solvents, pesticides, plastics, aerosols, paints, etc. is emitted from the end use of the product. Emissions are typically in the form of volatile organic compounds that eventually oxidize to CO_2 . A method is presented in the *States Workbook* to calculate emissions from such products based upon the quantity of fossil fuel contained in the products. This method was developed because non-energy fossil fuel consumption is usually included as part of the total energy and non-energy fuel consumption data and therefore sequestering in products must be accounted for. This is not true for Maryland where fossil fuel consumption data include only fossil fuel consumed for energy production and not the portion sequestered in products. Since information is not currently available for products consumed in Maryland, emissions from this source could not be calculated for this inventory.

Sequestering of the carbon also occurs as a result of waste disposal in landfills. The amount of the carbon sequestered in landfills is not determined in this inventory because it is assumed that a degradable carbon is released as either methane or carbon dioxide. This topic may warrant more investigation as it has become evident that "dry tomb" landfills prevent the degradation of waste. Direct emissions from waste disposal are theoretically captured in the landfill and waste incineration estimates given in Section 4 of this report.

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3. AGRICULTURE AND LIVESTOCK PRODUCTION

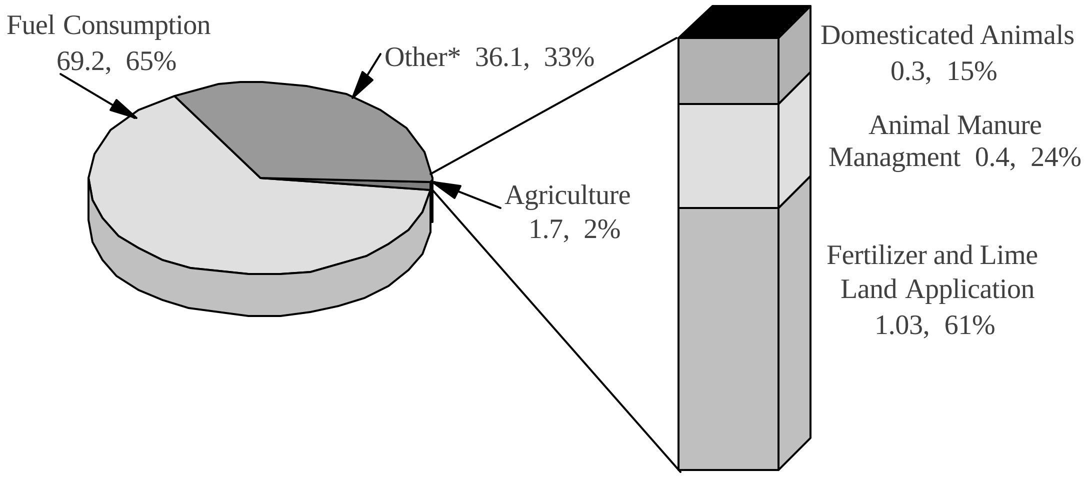
This section documents the methodology and data used to calculate greenhouse gas emissions associated with the raising of livestock and agricultural crops in the State of Maryland. The categories covered in this section include:

-- Domesticated Animals
-- Animal Manure Management
-- Fertilizer Use/ Agricultural Liming

Methane emissions arising from livestock production and nitrous oxide emissions from fertilizer and lime use are contributors to Maryland greenhouse gas emissions. Greenhouse gas emissions from agriculture and livestock production, are summarized by source category and gas in Figure 3.1.

Figure 3.1 Maryland 1990 Greenhouse Gas Emissions from Agriculture by Source Category

(million tons, CO2 equivalent)



* Includes Production Processes, Waste Disposal, and Land Use Change

3.1 Domesticated Animals

Overview

Livestock production contributes to greenhouse gas emissions as methane is produced during normal digestive process of animals. Ruminant animals (i.e., cattle, buffalo, sheep, and goat) are the major emitters of methane. Non-ruminant animals (including swine, horses and mules) also contribute to emissions, but their digestive physiology precludes them from emitting large quantities of methane (USEPA, 1992).

This section covers only the methane emissions attributable to domesticated animals in Maryland. These are mostly comprised of dairy, beef and range cattle, but also include sheep, swine, horses, goats and mules.

Methane is produced in the rumen (a large fore stomach) by methanogenic bacteria as a by-product of a microbial breakdown of carbohydrates (Crutzen, Aselmann, and Seiler, 1986). It is released to the atmosphere through the animal's eructation (belching) and exhalation (USEPA, 1992).

The quantity of methane produced during the digestive process depends on the type of animal; the type, amount, and level of digestibility of the feed consumed by the animal; and the production level of the animal (USEPA, 1992). In addition to the methane created by and emitted from the digestive tracts of animals, animal waste (manure) also contributes to methane emissions (USEPA, 1992). Emissions from animal wastes are covered in Section 3.2.

Methodology

Methane emissions can be estimated using detailed information on animal characteristics, feed characteristics, and animal activity level to calculate feed energy converted to methane by an animal (Crutzen, Aselmann, and Seiler, 1986). For this estimate, however, we used the methodology recommended in the EPA *States Workbook* (USEPA, 1992), which provides average emission factors for each animal type.

Maryland Agricultural Statistics Service of the Maryland Department of Agriculture provided the 1990 domesticated animals' population by animal type. The appropriate emission factors were provided in the EPA *States Workbook - Methodologies for Estimating Greenhouse Gas Emissions* (USEPA, 1992).

Methane emissions attributable to each animal type were estimated according to the following calculation

CH_4 emissions (lbs.) = Animal Population (head) x CH_4 EF (lbs. CH_4/head)

The results in lbs. were then divided by 2000 lbs/ton, for each type of animal, to obtain tons of methane. Total methane emissions from Domesticated animals were obtained by summing across all animal types.

Results

Maryland 1990 domesticated animal types, their population (head), emission factors (lbs. CH_4/head/year), and methane emissions are summarized in Table 3.1.

Table 3.1 1990 Maryland Methane Emissions From Domesticated Animals

Animal	Population	Emission Factor (lbs. CH_4/head)	CH_4 Emissions in lbs./year	CH_4 Emissions in tons/year
Dairy Cattle	106,000	184	19,504,000	9,752
Beef Cattle	56,000	142	7,952,000	3,976
Range Cattle	153,000	119	18,207,000	9,104
Horses	24,326	40	973,040	487
Mules/Asses	520	22	11,400	6
Sheep	32,000	18	576,000	288
Goats	5,151	11	56,661	28
Swine	180,000	3.3	594,000	297
		Total	**47,874,141**	**23,937**

3.2 Animal Manure Management

Overview

Manure decomposition is a process in which microorganisms derive energy and material for cellular growth by metabolizing organic material in the manure. When decomposition occurs without oxygen present (anaerobically), methane is an end-product in the process. In other words methane is produced during the anaerobic decomposition of the organic material in animal manure (USEPA, 1992). The factors that influence the quantity of methane produced from animal manure are (1) the type and quantity of manure produced (different animals produce manure with different methane producing potential) and (2) the manure handling system (different handling systems subject the manure to different levels of anaerobic conditions).

In addition to the manure produced by the domestic animals covered in the previous section (i.e., cattle, horses, mules, sheep, goats, and swine), manure produced by some poultry (e.g., chickens, turkeys, and ducks) is also handled in such a way that it is capable of producing methane.

The calculations in this section use the same population of animal types used in the previous section, but break them down into more detailed subcategories (for instance, beef cattle are broken into feedlot beef, bulls, steers, calves and cows) due to differences in animal mass and maximum potential methane emissions.

Methodology

Several calculation steps are required to estimate methane emissions from animal manure, for each animal type. All factors required in these calculations were taken from the tables provided in chapter 7 of the EPA *States Workbook* (USEPA, 1992). These calculations all follow the form below. Summary tables for each animal type are included in this section. Calculations and results for each animal type are given in Appendix D.

Step 1: Calculate the amount of volatile solids (VS_i) produced for animal type I.

$$Vs_i\ (lbs.) = Animal_i\ Pop * TAM_i * Vs_i$$

where: $Animal_i$ Pop = Maryland population of animal type I

TAM_i = Typical animal mass of animal type I (pounds/animal)

VS_i = Average annual volatile solids per unit animal mass (lbs per lb of animal mass)

Step 2: Estimate maximum potential methane emissions for each animal type I.

$$Max\ Potential\ (CH_4)_I\ \ (Cu\ ft\ CH_4) = VS_i * B_i$$

where: VS_i = Amount of volatile solids produced by animal type I; calculated in step 1 above (pounds)

B_i = Max. Methane producing potential of manure; depends on animal type (cu.ft. CH_4/lb. VS)

Step 3: Estimate CH_4 emissions for each manure management system for each animal type I.

$$Methane\ Emissions_i\ \ (Cu\ ft\ CH_4) = Max\ Potential\ (CH_4)_I * MCF_j * WS\%_{ij}$$

where: Max Potential $(CH_4)_I$ (cu.ft. CH_4) was calculated for animal type I in step1 above.

MCF_j = Methane conversion factor for manure management system j;
= % of maximum methane emission produced (depends on the anaerobic potential of the management system)

$WS\%_{ij}$ = % of animal manure type I managed in management system type j

Step 4: Convert to tons of methane.

For each animal type I and management system j, multiply by the density of methane (0.0413 lbs CH_4/ft^3) to convert to pounds, then divide by 2000 to convert to tons. Sum the emissions across all manure management systems for each animal type I to obtain total manure emissions for that animal type.

Results

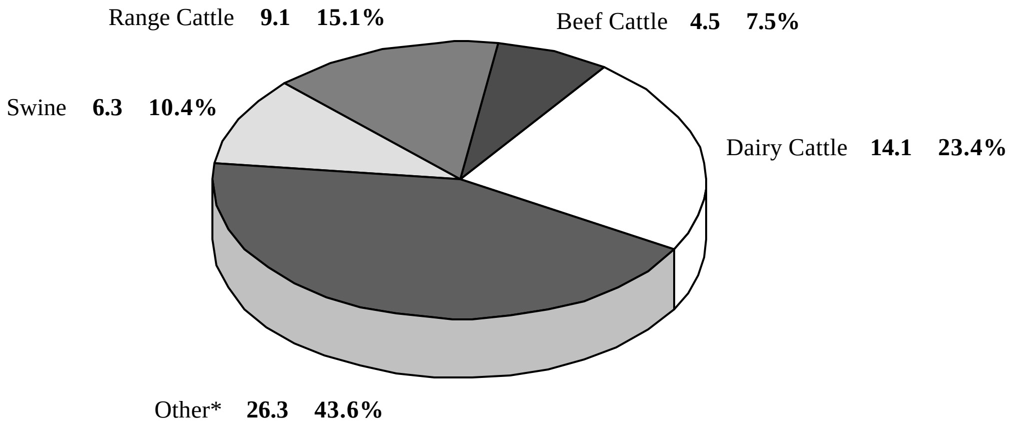
Table 3.2 presents Maryland's 1990 methane emissions from animal manure management. Methane emissions from both Domesticated Animal and Animal Manure Management sources are summarized by animal type in Figure 3.2.

Table 3.2 1990 Maryland Methane Emissions Due to Animal Manure Management Practices

Animal Type	CH4 (cu.ft./yr.)	CH4 (lbs./yr.)	CH4 (tons./yr.)
Feedlot Beef Cattle	9,819,707	405,554	203
Other Beef Cattle	16,961,804	700,523	350
Dairy Cattle	211,280,310	8,725,474	4,363
*****All Cattle*****	**238,061,820**	**9,831,953**	**4,916**
Swine	291,072,529	12,021,295	6,011
Poultry	1,228,873,454	50,752,474	25,376
Other	6,324,919	261,291	131
Total	**1,764,332,722**	**72,866,941**	**36,433**

Figure 3.2 Maryland 1990 Methane Emissions from Domesticated Animals and Manure Mngt. by Animal Type

(Thousand Tons, CH_4)



* Includes sheep, goats, horses, donkeys, mules, and poultry

3.3 Fertilizer and Lime Land Application

Overview

Many types of commercial fertilizer are used as soil additives to increase nitrogen availability for both agricultural and non-agricultural purposes. In 1990, land application of nitrogen fertilizer totaled approximately 10 million tons of nitrogen for the entire United States (USEPA, 1993). This increased flux in nitrogen cycle can result in increased levels of nitrous oxide (N_2O) emissions from soils above background levels.

Nitrous oxide is generated from different forms of nitrogen by natural aerobic (nitrification) and anaerobic (denitrification) microbial processes. However, it is considered that the majority of N_2O is formed by denitrification under anaerobic or near aerobic conditions (Umarov, 1990). Fertilizer nitrogen generally enters the N_2O generating mechanisms as ammonium (NH_4) or nitrate (NO_3) (USEPA, 1992). Two pathways presented by Umarov illustrate this:

Nitrification: NH_4^+ ---> NH_2OH ---> NOH ---> $N_2O + NO_2$
Denitrification: $C_{org} + NO_3$ ---> $(CH_2O)n + N_2O$

This N_2O generation is highly variable, depending on management practices and environmental conditions such as fertilizer type, application rate and frequency; crop system; soil type, moisture and carbon content, temperature, pH etc. Because the complex interaction and influence of these factors on N2O emissions are not well quantified at this time, emissions are estimated as a range for each nitrogen fertilizer type.

Limestone (calcium carbonate) application is also listed in Table D2-5 in the EPA *States Workbook* as a potential emitter of CO_2 (USEPA, 1992). Limestone is applied to farmland to neutralize organic acids resulting from crop growth that accumulate in the soil. Depending on crop type and soil characteristics, the addition of limestone is usually required every three to five years (Koran, 1993). In theory, the reaction of limestone ($CaCO_3$) with organic acids neutralizes the soil and releases carbon dioxide (CO_2). The equation for this reaction can be depicted as:

$$CaCO_3 + \text{organic acid} = CO_2 + \text{Ca-salt}$$

Methodology

Fertilizer

Nitrous oxide emissions from fertilizer application are estimated using the method provided in the EPA *States Workbook* (USEPA, 1992). This method applies an N_2O emission coefficient per unit mass of nitrogen for each fertilizer type to yield N_2O-N emissions. A molecular weight conversion factor is then applied to give emissions in terms of mass N_2O. Emissions are the summed for all fertilizer types.

$$N_2O\text{-}N\ (Tons) = \Sigma_f (F_f * E_f) * 44N_2O/28N$$

where: F = fertilizer nitrogen applied (tons) = Fertilizer Consumption * % Nitrogen Content
E = emission coefficient (tons N_2O-N released/ton-N applied
f = fertilizer type

Normally, using the EPA methodology, a three year average of consumption centered on the target year (1990) is used to calculate emissions. However, consumption data were not available in a usable form for years prior to 1991. Therefore the three year average was taken from 1991 to 1993. Averaging is used to minimize annual fluctuations in consumption due to economic and weather factors that affect agricultural activity. All fertilizer consumption data were obtained from the *Annual Fertilizer Tonnage Reports* published by the Maryland Department of Agriculture (DOA, 1991-93).

To calculate mass consumption of nitrogen, fertilizer use is multiplied by the percent content of nitrogen. The EPA method provides nitrogen content for many of the individual fertilizers reported by the Maryland DOA. The individually reported fertilizers were categorized into the six nitrogen fertilizer types. The calculation of nitrogen content and the calculation of three year averages by EPA nitrogen fertilizer type are shown in Table 3.3.

Table 3.3 Maryland Fertilizer Consumption

EPA Fertilizer Type	%N	Fertilizer Consumption (tons)			Fertilizer Consumption (tons-N)			3 Year
Commercial Fertilizers	Content	1991	1992	1993	1991	1992	1993	Average
Single-Nutrient Fertilizers								
Anhydrous and Aqua Ammonia								
Ammonia, Anhydrous	82%	1,515	1,798	3,393	1,242	1,474	2,782	1,833
Ammonia, Aqua	20.5%	364	463	0	75	95	0	57
Nitrogen Solution 30%N	30%	43,300	31,453	78,378	12,990	9,436	23,513	15,313
				Total=	14,307	11,005	26,296	17,203
Ammonium Nitrate Types								
Ammonium Nitrate	34%	2,157	1,705	2,401	733	580	816	710
				Total=	733	580	816	710
Ammonium Types								
Ammonium Sulfate	8%	1,476	2,339	2,192	118	187	175	160
Ammonium Sulfate	21%	9,877	6,816	9,856	2,074	1,431	2,070	1,858
				Total=	2,192	1,618	2,245	2,019
Urea								
Urea	46%	7,062	4,491	11,535	3,249	2,066	5,306	3,540
				Total=	3,249	2,066	5,306	3,540
Other Single-Nutrient Nitrogen Fertilizers								
2-0-0	2%	0	686	675	0	14	14	9
7-0-0	7%	0	0	353	0	0	25	8
12-0-0	12%	0	0	335	0	0	40	13
15-0-0	15%	0	1,352	1,615	0	203	242	148
20-0-0	20%	0	1,237	622	0	247	124	124
21-0-0	21%	0	1,172	746	0	246	157	134
24-0-0	24%	0	591	552	0	142	132	91
26-0-0	26%	0	1,277	730	0	332	190	174
27-0-0	27%	0	10,649	7,427	0	2,875	2,005	1,627
28-0-0	28%	0	301	1,275	0	84	357	147
32-0-0	32%	0	30,495	4,850	0	9,758	1,552	3,770
34-0-0	34%	0	0	2,338	0	0	795	265
				Total=	0	13,902	5,633	6,512
Multiple-Nutrient Nitrogen Fertilizers								
1-2-0	1%	0	11,869	9,059	0	119	91	70
1.5-5-15	1.5%	609	771	904	9	12	14	11
2-2-0	2%	0	12,495	19,654	0	250	393	214
2-4-12	2%	728	672	493	15	13	10	13
2-6-12	2%	3,607	6,609	5,957	72	132	119	108
3-6-12	3%	862	1,215	809	26	36	24	29

3-9-18	3%	1,021	0	517	31	0	16	15

Table 3.3 (Continued) **Maryland Fertilizer Consumption**

3-15-30	3%	1,025	423	476	31	13	14	19
4-6-4	4%	2,173	1,927	3,118	87	77	125	96
4-8-12	4%	457	823	842	18	33	34	28
4-14-42	4%	725	759	677	29	30	27	29
5-10-5	5%	1,144	567	452	57	28	23	36
5-10-10	5%	1,499	1,391	1,435	75	70	72	72
5-10-30	5%	1,991	1,184	900	100	59	45	68
5-15-30	5%	1,169	871	556	58	44	28	43
6-2-0	6%	1,245	941	1,059	75	56	64	65
6-15-30	6%	393	628	652	24	38	39	33
6-18-36	6%	795	855	314	48	51	19	39
6-26-26	6%	570	441	449	34	26	27	29
7-0-40	7%	2,666	2,217	2,541	187	155	178	173
8-0-24	8%	566	0	400	45	0	32	26
8-8-24	8%	1,396	1,044	784	112	84	63	86
8-13-27	8%	440	486	328	35	39	26	33
9-10-25	9%	1,068	1,710	460	96	154	41	97
9-18-27	9%	919	557	0	83	50	0	44
10-6-4	10%	2,588	1,545	2,194	259	155	219	211
10-10-10	10%	12,698	9,598	10,042	1,270	960	1,004	1,078
10-10-25	10%	1,602	1,473	943	160	147	94	134
10-10-30	10%	1,613	1,967	1,510	161	197	151	170
10-15-30	10%	1,339	489	454	134	49	45	76
10-20-10	10%	530	504	510	53	50	51	51
10-20-20	10%	5,145	3,413	2,868	515	341	287	381
10-20-30	10%	773	420	626	77	42	63	61
10-25-5	10%	1,116	936	0	112	94	0	68
10-26-26	10%	878	633	972	88	63	97	83
10-34-0	10%	4,790	1,955	547	479	196	55	243
10-49-0	10%	7,356	3,567	982	736	357	98	397
11-9-20	11%	1,361	1,394	848	150	153	93	132
11-52-0	11%	4,888	2,176	535	538	239	59	279
11.5-23-23	11.5%	485	601	538	56	69	62	62
12-4-8	12%	422	443	477	51	53	57	54
12-26-0	12%	694	644	605	83	77	73	78
12-30-0	12%	2,205	1,798	1,798	265	216	216	232
13-10-22	13%	610	0	494	79	0	64	48
14-0-44	14%	365	435	535	51	61	75	62
14-5-14	14%	810	1,637	1,370	113	229	192	178
14-7-7	14%	407	944	521	57	132	73	87
14-14-14	14%	726	549	485	102	77	68	82
15-0-15	15%	559	835	593	84	125	89	99
15-2-7	15%	1,798	344	0	270	52	0	107

Table 3.3 (Continued) Maryland Fertilizer Consumption

15-5-15	15%	946	652	360	142	98	54	98
15-6-17	15%	846	498	448	127	75	67	90
15-10-10	15%	335	1,057	560	50	159	84	98
15-15-15	15%	3,081	2,410	2,394	462	362	359	394
15-30-15	15%	3,089	2,431	1,895	463	365	284	371
16-8-8	16%	1,467	1,195	1,318	235	191	211	212
18-5-9	18%	390	396	363	70	71	65	69
18-46-0	18%	17,080	7,257	3,706	3,074	1,306	667	1,683
19-19-19	19%	2,401	1,989	2,331	456	378	443	426
20-10-10	20%	483	433	337	97	87	67	84
24-4-10	24%	1,212	725	1,077	291	174	258	241
28-3-3	28%	978	1,494	554	274	418	155	282
29-3-4	29%	749	1,032	0	217	299	0	172
30-10-10	30%	607	599	505	182	180	152	171
36-6-6	36%	338	379	0	122	136	0	86
				Total=	13,548	10,002	7,674	10,408

Lime

To calculate CO_2 emissions it is assumed that for every molecule of $CaCO_3$, one molecule of CO_2 is produced. For an initial conservative estimate of emissions from this source, it is also assumed that 100 percent of the calcium carbonate is converted to CO_2 in the same year the lime is applied. Although lime is not applied annually, the field will eventually return to the initial pH, thus requiring additional treatment. This indicates that all of the $CaCO_3$ has been converted or removed by other mechanisms. Because limestone application frequency is on a much shorter time frame than the life span of CO_2 relatively little error is introduced by the assumption that all CO_2 is emitted in the first year of application. Based on these assumptions, CO_2 emissions from lime application are:

$$CO_2 = CaCO_3 \text{ applied (tons)} * 44CO_2/100CaCO_3$$

This method probably overestimates the amount of CO_2 released because it does not account for leaching of calcium carbonate or the possibility of entering other chemical or biological pathways that do not result in CO_2 emissions.

Lime application would normally be calculated using a three-year average of consumption centered on the target year (1990) to calculate emissions. However, consumption data were not available in a usable form for years prior to 1991. Therefore, the three year average was taken from 1991 to 1993. Average lime consumption was 5,973 tons in Maryland. Averaging is used to minimize annual fluctuations in consumption due to economic and weather factors that affect agricultural activity. All lime consumption data were obtained from the *Annual Fertilizer Tonnage Reports* published by the Maryland Department of Agriculture (DOA, 1991)

Results

Fertilizer

Nitrous oxide emissions are reported as ranges. Emission factors giving low, median, and high emission estimates are provided for each of the six EPA nitrogen fertilizer categories. These emission factors are the result of field tests and laboratory experiments measuring soil emission for individual fertilizer types (Bouwman, 1990).

Maryland nitrous oxide emissions are presented in Table 3.4 in terms of nitrogen and N_2O for individual EPA fertilizer types. The range of emissions is quite wide with the low at 238 tons-N_2O and the high at 3,818 tons-N_2O.

Surprisingly, the sum of median emissions is at the lower end of the range, 483 tons-N_2O. Several factors contribute to this extreme range. First, the categories of the Other Single-Nutrient Nitrogen Fertilizers and Multiple-Nutrient Nitrogen Fertilizers include all complex fertilizers that do not readily fall into a specific fertilizer type. Consequently, the experimental range of emissions from these groups are very large compared to most other categories. In Maryland, these fertilizer groups comprise a large portion of fertilizer consumption. Second, the range of emission factors for the high consumption fertilizers (anhydrous and aqueous ammonia) is very large. However, median emission factors for all fertilizer types tend toward the lower end of the ranges, indicating that most emission occur at these levels, and only rarely do emission occur in the upper end of the range.

Table 3.4 Nitrous Oxide Emissions Fertilizer Use in Maryland

Fertilizer Type	Fertilizer Consumption 3 Yr. Average (tons-N)	Emission Factor (% N_2O-N)			N_2O-N Emissions (tons N_2O-N)			N_2O Emissions (tons-N_2O)		
		Median	Low	High	Median	Low	High	Median	Low	High
Anhydrous and Aqua Ammonia	17,203	1.63%	0.86%	6.84%	280	148	1,177	441	232	1,849
Ammonium Nitrate Types	710	0.26%	0.04%	1.71%	2	0	12	3	0	19
Ammonium Types	2,019	0.12%	0.02%	1.5%	2	0	30	4	1	48
Urea	3,540	0.11%	0.07%	1.5%	4	2	53	6	4	83
Other Single-Nutrient Nitrogen Fertilizers	6,512	0.11%	0.001%	6.84%	7	0	445	11	0	700
Multiple-Nutrient Nitrogen Fertilizers	10,408	0.11%	0.001%	6.84%	11	0	712	18	0	1,119
Total	40,392				307	151	2,430	483	238	3,818

Lime

CO_2 emissions from the initial estimates are 2,628 tons per year. The calculation is shown below.

CO_2 tons = 5,973 tons $CaCO_3$ * 44/100 = 2,628 tons

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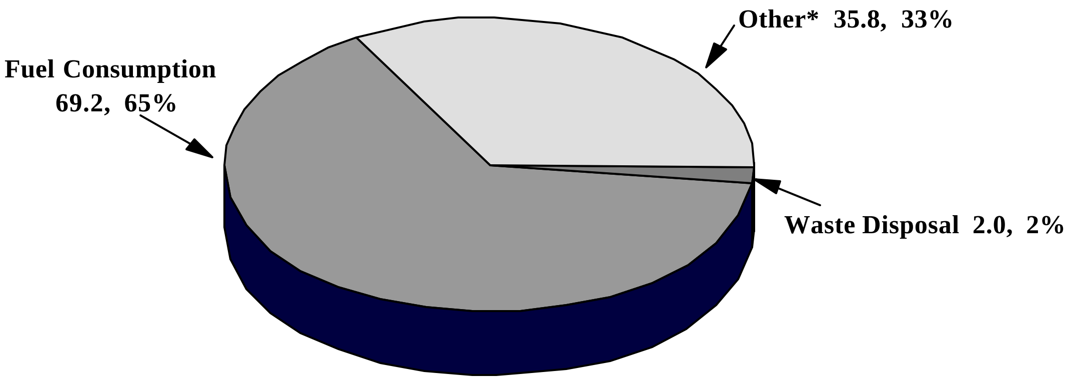
4. WASTE DISPOSAL, TREATMENT, AND RECOVERY

This section documents the methodology and data used to estimate greenhouse gas emissions associated with the disposal of anthropogenic waste through landfill. The open burning of agricultural crop residues in fields is also included in this category. Since open burning is not a common practice in Maryland, it generates negligible emissions. Greenhouse gas emissions from Waste Disposal, Treatment, and Recovery sources are summarized by source category and percent gas composition in Figure 4.1.

Of the sources included in this category, only land filling and the open burning of crop wastes are included in the EPA *States Workbook* (USEPA, 1992) as a source of greenhouse gases.

Figure 4.1 Maryland 1990 Greenhouse Gas Emissions from Waste Disposal by Source Category

(million tons, CO2 equivalent)



*** Includes Production Processes, Agriculture, and Land Use Change**

4.1 Landfills

Overview

Methane (CH_4) and carbon dioxide (CO_2) are produced from the anaerobic decomposition of organic material in landfills by methanogenic bacteria. Landfills are the largest single anthropogenic source of methane emissions in the U.S. (USEPA, 1993). While landfill gas contains equal amounts of CH_4 and CO_2 , CO_2 emissions from landfills are relatively small compared to CO_2 emissions from other sources.

Methane and carbon dioxide are produced as the organic content in paper, food wastes, yard wastes, and other organic materials are decomposed in an oxygen-free environment. Generally municipal solid waste (MSW) comprises the majority of the waste responsible for landfill gas emissions (USEPA, 1993), but some land filled industrial wastes are important contributors in Maryland as well.

Landfill gas production typically begins one or two years after waste placement in a landfill, and may last from 10 to 60 years (USEPA, 1993). Unless this gas is collected for energy recovery or flared to destroy the methane, these emissions are released directly to the atmosphere. During flaring, approximately 98% of the methane is converted to carbon dioxide (USEPA, 1992).

Landfill gas emissions can be summarized by the following equations:

$$CH_4 \text{ Emissions} = CH_4 \text{ Generation} - CH_4 \text{ Combustion due to flaring/recovery}$$
$$CO_2 \text{ Emissions} = CO_2 \text{ Generation} + CO_2 \text{ Production due to flaring/recovery}$$

Some factors influencing the rate of landfill gas generation by a given landfill include (USEPA, 1991):

1. Waste composition
2. Moisture content
3. Landfill Temperature
4. pH
5. Anaerobic vs. Aerobic conditions
6. Size and type of landfill

Due to many variables influencing gas generation, emission rates from landfills may vary widely in different regions in the country because of differences in climate, and also locally between landfills due to differences in waste composition and landfill design variables. Few measurements are available of actual CH_4 and CO_2 production from landfills (USEPA, 1993). Consequently, emissions can be estimated in one of three ways:

1. By making simplifying assumptions, i.e. % Degradable Organic Carbon (DOC)

content and % DOC dissimilated to form biogas (Bingemer and Crutzen, 1987).

2. By using computer models, with detailed specific landfill conditions as inputs, like the Landfill Air Emissions Estimation model, a theoretical first order kinetic model of methane production developed by the EPA, or like the Scholl-Canyaon model (Emcon Associates, 1980).

3. By inferring gas emission rates based on measured data from methane collection and recovery systems (USEPA, 1993).

For landfill gas emissions, the state of Maryland used method #2. The EPA *States Workbook* (USEPA, 1992) recommended using method #1, but this yielded higher emission estimates than seemed appropriate for Maryland.

Methodology

The methodology employed to calculate landfill greenhouse gas emissions was drawn from a theoretical first-order kinetic model of methane production, known as the Landfill Air Emissions Estimation model, developed by the EPA. This model was used for each landfill site in Maryland to calculate their greenhouse gas emissions.

A detailed study and description of the Landfill Air Emissions Estimation model is included in Appendix A of this report.

Results

The Landfill Air Emissions Estimation model was employed for each landfill sites in Maryland to calculate greenhouse gas emissions. Table 4.1 shows the CH_4 and CO_2 emissions in Mg/yr and Tons/yr.

Table 4.1 1990 Methane and Carbon Dioxide Emissions from Landfill Studies in Maryland

Study	CH_4 Mg/yr	CH_4 Tons/yr	CO_2 Mg/yr	CO_2 Tons/yr
AA-FORT	1,935	2,133	5,310	5,853
BLT-BAT	735	811	2,018	2,224
BLT-HERN	2,268	2,500	6,222	6,859
BLT-TEX	1,803	1,987	4,946	5,452
BLT-PARK	2,155	2,375	5,913	6,518
MON-GUDE	7,350	8,102	20,170	22,234
PG-BROWN	12,730	14,032	34,920	38,493
PG-BS2	NA	NA	NA	NA
MARY-CLE	265	292	727	801
ALL-VALE	2,854	3,146	7,830	8,631
ALL-WEST	844	930	2,314	2,551
BC-QUAR	167	184	459	506
CEC-CENT	1,977	2,179	5,425	5,980
GAR-RG	1,448	1,596	3,973	4,379
GAR-DS	NA	NA	NA	NA
HAR-HWD	838	924	2,299	2,534
CARL-HOB	1,900	2,094	5,213	5,746
MARY-AND	1,394	1,537	3,824	4,215
DOR-BEUL	721	795	1,979	2,181
DOR-GOLD	186	205	511	563
DOR-SECR	540	595	1,481	1,633
MARY-AN2	NA	NA	NA	NA
DOR-HUNT	NA	NA	NA	NA
AA-MIL	12,490	13,768	34,280	37,787
BLT-SW	1,757	1,937	4,821	5,314
CALV-BAR	1,143	1,260	3,137	3,458
CALV-APP	NA	NA	NA	NA
QA-GLD	133	146	364	401
QA-PC	46	51	127	140
QA-CENT	1,096	1,208	3,008	3,316
AA-ANAPL	1,391	1,533	3,818	4,209
SOMERSET	753	830	2,067	2,278
BLT-EAST	5,243	5,779	14,390	15,862
CAR-NORT	573	632	1,573	1,734
PG-BRWN	16,270	17,935	44,650	49,218
CHR-PIS	2,715	2,993	7,450	8,212
ALL-MNT	NA	NA	NA	NA
BC-WOOD	2,179	2,402	5,978	6,590
BC-BOW	1,114	1,228	3,056	3,369
NC-PENN	2,760	3,042	7,574	8,349
HOW-CARR	56	62	154	170
HOW-NEW	1,549	1,707	4,250	4,685
TAL-EAST	1,219	1,344	3,346	3,688
PG-SHILL	8,169	9,005	22,410	24,703
WASH-RES	3,146	3,468	8,632	9,515
WASH-HAN	192	212	527	581
WICOM-NE	3,805	4,194	10,440	11,508

Table 4.1 (Continued) 1990 Methane and Carbon Dioxide Emissions from Landfill Studies in Maryland

Study	CH_4 Mg/yr	CH_4 Tons/yr	CO_2 Mg/yr	CO_2 Tons/yr
WOR-CENT	NA	NA	NA	NA
HOW-ALPH	5,681	6,262	15,590	17,185
FRED-REC	4,962	5,470	13,620	15,013
CHR-WAL	NA	NA	NA	NA
AA-SUD	1,057	1,165	2,901	3,198
MDREGION	NA	NA	NA	NA
MON-OWK	10,490	11,563	28,770	31,713
TOTALS	132,100.	145,615	362,467	399,552

4.3 Open Burning of Agricultural Crop Residues

The EPA *States Workbook* (USEPA, 1992) lists crop residue burning as a significant source of methane, carbon monoxide, nitrogen oxides, nitrous oxide. Open burning of crop residues is not a common practice in the State of Maryland and therefore the emissions from this category are negligible.

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5. LAND USE CHANGES

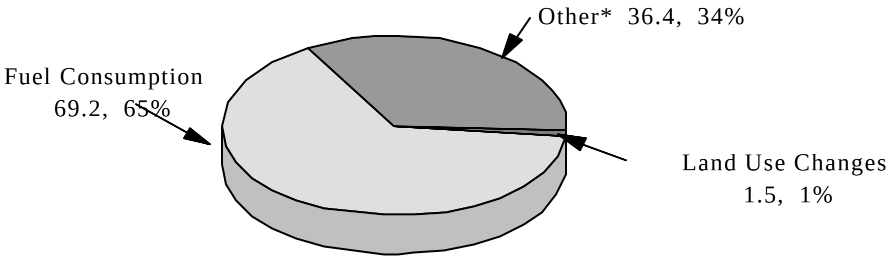
Land use changes that result in alterations in the amount of biomass (organic materials) on that land, produce a net exchange of greenhouse gases between the atmosphere and land surface (OEDC, 1991).

This report looks at the impact of the following land use changes: Greenhouse gas emissions from this land use change source are summarized in Figure 5.1.

-- Conversion of forest to permanent cropland, pasture, or other uses
-- Establishment of plantations and other tree-planting activities
-- Drainage of wetlands
-- conversion of pasture to cultivated land
-- conversion of nonforest land to urban and rural development

Figure 5.1 Maryland 1990 Greenhouse Gas Emissions from Land Use Changes by Source Category

(million tons, CO2 equivalent)



* Includes Production Processes, Agriculture, and Waste Disposal

Forest, pasture, cropland, wetland and development figures are from *Summary Report, 1992 National Resources Inventory* (NRI, July 1994). The EPA *States Workbook* has three additional land use change categories: Non-sustainable logging, forest degradation and mortality from air pollution, and flooding of lands.

Maryland practices sustainable logging, so no emissions were estimated for this category. When the forest is allowed to regrow, the growing vegetation absorbs atmospheric carbon dioxide, and over time CO_2 uptake equals CO_2 emissions (i.e., the net exchange of CO_2 is zero) (USEPA, 1992).

Emission due to forest degradation and mortality from air pollution were not included in this report. Though the forest inventory shows some mortality of the growing-stock over a five year period, most mortality was of unknown or natural causes. Wind, fire (natural, accidental, or arson), insects (budworms, borers, etc.), and other natural causes (Dutch elm disease, blister rust, cankers, etc.) have damaged some of the timberland in the past. Some of the observed damage was the result of human activities. These human activities are generally the result of deliberate changes in land use management and are accounted for in other categories in this section. Available information does not allow for determining the percent mortality attributable to pollution.

Emissions due to flooding lands were not significant for Maryland for the 1990 base year. Few acres are flooded annually and an equivalent amount of dammed areas are usually reclaimed. Most damming of Maryland waters took place earlier in this century and the impact regarding emissions has already taken place.

5.1 Forest Conversion

Overview

Forests covered 2.4 million acres in the latest Maryland forest inventory. The 1992 National Resources Inventory (NRI) is the latest in a series of inventories conducted by the U. S. Department of Agriculture's Natural Resources Conservation Service. It provides updated information on the status, condition, and trends of land, soil, water, and related resources on the Nation's nonfederal land. The 1992 NRI is unique in that it provides a nationally consistent database that was constructed to estimate 5- and 10-year trends from 1982 to 1992. As a more comprehensive and more recent land use change summary, this inventory was used to calculate the impact on greenhouse gases from land use conversions.

The most recent data available were used in this initial greenhouse gas inventory. In the future, it is recommended that a more up to date carbon emission estimate be calculated from biomass changes. Data are now being compiled on biomass / carbon conversions by tree type.

Maryland contains 6,694,500 acres of total area. Of this area 649,000 acres (NRI, 1994) are water and federal land. Forest changes on federal lands are assumed to be negligible for this study.

Methodology

The EPA *States Workbook* methodology was followed. This methodology requires the following steps to estimate net CO_2 emissions from forest gain and loss.

Step 1 Calculate Net Release of Above Ground Carbon

Assumptions used in these calculations were :

68,662 lbsC/acre is the average carbon storage in Maryland trees
(USEPA, 1992, Table 10-1)
41% of carbon contained in aboveground biomass (USEPA, 1992, page 10-2)
14.076 tons C/acre released (68662 x .41 / 2000 lb/ton)
2 tons C/acre assumed for regrowth

*CO_2 emissions = (forest acres lost) x [(ton C/acre released)-(ton C/acre regrowth)] * (44ton CO_2 /12 tonC)*

CO_2 = (27,000 acres)(14.076 - 2 tonC/acre)(44/12) = **1,195,524 tons CO_2**

Step 2: Calculate Emissions from Soil Disturbances

Assumptions used in this calculations were:

72.353 tons soil C/acre (USEPA, 1992, Table 10-2)
50 % of carbon is released from the soil (USEPA, 1992, page 10-20
36.177 tonC/acre released (72.353 x .50)
25 year average release (USEPA, 1992, page 10-2)
0.00154 tons N_2O-N/acre released

CO_2 emissions = (forest acres lost)x(ton C/acre released)/(average annual release)x(44ton CO_2/12tonC)
N_2O emissions = (forest acres lost)x(ton N_2O-N/acre released)x(44 ton N_2O / 14 ton N_2O-N)

CO_2 = [(27,000 acres)(36.177 tonC/acre)/(25 years)] (44/12) = **143,261 tons CO_2**

N_2O = (27,000 acres)(0.00154 ton N_2O-N/acre)(44/14) = **130.7 tons N_2O**

Results

Table 5.1 1990 Greenhouse Gas Emissions from Forest Conversion in Maryland

	Number of Acres	CH_4 Emissions tons	N_2O Emissions tons	CO_2 Emissions tons
Forest Land Lost	27,000 acres		130.7	1,338,785

5.2 Drainage of Wetlands

Overview

Maryland Statutes define a wetland as “an area where water is at, near, or above the land surface long enough to be capable of supporting aquatic or hydrophilic (water loving) vegetation and which has soils indicative of wet conditions.”

Wetland = wet soils + water near surface + potential for wetland plants

Freshwater wetlands are natural source of methane due to anaerobic decomposition of organic material in the wetland soils and sediments. Destruction of freshwater wetlands, through drainage or filling, results in a reduction of methane emissions, and an increase in carbon dioxide emissions due to increased oxidation of soil organic material (USEPA, 1992).

The 1992 National Resources Inventory (NRI) is the latest in a series of inventories conducted by the U. S. Department of Agriculture’s Natural Resources Conservation Service. It provides updated information on the wetlands and deep water habitats on nonfederal land and water areas. The 1992 NRI indicates that there were a total of 7,700 acres of wetlands lost in Maryland between 1982 and 1992.

Methodology

The EPA *States Workbook* methodology was followed. In this method, there is a methane emission reduction and a carbon dioxide emission increase due to wetland draining. 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.

Gain and 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 (USEPA, 1992).

Reduction in CH_4 emissions

Assumptions used in these calculations were:
0.08 lb CH_4-C/acre/day emitted before drainage (USEPA, 1992, page D10-19)
0.005 lb CH_4-C/acre/day emitted after drainage (USEPA, 1992, page D10-19)
169 days flooded (OECD, 1991)

CH_4 reduction = (acres drained) x [(ton/acre CH_4-C emission after drainage) - (ton/acre CH_4-C emission before drainage)] x (days flooded) x ($16CH_4/12C$)

CH_4 = (7,700 acres)(-0.0000375tonCH_4-C/acre/day)(169 days)(16/12) = **-65.07 tons CH_4**
(note: minus indicates methane reduction)

Increase in CO_2 emissions

Assumptions used in these calculations were:
0.0007 lbs CO_2-C/acre/day emitted before drainage (USEPA, 1992, page D10-19)
0.018 lbs CO_2-C/acre/day emitted after drainage (USEPA, 1992, page D10-19)
169 days flooded (OECD, 1991)

CO_2 emissions = (acres drained) x [(ton/acre CO_2 -C emission after drainage) - (ton/acre CO_2-C emission before drainage)] x (days flooded) x (44CO_2 -C/12C)

CO_2 = (7,700 acres)(0.0000086ton CO_2-C/acre/day)(169 days)(44/12) = **41 tons CO_2**

Results

The draining of wetlands reduces methane emissions to the atmosphere and increases carbon dioxide emissions. The draining of wetland in Maryland in recent years has not been a significant source of greenhouse gas emissions. In fact, it appears that the draining of wetlands results in a net decrease in greenhouse gas emissions because of the reductions in methane emissions which occur when wetlands are drained. This may in turn be offset by the loss of biomass carbon storage and deposition in wetland ecosystems.

Table 5.2 1990 Greenhouse Gas Emissions Due to Wetland Drainage in Maryland

	Number of Acres	CH_4 Emissions (tons)	N_2O Emissions (tons)	CO_2 Emissions (tons)
Wetland Lost	7,700 acres	-65		41

5.3 Conversion of Nonforestland to Urban and Rural Development

Overview

This category includes the conversion of cropland and pasture to urban development, farmstead buildings, roadways, etc. Forest land that was developed is included in Section 5.1, Forest Conversion. Development of nonforest land will affect net CO_2 , CH_4, and N_2O emissions. Such a land use change will likely result in CO_2 emissions due to a reduction in both biomass carbon and soil carbon. There is a reduction in methane uptake and a net carbon dioxide release whenever biomass / soil use are used. Emission factors for methane were not available.

Methodology

Net CO_2 Release

Assumptions used in these calculations were:

1.10 tonC/acre before pasture conversion (Handerson, 1993)
0.49 tonC/acre before cropland conversion (Jackson, 1992)
0.0 tonC/acre after development

CO_2 emissions= (acres converted) x [(ton/acre CO_2 -C emission before conversion) - (ton/acre CO_2 -C emission after conversion)] x ($44CO_2/12C$)

$CO_{2\ \text{pasture}}$ = (4,000 acres)(1.10 ton CO_2/acre)(44/12) = **16,133 tons CO_2**

$CO_{2\ \text{cropland}}$ = (67,000 acres)(0.49 ton CO_2/acre)(44/12) = **120,377 tons CO_2**

Results

This is another category which appears to have an insignificant contribution to greenhouse gas emissions in Maryland. There is no methodology at this time to calculate methane or nitrous oxide due to nonforest development.

Table 5.3 1990 Greenhouse Gas Emissions Due to Cultivated Pasture in Maryland

	Number of Acres	CH_4 Emissions (tons)	N_2O Emissions (tons)	CO_2 Emissions (tons)
Developed Pasture	4,000 acres	--	--	16,133
Developed Cropland	67,000 acres	--	--	120,377

References

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II. MARYLAND CARBON BUDGET

Overview

Carbon is an integral part of our environment. It is in the cells of our tissues, in the food we eat, in the plants and animals around us, and in the soil and rocks upon which we walk. Its roll, along with other gases in the atmosphere, has provided a hospitable climate in which we can live. It is the backbone in the fabric of our existence. Post-industrial human activities have had an impact on the natural cycle of carbon. Though the full extent of this impact is greatly debated, there is general agreement in the scientific community that an increase of carbon dioxide in the atmosphere has occurred.

This section provides a framework to put into perspective the impact of human activity on the biogenic carbon cycle. The Maryland Carbon Cycle Budget, Table II.8, presented at the end of this section will be used as a tool in Phase II of this study to help identify opportunities to mitigate climatic impacts by providing more carbon storage in the biosphere and decreasing carbon emissions into the atmosphere. For example, this information will allow Maryland to evaluate the impact of converting a cultivated grassland to prairie or forest.

The carbon cycle information presented in this section can be used to understand the complexities of the role carbon plays in our lives. Though there are many uncertainties in the identification of the locations and quantities of biogenic carbon, this section provides a context for looking at the issues involved in the carbon cycle. The carbon cycle can be viewed as a carbon budget. This choice of words reflects the fact that carbon is neither created nor destroyed, there is always a balance, whether it be a deficit or a surplus in the individual reservoirs.

A Global Perspective

Scientific research has focused on the global carbon cycle. Though these numbers are not available on a regional scale, it is useful to look at this information and the light in sheds on the anthropogenic impact on the global carbon cycle. Globally, anthropogenic sources represent only about five percent of the carbon cycle, but it is this seemingly minor contribution which appears to have caused an imbalance resulting in an increase in the concentration of carbon dioxide in the atmosphere. The global biogenic sources and sinks are approximately equal, i.e. the natural cycle appears to be in balance.

Worldwide Estimated Sources and Sinks of Carbon Dioxide
(billion metric tons of carbon per year)

Sources

Natural:	Biomass Respiration	22-65
	Biomass Decay	18-55
	Ocean Release	100-110
Anthropogenic:	Fossil Fuel Burning	5.5-6.5
	Industrial Sources	approx 0.1
	Deforestation and Land Use Changes	1.1-3.6

Sinks

Natural:	Biomass Photosynthesis	102.5-112.5
	Uptake by the Ocean	40-120
	Unidentified "Missing Sink"	2.2-3.7
	Atmospheric Increase	3.2-3.6

Source: USDOE, 1993 Note: 1 metric ton = 1.102 U.S. short ton

1. Anthropogenic Sinks

When carbon (usually in the form of carbon dioxide) is removed from the atmosphere and fixed in vegetation or land, it is called a carbon sink. There are a couple of ways in which humans can create carbon sinks. One way is by accumulation of carbon in anthropogenic reservoirs, i.e., forest products in buildings or organic material buried in landfills. Another way to create a carbon sink is by managing and enhancing the natural carbon fixing cycles, i.e., planting faster growing tree species or allowing trees to mature longer before harvesting. In the management of land-use, humans have direct impact on the biogenic carbon cycle. Anthropogenic carbon sinks have not been quantified in this greenhouse gas emission inventory. The potential for human activity to enhance the sequestering of carbon will be addressed in the second phase of this study.

2. Biogenic Sources and Sinks

There are five broad land ecosystems in Maryland: forest land; cropland; grassland; wetland; urban. Grassland includes grass, pasture, and prairie. Urban includes developed areas and minor land cover. Each of these types of ecosystems have their own carbon cycles and are treated individually. For most of these ecosystems, acreage figures from the 1992 National Resources Inventory (NRI, 1994) were used to estimate carbon fluxes in Maryland (see Table II.1). Carbon flux is the term used to describe the movement of carbon from one reservoir to another, i.e. from plants to soil or to the atmosphere, or from one form to another.

Table II.1 **1990 Maryland Land-Use by Land Class in Acres**

Land Class	Acreage Used in This Study
Forest Land	2,550,300
Cropland	1,739,800
Grassland	549,500
Wetlands	1,449,000
Water Area	489,700
Urban	1,029,600
Total Acres	6,694,500

Open Water

Lakes and streams comprise 489,700 acres, 7.3% of Maryland's 6,694,500 acres. Primary productivity is the amount of biomass created by plants in the ecosystem over a specified period of time. The mean net primary productivity for lakes and streams is 0.225 kg C/m^2/year (1.0 ton C/acre/year) (Woodwell, et al, 1972). The total carbon flux in Maryland from lakes and streams is 490,000 tonsC/year (see Table II.2).

Table II.2 **Carbon in Maryland's Surface Water**

Reservoir of Carbon					Unit Carbon Flux (TonsC/Acre/Year)			Total Carbon Flux (1,000 ton C/Year)		
Storage Location	Area/Vol	Unit Carbon Stored (TonC/Unit)	Total Stored	Average Residence Time (yr)	In	Out	Net	In	Out	Net
Plants	489,700 Acres						1.0			490

Sources: Acres -- *1992 National Resources Inventory*; lbs C/Acre -- *Carbon and the Biosphere*, Woodwell et al, 1972

Wetlands

Wetland vegetation and peat are major carbon sinks. Wetlands with continual standing water also provide anaerobic conditions for the production of methane (CH_4). The emission rate varies greatly with wetland type, hydrologic cycles, temperature, growing days, and soil organic content. Usually, wetlands with higher organic soil content and nutrient levels are more biologically productive and therefore also greater methane producers.

There are different surveys of the number of acres of wetlands in Maryland. The 1992 National Resources Inventory (NRI) reported Maryland to have 1,449,000 acres of wetlands and that acreage was used in this study.

Methane emission rates may vary from an average of 11 mgC/m^2/day (0.10 lbsC/acre/day) for bogs to 299 mgC/m^2/day (2.665 lbsC/acre/day) for marshes (OECD, 1991). Maryland's 1,449,000 acres of wetlands are estimated to produce 11,954 to 26,299 tons CH_4- per year.

The mean net primary productivity for swamp and marsh vegetation is 1.125 kg C/m^2/year (5.0 ton C/acre/year) (Woodwell et al., 1972).

$$ton\ C = acres * tonC/acre$$

Table II.3 Carbon in Maryland's Wetlands

Reservoir of Carbon					Unit Carbon Flux (TonsC/Acre/Year)			Total Carbon Flux (1,000 ton C/Year)		
Storage Location	Area/Vol	Unit Carbon Stored (TonC/Unit)	Total Stored	Average Residence Time (yr)	In	Out	Net	In	Out	Net
Plants	1,449,000 Acres						5.0			7,425

Sources: Acres -- *1992 National Resources Inventory*; lbs C/Acre --
Plants ton C/acre -- Woodwell et al, 1972; and OECD, 1991

Note: dissolved carbon in the water is included in surface water.

Forestland

Forestland is a major biogenic carbon sink in Maryland, with an average of 68,662 pounds of carbon stored both above (41%) and below (59%) ground per acre of forest ((USEPA, 1992, Table 10.1). In the 1992 National Resources Inventory (NRI), Maryland is reported to have 2,391,000 acres of nonfederal forestland and 159,300 acres of other federal forest land. These 2,550,300 acres account for 38.1% of Maryland's total acreage. Forestland is defined in the 1992 NRI as land with at least 10% single stemmed trees which will be at least 13 feet in height at maturity. This includes a minimum of 25% canopy.

A mature forest has a greater biomass and is therefore a better carbon storehouse than an immature forest. The 1992 National Resources Inventory (NRI) states that 2.6 million acres of timberland had an above ground green biomass, including all live trees at least 1 inch in diameter at breast height (d.b.h.), of 169 million green tons (an average of 65 tons per acre). Converting this number to 50% dry weight, and including both the 41% above and the 59% below ground carbon; and assuming 45% carbon per dry weight, yields 2.3 tonC/acre. This number may be high given that most timberland in Maryland is actively managed to be productive, and that forest inventory's definition of 'timberland' does not include woodlands and other 'forestland'.

EPA uses 68,662 lbsC/acre (34.33 tonC/acre) (USEPA, 1992) as the average amount of carbon stored in Maryland trees.

In addition to the carbon already stored in the forests, there is the annual production of biomass, called primary productivity. This is the rate at which biomass is accumulated, i.e., the flux of carbon from the atmosphere into the forest. For Maryland's woodlands and forests, this can range from 1.2 tons C/acre/year for woodland and shrubland to 2.6 tons C/acre/year for evergreen forest (Woodwell et al, 1972).

Carbon is held in wood products that are used in construction, from which the carbon will not be released into atmosphere until the product burns or decays. Maryland's wood products are used for fuel, paper, pulpwood, saw logs and veneer. Maryland practices sustainable logging, so there is a continual replenishment of biomass as it is removed for other uses.

In Maryland, 3,515 acres of forest burned in wildfires in 1990 (Maryland 1990 Annual Forest Fire Report). These acres are returning to forested land, therefore the carbon released through burning will be sequestered in to forest as it matures over a 45 to 60 year timespan (USEPA, 1992). This is apart of the carbon flux.

Things which can be changed to affect the total carbon stored in forests include: types of trees planted, average years to maturity(controlled by rate of harvest), growing conditions, and forest size.

Table II.4 Carbon in Maryland’s Forests

Reservoir of Carbon					Unit Carbon Flux (TonsC/Acre/Year)			Total Carbon Flux (1,000 ton C/Year)		
Storage Location	Area/Vol	Unit Carbon Stored (TonC/Unit)	Total Stored	Average Residence Time (yr)	In	Out	Net	In	Out	Net
Plants	2,550,300 Acres	34.33	87,551,800				1.2 to 2.6			3,060 to 6,631

Sources: Acres -- *1992 National Resources Inventory*; lbs C/Acre -- *Carbon and the Biosphere*, Woodwell et al, 1972

Grassland, Pasture and Prairie

There are 549,500 acres of ‘pastureland’, 8.2% of Maryland’s acreage. The 1992 National Resources Inventory defines this land cover as land used primarily for production of introduced or native forage plants, regardless of whether or not it’s being grazed by livestock. The ground cover includes grasses, legumes and other vegetable cover (NRI).

Though the carbon content of the pasture is not known, the dry-weight of biomass on prairies and other grasslands in Maryland can range from 100 g/m^2 (0.446 ton/acre) to 1,500 g/m^2 (6.685 ton/acre), depending on the soil moisture and fertility of the site. This yields a range of 0.201 to 3.008 tonC/acre of above ground biomass. The lower end of the range would fit for pasture and the high end would fit for a productive prairie. These numbers only include above ground biomass and do not take into account the soil carbon. An overall average of 550 g/m^2 (2.45 ton biomass/acre), with 45% of the dry weight being carbon (Jackson, 1992) was used.

Woodwell et al (1972) give a net primary productivity of 1.0 tonC/acre/year for temperate grassland.

Table II.5 Carbon in Maryland's Grass, Pastures and Prairies

Reservoir of Carbon					Unit Carbon Flux (TonsC/Acre/Year)			Total Carbon Flux (1,000 ton C/Year)		
Storage Location	Area/Vol	Unit Carbon Stored (TonC/Unit)	Total Stored	Average Residence Time (yr)	In	Out	Net	In	Out	Net
Plants	549,500 Acres						1.0			550

Sources: Acres -- *1992 National Resources Inventory*; lbs C/Acre --
Plants ton C/acre -- Woodwell et al, 1972; and OECD, 1991

Cultivated Cropland

The majority of arable crops are annuals and leave no standing live biomass as the plant is usually harvested at the end of each year. The harvested portion will either be exported from the farm, or will be used on the farm for feeding livestock. It is assumed that the portion of the crop fed to animals but undigested will be returned to the land and, along with the unharvested portion of the crop, will be incorporated into the soil. Changes in biomass carbon are assumed to occur within a short growing cycle (Adger et al, 1991).

Agroecosystems primarily exchange three gases -- CO_2 , CH_4, and CO -- with the atmosphere. Cultivated crops cycle CO_2 , retaining some of the carbon in the plant and soil. Soils also sequester carbon through the fixation of atmospheric CH_4, CO_2 and CO (Jackson, 1992). Cultivated plants become food for humans or animals, or become a waste product, returning the carbon to the soil. Fertilizers and animal manure are considered under anthropogenic sources in other sections of this report.

The size of the soil carbon sink depends on the physical, chemical and biological structure of the cultivated land. Cropland biomass varies with crop planted, fertilizer used, soil moisture, etc. Maryland agricultural net primary productivity ranged from 186 g dry biomass/m^2/year (0.829 ton/acre/yr) to 300 g/m^2/year (1.337 ton/acre/yr). The carbon fraction of this biomass is assumed to be 0.45 (Jackson, 1992). This would yield an agricultural net primary productivity for Maryland with a range of 0.373 to 0.602 tonC/acre/year.

The cultivated cropland carbon storage is always changing as it goes through the cycle from seed to maturity to compost. We assume on average that the carbon fixed by one year of primary productivity is tied up in this cycle as undecomposed plant matter.

Table II.6 Carbon in Maryland's Cultivated Cropland

Reservoir of Carbon					Unit Carbon Flux (TonsC/Acre/Year)			Total Carbon Flux (1,000 ton C/Year)		
Storage Location	Area/Vol	Unit Carbon Stored (TonC/Unit)	Total Stored (1000 ton C)	Average Residence Time (yr)	In	Out	Net	In	Out	Net
Plants	1,739,800 Acres	0.373 to 0.602	649 to 1,047				0.373 to 0.602			649 to 1,047

Sources: Acres -- *1992 National Resources Inventory*; lbs C/Acre -- *Carbon and the Biosphere*, Woodwell et al, 1972

Urban, Developed, Minor Land Cover and Roadways

There were 1,029,600 acres of land that fit in this category, 15.5% of Maryland's total acres (NRI,1992). This includes quarries, sand dunes, beaches, and built-up farmsteads (minor land cover), in addition to the urban development and roadways. Though there are ornamental trees, lawns and gardens on this land, there are no reliable data on carbon storage or flux.

Table II.7 Carbon in Maryland's Urban and Developed Land

Reservoir of Carbon					Unit Carbon Flux (TonsC/Acre/Year)			Total Carbon Flux (1,000 ton C/Year)		
Storage Location	Area/Vol	Unit Carbon Stored (TonC/Unit)	Total Stored (1000 ton C)	Average Residence Time (yr)	In	Out	Net	In	Out	Net
	1,029,600 Acres									

3. Carbon Budget Summary

Reservoirs and Fluxes

Reservoirs are places were carbon is stored. For Maryland, these reservoirs include the atmosphere, water, land, and rocks. These large reservoirs are divided into ecosystems (i.e. wetlands, forests...) to be able to more clearly see the impact of land use changes, both positive and negative, on the overall carbon budget for Maryland. The ecosystems are further broken down into carbon storage locations. These include plants, animals, soil, etc. and are the form carbon takes in the particular system. For example, in the surface water ecosystem, carbon is stored as dissolved carbon in the water itself; in marine plants, organisms, and fish; and in the sediment and rocks beneath the water.

For each of these storage locations, there is either an area (e.g. acres of forested land) or a volume (cubic feet of atmosphere) that searves as the unit of measure for each particular resource. There are two major inventories, one from each of the departments of forestry and agriculture, that provide much of this information for the State of Maryland.

There are two ways in which carbon enters the 'budget' equation. One is as a reservoir, where carbon is stored in the ecosystem. The other is as a 'flux', where carbon moves from one reservoir to another (from plants to soil or atmosphere), or from one form to another. Both fluxes and reservoirs are important in the overall picture of the carbon cycle. Total carbon stored is in units of tons of carbon, and total net carbon flux is in units of tons of carbon per year.

Residence time is the length of time that carbon is held in a particular storage location and has the unit of years. In looking at the carbon cycle, it is important to take the relative time that carbon is stored into account (i.e., carbon will be stored longer in a tree than in a fish), because this offsets the total amount of carbon tied up in each part of the cycle.

This section will be updated as more research is completed and better information on carbon reservoirs and fluxes is developed. A conclusive description of the Maryland carbon budget can not be drawn at this time, and that is not the purpose of this section. The purpose of this section in the report is to begin the process of developing Maryland's carbon budget. There are many blank spaces in the Maryland Carbon Cycle Budget (see Table II.8), which will be filled as additional information becomes available.

Table II.8 MARYLAND CARBON CYCLE BUDGET

BIOGENIC RESERVOIR						BIOGENIC FLUX							ANTHROPOGENIC FLUX			BALANCE
Places	Ecosystem	Storage Location	Area/ Volume	Unit Carbon Stored (TonC/Unit)	Total Carbon Stored (TonC)	Unit Carbon Flux (tons C/unit/year)			Total Carbon Flux (1.000 ton C/year)			Residence Time	Anthropogenic Flux			Net Biogenic & Anthropo-genic
						In	Out	Net	In	Out	Net		In	Out	Net	
ATMOSPHERE		Air Subtotal														
WATER	Surface Water	Dissolved Carbon														
		Vegetation (Plants)	489,700					1.0			490					
		Microbial/Animal														
		Sediment														
		Surface Water Subtotal														
	Groundwater	Dissolved Carbon														
		Microbial														
		Groundwater Subtotal														
LAND	Wetland	Vegetation (Plants)	1,449,000					5.0			7,425					
		Microbial/Animal														
		Soil/Geology														
		Wetland Subtotal														
	Forest	Vegetation (Plants)	2,550,300					1.2-2.6			3,060--6,631					
		Microbial/Animal														
		Soil/Geology														
		Forest Subtotal														
	Grass, Pasture	Vegetation (Plants)	549,500					1.0			550					
	and Prairie	Microbial/Animal														
		Soil/Geology														
		Ecosystem Subtotal														
	Cropland	Vegetation (Plants)	1,739,800					0.373--0.602			649--1,047					
		Microbial/Animal														
		Soil/Geology														
		Cropland Subtotal														
	Urban,	Vegetation (Plants)														
	Developed	Microbial/Animal														
		Soil/Geology														
		Development Subtotal														

SUBSURFACE	Lithosphere	Subsurface Subtotal														

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III. ANTHROPOGENIC SOURCES AND SINKS NOT INCLUDED IN THE MARYLAND INVENTORY

This section addresses potential anthropogenic sources and sinks of carbon dioxide, methane, nitrous oxide, and other anthropogenic gases that have a potential impact on global warming but are not included in the estimate of Maryland greenhouse gas emissions. Although the *Maryland Greenhouse Gas Emissions Inventory* captures the majority of anthropogenic greenhouse gas emissions, the omission of the sources in this section may bias the estimate. Therefore, these sources are addressed as information to provide the most comprehensive report possible.

These emissions are not included as part of the emissions estimates for one or more of several reasons: 1) emissions could not be quantified with a degree of certainty, 2) emissions have indirect effect on global warming, and/or 3) it is not clear if sources/sinks carbon cycle in a sustainable manner or result in net emissions. Carbon emitted in a non-sustainable manner due to human activity is included in the estimates in Section I if information is available. Emissions from sustainable activities are included as part of the carbon budget in Section II.

The purpose of this section is to make the Maryland inventory as complete as possible by including greenhouse gas emission sources whose emissions cannot be quantified with any degree of accuracy at this time. As information becomes available for estimating their potential warming effect, and if deemed appropriate, these sources will be added to the estimate of Maryland greenhouse gas emissions.

1. Contributing Global Warming Gases

CO, NOx, and VOC

Carbon monoxide, nitrogen oxides (NO_x), and volatile organic compounds (VOC) have a limited direct radiative warming effect on the climate, but have a potentially large indirect effect. This is due to their reactions with other compounds in the atmosphere that produce tropospheric ozone (O_3), which is a greenhouse gas that may increase radiative forcing, and the fact that these gases alter the atmospheric lifetime of other greenhouse gases.

The generation of ozone resulting from precursor gas emissions is very difficult to predict and is highly sensitive to local meteorological factors such as sunlight, rainfall, wind, temperature, etc. Therefore, quantification of global warming potential from anthropogenic ozone generation is not possible. However, as part of the ozone State Implementation Plan (SIP), an inventory of Maryland 1990 ozone precursor emissions (VOC, CO, and NO_x) from point, area, mobile, and biogenic sources was completed by Maryland ARMA as required by the Clean Air Act of 1990.

Results of the SIP inventory are given in Table III.1 for potential future use if a methodology to determine their warming impact becomes available. These estimates include most sources in the nonattainment counties of Maryland and most major sources of any pollutant for the balance of the state. The anthropogenic SIP precursor estimates for the entire state are summarized by source type in Table III.1.

In addition to being an ozone precursor, carbon monoxide plays a more direct role in global warming as it eventually oxidizes to carbon dioxide in the atmosphere (USDOE, 1993). The VOC carbon will also eventually be oxidized to CO_2 (USDOE, 1993), but the quantification of this is difficult because of the many different organic compounds which are emitted and complex factors that affect atmospheric removal and degradation.

Table III.1 1990 Maryland Ozone Precursor Emissions

Category Source	CO (Tons/Day)	NO_x (Tons/Day)	VOC (Tons/Day)
Point Sources	412	559	62
Area Sources	151	53	297
Off-Highway Transportation	944	139	109
Mobile Transportation	2617	354	301
Total	4124	1105	769

Sulfur Dioxide

Sulfur dioxide emissions have a cooling effect by reflecting sunlight into space, either directly or through enhancement of cloud formation. The extent of this effect in counteracting radiative heating is not known but is suspected to be significant (USDOE, 1993). Combustion of fossil fuels is the primary anthropogenic source of SO_2 emissions.

Water

Water vapor with an atmospheric concentration of approximately one percent is one of the primary absorbers of infrared radiation and consequently is a large factor in global warming. However, the impact of anthropogenic emissions on the enormous quantities of water fluxing in the natural cycle is thought to be negligible in comparison (USDOE, 1993). Although human impact on the ability of natural systems to cycle water does not significantly change the atmospheric concentration, it may affect the hydrologic component of ecosystems. This impact may alter ecosystem productivity, thereby eventually changing carbon contents and natural flux rates to an extent that may become significant. This type of effect would be more pronounced over an extended period of time, and is expected to have little or no impact over a period as short as one year.

2. Other Anthropogenic Greenhouse Gas Sources and Sinks

Some sources and sinks may have been addressed to some extent in the individual source category sections, but are included here to provide a complete review of additional potential sources and sinks. A list of identified potential sources and sinks and reasons for their exclusion from the emission inventory is provided in Table III.2. Several of the source sustainable basis, i.e. no net atmospheric emission of carbon. The Table is followed by a discussion, and in some cases, an estimate of emissions for categories where information is available. Any estimates in this section are “rough” and should only be considered as order of magnitude estimates to help determine the potential significance of these sources.

Biological Processes

Biological processes utilized in wastewater treatment or that occur in natural aquatic systems as a result of human activity are a potential source of CO_2 , CH_4, and N_2O. Prevalent sources include municipal and industrial biological wastewater treatment plants (WWTP), septic systems, and contaminated aquifers. Other sources may include storm water basins, irrigated areas, and aquifer infiltration basins, and polluted natural waters. There are no established methodologies to determine emissions from these sources. However, to aid in the future study of emission sources, the biological mechanisms involved are discussed and a rough estimate of Maryland WWTP emissions is presented.

Carbon dioxide and methane emissions from these sources are typically not included in greenhouse gas emission inventories because there is no accepted estimation method and a portion of emissions may be part of biogenic carbon cycling. However, these emissions should be included because their anthropogenic flux is greater than would occur naturally, contributing to a net increase in atmospheric CO_2 concentrations.

N_2O emissions from these sources are largely ignored despite a considerable preliminary global estimate of 0.3 to 3 Tg/yr from sewage disposal and 0.8 to 1.7 Tg/yr from contaminated aquifers supersaturated with N_2O (Khalil, 1992). A considerable portion of aquifer contamination is suspected to result from microbial conversion of nitrates leaching from agricultural fertilizers and septic systems. It is estimated that approximately 5 to 30% of nitrogen fertilizer leaches or runs off (OECD, 1991). The OECD reports that N_2O emissions from aquifers contaminated by animal and human waste, cultivation, and fertilizer runoff may be three times higher than from uncontaminated aquifers (OECD, 1991).

Carbon dioxide is the byproduct of both aerobic and anaerobic microbial processes while methane is produced from only anaerobic fermentation. The general stoichiometry of these reactions are (Metcalf, 1991):

Table III.2 Potential Anthropogenic Sources and Sinks Not Included in the Maryland Greenhouse Gas Emissions Inventory

Source/Sink Category	Greenhouse Gas			
	CO_2	CH_4	N_2O	
Rice Cultivation		E	E	None in Maryland
Agricultural burning	E	E	E	None in Maryland
Forest Fires	C	C	C	Biogenic cycling
Logging	C	C	C	Biogenic cycling/sustainable in Md.
Cultivated Soils	E	S		No methodology (change in carbon content)
Irrigate/Saturated Soils		E	E	No methodology
Wastewater Biotreatment	E	E	E	No methodology
Contaminated Aquifers		E	E	No methodology / a portion may be biogenic cycling
Human and Animal Respiration	C			May be biogenic cycling
Production Processes:	E	E	E	
CO_2 co-production	E			Includes natural gas and coal co-production/ No data or methodology.
Limestone consumption.	E			Includes SOx scrubbers, iron & lead smelting, glass production, wastewater Ph adjustment
Other	E	E	E	None in Md. or no methodology
Product End-Use	E	E		CO & VOCs under SIP inventory, no activity data available for quantity of emitting marketed products.
Biomass Sequestering:	S	S	S	
Wood Structures	S			Short term carbon sequestration
Paper Products	S			Short term carbon sequestration
Landfills	S			Degradable carbon is emitted
Anesthetic Usage			E	Negligible
Propellant Usage			E	Negligible
Associated Out-of State:				
Production Proc.	E	E	E	No data available
Agriculture	E	E	E	No data available
Municipal & Hazardous Waste Export	E	E	E	Negligible & no available data, respectively

E this is believed to be a net source of emissions

S   this is believed to be a net sink of emissions
C   Carbon is believed to be cycled on a sustainable basis, i.e. net is equal to zero, neither source nor sink

Aerobic: $C_{org} + O_2 + \text{nutrients} \text{ ----> new cells} + CO_2 + H_2O + NH_3$

Anaerobic: $C_{org} + H_2O + \text{nutrients} \text{ ----> new cells} + CO_2 + CH_4$

Nitrous oxide is thought to result mainly from microbial denitrification under anaerobic or near anaerobic (anoxic) conditions (Umarov, 1990). However, generation can also occur during the oxidation of NH_3 (ammonia), known as nitrification, under aerobic conditions (Umarov, 1990). In either case, N_2O is not the primary chemical product and is produced in relatively small quantities dependent on system conditions. The following are the proposed pathways of generation.

Denitrification: $NO_3^- \text{--->} NO_2^- \text{--->} NO \text{--->} N_2O \text{--->} N_2$
(Metcalf, 1991)

Nitrification: $NH_3^+ \text{--->} NH_2OH \text{--->} NOH \text{--->} N_2O + NO_2^-$
(Umarov, 1990)

Municipal & Industrial Biological WWTP Emissions: Emissions of carbon dioxide from WWTPs was calculated by assuming that biological oxygen demand (BOD) from the wastewater approximates the amount of oxygen utilized in the eventual oxidation of carbon. This is not entirely true as a portion of the oxygen consumed is expired in water. BOD is a measure of the five day biological oxygen demand due to microbial metabolism of carbonaceous material. Annual wastewater influent and effluent BOD loadings were obtained from a state maintained database of industrial and municipal WWTP. The resulting mass of removed BOD converted to carbon dioxide roughly represents emissions from wastewater treatment. Emissions of CO_2 are also calculated assuming eventual oxidation of municipal BOD effluent mass in the receiving waters. This was not done for industrial effluents, as they are often discharged to municipal plants for further treatment. The equation for calculating CO_2 emissions from annual BOD loading is as follows:

$$CO_2\ (Tons) = BOD * 44/32$$

where: BOD = Mass O_2 consumed by microbial metabolism
44/32 = molecular conversion from O_2 to CO_2

In cases where a BOD effluent was not provided, an average statewide BOD removal rate of 90% and 85% were used for municipal and industrial plants, respectively, to calculate the annual BOD removal. This analysis assumes that all BOD converted into biomass sludge eventually degrades and oxidizes to carbon dioxide whether it is disposed off by land application, landfill (may double count landfill emissions), or incineration. It also assumes that methane produces from anaerobic digestion is combusted on-site to CO_2 for electric generation or heating processes.

Formation of N_2O is expected during anaerobic digestion, but may also occur anytime there are anaerobic conditions, such as sludge lagoons. Emissions are expected to increase as alternating aerobic/anaerobic treatment schemes used for enhanced nutrient removal are increasingly used to meet more stringent future effluent requirements. There is no method to calculate emissions, but a rough approximation can be made by allocating estimated global sewage disposal emissions by population. This calculation is as follows:

N_2O *(tons) = Global Emissions * Pop. Fraction*
*= 1.65 Tg-N/Yr. * 1.1E6 Tons/Tg * 9.35E-4 * 44/28 (N_2O)/N)*
=2667

N_2O (equivalent tons-CO_2) = 2667 * 270 = 720,005

where: Global Emissions = 1.65 = Mass O_2 consumed by microbial metabolism
Pop. Fraction = 4,781,468 (Md.) / 5.114E9 (Global- 1988) = 9.35 E-4
Global Population (Khalil,1990)
GWP for N_2O = 270

Emissions of CO, NOx, and VOCs from wastewater treatment plants and their potential impact are included in the SIP ozone precursor estimate in Table III.1. Carbon monoxide generation is also included as part of the CO_2 estimation of this section and should not be double counted if these numbers are eventually included in the Maryland Inventory.

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APPENDIX A

(Excerpt from Compilation of Air Pollution Emission Factors, Volume 1, 5th Edition, January 1995, PP. 2.4-1 to 2.4-14)

Landfills

1. General[1-4]

A municipal solid waste (MSW) landfill unit is a discrete area of land or an excavation that receives household waste, and that is not a land application unit, surface impoundment, injection well, or waste pile. An MSW landfill unit may also receive other types of wastes, such as commercial solid waste, nonhazardous sludge, and industrial solid waste. The municipal solid waste types potentially accepted by MSW landfills include:

- MSW,
- Household hazardous waste,
- Municipal sludge,
- Municipal waste combustion ash,
- Infectious waste,
- Waste tires,
- Industrial nonhazardous waste,
- Conditionally exempt small quantity generator (CESQG) hazardous waste,
- Construction and demolition waste,
- Agricultural wastes,
- Oil and gas wastes, and
- Mining wastes.

Municipal solid waste management in the United States is dominated by disposal in landfills. Approximately 67 percent of solid waste is land filled, 16 percent is incinerated, and 17 percent is recycled or composted. There were an estimated 5,345 active MSW landfills in the United States in 1992. In 1990, active landfills were receiving an estimated 118 million megagrams (Mg) (130 million tons) of waste annually, with 55 to 60 percent reported as household waste, and 35 to 45 percent reported as commercial waste.

2. Process Description[2,5]

There are three major designs for municipal landfills. These are the area, trench, and ramp methods. All of these methods utilize a three step process, which includes spreading the waste, compacting the waste, and covering the waste with soil. The trench and ramp methods are not commonly used, and are not the preferred methods when liners and leachate collection systems are utilized or required by law. The area fill method involves placing waste on the ground surface or landfill liner, spreading it in layers, and compacting with heavy equipment. A daily soil cover is spread over the compacted waste. The trench method entails excavating trenches designed to receive a day's worth of waste. The soil from the excavation is often used for cover material and wind breaks. The ramp method is typically employed on sloping land, where waste is spread and compacted similar to the area method; however, the cover material obtained is generally from the front of the working face of the filling operation.

Modern landfill design often incorporates liners constructed of soil (e. g., recompacted clay), or synthetics (e. g., high density polyethylene), or both to provide an impermeable barrier to leachate (I. e., water that has passed through the landfill) and gas migration from the landfill.

3. Control Technology[1,2,6]

The Resource Conservation and Recovery Act (RCRA) Subtitle D regulations promulgated on October 9, 1991, require that the concentration of methane generated by MSW landfills not exceed 25 percent of the lower explosive limit (LEL) in on-site structures, such as scale houses, or the LEL at the facility property boundary.

Proposed New Source Performance Standards (NSPS) and emission guidelines for air emissions from MSW landfills for certain new and existing landfills were published in the Federal Register on May 30, 1991. The regulation, if adopted, will require that Best Demonstrated Technology (BDT) be used to reduce MSW landfill emissions from affected new and existing MSW landfills emitting greater than or equal to 150 Mg/yr (165 tons/yr) of non-methanogenic organic compounds (NMOCs). The MSW landfills that would be affected by the proposed NSPS would be each new MSW landfill, and each existing MSW landfill that has accepted waste since November 8, 1987, or that has capacity available for future use. Control systems would require: (1) a well-designed and well-operated gas collection system, and (2) a control device capable of reducing NMOCs in the collected gas by 98 weight-percent.

Landfill gas collection systems are either active or passive systems. Active collection systems provide a pressure gradient in order to extract landfill gas by use of mechanical blowers or compressors. Passive systems allow the natural pressure gradient created by the increase in landfill pressure from landfill gas generation to mobilize the gas for collection.

Landfill gas control and treatment options include (1) combustion of the landfill gas, and (2) purification of the landfill gas. Combustion techniques include techniques that do not recover energy (I. e., flares and thermal incinerators), and techniques that recover energy (I. e., gas turbines and internal combustion engines) and generate electricity from the combustion of the landfill gas. Boilers can also be employed to recover energy from landfill gas in the form of steam. Flares involve an open combustion process that requires oxygen for combustion, and can be open or enclosed. Thermal incinerators heat an organic chemical to a high enough temperature in the presence of sufficient oxygen to oxidize the chemical to carbon dioxide (CO_2) and water. Purification techniques can also be used to process raw landfill gas to pipeline quality natural gas by using adsorption, absorption, and membranes.

4. Emissions[2,7]

Methane (CH_4) and CO_2 are the primary constituents of landfill gas, and are produced by microorganisms within the landfill under anaerobic conditions. Transformations of CH_4 and CO_2 are mediated by microbial populations that are adapted to the cycling of materials in anaerobic environments. Landfill gas generation, including rate and composition, proceeds through four phases.

The first phase is aerobic (e. g., with oxygen [O_2] available) and the primary gas produced is CO_2. The second phase is characterized by O_2 depletion, resulting in an anaerobic environment, where large amounts of CO_2 and some hydrogen (H_2) are produced. In the third phase, CH_4 production begins, with an accompanying reduction in the amount of CO_2 produced. Nitrogen (N_2) content is initially high in landfill gas in the first phase, and declines sharply as the landfill proceeds through the second and third phases. In the fourth phase, gas production of CH_4, CO_2, and N_2 becomes fairly steady. The total time and phase duration of gas generation varies with landfill conditions (e. g., waste composition, design management, and anaerobic state).

The rate of emissions from a landfill is governed by gas production and transport mechanisms. Production mechanisms involve the production of the emission constituent in its vapor phase through vaporization, biological decomposition, or chemical reaction. Transport mechanisms involve the transportation of a volatile constituent in its vapor phase to the surface of the landfill, through the air boundary layer above the landfill, and into the atmosphere. The three major transport mechanisms that enable transport of a volatile constituent in its vapor phase are diffusion, convection, and displacement.

4.1 Uncontrolled Emissions -

To estimate uncontrolled emissions of the various compounds present in landfill gas, total landfill gas emissions must first be estimated. Uncontrolled CH_4 emissions may be estimated for individual landfills by using a theoretical first-order kinetic model of methane production developed by the EPA.[2] This model is known as the Landfill Air Emissions Estimation model, and can be accessed from the EPA's Control Technology Center bulletin board. The Landfill Air Emissions Estimation model equation is as follows:

$$Q_{CH4} = L_o\ R\ (e^{-kc} - e^{-kt}) \tag{1}$$

where:

Q_{CH4} = Methane generation rate at time t, m^3/yr;
L_o = Methane generation potential, m^3 CH_4/Mg refuse;
R = Average annual refuse acceptance rate during active life, Mg/yr;
e = Base log, unitless;
k = Methane generation rate constant, yr^{-1};
c = Time since landfill closure, yrs (c = 0 for active landfills); and
t = Time since the initial refuse placement, yrs.

Site-specific landfill information is generally available for variables R, c, and t. When refuse acceptance rate information is scant or unknown, R can be determined by dividing the refuse in place by the age of the landfill. Also, nondegradable refuse should be subtracted from the mass of acceptance rate to prevent overestimation of CH_4 generation. The average annual acceptance rate should only be estimated by this method when there is inadequate information available on the actual average acceptance rate.

Values for variables L_o and k must be estimated. Estimation of the potential CH_4 generation capacity of refuse (L_o) is generally treated as a function of the moisture and organic content of the refuse. Estimation of the CH_4 generation constant (k) is a function of a variety of factors, including moisture, pH, temperature, and other environmental factors, and landfill operating conditions. Specific CH_4 generation constants can be computed by use of the EPA Method 2E.

The Landfill Air Emission Estimation model uses the proposed regulatory default values for L_o and k. However, the defaults were developed for regulatory compliance purposes. As a result, it contains conservative L_o and k default values in order to protect human health, to encompass a wide range of landfills, and to encourage the use of site-specific data. Therefore, different L_o and k values may be appropriate in estimating landfill emissions for particular landfills and for use in an emissions inventory.

A k value of 0.04/yr is appropriate for areas with normal or above normal precipitation rather than the default value of 0.02/yr. For landfills with drier waste, a k value of 0.02/yr is more appropriate. An L_o value of 125 m^3/Mg (4,411 ft^3/Mg) refuse is appropriate for most landfills. It should be emphasized that in order to comply with the NSPS, the model defaults for k and L_o must be applied as specified in the final rule.

Landfill gas consists of approximately 50 percent by volume CO_2, 50 percent CH_4, and trace amounts of NMOCs when gas generation reaches steady state conditions. Therefore, the estimate derived for CH_4 generation using the Landfill Air Emissions Estimation model can also be used to represent CO_2 generation. Addition of the CH_4 and CO_2 emissions will yield an estimate of total landfill gas emissions. If site-specific information is available to suggest that the CH_4 content of landfill gas is not 50 percent, then the site-specific information should be used, and the CO_2 emission estimate should be adjusted accordingly.

Emissions of NMOCs result from NMOCs contained in the land filled waste, and from their creation from biological processes and chemical reactions within the landfill cell. The Landfill Air Emissions Estimation model contains a proposed regulatory default value for total NMOCs of 8000 ppmv, expressed as hexane. However, there is a wide range for total NMOC values from landfills. The proposed regulatory default value for NMOC concentration was developed for regulatory compliance and to provide the most cost-effective default values on a national basis. For emissions inventory purposes, it would be preferable that site-specific information be taken into account when determining the total NMOC concentration. A value of 4,400 ppmv as hexane is preferable for landfills known to have co-disposal of MSW and commercial/industrial organic wastes. If the landfill is known to contain only MSW or have very little organic commercial/industrial wastes, then a total NMOC value of 1,170 ppmv as hexane should be used.

If a site-specific total NMOC concentration is available (I. e., as measured by EPA Reference Method 25C), it must be corrected for air infiltration into the collected landfill gas before it can be combined with the estimated landfill gas emissions to estimate total NMOC emissions. The total NMOC concentration is adjusted for air infiltration by assuming that CO_2 and CH_4 are the primary (100 percent) constituents of landfill gas, and the following equation is used:

$$\frac{C_{NMOC}(\text{ppmv as hexane})\ (1 \times 10^6)}{C_{CO_2}(\text{ppmv}) + C_{CH_4}(\text{ppmv})} = \begin{array}{c} C_{NMOC}\ \text{ppmv as hexane} \\ \text{(corrected for air infiltrati on)} \end{array}$$

where:

C_{NMOC} = Total NMOC concentration in landfill gas, ppmv as hexane;

C_{CO_2} = CO_2 concentration in landfill gas, ppmv;

C_{CH_4} = CH_4 Concentration in landfill gas, ppmv; and

1×10^6 = Constant used to correct NMOC concentration to units of ppmv.

Values for C_{CO_2} and C_{CH_4} can be usually be found in the source test report for the particular landfill along with the total NMOC concentration data.

To estimate total NMOC emissions, the following equation should be used:

$$Q_{NMOC} = 2\ Q_{CH_4} * C_{NMOC}/(1 \times 10^6) \qquad (3)$$

where:

Q_{NMOC} = NMOC emission rate, m^3/yr;
Q_{CH_4} = CH_4 generation rate, m^3/yr (from the Landfill Air Emissions Estimation model);
C_{NMOC} = Total NMOC concentration in landfill gas, ppmv as hexane; and
2 = Multiplication factor (assumes that approximately 50 percent of landfill gas is CH_4).

$$M_{NMOC} = Q_{NMOC} * \left[\frac{1050.2}{(273 + T)}\right]$$

The mass emissions per year of total NMOCs (as hexane) can be estimated by the following equation:

where:

M_{NMOC} = NMOC (total) mass emissions (kg/yr);
Q_{NMOC} = NMOC emission rate (m^3/yr); and
T = Temperature of landfill gas (^oC).

This equation assumes that the operating pressure of the system is approximately 1 atmosphere, and represents total NMOCs, based on the molecular weight of hexane. If the temperature of the landfill gas is not known, a temperature of 25°C (75°F) is recommended.

Uncontrolled emission concentrations of individual NMOCs along with some inorganic compounds are presented in Table 2.4-1. These individual NMOC and inorganic concentrations have already been corrected for air infiltration and can be used as input parameters in the Landfill Air Emission Estimation model for estimating individual NMOC emissions from landfills when site-specific data are not available. An analysis of the data based on the co-disposal history (with hazardous wastes) of the individual landfills from which the concentration data were derived indicates that for benzene and toluene, there is a difference in the uncontrolled concentration. Table 2.4-2 presents the corrected concentrations for benzene and toluene to use based on the site's co-disposal history.

Similar to the estimation of total NMOC emissions, individual NMOC emissions can be estimated by the following equation:

$$Q_{NMOC} = 2\ Q_{CH_4} * C_{NMOC}/(1 \text{ x } 10^6) \tag{5}$$

where:

Q_{NMOC} = NMOC emission rate, m^3/yr;
QCH_4 = CH_4 generation rate, m^3/yr (from the Landfill Air Emission Estimation model);
C_{NMOC} = NMOC concentration in landfill gas, ppmv; and
2 = Multiplication factor (assumes that approximately 50 percent of landfill gas is CH_4).

The mass emissions per year of each individual landfill gas compound can be estimated by the following equation:

$$I_{NMOC} = Q_{NMOC} * \frac{\text{(Molecular weight of compound)}}{(8.205 \text{ x } 10^{-5} \text{ m}^3\text{-atm/mol-}^{\circ}\text{K})\ (1000 \text{ g})\ (273 + T)} \tag{6}$$

where:

I_{NMOC} = Individual NMOC mass emissions (kg/yr);
Q_{NMOC} = NMOC emission rate (m^3/yr); and
T = Temperature of landfill gas (^{o}C).

Table 1. UNCONTROLLED LANDFILL GAS CONCENTRATIONS[a]

Compound	Molecular Weight	Median ppmv	EMISSION FACTOR RATING
1,1,1-Trichloroethane (methyl chloroform)*	133.42	0.27	B
1,1,2,2-Tetrachloroethane*	167.85	0.20	C
1,1,2-Trichloroethane*	133.42	0.10	E
1,1-Dichloroethane (ethylidene dichloride)*	98.95	2.07	B
1,1-Dichloroethene (vinylidene chloride)*	96.94	0.22	B
1,2-Dichloroethane (ethylene dichloride)*	98.96	0.79	B
1,2-Dichloropropane (propylene dichloride)*	112.98	0.17	C
Acetone	58.08	6.89	B
Acrylonitrile*	53.06	7.56	D
Bromodichloromethane	163.87	2.06	C
Butane	58.12	3.83	B
Carbon disulfide*	76.13	1.00	E
Carbon monoxide	28.01	309.32	C
Carbon tetrachloride*	153.84	0	B
Carbonyl sulfide*	60.07	24.00	E
Chlorobenzene*	112.56	0.20	D
Chlorodiflouromethane	67.47	1.22	B
Chloroethane (ethyl chloride)*	64.52	1.17	B
Chloroform*	119.39	0.27	B
Chloromethane	50.49	1.14	B
Dichlorodifluoromethane	120.91	12.17	B
Dichlorofluoromethane	102.92	4.37	C
Dichloromethane (methylene chloride)*	84.94	14.30	C
Dimethyl sulfide (methyl sulfide)	62.13	76.16	B
Ethane	30.07	227.65	D
Ethyl mercaptan (ethanethiol)	62.13	0.86	C
Ethyl benzene*	106.16	4.49	B
Fluorotrichloromethane	137.38	0.73	B
Hexane*	86.17	6.64	B

Compound	Molecular Weight	Median ppmv	EMISSION FACTOR RATING
Hydrogen sulfide	34.08	36.51	B
Methyl ethyl ketone*	72.10	6.13	B
Methyl isobutyl ketone*	100.16	1.22	B
Methyl mercaptan	48.10	10.43	B
NMOC (as hexane)	86.17	1170	D
Pentane	72.15	3.32	B
Perchloroethylene (tetrachloroethylene)*	165.83	3.44	B
Propane	44.09	10.60	B
Trichloroethylene*	131.40	2.08	B
t-1,2-Dichloroethene	96.94	4.01	B
Vinyl chloride*	62.50	7.37	B
Xylene*	106.16	12.25	B

[a] References 9-35. Source Classification Code 5-02-006-02. * = Hazardous air pollutants listed in the *Clean Air Act*.

Table 2. UNCONTROLLED CONCENTRATIONS OF BENZENE AND TOLUENE BASED ON HAZARDOUS WASTE DISPOSAL HISTORY[a]

Compound	Molecular Weight	Concentration ppmv	EMISSION FACTOR RATING
Benzene*	78.11		
Co-disposal		24.99	D
Unknown		2.25	B
No co-disposal		0.37	D
Toluene*	92.13		
Co-disposal		102.62	D
Unknown		31.63	B
No co-disposal		8.93	D

[a] References 9-35. Source Classification Code 5-02-006-02. * = Hazardous air pollutants listed in the *Clean Air Act*.

4.2 Controlled Emissions

Emissions from landfills are typically controlled by installing a gas collection system, and destroying the collected gas through the use of internal combustion engines, flares, or turbines. Gas collection systems are not 100 percent efficient in collecting landfill gas, so emissions of CH_4 and NMOCs at a landfill with a gas recovery system still occur. To estimate controlled emissions of CH_4, NMOCs, and other constituents in landfill gas, the collection efficiency of the system must first be estimated. Reported collection efficiencies typically range from 60 to 85 percent, with an average of 75 percent most commonly assumed. If site-specific collection efficiencies are available, they should be used instead of the 75 percent average.

Uncollected CH_4, CO_2, and NMOCs can be calculated with the following equation:

$$1 - \frac{\text{Collection Efficiency}}{100}$$

Controlled emission estimates also need to take into account the control efficiency of the control device. Control efficiencies of CH_4 and NMOCs with differing control devices are presented in Table 2.4-3. Emissions from the control devices need to be added to the uncollected emissions to estimate total controlled emissions.

Emission factors for secondary compounds (CO_2, CO, and NO_x) exiting the control device are presented in Tables 2.4-4 and 2.4-5.

The reader is referred to Sections 13.2-2 (Unpaved Roads, SCC 5-01-004-01), and Section 13.2.3 (Heavy Construction Operations) of Volume I, and Section II-7 (Heavy-duty Construction Equipment) of Volume II, of the AP-42 document for determination of associated dust and exhaust emissions from these emission sources at MSW landfills.

Table 3. CONTROL EFFICIENCIES FOR LANDFILL GAS CONSTITUENTS[a]

Control Device	Compound	Average Control Efficiency	EMISSION FACTOR RATING
IC Engine (no SCC)	Benzene*	83.83	E
	Trichloroethylene*	89.60	E
	Perchloroethylene*	89.41	E
	NMOCs (as hexane*)	79.75	E
	1,1,1-Trichloroethane*	92.47	E
	Chloroform*	99.00	E
	Toluene*	79.71	E
	Carbon tetrachloride*	98.50	E
Turbine (no SCC)	Perchloroethylene*	99.97	E
	Toluene*	99.91	E
	1,1,1-Trichloroethane*	95.18	E
	Trichloroethylene*	99.92	E
	Vinyl chloride*	98.00	E
Flare (5-02-006-01) (5-03-006-01)	Chloroform*	93.04	D
	Perchloroethylene*	85.02	C
	Toluene*	93.55	C
	Xylene*	99.28	E
	1,1,1-Trichloroethane*	85.24	C
	1,2-Dichloroethane*	88.68	E
	Benzene*	89.50	C
	Carbon tetrachloride*	95.05	D
	Methylene chloride*	97.60	E
	NMOCs (as hexane*)	83.16	E
	Trichloroethylene*	96.20	C
	t-1,2-Dichloroethene*	99.59	E
	Vinyl chloride*	97.61	C

[a] References 9-35. Source Classification Codes in parentheses. * = Hazardous air pollutant listed in the *Clean Air Act*.

Table 4 (Metric Units). EMISSION RATES FOR SECONDARY COMPOUNDS EXITING CONTROL DEVICES[a]

Control Device	Compound	Average Rate, kg/hr/dscmm Uncontrolled Methane	EMISSION FACTOR RATING
Flare (5-02-006-01) (5-03-006-01)	Carbon dioxide	85.7[b]	B
	Carbon monoxide	0.80	B
	Nitrogen dioxide	0.11	C
	Methane	1.60	C
	Sulfur dioxide	0.03	E
IC Engine (no SCC)	Carbon dioxide	85.7[b]	B
	Nitrogen dioxide	0.80	E
Turbine (no SCC)	Carbon dioxide	85.7[b]	B
	Carbon monoxide	0.32	E

[a] Source Classification Codes in parentheses.

[b] Carbon dioxide emission factors are based on a mass balance on the combustion of a 50/50 mixture of methane and CO_2.

Table 5 (English Units). EMISSION RATES FOR SECONDARY COMPOUNDS EXITING CONTROL DEVICES[a]

Control Device	Compound	Average Rate, lb/hr/dscfm Uncontrolled Methane	EMISSION FACTOR RATING
Flare (5-02-006-01) (5-03-006-01)	Carbon dioxide	5.3[b]	B
	Carbon monoxide	0.050	B
	Nitrogen dioxide	0.007	C
	Methane	0.105	C
	Sulfur dioxide	0.002	E
IC Engine (no SCC)	Carbon dioxide	5.3[b]	B
	Nitrogen dioxide	0.050	E
Turbine (no SCC)	Carbon dioxide	5.3[b]	B
	Carbon monoxide	0.021	E

[a] Source Classification Codes in parentheses.

[b] Carbon dioxide emission factors are based on a mass balance on the combustion of a 50/50 mixture

of methane and CO_2.

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APPENDIX B

1990 Greenhouse Gas Emissions Inventory
CO2 Emissions from Fossil Fuels and Biomass Fuels in Maryland

Residential	Consumption	Units	Conversion Factor Million BTU/Unit	million BTUs	Emission Coefficient (LBC C/MMBTU)	Total Carbon (TONS C)	Total C Oxidised (TONS C)	CO2 Emissions (TONS CO2)
Gasoline		Barrels	5.253	0	41.8	0.00	0.00	0.00
Distillate Oil	4284000	Barrels	5.825	24,954,300	44.2	551,490.03	545,975.13	2,001,908.81
Residual Oil		Barrels	6.287	0	46.6	0.00	0.00	0.00
LPG	1088000	Barrels	4.011	4,363,968	38	82,915.39	82,086.24	300,982.87
Kerosene	385000	Barrels	5.67	2,182,950	43.1	47,042.57	46,572.15	170,764.54
Bitu. Coal & Lignite	15000	Short tons	17.345	260,175	59	7,675.16	7,598.41	27,860.84
Anthracite Coal	2000	Short tons	21.69	43,380	59.2	1,284.05	1,271.21	4,661.09
Natural Gas	66	Billion Cu. Ft.	1030000	67,980,000	32	1,087,680.00	1,076,803.20	3,948,278.40

Commercial	Consumption	Units	Conversion Factor Million BTU/Unit	million BTUs	Emission Coefficient (LBC C/MMBTU)	Total Carbon (TONS C)	Total C Oxidised (TONS C)	CO2 Emissions (TONS CO2)
Gasoline	230000	Barrels	5.253	1,208,190	41.8	25,251.17	24,998.66	91,661.75
Distillate Oil	2095000	Barrels	5.825	12,203,375	44.2	269,694.59	266,997.64	978,991.35
Residual Oil	552000	Barrels	6.287	3,470,424	46.6	80,860.88	80,052.27	293,524.99
LPG	192000	Barrels	4.011	770,112	38	14,632.13	14,485.81	53,114.62
Kerosene	48000	Barrels	5.67	272,160	43.1	5,865.05	5,806.40	21,290.12
Bitu. Coal & Lignite	29000	Short tons	17.345	503,005	59	14,838.65	14,690.26	53,864.29
Anthracite Coal	2000	Short tons	21.69	43,380	59.2	1,284.05	1,271.21	4,661.09
Natural Gas	24	Billion Cu. Ft.	1030000	24,720,000	32	395,520.00	391,564.80	1,435,737.60

Industrial	Consumption	Units	Conversion Factor Million BTU/Unit	million BTUs	Emission Coefficient (LBC C/MMBTU)	Total Carbon (TONS C)	Total C Oxidised (TONS C)	CO2 Emissions (TONS CO2)
Gasoline	295000	Barrels	5.253	1,549,635	41.8	32,387.37	32,063.50	117,566.16
Distillate Oil	1733000	Barrels	5.825	10,094,725	44.2	223,093.42	220,862.49	809,829.12
Residual Oil	1233000	Barrels	6.287	7,751,871	46.6	180,618.59	178,812.41	655,645.50
LPG	685000	Barrels	4.011	2,747,535	38	52,203.17	51,681.13	189,497.49
Kerosene	33000	Barrels	5.67	187,110	43.1	4,032.22	3,991.90	14,636.96
Asphalt and Road Oil	5008000	Barrels	5.8	29,046,400	44.2	641,925.44	635,506.19	2,330,189.35
Lubricants	424000	Barrels	5.8	2,459,200	44.2	54,348.32	53,804.84	197,284.40
Other Liquids	4294000	Barrels	5.8	24,905,200	44.2	550,404.92	544,900.87	1,997,969.86
Bitu. Coal & Lignite	2199000	Short tons	17.345	38,141,655	59	1,125,178.82	1,113,927.03	4,084,399.13
Anthracite Coal	1000	Short tons	21.69	21,690	59.2	642.02	635.60	2,330.55
Natural Gas	62	Billion Cu. Ft.	1030000	63,860,000	32	1,021,760.00	1,011,542.40	3,708,988.80

Trasportation	Consumption	Units	Conversion Factor Million BTU/Unit	million BTUs	Emission Coefficient (LBC C/MMBTU)	Total Carbon (TONS C)	Total C Oxidised (TONS C)	CO2 Emissions (TONS CO2)
Gasoline	46617000	Barrels	5.253	244,879,101	41.8	5,117,973.21	5,066,793.48	18,578,242.76
Distillate Oil	8293000	Barrels	5.825	48,306,725	44.2	1,067,578.62	1,056,902.84	3,875,310.40
Residual Oil	1839000	Barrels	6.287	11,561,793	46.6	269,389.78	266,695.88	977,884.89
LPG	52000	Barrels	4.011	208,572	38	3,962.87	3,923.24	14,385.21
Aviation Gasoline	74000	Barrels	5.253	388,722	41.8	8,124.29	8,043.05	29,491.17

Jet Fuel	3637000	Barrels	5.67	20,621,790	44.2	455,741.56	451,184.14	1,654,341.86
Lubricants	318000	Barrels	5.8	1,844,400	44.2	40,761.24	40,353.63	147,963.30
Bitu. Coal & Lignite	0	Short tons	17.345	0	59	0.00	0.00	0.00
Natural Gas	2	Billion Cu. Ft.	1030000	2,060,000	32	32,960.00	32,630.40	119,644.80

1990 Greenhouse Gas Emissions Inventory
CO2 Emissions from Fossil Fuels and Biomass Fuels in Maryland

Utilities	Consumption	Units	Conversion Factor Million BTU/Unit	million BTUs	Emission Coefficient (LBC C/MMBTU)	Total Carbon (TONS C)	Total C Oxidised (TONS C)	Emissions (TONS CO2)
Gasoline	0	Barrels	5.253	0	41.8	0.00	0.00	0.00
Distillate Oil	598000	Barrels	5.825	3,483,350	44.2	76,982.04	76,212.21	279,444.79
Residual Oil	6234000	Barrels	6.287	39,193,158	46.6	913,200.58	904,068.58	3,314,918.11
LPG	0	Barrels	4.011	0	38	0.00	0.00	0.00
Other Liquids	0	Barrels	5.8	0	44.2	0.00	0.00	0.00
Bitu. Coal & Lignite	8945	Short tons	17.345	155,151	59	4,576.96	4,531.19	16,614.35
Anthracite Coal	0	Short tons	21.69	0	59.2	0.00	0.00	0.00
Natural Gas	18	Billion Cu. Ft.	1030000	18,540,000	32	296,640.00	293,673.60	1,076,803.20

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APPENDIX C

Table C.1 1990 Maryland Vehicle Miles Traveled (VMT) by Vehicle Type

*VMT by Vehicle Type = Total VMT * SUM(% VMT on Road System by Vehicle Type))*

	LDGV	LDGT1	LDGT2	HDGV	LDDV	LDDT	HDDV	MC
URBAN								
% PA I System	68.5000	14.6000	7.2000	3.2000	0.8000	0.2000	5.4000	0.2000
% VMT	0.2024	0.2024	0.2024	0.2024	0.2024	0.2024	0.2024	0.2024
% VMT on road system	13.8644	2.9550	1.4573	0.6477	0.1619	0.0405	1.0930	0.0405
% PA Expwy Fwy	74.1000	13.6000	6.7000	1.7000	0.8000	0.2000	2.8000	0.2000
% VMT	0.0695	0.0695	0.0695	0.0695	0.0695	0.0695	0.0695	0.0695
% VMT on road system	5.1500	0.9452	0.4657	0.1182	0.0556	0.0139	0.1946	0.0139
% PA(Principal Arterial)	72.9000	14.7000	7.2000	1.5000	0.8000	0.2000	2.5000	0.2000
% VMT	0.2010	0.2010	0.2010	0.2010	0.2010	0.2010	0.2010	0.2010
% VMT on road system	14.6529	2.9547	1.4472	0.3015	0.1608	0.0402	0.5025	0.0402
% Minor Arterial	74.4000	13.7000	6.7000	1.5000	0.8000	0.2000	2.5000	0.2000
% VMT	0.0948	0.0948	0.0948	0.0948	0.0948	0.0948	0.0948	0.0948
% VMT on road system	7.0531	1.2988	0.6352	0.1422	0.0758	0.0190	0.2370	0.0190
% Collector	75.0000	13.2000	6.4000	1.6000	0.8000	0.2000	2.7000	0.1000
% VMT	0.0490	0.0490	0.0490	0.0490	0.0490	0.0490	0.0490	0.0490
% VMT on road system	3.6750	0.6468	0.3136	0.0784	0.0392	0.0098	0.1323	0.0049
% Local Roadway	79.7000	10.2000	4.9000	1.5000	0.9000	0.2000	2.6000	0.1000
% VMT	0.0431	0.0431	0.0431	0.0431	0.0431	0.0431	0.0431	0.0431
% VMT on road system	3.4351	0.4396	0.2112	0.0647	0.0388	0.0086	0.1121	0.0043
RURAL								
% PA I System	67.7000	14.5000	7.1000	3.5000	0.8000	0.2000	5.7000	0.5000
% VMT	0.0689	0.0689	0.0689	0.0689	0.0689	0.0689	0.0689	0.0689
% VMT on road system	4.6645	0.9991	0.4892	0.2412	0.0551	0.0138	0.3927	0.0345
% PA(Principal Arterial)	65.6000	17.0000	8.4000	2.9000	0.7000	0.2000	4.9000	0.3000
% VMT	0.0864	0.0864	0.0864	0.0864	0.0864	0.0864	0.0864	0.0864
% VMT on road system	5.6678	1.4688	0.7258	0.2506	0.0605	0.0173	0.4234	0.0259
% Minor Arterial	63.9000	18.8000	9.2000	2.6000	0.7000	0.2000	4.3000	0.3000
% VMT	0.0773	0.0773	0.0773	0.0773	0.0773	0.0773	0.0773	0.0773
% VMT on road system	4.9395	1.4532	0.7112	0.2010	0.0541	0.0155	0.3324	0.0232
% Major Collector	70.9000	14.6000	7.2000	2.3000	0.8000	0.2000	3.8000	0.3000
% VMT	0.0570	0.0570	0.0570	0.0570	0.0570	0.0570	0.0570	0.0570
% VMT on road system	4.0413	0.8322	0.4104	0.1311	0.0456	0.0114	0.2166	0.0171
% Minor Collector	65.0000	19.4000	9.5000	1.6000	0.7000	0.3000	2.8000	0.7000
% VMT	0.0188	0.0188	0.0188	0.0188	0.0188	0.0188	0.0188	0.0188
% VMT on road system	1.2220	0.3647	0.1786	0.0301	0.0132	0.0056	0.0526	0.0132
% Local Roadway	65.7000	14.8000	7.6000	4.3000	0.3000	0.0000	7.2000	0.1000
% VMT	0.0317	0.0317	0.0317	0.0317	0.0317	0.0317	0.0317	0.0317
% VMT on road system	2.0827	0.4692	0.2409	0.1363	0.0095	0.0000	0.2282	0.0032
% % VMT by Vehicle Type	70.4483	14.8273	7.2861	2.3428	0.7701	0.1955	3.9174	0.2397
TOTAL VMT BY VEHICLE TYPE	**28556.48**	**6010.30**	**2953.45**	**949.65**	**312.18**	**79.25**	**1587.93**	**97.18**
(MILLION MILES)								

Table C.2 1990 Maryland Mobile Fuel Consumption by Vehicle Type

		Fraction of	1990 VMT by	Fuel	Gallons
Vehicle Type		Registration	Vehicle Type	Economy	Consumed
		Distribtn	(million miles)	(miles/gal)	(million gal)
LDGV	Auto (gas)				
<1975	Uncontrolled & Non-catalyst contr	0.059	28556.48	20.92	81
1975-1980	Oxidation catalyst	0.154	28556.48	20.92	210
1981-1988	Early three-way catalyst	0.631	28556.48	22.11	815
1989-1990	Advanced three-way catalyst	0.156	28556.48	27.99	159
					1265
LDGT1,LDGT2	Light trucks under 8500 lbs				
<1975	Uncontrolled & Non-catalyst contr	0.060	8963.75	14.09	38
1975-1980	Oxidation catalyst	0.150	8963.75	14.09	96
1981-1988	Early three-way catalyst	0.594	8963.75	16.28	327
1989-1990	Advanced three-way catalyst	0.195	8963.75	22.11	79
					540
HDGV	Heavy Duty Gas Trucks 8500+ lbs.				
<1979	Uncontrolled	0.330	949.65	10.62	30
1979-1989	Non-catalyst controls	0.620	949.65	10.62	55
1990	Three-way catalyst	0.049	949.65	10.62	4
					89
MCYC	Motorcycles				
<1978	Uncontrolled	0.167	97.18	30.11	1
1978-1990	Non-catalyst controls	0.833	97.18	50	2
					2
Total Highway Gasoline Use			**38567**		**1896**
LDDV	Diesel Autos				
<1982	Uncontrolled	0.450	312.18	20.92	7
1982-1984	Moderate controls	0.364	312.18	20.92	5
1985-1990	Advanced controls	0.186	312.18	24.93	2
					14
LDDT	Light Duty Diesel Trucks (<8500 lbs)				
<1982	Uncontrolled	0.210	79.25	14.09	1
1982-1984	Moderate controls	0.379	79.25	14.09	2
1985-1990	Advanced controls	0.411	79.25	18.11	2
					5
HDDV	Heavy Duty Diesel Trucks & Buses 8500+ lbs)				
<1979	Uncontrolled	0.092	1587.93	6.89	21
1979-1984	Moderate controls	0.238	1587.93	7.25	52
1985-1990	Advanced controls	0.670	1587.93	10.62	100

					174
Total Highway Diesel Use			**1979.41**		**193**

```
MODELYR  BY  MOBILWGT

                MOBILWGT
        COUNT I
      COL PCT I  LDGV     LDGT1    LDGT2    HDGV     LDDV     LDDT     HDDV     MC
              I                                                                       ROW
              I      1 I      2 I      3 I      4 I      5 I      6 I      7 I      8 I  TOTAL
MODELYR       --------+--------+--------+--------+--------+--------+--------+--------+
           66 I   35273I     499I    3995I    3394I      20I       7I      80I    1055I   44323
              I     1.5I      .2I      .9I     3.8I      .1I      .1I      .3I     2.0I     1.4
              +--------+--------+--------+--------+--------+--------+--------+--------+
           67 I    7104I     169I    1732I     866I       2I       1I      35I     139I   10048
              I      .3I      .1I      .4I     1.0I      .0I      .0I      .1I      .3I      .3
              +--------+--------+--------+--------+--------+--------+--------+--------+
           68 I    8006I     207I    2224I    1058I       5I       1I      32I     174I   11707
              I      .3I      .1I      .5I     1.2I      .0I      .0I      .1I      .3I      .4
              +--------+--------+--------+--------+--------+--------+--------+--------+
           69 I    9615I     427I    2884I    1269I      12I        I      50I     179I   14436
              I      .4I      .2I      .7I     1.4I      .0I        I      .2I      .3I      .4
              +--------+--------+--------+--------+--------+--------+--------+--------+
           70 I   10655I     462I    3254I    1490I      11I       1I     106I     288I   16267
              I      .5I      .2I      .7I     1.7I      .0I      .0I      .4I      .5I      .5
              +--------+--------+--------+--------+--------+--------+--------+--------+
           71 I   12556I     891I    3649I    1586I      17I       2I     132I     421I   19254
              I      .5I      .3I      .8I     1.8I      .1I      .0I      .5I      .8I      .6
              +--------+--------+--------+--------+--------+--------+--------+--------+
           72 I   17073I    1339I    4985I    1960I      56I       1I     195I     678I   26287
              I      .7I      .5I     1.1I     2.2I      .2I      .0I      .7I     1.3I      .8
              +--------+--------+--------+--------+--------+--------+--------+--------+
           73 I   20015I    1727I    5355I    2535I      46I       2I     280I     842I   30802
              I      .8I      .6I     1.2I     2.8I      .2I      .0I     1.0I     1.6I      .9
              +--------+--------+--------+--------+--------+--------+--------+--------+
           74 I   19799I    1690I    6710I    2657I     114I       4I     326I     994I   32294
              I      .8I      .6I     1.5I     3.0I      .4I      .1I     1.1I     1.9I     1.0
              +--------+--------+--------+--------+--------+--------+--------+--------+
           75 I   22046I    1913I    5931I    2821I     266I       6I     251I    1378I   34612
              I      .9I      .7I     1.4I     3.2I     1.0I      .1I      .9I     2.6I     1.1
              +--------+--------+--------+--------+--------+--------+--------+--------+
           76 I   37715I    3355I    9588I    2509I     337I      14I     197I    1263I   54978
              I     1.6I     1.2I     2.2I     2.8I     1.2I      .2I      .7I     2.4I     1.7
              +--------+--------+--------+--------+--------+--------+--------+--------+
           77 I   58022I    4784I   13833I    3339I     420I      15I     355I    1503I   82271
              I     2.5I     1.8I     3.2I     3.7I     1.5I      .2I     1.2I     2.8I     2.5
              +--------+--------+--------+--------+--------+--------+--------+--------+
           78 I   74530I    6153I   16575I    4064I     791I      98I     621I    2175I  105007
              I     3.2I     2.3I     3.8I     4.5I     2.9I     1.4I     2.1I     4.1I     3.2
              +--------+--------+--------+--------+--------+--------+--------+--------+
           79 I   87161I    8337I   19775I    4902I    1911I     254I    1102I    2288I  125730
              I     3.7I     3.1I     4.6I     5.5I     7.0I     3.7I     3.8I     4.3I     3.8
              +--------+--------+--------+--------+--------+--------+--------+--------+
       COLUMN   2356833   269203   434059    89434    27328     6932    28887    53314  3265990
        TOTAL      72.2      8.2     13.3      2.7       .8       .2       .9      1.6    100.0
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Table C.3 1990 Maryland Mobile Registrations: Model Year by Mobile Weight

```
MODELYR  BY  MOBILWGT

                MOBILWGT
        COUNT I
      COL PCT I  LDGV     LDGT1    LDGT2    HDGV     LDDV     LDDT     HDDV     MC
              I                                                                            ROW
              I       1 I       2 I       3 I       4 I       5 I       6 I       7 I       8 I   TOTAL
MODELYR ------+--------+--------+--------+--------+--------+--------+--------+--------+
          80  I   83615I    3256I   12325I    3336I    3585I     344I     891I    3302I  110654
              I     3.5I     1.2I     2.8I     3.7I    13.1I     5.0I     3.1I     6.2I     3.4
              +--------+--------+--------+--------+--------+--------+--------+--------+
          81  I   92264I    3211I   12787I    2552I    4717I     704I     960I    3768I  120983
              I     3.9I     1.2I     2.9I     2.9I    17.3I    10.2I     3.3I     7.1I     3.7
              +--------+--------+--------+--------+--------+--------+--------+--------+
          82  I  100044I    4141I   14498I    2494I    3811I    1084I     956I    4874I  131902
              I     4.2I     1.5I     3.3I     2.8I    13.9I    15.6I     3.3I     9.1I     4.0
              +--------+--------+--------+--------+--------+--------+--------+--------+
          83  I  129039I    8125I   20709I    3078I    2655I     596I    1076I    3793I  169071
              I     5.5I     3.0I     4.8I     3.4I     9.7I     8.6I     3.7I     7.1I     5.2
              +--------+--------+--------+--------+--------+--------+--------+--------+
          84  I  193159I   16708I   30200I    4792I    3472I     948I    1888I    3114I  254281
              I     8.2I     6.2I     7.0I     5.4I    12.7I    13.7I     6.5I     5.8I     7.8
              +--------+--------+--------+--------+--------+--------+--------+--------+
          85  I  209477I   22371I   34498I    5887I    2797I     728I    3007I    4509I  283274
              I     8.9I     8.3I     7.9I     6.6I    10.2I    10.5I    10.4I     8.5I     8.7
              +--------+--------+--------+--------+--------+--------+--------+--------+
          86  I  247245I   27899I   49557I    7174I    1100I     745I    3602I    5934I  343256
              I    10.5I    10.4I    11.4I     8.0I     4.0I    10.7I    12.5I    11.1I    10.5
              +--------+--------+--------+--------+--------+--------+--------+--------+
          87  I  260623I   37697I   45598I    6079I     957I     489I    4131I    3540I  359114
              I    11.1I    14.0I    10.5I     6.8I     3.5I     7.1I    14.3I     6.6I    11.0
              +--------+--------+--------+--------+--------+--------+--------+--------+
          88  I  255187I   42637I   47149I    7893I      59I     383I    3571I    2855I  359734
              I    10.8I    15.8I    10.9I     8.8I      .2I     5.5I    12.4I     5.4I    11.0
              +--------+--------+--------+--------+--------+--------+--------+--------+
          89  I  227869I   43667I   43083I    7299I     116I     450I    3244I    2653I  328381
              I     9.7I    16.2I     9.9I     8.2I      .4I     6.5I    11.2I     5.0I    10.1
              +--------+--------+--------+--------+--------+--------+--------+--------+
          90  I  138741I   27538I   23165I    4400I      51I      55I    1799I    1575I  197324
              I     5.9I    10.2I     5.3I     4.9I      .2I      .8I     6.2I     3.0I     6.0
              +--------+--------+--------+--------+--------+--------+--------+--------+
        COLUMN  2356833   269203   434059    89434    27328     6932    28887    53314  3265990
         TOTAL     72.2      8.2     13.3      2.7       .8       .2       .9      1.6    100.0

NUMBER OF MISSING OBSERVATIONS:  11558
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Table C.3 (Continued) 1990 Maryland Mobile Registrations: Model Year by Mobile Weight

Jurisdiction	LDGV	LDGT1	LDGT2	HDGV	LDDV	LDDT	HDDV	MC	All Vehicles
Allegany	36,346	4,291	9,959	2,173	29	12	88	1,282	54,180
Anne Arundel	229,146	31,091	47,554	7,107	3,789	1,032	2,742	5,971	328,432
Baltimore	407,125	42,113	58,848	11,304	4,303	1,106	4,344	7,964	537,107
Calvert	25,453	4,201	9,796	1,190	243	71	291	874	42,119
Caroline	12,501	1,737	5,459	1,353	87	44	225	425	21,831
Carroll	63,955	10,080	19,694	4,383	831	422	1,113	2,442	102,920
Cecil	32,356	4,610	12,518	1,472	200	76	352	1,308	52,892
Charles	49,263	6,913	15,746	2,216	218	75	600	1,429	76,460
Dorchester	14,222	1,699	5,130	1,197	79	35	170	377	22,909
Frederick	81,088	11,996	23,939	5,623	433	152	910	3,033	127,174
Garrett	10,722	1,961	5,526	1,198	18	16	77	385	19,903
Harford	91,567	12,155	20,750	3,137	1,266	541	1,170	2,641	133,227
Howard	108,049	13,262	15,411	3,270	1,667	399	1,403	2,248	145,709
Kent	8,464	1,092	3,511	776	89	49	203	192	14,376
Montgomery	431,063	43,889	38,455	8,807	7,144	954	3,140	7,337	540,789
Prince George's	361,328	37,193	54,231	12,515	4,244	1,179	5,660	6,734	483,084
Queen Anne's	16,135	2,512	6,974	1,222	218	82	297	452	27,892
Saint Mary's	31,318	4,368	12,180	1,611	154	72	276	981	50,960
Somerset	8,668	856	3,448	658	42	22	45	176	13,915
Talbot	15,930	2,119	5,024	1,147	223	48	238	423	25,152
Washington	58,650	7,031	18,706	3,619	141	62	493	2,562	91,264
Wicomico	34,610	4,687	10,779	2,682	175	50	401	906	54,290
Worcester	19,564	3,022	6,563	1,392	124	36	202	471	31,374
Baltimore City	209,314	16,323	23,857	9,382	1,611	397	4,447	2,701	268,032
Statewide	2,356,837	269,201	434,058	89,434	27,328	6,932	28,887	53,314	3,265,991

Table C.4 1990 Maryland Mobile Registrations: Jurisdiction by Mobile Weight

APPENDIX D

Table D.1 1990 Maryland Methane Emissions From Animal Manure Management

Animal Type		Population (head)	Typical Animal Mass (TAM) (lbs/head)	Volatile Solids(vs) (lbs vs/ lb mass)	Total VS Produced (lbs)	CH4 Producing Capacity (Bo) (cu,ft./lb-vs)	Max. Potential Emissions (cu.ft.)
Feedlot Beef Cattle	steers	22,000	915	2.6	52,338,000	5.29	276,868,020
	Heifers	15,000	915	2.6	35,685,000	5.29	188,773,650
	Cows/Other	19,000	1102	2.6	54,438,800	5.29	287,981,252
Other Beef Cattle	Calves	231,000	397	2.6	238,438,200	2.72	648,551,904
	Heifers	6,000	794	2.6	12,386,400	2.72	33,691,008
	Steers	22,000	794	2.6	45,416,800	2.72	123,533,696
	Cows	55,000	1102	2.6	157,586,000	2.72	428,633,920
	Bulls	6,000	1587	2.6	24,757,200	2.72	67,339,584
Dairy Cattle	Heifers	40,000	903	3.65	131,838,000	3.84	506,257,920
	Cows	66,000	1345	3.65	324,010,500	3.84	1,244,200,320
Swine	Market	155,000	101	3.1	48,530,500	7.53	365,434,665
	Breeding	25,000	399	3.1	30,922,500	5.77	178,422,825
Poultry	Layers	3,227,000	3.5	4.4	49,695,800	5.45	270,842,110
	Broilers	265,400,000	1.5	6.2	2,468,220,000	4.81	11,872,138,200
	Ducks	1,246,000	3.1	6.75	26,072,550	5.13	133,752,182
	Turkeys	110,000	7.5	3.32	2,739,000	4.81	13,174,590
Other	Sheep	32,000	154	3.36	16,558,080	5.77	95,540,122
	Goats	5,151	141	3.48	2,527,493	2.72	6,874,780
	Donkeys	520	661	3.65	1,254,578	5.29	6,636,718
	Horses/Mules	24,326	992	3.65	88,079,581	5.29	465,940,982

Table D.2 1990 Maryland Methane Emissions From Animal Manure Management

Animal Type		Manure System	Max. Potential Emissions (cu.ft.)	Methane Conv. Factor (MCF) (%)	Waste System Usage (%)	Methane Emissions (cu.ft.)	Methane Emissions (lbs)
Feedlot Beef Cattle	steers	Drylot	276,868,020	1.2%	4%	132,897	5,489
	steers	Liquid/Slurry	276,868,020	21.0%	1%	581,423	24,013
	steers	Pasture	276,868,020	1.1%	95%	2,893,271	119,492
	Heifers	Drylot	188,773,650	1.2%	4%	90,611	3,742
	Heifers	Liquid/Slurry	188,773,650	21.0%	1%	396,425	16,372
	Heifers	Pasture	188,773,650	1.1%	95%	1,972,685	81,472
	Cows/Other	Drylot	287,981,252	1.2%	4%	138,231	5,709
	Cows/Other	Liquid/Slurry	287,981,252	21.0%	1%	604,761	24,977
	Cows/Other	Pasture	287,981,252	1.1%	95%	3,009,404	124,288
Other Beef Cattle	Calves	Drylot	648,551,904	1.2%	4%	311,305	12,857
	Calves	Liquid/Slurry	648,551,904	21.0%	1%	1,361,959	56,249
	Calves	Pasture	648,551,904	1.1%	95%	6,777,367	279,905
	Heifers	Drylot	33,691,008	1.2%	4%	16,172	668
	Heifers	Liquid/Slurry	33,691,008	21.0%	1%	70,751	2,922
	Heifers	Pasture	33,691,008	1.1%	95%	352,071	14,541
	Steers	Drylot	123,533,696	1.2%	4%	59,296	2,449
	Steers	Liquid/Slurry	123,533,696	21.0%	1%	259,421	10,714
	Steers	Pasture	123,533,696	1.1%	95%	1,290,927	53,315
	Cows	Drylot	428,633,920	1.2%	4%	205,744	8,497
	Cows	Liquid/Slurry	428,633,920	21.0%	1%	900,131	37,175
	Cows	Pasture	428,633,920	1.1%	95%	4,479,224	184,992
	Bulls	Drylot	67,339,584	1.2%	4%	32,323	1,335
	Bulls	Liquid/Slurry	67,339,584	21.0%	1%	141,413	5,840
	Bulls	Pasture	67,339,584	1.1%	95%	703,699	29,063
Dairy Cattle	Heifers	Anaerobic lagoon	506,257,920	90.0%	2%	9,112,643	376,352
	Heifers	Liquid/Slurry	506,257,920	21.0%	48%	51,030,798	2,107,572
	Heifers	Daily Spread	506,257,920	0.3%	45%	683,448	28,226
	Heifers	Solid Storage	506,257,920	1.1%	5%	278,442	11,500
	Cows	Anaerobic lagoon	1,244,200,320	90.0%	2%	22,395,606	924,939
	Cows	Liquid/Slurry	1,244,200,320	21.0%	48%	125,415,392	5,179,656
	Cows	Daily Spread	1,244,200,320	0.3%	45%	1,679,670	69,370
	Cows	Solid Storage	1,244,200,320	1.1%	5%	684,310	28,262
Swine	Market	Anaerobic lagoon	365,434,665	90.0%	50%	164,445,599	6,791,603
	Market	Drylot	365,434,665	1.2%	10%	438,522	18,111
	Market	Pit Storage >1 mo	365,434,665	21.0%	40%	30,696,512	1,267,766
	Breeding	Anaerobic lagoon	178,422,825	90.0%	50%	80,290,271	3,315,988
	Breeding	Drylot	178,422,825	1.2%	10%	214,107	8,843
	Breeding	Pit Storage >1 mo	178,422,825	21.0%	40%	14,987,517	618,984
Poultry	Layers	Deep Pit Stacks	270,842,110	10.0%	100%	27,084,211	1,118,578
	Broilers	litter	11,872,138,200	10.0%	100%	1,187,213,820	49,031,931
	Ducks	litter	133,752,182	10.0%	100%	13,375,218	552,397
	Turkeys	litter	13,174,590	10.0%	90%	1,185,713	48,970
	Turkeys	Range	13,174,590	1.1%	10%	14,492	599
Other	Sheep	Pasture	95,540,122	1.1%	100%	1,050,941	43,404
	Goats	Pasture	6,874,780	1.1%	100%	75,623	3,123
	Donkeys	Paddock	6,636,718	1.1%	35%	25,551	1,055
	Donkeys	Pasture	6,636,718	1.1%	65%	47,453	1,960
	Horses/Mules	Paddock	465,940,982	1.1%	35%	1,793,873	74,087
	Horses/Mules	Pasture	465,940,982	1.1%	65%	3,331,478	137,590
					Total Mehane Emissions(lbs.)		72,866,941
					Total Mehane Emissions(tons)		36,433