California Environmental Protection Agency

Air Resources Board

# California's 2000-2009
# Greenhouse Gas Emissions Inventory

## Technical Support Document

State of California
Air Resources Board
Planning and Technical Support Division

December 2011

# Acknowledgments

This document was developed by the following Air Resources Board staff members:

Marc Vayssières, Ph.D. (project lead)
Larry Hunsaker, P.E.
Klaus Scott
Kevin Eslinger
Karen Lutter, P.E.
David Edwards, Ph.D.
Matthew Malchow, Ph.D.

The Staff of the Air Resources Board wishes to express their appreciation to the many stakeholders that were an integral part of developing the GHG Emissions Inventory. Stakeholders played a key role in workshops, technical discussions and conference calls to assist staff in developing the inventory and the 1990 statewide emissions level. The following organizations in particular were critical to the success of this effort, both in their technical advice and their constructive participation throughout the process:
California Energy Commission
California Integrated Waste Management Board
California Public Utilities Commission
California Department of Forestry & Fire Protection
U.S. Environmental Protection Agency
U.S. Energy Information Administration
U.S. Forest Service
U.S. Geological Survey
Climate Action Reserve
Lawrence Berkeley National Lab
University of California-Berkeley
Western States Petroleum Association
Waste Management, Inc.
Los Angeles County Sanitation District
Los Angeles Department of Water and Power
Portland Cement Association
National Lime Association
Californians Against Waste
Natural Resources Defense Council
Environmental Defense
Sacramento Municipal Utilities District

# Disclaimer

# TABLE OF CONTENTS

# INTRODUCTION

The Global Warming Solutions Act of 2006 (AB 32, Nunez, Statutes of 2006, chapter 488) requires that the California Air Resources Board (ARB or the Board) determine the statewide 1990 greenhouse gas emissions level and approve a statewide greenhouse gas emissions limit, equal to that level, to be achieved by 2020. Assembly Bill 1803, which became law in 2006, transferred the responsibility to prepare, adopt, and update California's greenhouse gas inventory from the California Energy Commission (CEC) to the ARB beginning in January 2007.

In developing ARB's first edition of California's GHG inventory, staff consulted with other State agencies, and engaged stakeholders and the public through a series of workshops and technical discussions. That public process resulted in major revisions to the CEC inventory, including changes to the classification of emissions and sinks, selected emission estimation methods, GHG emission factors, and other parameters. These revisions aligned the inventory with the International Panel on Climate Change (IPCC) latest guidelines, published in 2006. Revisions also incorporated methodologies and data from the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005*, published in April 2007 by the U.S. Environmental Protection Agency (USEPA). This first edition of California's GHG inventory, covering years 1990 to 2004, is still available on ARB's website (http://www.arb.ca.gov/cc/inventory/archive/archive.htm) because it served as the basis for the total statewide greenhouse gas 1990 emissions level and 2020 emissions limit (http://www.arb.ca.gov/cc/inventory/1990level/1990level.htm).

This technical support document presents a comprehensive and detailed discussion of the methods, equations, data sources, and references that ARB staff employed to develop ARB's fourth edition of California's greenhouse gas (GHG) inventory, covering years 2000 to 2009. The structure of this report follows the categorization of GHG emissions to —and removal from— the atmosphere contained in the *2006 IPCC Guidelines*. The technical background of each category is presented followed by a discussion of the methodology used to estimate emissions or removals of GHG, including calculation equations, data sources, tables of intermediary results, etc. For each category, the complete list of activity and parameter values used in the equations is made available in an online documentation annex linked to this report.

In preparation for each new edition of the inventory, recalculations are made to correct errors, incorporate new methodologies or, most commonly, to reflect changes in statistical data supplied by other agencies. Emission and sink estimates are recalculated for all years in order to maintain a consistent time-series of estimates within the inventory. This approach follows the recommendation for developing GHG inventories discussed in Chapter 7 of the IPCC Good Practice Guidance document: "In order to assess emission trends it is important that the entire time series of emissions, not just the most recent years, be calculated using the changed or refined methods. It is good practice to recalculate historic emissions when methods are changed or refined, when new source categories are included in the national inventory, or when errors in the estimates are identified and corrected." As a consequence, successive editions of the inventory may report a different amount of emissions/removal for an earlier year than earlier inventories.

ARB's second edition of California's GHG inventory, covering years 2000 to 2006, and its third edition (for years 2000 to 2008) saw a number of such changes to the data and methods used for the estimates. New data or methods were described in the online documentation published with these inventories on ARB's website. In this fourth edition, the major change was the integration of data collected under the Regulation for Mandatory Reporting of Greenhouse Gas Emissions, including information from: cement plants (for 2008 and 2009), refineries (2009), electricity generation and electricity imports (2009). In this technical support document, all changes in methodology and data since the first edition of the inventory are described and their impacts on emissions estimates are quantified.

# SUMMARY OF DATA SOURCES AND ESTIMATION METHODS

## A “top-down” inventory

The methods used to estimate greenhouse gas (GHG) emissions in this inventory generally follow a top-down approach. In the top down approach, estimates are made on the basis of nation-wide or state-wide activity data. For instance, aggregate data from the U.S. Energy Information Administration (EIA) for various fuels combusted in California are used to estimate emissions. In a bottom-up approach to estimating GHG emissions, data from individual activity units are used to compute unit level emissions that are then aggregated to the national or state level. For example, a bottom-up inventory for in-state electricity production would calculate greenhouse gas emissions from the fuel combustion at each individual power plant and sum the emissions of all such facilities in the state.

In the absence of a comprehensive GHG emission reporting system, a top-down approach is usually more accurate than a bottom-up approach. Aggregate levels of activity are in general more robust because they are augmented by, or checked against, other statistics. For instance, survey and census data can be supplemented with sales tax records, or with the balance of national production plus imports and minus exports. This makes top-down inventories more comprehensive, and less likely to undercount emissions. However, these national level statistics are not always available at the state level. This is true in particular of import–export records between California and other states, since interstate commerce is under federal jurisdiction. For this reason, state-level inventories are often more difficult to develop than national inventories. In the case of some categories, as state-level data were lacking, staff opted to use national-level aggregate data adjusted pro-rata to the population or to production capacity, to estimate California’s emissions.

With the implementation of ARB’s Mandatory Greenhouse Gas Reporting Program, bottom-up GHG emissions data are becoming available for use in the statewide inventory. Mandatory Reporting of GHG emissions began with year 2008 emissions. Emissions reported for 2009 were verified by independent verifiers for the first time, which greatly increases their validity. However, only facilities emitting more than the regulation’s thresholds (25,000 tonnes of $CO_2$ for general combustion and 2,500 tonnes —with at least 1 MW of generating capacity— for electricity production) are required to report their emissions. As a consequence, reported emissions represent the totality of emissions in sectors where all facilities are over the threshold (i.e. cement manufacturing and petroleum refining) but not in the other sectors —such as electricity generation. For this edition of California’s GHG inventory, staff used bottom-up data from the Mandatory Reporting Program in two ways: exclusively in the case of cement plants and refineries, and as a complement to top-down sources for in-state electricity generation and imported electricity.

## Consistent with the International Panel on Climate Change (IPCC) guidelines

The IPCC guidelines are the recognized international standard for developing national greenhouse gas inventories. They were developed through an international process which included work by teams of experts from many countries; technical and regional workshops held in Africa, Asia, Latin America, Central Europe and Western Europe; testing of the methods through the actual development of inventories; and country studies to assess the methods in a variety of national contexts.

The first version of the IPCC Guidelines was accepted in 1994 and published in 1995, and underwent a first major revision in 1996 (IPCC, 1997). The Third Conference of Parties (COP-3) of the United Nations Framework Convention on Climate Change (UNFCCC) adopted the Kyoto Protocol in 1997 and reaffirmed that the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* should be used as "methodologies for estimating anthropogenic emissions by sources and removals by sinks of greenhouse gases" in the calculation of legally-binding targets. In 2000, the IPCC published its *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* report (IPCC, 2000) and, in 2003, the *Good Practice Guidance for Land Use, Land Use Change and Forestry* (IPCC, 2003) as supplements to the Revised 1996 Guidelines. A second major revision of the guidelines was initiated in 2003, building upon the Revised 1996 Guidelines and the subsequent Good Practice reports and incorporating improved scientific and technical knowledge. The new *2006 IPCC Guidelines* (IPCC, 2006a) include new sources and gases as well as updates to the previously published methods and default emission factors.

The IPCC Guidelines provide advice on estimation methods. They include summaries of the methods' scientific background, estimation equations, default emission factors and other parameters to use in generating the estimates, and sources of activity data. The Guidelines' methods are ranked in three tiers:

- Tier 1 methods are the simplest and most accessible. Mostly based on activity levels and emission factors, they use the provided default values for emissions factors and other parameters.
- Tier 2 methods are intermediate in complexity and data requirements. Refinements include disaggregating activity data among contrasting processes, using process- or country-specific emission factors and/or parameter values, etc.
- Tier 3 methods are the most complex. Often based on mathematical models of the processes involved, they typically require having extensive knowledge of management practices and detailed activity data.

Properly implemented, all tiers are intended to provide unbiased estimates, and accuracy and precision should, in general, improve from Tier 1 to Tier 3. The IPPC recommends using Tier 2 or Tier 3 methods for *key categories*. Key categories are defined as are those with a significant influence on a country's total inventory of greenhouse gases in terms of the absolute level, the trend, or the uncertainty in emissions and removals.

In compiling the first edition of California's GHG inventory, California Air Resources Board (ARB) staff strived to be consistent with the new 2006 guidelines. However, because of time constraints, a few categories still followed the Revised 1996 guidelines. Estimation methods were updated in the second and third editions of California's GHG inventory. In this edition, all methods are consistent with the 2006 guidelines.

### Built upon previous work

ARB's first edition of California's Greenhouse Gas Inventory was a refinement of previous statewide inventory work. The California Energy Commission (CEC) published the first multi-year inventory of California GHG emissions (CEC, 1998), covering years 1990 through 1994 and forecasting emissions for 2000, 2005 and 2010. The emission estimates presented in that report were based on methods from USEPA's "State Workbook: Methodologies for Estimating Greenhouse Gas Emissions" (USEPA, 1995). This first multi-year GHG inventory was following the publication of two single year estimates: one for 1988 (CEC, 1990) the other for 1990 (CEC, 1997).

In September 2000, the California Legislature passed Senate Bill 1771 requiring the CEC, in consultation with other state agencies, to update California's inventory of greenhouse gas emissions. The CEC's second inventory of California GHG emissions (CEC, 2002), compiled with the assistance of consulting firms, covered years 1990 to 1999. It was based on emissions estimation methods from the 1996 Revised IPCC Guidelines (IPCC, 1997), the 1990-1999 national GHG inventory (USEPA, 2001), and USEPA's Emission Inventory Improvement Program (USEPA, 1999). The methodology used to estimate net carbon flux from forest lands came from the USDA-Forest Service (Birdsey and Lewis, 2001, 2003).

The CEC's third inventory of California GHG emissions extended the covered period through 2002 (CEC, 2005a). This inventory initiated the inclusion of GHG emissions from out-of-state electricity imported in California along with in-state GHG emissions, and discussed methods to make these estimates. It also excluded all international fuel uses from the inventory totals, reporting them on separate lines.

The CEC's fourth inventory of California GHG emissions (CEC, 2006) covered the 1990-2004 period. The main methodological changes introduced with that inventory were the use of the *California Energy Balance* database work (Murtishaw et al. 2005) to disaggregate fuel use information by sector of activity, and the *Baseline GHG emissions for forest, range and agricultural lands in California* report (CEC, 2004) to estimate land use, land use change and forestry emissions and sinks.

In 2006, Assembly Bill 1803 transferred the responsibility to prepare, adopt, and update California's greenhouse gas inventory from the CEC to the California Air Resources Board. The same year, Assembly Bill 32 required that the Air Resources Board determine the statewide greenhouse gas emissions level in 1990 and approve a statewide greenhouse gas emissions limit, equal to that level, to be achieved by 2020. ARB staff endeavored to satisfy these requirements by reviewing and revising the last edition of CEC's GHG inventory, consulting with other State agencies and engaging stakeholders and the public through a series of workshops and technical workgroups.

Updates to the 1990-2004 California GHG inventory included changes to the classification of emissions and sinks, methods, emission factors and other parameters to bring them in accord with the 2006 IPCC guidelines. In April 2007, the USEPA published the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005* (USEPA, 2007a), which included updated methodologies consistent with the new 2006 IPCC Guidelines. Inputs from the national inventory were particularly useful in two main cases:

- Activity data were lacking at the state level for a particular GHG generating activity (e.g., nitric acid production, $CO_2$ consumption). ARB staff used the latest national-level data by adjusting them pro-rata to the population or to production capacity.
- USEPA and its contractors had developed complex models for estimating some categories of emissions. Enteric fermentation is an example of such a model for which USEPA had California specific data that they shared with ARB. The use of ODS substitutes is another example for which national data was adjusted pro-rata to the population.

Since then ARB staff has continued to work closely with USEPA staff, adopting improved methods from the successive version of the national GHG inventory when appropriate.

## An on-going improvement process

Staff has made many improvements to emissions estimates since ARB's first edition of California's GHG inventory (covering years 1990-2004) and the accompanying technical support document. In particular:

- In estimating emissions from in-state electricity production: the various types of coal have been combined into a single "coal" category; the "Distillate Oils" group was broken up into its component parts (distillate, jet fuel, kerosene, residual fuel oil, and waste oil) as data to do this became available; two types of non-combustion emissions were added —$CO_2$ from acid gas control devices and fugitive $CH_4$ from coal piles; data from ARB's Mandatory Reporting Program were also used in compiling 2009 emissions.
- In the case of electricity imports: staff corrected an error in the source mix of unspecified imports from the PSW in 2000-2001, and errors in specified imports from Hoover (Hydro) and Palo Verde (Nuclear); included two new

plants located in Mexico and a geothermal plant in Nevada; integrated revisions to the table of "Total Production by Resource Type" (table J-11), published by the California Department of Finance (CDOF) on the basis of data prepared by CEC; and used data from CEC's Net System Power reports to directly calculate the unspecified imports emission factor.

- In estimating emissions from fuel combustion in transportation and in the industrial, commercial, residential and agricultural sectors: gasoline-ethanol blends are no longer listed under the generic term of "gasoline" to allow for emissions from gasoline and ethanol to be analyzed separately; also, data on fuel use by petroleum refineries in 2009, and cement plants in 2008 and 2009, were summarized from values reported to ARB's Mandatory Reporting Program.
- Two changes were made to the estimation of emissions from aviation: first, California jet fuel sales data were obtained from the Energy Information Administration rather than from the California Energy Balance; second, the methods used for the apportionment of aviation jet fuel among intrastate, interstate and international commercial flights were much improved by using specific fuel consumption rates for many aircraft types rather than simply the distance flown.
- For emissions from oil and gas production: staff used data from the Division of Oil, Gas & Geothermal Resources of California's Department of Conservation for associated gas, and included a complete data set of fuel use by pipeline compressor stations from the EIA.
- In the case of fugitive emissions from fuel and energy production: new categories were added, and changes were made to the methodology used for some of the other categories using data from ARB's Mandatory Reporting Program. Mandatory Reporting data was also used for 2009 emissions from geothermal plants.
- For 2008 and 2009 emissions from clinker production, staff used data collected under ARB's GHG Mandatory Reporting regulation exclusively.
- Emissions of $CO_2$ from lime production rely now upon industry calculations based on plant-specific emission factors and include emissions from LKD by-product generation.
- For emissions from the non-energy use of fossil fuels: staff determined that several fuels that were thought to be used for non-energy purposes were actually used as refinery feedstock or as fuel blending agents, and removed them from this section; staff introduced emission estimates for solvent use as part of this section.
- In the case of nitric acid production: staff learned that all nitric acid plants in California are using non-selective catalytic reduction (NSCR) air pollution abatement devices since the 1980s and modified their $N_2O$ emission factor accordingly.
- Emissions from the semiconductor manufacturing sector are now speciated by gas instead of a single emission value for all halogenated compounds, and nitrogen trifluoride (NF3) was introduced as a new GHG compound in accord

with the 4th IPCC Assessment report and California Senate Bill 104 passed in 2009.

- The inventory of emissions of substitutes to ozone depleting substances relies on USEPA's Vintaging Model which was modified to incorporate changes in the assumptions used for a variety of refrigeration and air conditioning end uses based on input from industry and updated research.
- Emissions from carbon dioxide consumption: staff changed the ratio used to estimate California emissions by scaling down national emissions from the ratio of respective production capacities to that of populations.
- In the case of fuel consumption as feedstock for hydrogen production: staff used Mandatory Reporting data to estimate the proportion of natural gas and refinery gas for each year and made direct use of Mandatory Reporting data for 2009.
- Emissions of methane from livestock enteric fermentation are based on USEPA models, changes included: adjustments to the population and typical weights of several classes of livestock; improvements to the inputs to the models used to predict methane production from cattle; and a change of method to estimate California's horse population.
- Major changes in data and methods used in the estimation of emissions from manure management include: addition of anaerobic digesters to the list of waste management systems; changes in the distribution of some livestock classes among manure management systems; use of outputs from USEPA's Cattle Enteric Fermentation Model as inputs to the manure management emissions calculations —which increases the methodological consistency with the enteric fermentation modeling; revision of population numbers and manure characteristics of several classes of livestock; and reporting of emissions of $CH_4$ and $N_2O$ by animal group *and* by manure management system.
- Staff made revisions to the type of crop data used to estimate emissions from agricultural residue burning.
- The main changes in data and methods used in the estimation of emissions of $N_2O$ from agricultural soil management include: removal of biological nitrogen fixation as a direct source of $N_2O$ —following 2006 IPCC guidelines; differentiation between the amount of N in un-managed manure from cattle, poultry and pigs and that from sheep, goats and horse; use of results from the manure management emissions calculations to determine the amount of nitrogen in animal manure that is applied to soils; update of the estimation of the amount of nitrogen returned to soils by crop residues to an improved method based on the 2006 IPCC guidelines; and update of the estimate of the area of drained organic soils to an objective method using GIS analysis of detailed spatial datasets.
- To estimate emissions from landfills staff obtained new survey data, updated information on landfill controls and a new waste characterization study from CalRecycle.

- A new category was added to California’s GHG inventory for emissions resulting from the composting of organic waste such as food scraps, yard trimmings, branches, leaves, grass and organic municipal solid waste.
- Extensive changes to both the domestic and industrial wastewater emission equations occurred since the publication of the 1990-2004 edition of the GHG Inventory: four domestic wastewater treatment options are now considered each with a separate equation (septic systems, centrally treated aerobic systems, centrally treated anaerobic systems and anaerobic digesters); a distinction is made between plants with and without nitrification/denitrification; the per capita protein consumption factor was modified; methane emissions from the pulp and paper manufacturing industries are now included and the estimation of emissions from wastewater treatment facilities of petroleum refineries is based on a new approach; other data used in the calculations were updated.

Emission inventories are, by nature, the reflection of the best available data and the most applicable methods at the time of their compilation. As data grow and understanding develops they can be updated and improved. Throughout this report, sections about “future improvements” summarize staff’s assessment of current methodologies and potential developments for future versions of California’s GHG inventory.

# GHG ESTIMATION METHODS AND SUPPORTING DATA SOURCES

## I. Energy

### *A. Electricity and Heat Production – In State (IPCC 1A1a)*

#### 1. Background

The sources of energy used for electricity generation are varied in nature and origin: fuel combustion, hydropower, nuclear, solar, wind, and geothermal. The dominant source of energy for electricity and heat production in California is fuel combustion, and greenhouse gases (GHG) are emitted during this process. With the exception of fugitive emissions of $CO_2$ released from geologic formations tapped for geothermal energy, other energy sources do not emit GHG in the energy conversion process. Emissions from fuel combustion activities are estimated and tallied under this category (1A1a); $CO_2$ emissions from geothermal power are included in the inventory and reported under category 1B3 (Other Emissions from Energy Production). Note also that the $SF_6$ emissions associated with the distribution of electricity through the power grid are reported under IPCC code 2G1b (Use of Electrical Equipment).

The California GHG inventory includes the emissions of $CO_2$, $CH_4$ and $N_2O$ resulting from the combustion of fossil fuels, including gaseous fuels (natural gas, refinery gas, etc.), liquid fuels (distillate, residual fuel oil, jet fuel, etc.), and solid fuels (coal, petroleum coke, etc.). Various renewable fuels (wood, agricultural biomass and landfill or digester gas) are also used to produce heat and electricity. The GHG inventory includes only the $CH_4$ and $N_2O$ emissions resulting from the combustion of renewable fuels since the $CO_2$ emissions would have occurred eventually as the biomass decayed. These $CO_2$ emissions, labeled “from biogenic materials”, are estimated and tracked, but are not included in California’s GHG inventory total.

Within this inventory category (IPCC 1A1a), power plants are classified by fuel, and by type of generation: either electricity generation or combined heat and power (CHP). The CHP process makes use of otherwise wasted exhaust heat, making it one of the most efficient means of generating electricity. The GHG emissions associated with “useful thermal output” (UTO) from CHP are not attributed to the electric power sector; they are reported separately for the sector (industrial or commercial) in which the UTO is used. CHP plants are classified by the sector to which they provide their UTO, and thus labeled either as “CHP: Commercial” or “CHP: Industrial”. Non-CHP power plants are classified under IPCC code 1A1ai (Electricity Generation), CHP plants are classified under IPCC code 1A1aii (Combined Heat and Power Generation). Geothermal emissions are classified under IPCC code 1B3 (Other Emissions from Energy Production).

Power plants are also classified into two ownership categories: “Utility owned” or “Merchant owned”. Utility owned plants are those under direct ownership of a public or investor-owned utility responsible for providing electricity to their customers. Merchant owned plants are under private or corporate ownership, engaging in the buying and selling of electricity in the open market, and eventually selling to utilities that cannot provide all the electricity they need through their own plants.

## 2. Methodology

### 2.1 Stationary combustion emissions

The method for estimating stationary combustion emissions follows IPCC 2006 guidelines (IPCC, 2006a). California or US-specific emission factors and heat content values are used when available.

*Equation 1: Emissions from stationary combustion*

$$\boxed{E_{GHG,\ fuel} = FC_{fuel} \bullet HC_{fuel} \bullet EF_{GHG,\ fuel}}$$

Where,

$E_{GHG,\ fuel}$ = Emissions of the given GHG for the type of fuel (g of GHG)

$FC_{fuel}$ = Amount of fuel combusted (in units of tons for solid fuels, gallons for liquid fuels or standard cubic feet for gaseous fuels)

$HC_{fuel}$ = Heat content (higher heating value) of the type of fuel (BTU / unit)

$EF_{GHG,\ fuel}$ = Emission factor of the given GHG by the type of fuel (g GHG / BTU)

With,

GHG = [$CO_2$, $CH_4$, $N_2O$]

Fuel = [associated gas, biomass, coal, crude oil, digester gas, distillate, jet fuel, kerosene, landfill gas, municipal solid waste, natural gas, petroleum coke, propane, refinery gas, residual fuel oil, tires, waste oil]

A variant of this estimation method was used to estimate $CO_2$ emissions in the case of partially renewable fuels. These fuels are a mix of materials from renewable and fossil origins. Municipal solid waste (MSW) and used tires are two such fuels.

*Equation 2: Variant for partially renewable fuels*

$$\boxed{E_{GHG,\ fuel,\ origin} = E_{GHG,\ fuel} \bullet P_{fuel,\ origin}}$$

Where,

$E_{GHG,\ fuel,\ origin}$ = Emissions of the given GHG for the proportion of materials of given origin for the type of fuel (g of GHG)

$E_{GHG,\ fuel}$ = Emissions of the given GHG for the type of fuel (g of GHG)

$P_{fuel,\ origin}$ = proportion of material of given origin in the type of fuel (fraction)

With,

GHG = [$CO_2$]

Fuel = [MSW, tires]

Origin = [Fossil, Renewable]

For a list of yearly activity, heat content and emission factor values used in the emission estimation equations, please consult the online documentation annex at: http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_1a_electricity_and_heat_production_in_state.pdf

### *2.2 Other emissions*

Non-combustion emissions from electricity and heat production include $CO_2$ from acid gas control devices and fugitive emissions of $CH_4$ from coal storage piles. Information about these sources of emissions became available in 2009 through the ARB Mandatory Reporting Program (ARB, 2007d).

To estimate emissions from these sources for previous years, staff assumed that these emissions would scale with the amount of activity associated with each source. For acid gas control, the 2009 Mandatory Reporting data showed that only coal, coke, biomass and MSW fuels were associated with this process. Thus, emissions from this source were estimated for years 2000 to 2008 pro rata the total amount of heat (BTU) generated by these fuels in each of these years. This same method was applied to scale the fugitive methane emissions from coal storage piles for 2000 to 2008, using only the heat generated from coal for this purpose. That is:

*Equation 3: Back-scaling of non-combustion emissions*

$$\boxed{E_{GHG,\ source,\ year} = E_{GHG,\ source,\ 2009} \bullet \frac{H_{source,\ year}}{H_{source,\ 2009}}}$$

Where,

$E_{GHG,\ source,\ year}$ = Emissions of the given GHG from the particular sources in the given year (g of GHG)
$E_{GHG,\ source,\ 2009}$ = Emissions of the given GHG from the particular source in 2009 (g of GHG)
$H_{source,\ year}$ = amount of combustion heat associated with the source in the given year (BTU)
$H_{source,\ 2009}$ = amount of combustion heat associated with the source in 2009 (BTU)

With,

GHG = [$CO_2$ or $CH_4$]
Source = [Acid gas control device, Coal pile]
Year = [2000-2009]

## 3. Data Sources

Fuel-use data for 2000 was obtained through personal correspondence with the U.S. Energy Information Administration, the statistical arm of the U.S. Department of Energy (Schnapp, 2008). Fuel use data for 2001-2008 was downloaded from U.S. Energy Information Administration (EIA) databases published online (EIA, 2011a). These fuel-use datasets are available online in full detail starting with year 2001, but are not available at the same level of detail for previous years. Detailed data for these years are available from the EIA upon special request.

Heat content data also came from the U.S. Energy Information Administration (Schnapp, 2008; EIA, 2011a). $CO_2$ Emissions factors are from USEPA 1990-2005 greenhouse gas inventory (USEPA, 2007b). $CH_4$ and $N_2O$ emissions factors come from the IPCC 2006 guidelines for stationary combustion (IPCC, 2006b).

The data source for 2009 fuel-use, heat content, and emissions are primarily from ARB's Mandatory Reporting Program data (ARB, 2011b). The threshold of reporting for power plants excludes plants with emissions less than 2,500 metric tons per year, so for these plants (which amount to less than 2 percent of the emissions from in-state electricity generation) EIA data were used (EIA, 2011a).

### 3.1 Mapping EIA codes to ARB categories

Fuel use and heat content data reported by the EIA are grouped as indicated in Table 1 and Table 2. The EIA fuel codes and sector codes provide the information necessary to apportion ARB's emissions estimates into the categories presented in the inventory.

*Table 1: EIA to ARB fuel mapping*

| ARB GHG Inventory Fuel | EIA Fuel Code(s) Included |
|---:|---|
| Associated Gas | OG (for EIA ID: 56090 only) |
| Biomass | AB, BLQ, OBL, OBS, ORW, SLW, WDL, WDS, WWW |
| Coal | BIT, LIG, SUB, SC, WC |
| Crude Oil | OTH |
| Digester Gas | OBG |
| Distillate | DFO |
| Geothermal | GEO |
| Jet Fuel | JF |
| Kerosene | KER |
| Landfill Gas | LFG, MLG |
| Municipal Solid Waste (MSW) | MSB, MSN, MSW |
| Natural Gas | NG |
| Petroleum Coke | PC |
| Propane | PG |
| Refinery Gas | BFG, OG |
| Residual Fuel Oil | RFO |
| Tires | TDF |
| Waste Oil | WO |

*Table 2: EIA to ARB category mapping*

| ARB GHG Inventory Category | EIA Sector Code (EIA #) |
|---:|---:|
| Utility Owned | 1 |
| Merchant Owned | 2, 4, 6 |

| ARB GHG Inventory Category | EIA Sector Code (EIA #) |
|---|---|
| CHP: Commercial | 5 |
| CHP: Industrial | 3, 7 |

### 3.2 Combined Heat and Power

CHP plants report separate amounts of fuel and heat for electricity generation and for useful thermal output (UTO) to the EIA. Staff attributed the amount reported under electricity generation to the electric power sector and the remainder to either the industrial or commercial sector under "useful thermal output" based on the EIA sector code in Table 2. Starting with year 2009 staff also used data from ARB's Mandatory Reporting Program for CHP facilities with emissions greater than 2,500 metric tons per year.

The percentage of emissions from CHP associated with electricity for each year is listed in Table 3:

*Table 3: Percent of CHP emissions associated with electricity generation*

| Category | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 |
|---|---|---|---|---|---|---|---|---|---|---|
| CHP: Commercial | 40.1 | 38.9 | 41.9 | 76.7 | 52.5 | 64.4 | 63.0 | 61.1 | 67.2 | 53.2 |
| CHP: Industrial | 60.6 | 61.1 | 65.4 | 62.3 | 53.9 | 54.0 | 52.9 | 55.0 | 56.4 | 62.4 |

### 3.3 Partially renewable fuels

Certain fuels, namely, municipal solid waste (MSW) and used tires, are not completely composed of fossil carbon, but contain carbon from renewable sources as well. Staff determined that tires contain approximately 20 percent renewable natural rubber based on data from the Rubber Manufacturers Association (RMA, 2007). Staff used source test data provided by Covanta Energy (Hahn, 2007) from the three power plants burning MSW in the state to estimate that, on a carbon basis, about 66 percent of the MSW burned in California for energy is from renewable biomass origin.

For 2009, staff used Mandatory Reporting data supplied updated values for these fuels based on source tests done by each reporting facility.

## 4. Changes in Estimates

When compared with the 1990-2004 edition of the GHG inventory, only minor changes have been made to the estimates:

- In this edition, to avoid confusion, the various types of coal have been combined into a single "coal" category. No emission changes resulted from this aggregation. Conversely, staff divided up the "Distillate Oils" group into its component parts (distillate, jet fuel, kerosene, residual fuel oil, and waste oil) as data to do this became available. This did not result in changes in emissions.

- The fuel type “OTH” (other) is now associated with crude oil, and not with biomass as in the first edition of the inventory. Staff discovered that this unspecified fuel type covers the burning of waste streams containing crude oil in the case of California power plants.
- Facility level fuel and emission data, reported by facility operators under ARB’s Mandatory Reporting Program, were used for the first time in compiling this inventory. These data were available for 2009 from all generating facilities with emissions greater than the threshold of 2,500 tonnes of $CO_2$ per year and having a generating capacity of at least 1MW. Other facilities are not required to report their emissions.
- Two types of non-combustion emissions were added in this version of the inventory: $CO_2$ from acid gas control devices and fugitive $CH_4$ from coal piles.

All together these changes and updates made by data sources resulted in minor changes in emissions estimates for the categories included in this section: - 2.9 percent on average over the years 2000 to 2004 when compared with the estimates in the first edition of ARB’s GHG inventory.

### 5. Future Improvements

ARB’s Mandatory Reporting Program includes detailed methods for reporting fuel use and allocating emissions between the electric power and UTO components of cogeneration plants. These data were used for 2009 and will be incorporated into future GHG inventory editions for all years after 2009.

## B. Electricity Production – Imports (IPCC 1A1a)

### 1. Background

California’s highly interconnected electricity system relies on imports as well as on electricity generated in state. The Global Warming Solutions Act of 2006 (AB 32) requires that ARB include estimates of out-of-state GHG emissions from imported electricity in California’s GHG inventory. Imported power may come from a variety of energy sources but, while the sources of in-state generation are well known, the origin of imported electricity is often unknown. Emissions from imports that can be directly linked to a known out-of-state power plant are tallied under “specified imports” (I.B.3.1 below); emissions from all other imports are discussed in the “unspecified imports” (I.B.3.2 below).

Specified imports are those with a well-known and documented generation source. In these cases, the specific amount of fuel used to generate the imported power can be obtained and used to determine emissions. The specified imports consist of those listed in Table 4 below.

Two natural gas plants, La Rosita and Termoeléctrica de Mexicali are located in Mexico (MEX) and thus do not report to the EIA (and do not have an EIA ID). Data for these plants comes from the California Energy Commission’s Quarterly Fuels and Energy Report (QFER) database (Nyberg, 2009). The CEC

ID of these two facilities is included instead of the EIA ID. The Armstrong Woodwaste Cogeneration Plant is a biomass plant in Canada (CAN), and does not have an EIA ID; it does not report to the CEC either. The emission factor for this plant was estimated by taking the average of the same plant types from plants that reported to the EIA. The Thermo No. 1 Raser plant in Utah (UT) does not currently report to the EIA, and until data are available, the emission factor for it is estimated as the average of all geothermal plants that report to the EIA.

*Table 4: Specified imports*

| ***Plant Name-Primary Fuel (EIA ID)*** | ***State/Country (Import Region)*** |
|---:|---:|
| Armstrong Woodwaste Cogeneration - Biomass (NA) | CAN (Pacific Northwest) |
| Boardman - Coal (6106) | OR (Pacific Northwest) |
| Colstrip - Coal (6076) | MT (Pacific Northwest) |
| Klamath Falls Cogen - Natural Gas (55103) | OR (Pacific Northwest) |
| Simpson - Biomass (57099) | WA (Pacific Northwest) |
| Transalta Centralia Generation - Coal (3845) | WA (Pacific Northwest) |
| Weyerhaeuser Long View - Biomass/Coal/Natural Gas (50187) | WA (Pacific Northwest) |
| Apache Station - Coal (160) | AZ (Pacific Southwest) |
| Apex Generating Station - Natural Gas (55514) | NV (Pacific Southwest) |
| Arlington Valley Energy Facility - Natural Gas (55282) | AZ (Pacific Southwest) |
| Blundell - Geothermal (299) | UT (Pacific Southwest) |
| Bonanza - Coal (7790) | UT (Pacific Southwest) |
| Caithness Dixie Valley - Geothermal (52015) | NV (Pacific Southwest) |
| El Dorado Energy - Natural Gas (55077) | NV (Pacific Southwest) |
| Four Corners - Coal (2442) | NM (Pacific Southwest) |
| Griffith Energy - Natural Gas (55124) | AZ (Pacific Southwest) |
| Harquahala Generating Project - Natural Gas (55372) | AZ (Pacific Southwest) |
| Hunter - Coal (6165) | UT (Pacific Southwest) |
| Intermountain - Coal (6481) | UT (Pacific Southwest) |
| La Rosita - Natural Gas (G9787) | MEX (Pacific Southwest) |
| Mesquite Generating Station - Natural Gas (55481) | AZ (Pacific Southwest) |
| Mohave - Coal (2341) | NV (Pacific Southwest) |
| Navajo - Coal (4941) | AZ (Pacific Southwest) |
| Nebo Power Station - Natural Gas (56177) | UT (Pacific Southwest) |
| Red Hawk - Natural Gas (55455) | AZ (Pacific Southwest) |
| Reid Gardner - Coal (2324) | NV (Pacific Southwest) |
| San Juan - Coal (2451) | NM (Pacific Southwest) |
| Termoeléctrica de Mexicali - Natural Gas (G9786) | MEX (Pacific Southwest) |
| Thermo No. 1 Raser - Geothermal (NA) | UT (Pacific Southwest) |
| Yucca/Yuma Axis - Natural Gas (120 & 121) | AZ (Pacific Southwest) |
| Yuma Cogeneration Associates - Natural Gas (54694) | AZ (Pacific Southwest) |

Unspecified imports, because they cannot be exactly linked to a plant of origin, are not assigned an actual fuel value in the inventory. For years 2000 to 2008, a composite emission factor was developed, based on data provided by the CEC. For 2009, staff used an emission factor developed by the Western

Climate Initiative (WCI) (WCI, 2011). This change of method was motivated by two reasons: (a) the discontinuation in 2009 of the CEC data reporting (Net System Power) on which the previous emission factors were based; and (b), to maintain consistency with the upcoming cap and trade program, which uses the WCI emission factor. The WCI has estimated unspecified imports emission factors for 2006 to 2008, and staff used the average of these 3 values as the 2009 emission factor.

As electrical power is transmitted through power lines, losses occur because of resistance and other physical factors. Therefore, more electrical power must be generated than is actually delivered and consumed in California. Staff accounted for these losses and the emissions associated with them in the inventory since they occur as a result of California's demand for imports. In the case of most specified imports, the amount of electricity generated at the plant of origin was known and thus there was no need for line loss corrections. In three cases (Colstrip, Bonanza and Hunter) the amount of electricity produced at the plant of origin was not known: only the amount received by the purchasing agency at the point of reception was available. In those cases, the actual amount of electricity generated at the plant of origin can be estimated by applying a plant specific line loss factor to the amount of electrical power received from the plant. Staff used line loss factors of 7.5 percent for imports from Colstrip and Hunter, and 3 percent for imports from Bonanza. This last factor reflects the line loss estimates included in the contract for power purchased from the Bonanza plant by LADWP (Parsons, 2009). Line losses from the remaining two specified imports (Colstrip and Hunter) and all unspecified imports were estimated using the CEC suggested loss factor of 7.5 percent. These line loss corrections were only required for 2000-2008 data, as 2009 Mandatory Reporting electricity imports data include line losses, eliminating the need for such a correction.

Statewide electricity imports are typically reported as net imports (gross imports – exports). However, accounting for all emissions resulting from the generation of electrical power for California requires estimating the gross import value. Actual export data was obtained from the California Department of Finance (CDOF) California Statistical Abstract – Table J-11 (CDOF, 2010) for 2001-2008. These export estimates were then added to the net import value to obtain the gross import number. For 2000, the average of the 2002-2004 exports were used as an estimate, and for 2009, this procedure was no longer necessary as the Mandatory Reporting Program captured gross imports directly.

All imports of electricity are classified under IPCC code 1A1ai (Electricity Generation), while $SF_6$ emissions from imported power are under IPCC code 2G1b (Use of Electrical Equipment). These $SF_6$ emissions are attributed to the electric power sector.

## 2. Data Sources

Imported electric power emissions estimates are based primarily on fuel use, heat and electricity generation data obtained from the U.S. Energy Information Administration (EIA). Data for 2000 were obtained through personal correspondence with Robert Schnapp of the U.S. Energy Information Administration (Schnapp, 2008). Data for 2001 to 2008 were downloaded from U.S. Energy Information Administration databases published online (EIA, 2011a). The Los Angeles Department of Water and Power (LADWP), an importer of out-of-state power, provided fuel use and heat content data for plants (Intermountain, Mohave, and Navajo) for which they have ownership (Parsons, 2009). Imported generation contract data was provided by LADWP (Parsons, 2009) for the Bonanza and Colstrip plants and by the City of Riverside (Mendez, 2009) for the Hunter plant. For 2009, Mandatory Reporting data (ARB, 2011b) was used to determine the amount of electricity (MWh) imported while the emission factors applied to these imports were estimated from the EIA data (EIA, 2011a) or the CEC data (Nyberg, 2009) for these plants.

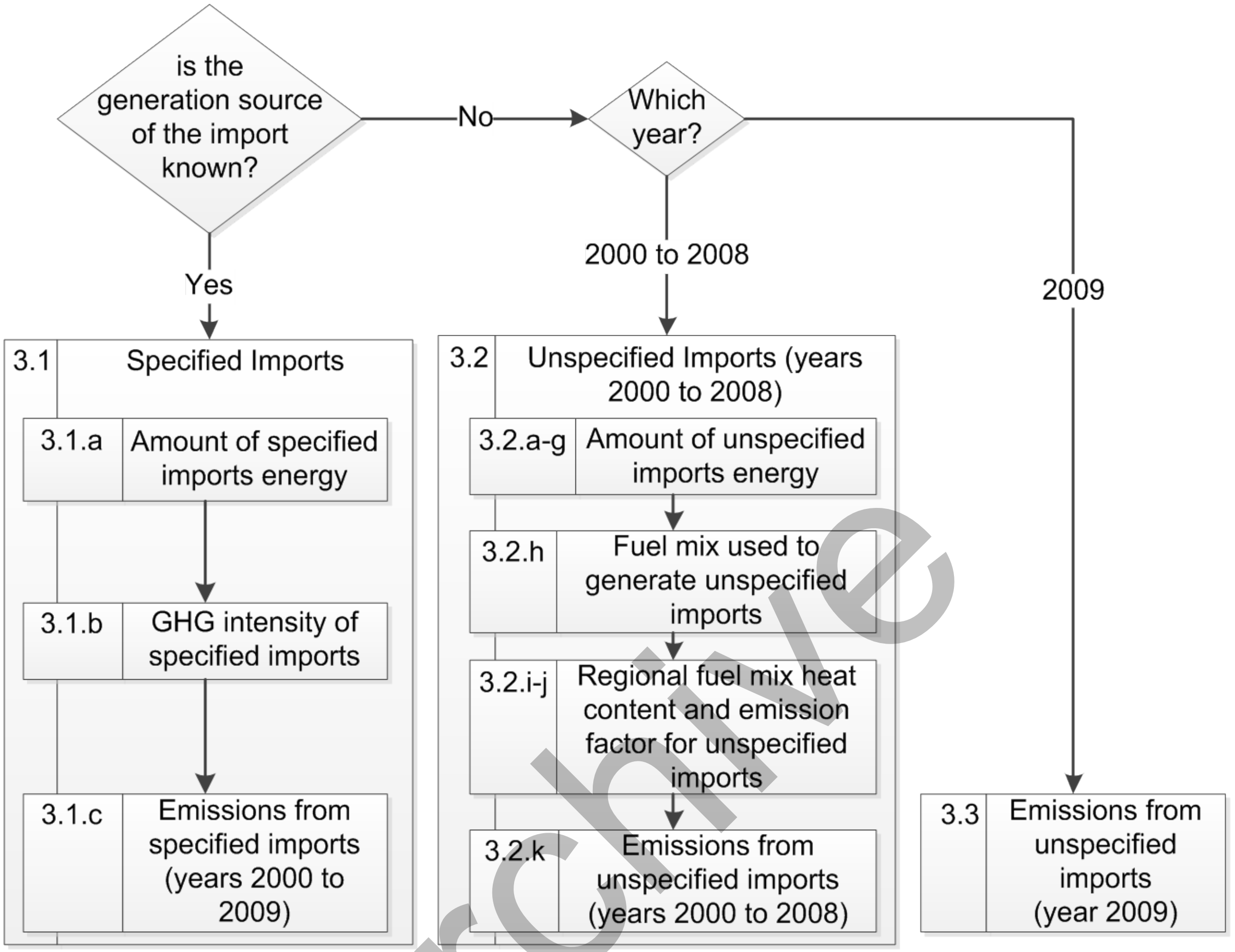
Fuel $CO_2$ Emissions factors are from USEPA 1990-2005 greenhouse gas inventory (USEPA, 2007b). Fuel $CH_4$ and $N_2O$ emissions factors come from the IPCC 2006 guidelines for stationary combustion (IPCC, 2006b).

Net Imports data are from the California Department of Finance's (CDOF) California Statistical Abstract Table J-11 (CDOF, 2010). The California Energy Commission (CEC) provided data on line losses, exports (Alvarado, 2007), ownership and entitlement shares (Griffin, 2007), and assumptions for the fuel mix of unspecified imports for 2000 and 2001 (CEC, 2000) and for 2002 to 2008 (CEC, 2002-08). The emission factor used for 2009 unspecified imports comes from the Western Climate Initiative (WCI) (WCI, 2011).

## 3. Methodology

The methodological steps involved in estimating emissions from electricity imports depends upon whether the generation source of the imports is known or not and with the year of the estimate (see Figure 1).

*Figure 1: Methodological steps involved in estimating emissions from electricity imports*



### *3.1 Specified Imports*

(a) Amount of specified imports energy

For 2000-2008, ownership, entitlement or contracted import amounts were provided by the CEC except for the Intermountain, Mohave, Navajo, Colstrip, and Bonanza plants, for which data were obtained from the LADWP (Parsons, 2009), and for the Hunter plant which information was provided by the City of Riverside (Mendez, 2009). For Colstrip, Bonanza and Hunter, the amount of imported power received, rather than generated, was the value documented. Line loss factors were used to adjust these amounts to estimate the actual plant generation required to supply LADWP or the City of Riverside with imported power. For all other specified plants, the ownership share, entitlement share or plant generation share was used, and because these apply directly to the plant itself, no line loss adjustment was needed. These data allow one to calculate the percentage of a given plant's electricity generation imported into California that year. A subset of these percentages is shown in Table 5 below. Note that Hoover (hydropower) and Palo Verde (nuclear) are included below even though they are not shown in the inventory itself because they generate no emissions.

*Table 5: Percent of plant electricity generation imported by California*

| **Plant Name (State) – Fuel** | **2000** | **2001** | **2002** | **2003** | **2004** | **2005** | **2006** | **2007** | **2008** |
|---|---|---|---|---|---|---|---|---|---|
| Boardman (OR) - Coal | 27.29 | 23.50 | 23.50 | 23.50 | 23.50 | 23.50 | 23.50 | 23.50 | 23.50 |
| Bonanza (UT) - Coal | 7.49 | 5.59 | 5.24 | 5.80 | 5.79 | 5.76 | 5.42 | 5.61 | 5.61 |
| Caithness Dixie Valley (NV) - Geothermal | 97.83 | 95.10 | 96.02 | 96.89 | 100 | 98.04 | 99.44 | 97.79 | 99.46 |
| Colstrip (MT) - Coal | 0* | 0* | 0* | 0* | 0* | 0* | 0* | 0* | 0* |
| Four Corners (NM) - Coal | 34.61 | 36.05 | 36.05 | 36.05 | 36.05 | 36.05 | 36.05 | 36.05 | 36.05 |
| Hoover (AZ/NV) - Hydro | 76.57 | 76.57 | 76.57 | 76.57 | 76.57 | 76.57 | 76.57 | 76.57 | 76.57 |
| Hunter (UT) - Coal | 2.42 | 2.78 | 2.29 | 2.15 | 2.28 | 2.31 | 2.24 | 2.09 | 2.15 |
| Intermountain (UT) - Coal | 99.11 | 96.83 | 96.38 | 97.08 | 93.75 | 94.76 | 93.79 | 89.59 | 88.57 |
| La Rosita (MEX) - Natural Gas | 0* | 0* | 0* | 0* | 0* | 0* | 0* | 0* | 52.38 |
| Mohave (NV) - Coal | 76.02 | 75.35 | 66.02 | 66.12 | 66.11 | 66.11 | 0* | 0* | 0* |
| Navajo (AZ) - Coal | 21.19 | 21.18 | 21.37 | 21.40 | 20.74 | 19.70 | 20.41 | 20.83 | 20.97 |
| Palo Verde (AZ) - Nuclear | 27.41 | 27.41 | 27.41 | 27.41 | 27.41 | 27.41 | 27.41 | 27.41 | 27.41 |
| Reid Gardner (NV) - Coal | 29.22 | 28.88 | 28.88 | 28.88 | 28.88 | 28.88 | 28.88 | 28.88 | 28.88 |
| San Juan (NM) - Coal | 4.37 | 24.08 | 24.08 | 24.08 | 24.08 | 24.08 | 24.08 | 24.08 | 24.08 |
| Termoeléctrica de Mexicali (MEX) - Natural Gas | 0* | 0* | 0* | 0* | 0* | 0* | 0* | 100 | 100 |
| Yucca/Yuma Axis (AZ) - Natural Gas | 42.61 | 42.61 | 42.61 | 42.61 | 42.61 | 42.61 | 42.61 | 42.61 | 42.61 |

*LADWP imported from Colstrip for years 1990-1999 (about 5.8 percent on average) and from Mohave for years 1990-2005. Termoeléctrica de Mexicali began exporting in 2007 and La Rosita began in 2008.

For 2009, the amount of electricity imported into the state from each specified source was queried from ARB's Mandatory Reporting Program's database (ARB, 2011b).

(b) <u>GHG intensity of specified imports</u>

Staff used fuel use and heat content data from EIA or CEC, and fuel specific emission factors to estimate the GHG intensity per MWh of electricity from each plant as follows:

*Equation 4: GHG intensity of specified imports*

$$I_{GHG,\,plant} = \frac{\sum_{fuel} Q_{fuel,\,plant} \bullet HC_{fuel,\,plant} \bullet EF_{GHG,\,fuel,\,plant}}{TG_{plant}}$$

Where,

$I_{GHG,\ plant}$ = GHG intensity of electricity from the given plant, for the particular GHG (g of GHG per MWh)
$Q_{fuel,\ plant}$ = Amount of fuel combusted at the given plant (in units of tons for solid fuels, gallons for liquid fuels or standard cubic feet for gaseous fuels)
$HC_{fuel}$ = Heat content of the type of fuel at the given plant (BTU / unit)
$EF_{GHG,\ fuel}$ = Emission factor of the particular GHG by combustion of the given fuel (g GHG / BTU)
$TG_{plant}$ = Total net generation of electricity at the given plant (MWh)

With,
GHG = [$CO_2$, $CH_4$, $N_2O$]
Fuel = [biomass, coal, distillate, natural gas, residual fuel oil]
Plant = [Boardman, Bonanza, Four Corners, Hunter, Intermountain, La Rosita, Mohave, Navajo, Reid Gardner, San Juan, Termoeléctrica de Mexicali, Yucca/Yuma Axis]

Some of the specified imports came from a geothermal plant, Caithness Dixie Valley. GHG intensity was estimated by calculating emissions from that plant with the method described in section I.G below and dividing by the total net amount of electricity produced.

(c) Emissions from specified imports

Emissions from specified imports are then estimated using the following equation:

*Equation 5: Emissions from specified imports*

$$\boxed{E_{GHG,\ plant} = I_{GHG,\ plant} \bullet IG_{plant}}$$

Where,
$E_{GHG,\ plant}$ = Emissions of the particular GHG from the specified imports from the given plant (g)
$I_{GHG,\ plant}$ = GHG intensity of electricity from the given plant, for the particular GHG (g of GHG per MWh)
$IG_{plant}$ = Imported amount of the net electricity generated by the given plant (MWh)

With,
GHG = [$CO_2$, $CH_4$, $N_2O$]
Plant = [Boardman, Bonanza, Four Corners, Hunter, Intermountain, La Rosita, Mohave, Navajo, Reid Gardner, San Juan, Termoeléctrica de Mexicali, Yucca/Yuma Axis]

Values for the EIA or plant specific heat inputs and emission factors are available upon request. For a list of yearly activity and GHG intensities used in the emission estimation equation, please consult the online documentation annex at: http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_1b_electricity_production_imports.pdf

### 3.2 Unspecified Imports (years 2000 to 2008)

For years 2000 and 2001, the fuel mix used for unspecified imports and the resulting GHG emissions are based on CEC's *1999 Net System Power Calculation* (CEC, 2000), and on CEC's *Net System Power Reports* for years 2002 to 2008 (CEC, 2002-08). ARB staff relies on the expertise of CEC staff in this matter. Any future updates on fuels used in the production of unspecified power will involve collaboration between staff of ARB and CEC. Detailed data used for all calculations are available upon request.

Electricity imported into California originates from two regions: the Pacific Northwest (PNW) and Pacific Southwest (PSW).

(a) Net electricity imports

Net imports data come from the California Department of Finance (CDOF) California Statistical Abstract – Table J-11 (CDOF, 2010). Table J-11 is based on data supplied to CDOF by the CEC.

*Table 6: Net imports (GWh)*

| **Region** | **2000** | **2001** | **2002** | **2003** | **2004** | **2005** | **2006** | **2007** | **2008** |
|---|---|---|---|---|---|---|---|---|---|
| PNW | 18,777 | 6,826 | 27,186 | 22,303 | 20,831 | 20,286 | 19,803 | 24,669 | 23,959 |
| PSW | 7,997 | 58,107 | 60,408 | 63,097 | 70,458 | 66,795 | 59,911 | 67,547 | 74,113 |

(b) Electricity exports – years with data

Known exports data for years 2001 to 2008 were also taken from CDOF's table J-11, values for year 2000 are not available:

*Table 7: California exports (GWh)*

| **Region** | **2000** | **2001** | **2002** | **2003** | **2004** | **2005** | **2006** | **2007** | **2008** |
|---|---|---|---|---|---|---|---|---|---|
| PNW | Unknown | 5,846 | 1,020 | 1,471 | 1,532 | 2,061 | 2,518 | 2,620 | 2,242 |
| PSW | Unknown | 9,007 | 5,514 | 4,555 | 3,292 | 3,623 | 2,539 | 2,966 | 2,822 |

(c) Electricity exports – estimation for years without data

First, staff used years 2002 to 2004 of data from Table 6 and Table 7 to determine the average ratio of exports to net imports in gigawatt-hours (GWh) for each region as follows:

*Equation 6: Average ratio of exports to net imports of electricity*

$$Ratio = \frac{\sum_{year=2002}^{2008} Exports_{year}}{\sum_{year=2002}^{2008} Net\_imports_{year}}$$

Note that there was an electricity supply crisis in California in 2001, and for that reason export and import data for that year were not used in the ratio determination. The average export-to-import ratios were 6 percent (0.06) for the PNW and 7 percent (0.07) for the PSW.

These export-to-import ratios were then applied to the net imports for year 2000 from each of these regions to estimate the exports for that year.

*Table 8: Estimate of California exports (GWh)*

| **Region** | **2000** | **2001-2008** |
|---|---|---|
| PNW | 1,074 | See Table 7 |
| PSW | 3,418 | See Table 7 |

(d) Gross imports

Gross imports are equal to net imports (Table 6) plus exports (Table 7 or Table 8)

*Table 9: Gross imports (GWh)*

| **Region** | **2000** | **2001** | **2002** | **2003** | **2004** | **2005** | **2006** | **2007** | **2008** |
|---|---|---|---|---|---|---|---|---|---|
| PNW | 19,851 | 12,672 | 28,206 | 23,774 | 22,363 | 22,347 | 22,321 | 27,289 | 26,201 |
| PSW | 11,415 | 67,114 | 65,922 | 67,652 | 73,750 | 70,418 | 62,450 | 70,513 | 76,935 |

(e) Amount of generation related to gross imports

Gross generation for imports, the actual power generated by out-of-state sources for California's electricity imports, is estimated by adding an assumed 7.5 percent line loss to the gross import number. This was done by dividing the values of Table 9 by 0.925 (i.e., 1 – 0.075):

*Table 10: Gross generation for imports (GWh)*

| **Region** | **2000** | **2001** | **2002** | **2003** | **2004** | **2005** | **2006** | **2007** | **2008** |
|---|---|---|---|---|---|---|---|---|---|
| PNW | 21,461 | 13,699 | 30,493 | 25,702 | 24,176 | 24,159 | 24,131 | 29,502 | 28,325 |
| PSW | 12,341 | 72,556 | 71,267 | 73,137 | 79,730 | 76,128 | 67,514 | 76,230 | 83,173 |

(f) Amount of specified imports included in net imports data

To avoid double counting emissions, specified imports (see section 3.1 above) were removed from the amount listed in CDOF's table J-11. Per CEC staff, import data in CDOF's table J-11 did not include ownership share or entitlement generation prior to 2001. On the basis of this information, ARB staff determined that, before 2001, only contracted imports were included in table J-11 and needed to be removed. These include three plants: Bonanza, Colstrip and Hunter.

For 2000, only Bonanza, Colstrip and Hunter were removed. For years 2001 to 2008, all the specified imports were removed:

*Table 11: Specified imports included in CDOF table J-11 (GWh)*

| **Region** | **2000** | **2001** | **2002** | **2003** | **2004** | **2005** | **2006** | **2007** | **2008** |
|---|---|---|---|---|---|---|---|---|---|
| PNW | 0 | 1,040 | 887 | 1,011 | 832 | 814 | 558 | 1,023 | 951 |

| Region | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|---|---|---|
| PSW | 451 | 46,505 | 45,425 | 44,513 | 45,397 | 43,992 | 37,671 | 40,164 | 43,918 |

(g) Amount of unspecified imports energy

Unspecified imports were calculated by subtracting Table 11 from Table 10 values, which gives:

*Table 12: Unspecified imports (GWh)*

| Region | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|---|---|---|
| PNW | 21,461 | 12,659 | 29,606 | 24,691 | 23,344 | 23,345 | 23,573 | 28,478 | 27,374 |
| PSW | 11,890 | 26,051 | 25,842 | 28,624 | 34,333 | 32,135 | 29,842 | 36,066 | 39,255 |

(h) Fuel Mix used to generate unspecified imports

The fuel mix of unspecified imports was based directly on the CEC's *1999 Net System Power Calculation* (CEC, 2000) for years 2000 and 2001 and through a reconciliation methodology with their *Net System Power Reports* (NSP) for years 2002 to 2008 (CEC, 2002-08). NSP was not used for 2001 due to the potential for aberrant values resulting from the California energy market crisis.

The methodology for determining the unspecified imports fuel mix for 2002-2008 using the NSP data is described briefly here.

First, the total gigawatt-hours (GWh) of imports by fuel type (Coal, Natural Gas, and Non-Emitting) and by region were compiled from the NSP reports for 2002-2008:

*Table 13: Net System Power (GWh by fuel type and region)*

| Region | Fuel | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|---|---|
| PNW | Coal | 5,283 | 7,488 | 5,154 | 4,926 | 5,467 | 6,546 | 8,581 |
|  | Natural Gas | 1,717 | 1,911 | 1,926 | 1,786 | 2,051 | 1,837 | 2,939 |
|  | Non-Emitting | 20,186 | 12,904 | 10,346 | 13,574 | 12,286 | 16,286 | 12,425 |
| PSW | Coal | 21,582 | 24,306 | 20,760 | 24,796 | 23,195 | 39,275 | 43,271 |
|  | Natural Gas | 6,865 | 7,738 | 8,400 | 10,812 | 13,207 | 16,363 | 15,060 |
|  | Non-Emitting | 7,226 | 7,464 | 5,912 | 6,562 | 8,557 | 11,909 | 15,782 |

Second, these values, which represent the amount of electricity measured at the California border (and thus is missing the line losses), were increased to estimate the amount of electricity generated at the plant of origin, so a full reckoning (including line losses) could be developed. The values in Table 13 were divided by 0.925 to account for line losses using the CEC suggested line loss value of 7.5 percent (Alvarado, 2007).

Additionally, the amount of generation from two plants (Intermountain and Mohave) was added to the NSP report values for years 2002 to 2006 to stay consistent with CDOF's table J-11. This table includes all imports, whereas the NSP reports for 2002 to 2006 exclude the generation from those two plants, considering them as utility owned rather than imports. The NSP reports for

2007 and 2008 do include these two plants into the totals and future reports will continue to do so. Thus this adjustment is needed only for years 2002 to 2006. Table 14 below incorporates both the line loss adjustment and the addition of the two missing specified imports from Intermountain and Mohave:

*Table 14: Net System Power (adjusted to account for missing specified imports & line losses)*

| Region | Fuel | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|---|---|
| PNW | Coal | 5,926 | 8,629 | 6,062 | 5,866 | 6,662 | 7,828 | 10,145 |
| | Natural Gas | 1,926 | 2,202 | 2,265 | 2,127 | 2,499 | 2,197 | 3,475 |
| | Non-Emitting | 22,641 | 14,870 | 12,168 | 16,165 | 14,971 | 19,476 | 14,690 |
| PSW | Coal | 46,598 | 48,915 | 44,852 | 49,023 | 40,046 | 44,324 | 48,561 |
| | Natural Gas | 8,569 | 9,330 | 9,933 | 12,693 | 15,084 | 18,466 | 16,901 |
| | Non-Emitting | 9,019 | 9,000 | 6,991 | 7,704 | 9,773 | 13,440 | 17,711 |

Third, the Specified Imports by fuel type for years 2002 to 2008 were determined. The values in Table 15 below match those of Table 11, except that the Table 15 values are shown in greater detail:

*Table 15: Specified imports by fuel type and region (GWh)*

| Region | Fuel | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|---|---|
| PNW | Coal | 887 | 1,011 | 832 | 814 | 558 | 1,023 | 951 |
| | Natural Gas | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Non-Emitting | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| PSW | Coal | 32,782 | 33,125 | 34,121 | 33,586 | 27,460 | 26,057 | 25,769 |
| | Natural Gas | 171 | 99 | 109 | 105 | 126 | 3,417 | 6,881 |
| | Non-Emitting | 12,472 | 11,289 | 11,167 | 10,302 | 10,086 | 10,691 | 11,268 |

Fourth, Specified Imports (Table 15) were deducted from total imports (Table 14) to obtain the values of Unspecified Imports:

*Table 16: Unspecified imports by fuel type and region (GWh)*

| Region | Fuel | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|---|---|
| PNW | Coal | 5,039 | 7,618 | 5,229 | 5,052 | 6,104 | 6,805 | 9,194 |
| | Natural Gas | 1,926 | 2,202 | 2,265 | 2,127 | 2,499 | 2,197 | 3,475 |
| | Non-Emitting | 22,641 | 14,870 | 12,168 | 16,165 | 14,971 | 19,476 | 14,690 |
| | **Total** | **29,606** | **24,691** | **19,663** | **23,345** | **23,574** | **28,478** | **27,359** |
| PSW | Coal | 13,816 | 15,790 | 10,731 | 15,437 | 12,586 | 18,267 | 22,792 |
| | Natural Gas | 8,398 | 9,231 | 9,824 | 12,588 | 14,958 | 15,050 | 10,020 |
| | Non-Emitting | 0 | 0 | 0 | 0 | 161 | 2,749 | 6,443 |
| | **Total** | **22,214** | **25,021** | **20,555** | **28,025** | **27,705** | **36,066** | **39,255** |

Finally, taking the fuel and region specific values in Table 16 and dividing each by the total for that region produced the percentages in Table 17, which were used to calculate the emissions from Unspecified Imports for 2002 to 2008. The values for 2000 and 2001 were taken directly from the CEC's 1999 Net System Power Calculation (CEC, 2000) and required no additional calculations:

*Table 17: Fuel-mix of unspecified imports (percentage)*

| Region | Fuel | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|---|---|---|---|
| PNW | Coal | 20% | 20% | 17% | 31% | 27% | 22% | 26% | 24% | 34% |
| | Natural Gas | 0% | 0% | 7% | 9% | 12% | 9% | 11% | 8% | 13% |
| | Non-Emitting | 80% | 80% | 76% | 60% | 62% | 69% | 64% | 68% | 54% |
| PSW | Coal | 74% | 74% | 62% | 63% | 52% | 55% | 45% | 51% | 58% |
| | Natural Gas | 26% | 26% | 38% | 37% | 48% | 45% | 54% | 42% | 26% |
| | Non-Emitting | 0% | 0% | 0% | 0% | 0% | 0% | 1% | 8% | 16% |

## (i) Average heat content and emission factors for unspecified imports

### *(i.i) Weighted average heat content*

Weighted average heat contents (in BTU per MWh) were calculated by region by year for coal and natural gas. Staff obtained plant specific data for amounts of fuel combusted, heat content values and generated power from the EIA. Data from Oregon, Washington, Idaho and Montana were included in calculations for the PNW region; and data from Arizona, Colorado, New Mexico, Nevada and Utah for the PSW region. The weighted average heat contents were calculated as follows:

*Equation 7: Weighted average heat contents of fuels*

$$WHC_{fuel} = \frac{\sum_{type,plant}(Q_{fuel,type,plant} \bullet HC_{fuel,type,plant})}{\sum_{type,plant} G_{fuel,type,plant}}$$

Where,

$WHC_{fuel}$ = Weighted average heat content for the given fuel (btu per MWh)

$Q_{fuel, type, plant}$ = Quantity of the given fuel of the particular type combusted by the given plant (tons for coal, scf for natural gas)

$HC_{fuel, type, plant}$ = Heat content of the given fuel of the particular type combusted by the given plant (btu / ton for coal, btu / scf for natural gas)

$G_{fuel, type, plant}$ = Power generated with given fuel of the particular type by the given plant (MWh)

With,

fuel = [coal, natural gas]

type = [bituminous, lignite, etc.], applies only to coal

plant: power plants in either Pacific Northwest or Pacific Southwest region

### *(i.ii) Weighted average emission factor*

Weighted average emission factors (in grams per BTU) were calculated by region and by year for coal and natural gas. Staff obtained fuel specific emission factor values from the EIA for $CO_2$ and from the IPCC guidelines for $CH_4$ and $N_2O$. Emission factors for non-emitting sources of electrical power were assumed to be zero. Staff included data from Oregon, Washington, Idaho and Montana in calculations for the PNW region; and from Arizona, Colorado, New Mexico, Nevada and Utah for the PSW region. The weighted average emissions factors were calculated as follows:

*Equation 8: Weighted average fuel emission factors of unspecified imports*

$$\boxed{WEF_{GHG,\,fuel} = \frac{\sum_{plant}(Q_{fuel,\,plant} \bullet HC_{fuel,\,plant} \bullet EF_{GHG,\,fuel,\,plant})}{\sum_{plant}(Q_{fuel,\,plant} \bullet HC_{fuel,\,plant})}}$$

Where,

$WEF_{GHG,\,fuel}$ = Weighted average emission factor for one of the given GHG, for a given fuel (grams per btu)

$Q_{fuel,\,plant}$ = Amount of the given fuel combusted by the particular plant (tons for coal, scf for natural gas)

$HC_{fuel,\,plant}$ = Heat content of the given fuel combusted by the particular plant (btu / ton for coal, btu / scf for natural gas)

$EF_{GHG,\,fuel,\,plant}$ = Emission factor of a given GHG from the given fuel combusted by the particular plant (g of GHG per btu)

With,

fuel = [coal, natural gas]

GHG = [$CO_2$, $CH_4$, $N_2O$]

plant: power plants in either Pacific Northwest or Pacific Southwest region

### *(i.iii) Combined GHG emission factors*

Combined-GHG emission factors (in lbs of $CO_2$ equivalent per MWh) may be computed from the GHG-specific factors above for the purpose of comparison with other such published factors. For each year and each region, they are the result of:

*Equation 9: Combined-GHG emission factors of unspecified imports*

$$\boxed{CEF_{fuel} = \frac{\sum_{GHG}(WHC_{fuel} \bullet WEF_{GHG,\,fuel} \bullet GWP_{GHG})}{453.6}}$$

Where,

$CEF_{fuel}$ = Combined-GHG emission factor of the given fuel (lbs $CO_2e$ per MWh)

$WHC_{fuel}$ = Weighted average heat content for the given fuel (btu per MWh)

$WEF_{GHG,\,fuel}$ = Weighted average emission factor for the given GHG, for a given fuel (grams per btu)

$GWP_{GHG}$ = Global Warming Potential of a given GHG (unitless)

453.6 = number of grams in a pound

With,

fuel = [coal, natural gas, non-emitting]

GHG = [$CO_2$, $CH_4$, $N_2O$]

The combined-GHG emission factors are listed below, in units of pounds of $CO_2$ equivalents (lbs $CO_2e$) per MWh:

*Table 18: Fuel-specific combined-GHG emission factors for Unspecified Imports (lbs $CO_2e$ / MWh)*

| Region | Fuel | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|---|---|---|---|
| PNW | Coal | 2,169 | 2,268 | 2,339 | 2,301 | 2,316 | 2,310 | 2,344 | 2,316 | 2,301 |
| | Natural Gas | 1,024 | 1,014 | 947 | 923 | 838 | 838 | 852 | 857 | 835 |
| | Non-Emitting | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| PSW | Coal | 2,116 | 2,201 | 2,208 | 2,207 | 2,195 | 2,210 | 2,218 | 2,223 | 2,209 |
| | Natural Gas | 1,141 | 1,162 | 1,049 | 1,062 | 1,009 | 943 | 939 | 923 | 916 |
| | Non-Emitting | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

### (j) Regional fuel-mix heat content and emission factors for unspecified imports

Regional fuel-mix heat contents for the Pacific Northwest and Pacific Southwest regions can be estimated by multiplying the weighted average heat contents computed in Section I.B.3.2(i.i) above by the regional fuel mix values of Table 17.

*Equation 10: Regional fuel-mix heat contents for unspecified imports*

$$\boxed{RHC_{region} = \sum_{fuel} WHC_{fuel} \bullet P_{fuel,region}}$$

Where,

$RHC_{region}$ = Regional fuel-mix heat content for the particular region (btu per MWh)

$WHC_{fuel}$ = Weighted average heat content for the given fuel (btu per MWh)

$P_{fuel,\ region}$ = Proportion of power generated in a particular region using the given fuel (percent)

With,

fuel = [coal, natural gas]

region = [PNW, PSW]

Regional fuel-mix emission factors for the Pacific Northwest and Pacific Southwest regions may be estimated by multiplying the weighted average emission factors computed in Section I.B.3.2(i.ii) above by the regional fuel mix values of Table 17.

*Equation 11: Regional fuel-mix emission factors for unspecified imports*

$$\boxed{REF_{GHG,region} = \sum_{fuel} WEF_{GHG,\,fuel} \bullet P_{fuel,region}}$$

Where,

$REF_{GHG,\ region}$ = Regional fuel-mix emission factor for the given GHG in the particular region (g GHG / btu)

$WEF_{GHG,\ fuel}$ = Weighted average emission factor for the given GHG for the given fuel (g GHG / btu)

$P_{fuel,\ region}$ = Proportion of power generated in a particular region using the given fuel (percent)

With,

fuel = [coal, natural gas, non-emitting]

GHG = [$CO_2$, $CH_4$, $N_2O$]
region = [PNW, PSW]

Regional combined-GHG emission factors for unspecified import (in lbs of $CO_2$ equivalent per MWh) may be computed for the purpose of comparison with other such published factors. These factors are the result of multiplying the fuel-mix percentages (Table 17) by the corresponding combined-GHG fuel-specific emissions factors (Table 18) and summing to arrive at a single factor for each region for each year. The Total Imports row in Table 19 shows the yearly system-wide average emission factors for California's unspecified imports.

*Table 19: Regional emission factors for Unspecified Imports (lb $CO_2e$ / MWh)*

| **Region** | **2000** | **2001** | **2002** | **2003** | **2004** | **2005** | **2006** | **2007** | **2008** |
|---|---|---|---|---|---|---|---|---|---|
| PNW | 434 | 454 | 460 | 792 | 713 | 576 | 697 | 620 | 879 |
| PSW | 1,862 | 1,931 | 1,770 | 1,785 | 1,628 | 1,641 | 1,514 | 1,511 | 1,517 |
| Total Imports | **943** | **1,448** | **1,070** | **1,325** | **1,258** | **1,193** | **1,154** | **1,118** | **1,255** |

(k) Emissions from unspecified imports

Emissions from unspecified imports were estimated by multiplying the amount of unspecified import power (Table 12) by the regional fuel-mix heat content and the corresponding regional fuel-mix emission factors:

*Equation 12: Emissions from unspecified imports*

$$E_{GHG,region} = UI_{region} \bullet RHC_{region} \bullet REF_{GHG,region}$$

Where,

$E_{GHG,\ region}$ = Emissions of the given GHG for unspecified imports from the particular region (g of GHG)
$UI_{region}$ = Amount of unspecified power imported from the particular region (MWh)
$RHC_r$ = Regional fuel-mix heat content for the particular region (btu per MWh)
$REF_{g,r}$ = Regional fuel-mix emission factor for the given GHG in the particular region (g / btu)

With,

GHG = [$CO_2$, $CH_4$, $N_2O$]
region = [PNW, PSW]

### *3.3 Emissions from unspecified imports (year 2009)*

The above detailed method (used for 2000 to 2008) cannot be used 2009 and future years because the CEC no longer generates the Net System Power report required to use the previous methodology.

For 2009, Mandatory Reporting data was used to determine the total amount of unspecified electricity imported into the state. These unspecified imports were converted into emissions using the WCI emission factor (WCI, 2006-2008).

For a list of yearly activity, heat content and emission factor values used in the inventory estimates, please consult the online documentation annex at: http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_1b_electricity_production_imports.pdf

## 4. Changes in Estimates

The major changes in the current estimates of imported electricity emissions when compared with those made for the 1990-2004 edition of GHG Inventory are:

- Staff corrected an error in the source mix of unspecified imports from the PSW in 2000-2001: a 26 percent share of the imports attributed to hydropower should have been attributed to natural gas combustion. This error originated from the data used for the calculation and was detected when staff reviewed data for this edition. Correcting this error resulted in a substantial increase in estimated emissions for unspecified imports in 2000-2001.
- In the 1990-2004 edition of the inventory, staff incorrectly concluded that the specified imports from Hoover (Hydro) and Palo Verde (Nuclear) were contained in CDOF's table J-11 (as used in section I.B.3.2(f)), and subtracted them out for years 1990 to 2000. Staff has since learned that this was not the case, and thus did not remove these plants' imports for year 2000 in this edition. This correction resulted in a slight emissions increase for that year.
- Two new plants located in Mexico (Termoeléctrica de Mexicali and La Rosita) have exported electricity to California since 2007 and have been included in the list of specified imports sources. Also, staff learned of specified imports from Caithness Dixie Valley Plant in Nevada, a geothermal plant. This plant is now included in this edition's estimates but its emissions are discussed in section I.G.
- The table of "Total Production by Resource Type" (table J-11), published by CDOF on the basis of data prepared by CEC, has itself been revised since staff used it for the 1990-2004 edition of the inventory. It now includes any electric power that comes in through California's border as imported. Previous versions did not consider power coming from out-of-state plants owned by California utilities, such as Intermountain and Mohave, as imports. ARB staff changed its calculations accordingly and this revision did not impact the estimates.
- Finally, ARB staff now uses data from CEC's Net System Power reports to directly calculate the unspecified imports emission factor, rather than taking the value contained in CEC's 1990-2004 GHG inventory. For the current edition, ARB staff has developed a consistent method, based on the CEC Net System Power reports, which can be used for 2002-2008 inventories. This change resulted in a slight increase in the estimates for unspecified imports when compared with the numbers published in the 2000-2004 edition of ARB's GHG inventory.

All together these changes and updates made by data sources resulted in limited adjustments in emissions estimates for the categories included in this section: +13.0 percent on average over the years 2000 to 2004 when compared with the estimates in the first edition of ARB's GHG inventory.

### 5. Future Improvements

Future improvements will include improved estimates of region specific emission factors for unspecified imports of power, better assessment of line losses, and use of ARB's GHG Mandatory Reporting data for imported power (specified and unspecified).

## C. Fuel Combustion in Industrial, Commercial, Residential, Agricultural and Other Sectors (IPCC 1A1b, 1A2, 1A4 & 1A5)

### 1. Background

Fuel combustion is used as a source of energy to power machinery and heat buildings throughout California. In this section we discuss the emissions from fuel combustion by petroleum refineries (IPCC 1A1b); manufacturing industries and construction (IPCC category 1A2); in agriculture, forestry, commercial and institutional settings and residential dwellings (category 1A4); and other non-identified activities (category 1A5). Emissions from fuel combustion for transportation (category 1A3) are discussed in section I.D below.

Petroleum refineries used catalyst coke, distillate, LPG, natural gas, petroleum coke, refinery gas and residual fuel oil. Fuels used by manufacturing industries and construction include: biomass waste fuel, coal, distillate, ethanol, gasoline, kerosene, LPG, natural gas, petroleum coke, residual fuel oil, tires, and wood. Fuels used in commercial, institutional and residential settings are: coal, distillate, ethanol, gasoline, kerosene, LPG, natural gas, residual fuel oil, and wood.

The inventory includes the emissions of $CO_2$, $CH_4$ and $N_2O$ resulting from the combustion of fossil fuels. Some renewable fuels (biomass waste fuel, wood) are also used as a source of energy. The GHG inventory includes only the $CH_4$ and $N_2O$ emissions resulting from the combustion of renewable fuels since the $CO_2$ emissions would have occurred eventually as the biomass decayed. These $CO_2$ emissions, labeled "from biogenic materials", are estimated and tracked, but are not included in California's GHG inventory total. Other combustibles used as fuels, such as used tires, are made in part from renewable materials (e.g., natural rubber). In this case, two values for $CO_2$ emissions are estimated in proportion to the renewable and fossil components. Only the $CO_2$ from the fossil component is included in the inventory total.

## 2. Methodology

The method for estimating emissions follows IPCC 2006 guidelines for stationary combustion (IPCC, 2006a). California or US-specific emission factors and heat content values were used when available.

*Equation 13: Emissions from stationary combustion*

$$\boxed{E_{GHG,\ fuel} = Q_{fuel} \bullet HC_{fuel} \bullet EF_{GHG,\ fuel}}$$

Where,

$E_{GHG,\ fuel}$ = Emissions of the given GHG for the type of fuel (g of GHG)
$Q_{fuel}$ = Quantity of the type of fuel combusted (in units of tons for solid fuels, gallons for liquid fuels or standard cubic feet for gaseous fuels)
$HC_{fuel}$ = Heat content of the type of fuel (BTU / unit)
$EF_{GHG,\ fuel}$ = Emission factor of the given GHG by the type of fuel (g GHG / BTU)

With,

GHG = [$CO_2$, $CH_4$, $N_2O$]
Fuel = [biomass waste fuel, catalyst coke, coal, distillate, ethanol, gasoline, jet fuel, kerosene, LPG, natural gas, petroleum coke, refinery gas, residual fuel oil, and wood]

A variant of this estimation method was used to estimate $CO_2$ emissions in the case of partially renewable fuels. These fuels are a mix of materials from renewable and fossil origins. Used tires are such a fuel.

*Equation 14: Variant for partially renewable fuels*

$$\boxed{E_{GHG,\ fuel,\ origin} = E_{GHG,\ fuel} \bullet P_{fuel,\ origin}}$$

Where,

$E_{GHG,\ fuel,\ origin}$ = Emissions of the given GHG for proportion of materials of given origin for the type of fuel (g of GHG)
$E_{GHG,\ fuel}$ = Emissions of the given GHG for the type of fuel (g of GHG)
$P_{fuel,\ origin}$ = proportion of material of given origin in the type of fuel (fraction)

With,

GHG = [$CO_2$]
Fuel = [tires]
Origin = [Fossil, Renewable]

## 3. Data Sources

The data sources for estimating emissions include the California Energy Commission's Quarterly Fuels and Energy Report (QFER), the California Energy Commission's Petroleum Industry Information Reporting Act (PIIRA), the Energy Information Administration State Energy Data System (EIA SEDS), the US Environmental Protection Agency, the Intergovernmental Panel on Climate Change (IPCC), ARB's Mandatory Reporting Program, and selected industry associations.

Fuel use data are primarily from the EIA and CEC. Data on fuel use by petroleum refineries were summarized from the PIIRA database (O'Brien, 2010) for 2000-2008, and from ARB's Mandatory Reporting Program (ARB, 2011b) for 2009. Natural gas use data were summarized from the QFER database (Gough, 2011), except for natural gas use by natural gas pipeline compressor stations, which came from the EIA SEDS (EIA, 2011e).

Data for natural gas use by petroleum refineries, taken from PIIRA for 2000-2008, were adjusted to avoid double counting of the amounts that went to cogeneration and hydrogen production by refineries, as they are accounted for in other sections of this inventory. These adjustments were made by calculating the ratio of the amount of natural gas used for these purposes, as reported for 2009 in the Mandatory Reporting database by refineries, to the amount reported to PIIRA in 2009. That ratio was then used to adjust the natural gas use data from PIIRA for 2000 to 2008. Data on fuel use by California's cement plants were supplied by the Portland Cement Association (O'Hare, 2007) for years 2000 and 2005, and by an ARB survey (ARB, 2008) for year 2006. Data reported by cement plants to ARB Mandatory Reporting Program were used for 2008 and 2009, and fuel consumption for other years (2001-2004, and 2007) was interpolated between these data values. All other fuel use, except gasoline and ethanol, came from the EIA SEDS (EIA, 2011e).

Yearly data on the use of gasoline-ethanol blend came from the Federal Highway Administration (FHWA, various years) for blend use, and the California Energy Commission (O'Brien, 2010) for percent of ethanol in the blend. However, the ethanol used in gasoline blends is actually a denatured ethanol which includes up to 5 percent of denaturant (natural gasoline, gasoline components or unleaded gasoline) which renders it undrinkable, in order to avoid alcohol taxes. Thus the percentages of denatured ethanol provided by the CEC were adjusted to calculate the amounts of pure ethanol blended in California "gasoline". This adjustment was based on ASTM D4806 Standard Specification for denatured fuel ethanol for blending with gasoline for use as automotive spark-ignition engine fuel. For 2000 to 2008 the minimum percent volume of pure ethanol in the denatured ethanol had to be 92.1 percent, allowing for up to 5 percent denaturant, 1 percent water, 0.5 percent methanol and 1.4 percent other. In 2009 the percent denaturant was reduced to 2.5 percent, resulting in 94.6 percent pure ethanol in denatured ethanol.

*Table 20: Proportion of ethanol in California's gasoline-ethanol blend*

| ***Year*** | ***Percent denatured ethanol in the blend*** | ***Percent ethanol in denatured ethanol*** | ***Percent pure ethanol in blend*** |
|---|---|---|---|
| 2000 | 0.41% | 92.10% | 0.38% |
| 2001 | 0.55% | 92.10% | 0.51% |
| 2002 | 0.64% | 92.10% | 0.59% |

| Year | Percent denatured ethanol in the blend | Percent ethanol in denatured ethanol | Percent pure ethanol in blend |
|---|---|---|---|
| 2003 | 3.75% | 92.10% | 3.46% |
| 2004 | 5.65% | 92.10% | 5.21% |
| 2005 | 6.00% | 92.10% | 5.53% |
| 2006 | 6.00% | 92.10% | 5.53% |
| 2007 | 6.00% | 92.10% | 5.53% |
| 2008 | 6.50% | 92.10% | 5.99% |
| 2009 | 6.50% | 94.60% | 6.15% |

The FHWA “gasoline” consumption data include the blended ethanol, so the pure ethanol amounts were subtracted from the volumes provided by the FHWA to obtain the amounts of pure gasoline consumed in the state. Staff assumed that all inventory categories using “gasoline” did use a mix of gasoline and ethanol blended in the same proportions.

2000-2008 heat content values for natural gas are from EIA SEDS (EIA, 2011e). Heat content for biomass waste fuel and wood are from the USEPA Climate Leaders GHG Inventory Protocol (USEPA, 2008b). Heat content for tires is from EIA’s power plant database (EIA, 2011a). Heat content for ethanol is from (EIA, 2011b). Heat content for the various other fuels, except fossil waste fuel and gasoline, are from USEPA (USEPA, 2007d). Values for 2009 also come from the above sources, except for those in the petroleum refining and cement manufacturing sectors, where the data comes from ARB’s Mandatory Reporting Program.

Unable to locate an authoritative reference for the heat content of the fossil waste fuel used by the cement manufacturing sector, staff assumed that the heat content of an equal mixture of solid biomass and solid fossil fuels would be the best approximation. Thus the heat content for fossil waste fuel is simply the average of those of wood and petroleum coke.

The heat content of gasoline required a minor derivation to reflect pure gasoline since the heat content of “gasoline” in our primary reference (EIA, 2011g) was for a gasoline-ethanol blend. Since the USEPA reference values were established at the national level, national level gasoline (EIA, 2011d) and ethanol (EIA, 2011f) volumes (in millions of gallons, MMGal) were used to derive the pure gasoline heat contents from the gasoline-ethanol blend heat contents given in the reference.

*Equation 15: Derivation of pure gasoline heat content*

$$HC_{Gas,year} = \frac{(V_{Blend,year} \bullet HC_{Blend,year}) - (V_{Ethanol,year} \bullet HC_{Ethanol,year})}{V_{Blend,year} - V_{Ethanol,year}}$$

Where,

$HC_{\text{Gas, year}}$ = Heat Content of the pure (unblended) gasoline (Btu / gal) for a particular year
$V_{\text{Blend, year}}$ = Volume of gasoline-ethanol blend consumed in the US in a particular year (gal)
$V_{\text{Ethanol, year}}$ = Volume of ethanol consumed in the US in a particular year (gal)
$HC_{\text{Blend, year}}$ = Heat Content of the gasoline-ethanol blend consumed in the US in a particular year (Btu / gal)
$V_{\text{Ethanol, year}}$ = Heat Content of the ethanol consumed in the US in a particular year (Btu / gal)

*Table 21: Derivation of pure gasoline heat content*

| Year | $[V_{Blend}]$ Volume of gasoline-ethanol blend (million gallons) | $[V_{Ethanol}]$ Volume of ethanol (million gallons) | $[HC_{Blend}]$ Heat content of gasoline-ethanol blend (Btu/gal) | $[HC_{Ethanol}]$ Heat content of ethanol (Btu/gal) | $[HC_{Gas}]$ Heat content of gasoline (Btu/gal) |
|---|---|---|---|---|---|
| 2000 | 129,173 | 1,653 | 124,048 | 84,262 | 124,563 |
| 2001 | 132,029 | 1,741 | 124,048 | 84,262 | 124,579 |
| 2002 | 135,164 | 2,073 | 124,000 | 84,262 | 124,619 |
| 2003 | 135,393 | 2,826 | 123,976 | 84,262 | 124,823 |
| 2004 | 135,893 | 3,552 | 124,167 | 84,262 | 125,238 |
| 2005 | 138,143 | 4,059 | 124,238 | 84,262 | 125,448 |
| 2006 | 137,827 | 5,481 | 124,238 | 84,262 | 125,894 |
| 2007 | 137,472 | 6,886 | 124,262 | 84,262 | 126,371 |
| 2008 | 132,484 | 9,683 | 124,238 | 84,262 | 127,390 |
| 2009 | 132,421 | 11,037 | 124,238 | 84,262 | 127,873 |

The last column in Table 21 above is the derived heat content of the pure (unblended) gasoline using Equation 15 and data in the other columns.

2000-2008 $CO_2$ emission factor values for biomass waste fuel and fossil waste fuel burned in cement plants are from PCA (O'Hare, 2007), and from USEPA (USEPA, 2007b) for other fuels, except catalyst coke and ethanol. Values for 2009 also come from the above sources, except for those in the petroleum refining and cement manufacturing sectors, where the data comes from the Mandatory Reporting Program.

The $CO_2$ emission factor value for catalyst coke is estimated to be that of petroleum coke adjusted by a factor of 0.85. This 85 percent factor is a best estimate of how much less pure carbon is present in catalyst coke as compared to petroleum coke. WSPA recommended using this value to account for the fact that catalyst coke still contains hydrogen and thus less carbon per unit mass than petroleum coke.

The carbon content of ethanol was derived from its chemical formula $C_2H_5OH$ and its combustion reaction formula:

*Equation 16: Combustion of ethanol*

$$\boxed{C_2H_5OH + 3O_2 \rightarrow 2CO_2 + 3H_2O}$$

Two moles of carbon dioxide are produced from each mole of ethanol burned. Ethanol has a molecular mass of 46.06844 g per mole and carbon dioxide has a molecular mass of 44.0095 g per mole (IUPAC, 2006). So 44.0095 x 2 / 46.06844 = 1.9106 grams of carbon dioxide are produced for each gram of ethanol burned.

The density of ethanol is 0.79 g per ml and there are 3785.4 ml per gallon, thus the $CO_2$ emission factor per gallon is: 2990.5 g of ethanol per gal x 1.9106 g of $CO_2$/g of ethanol = 5,713.6 g $CO_2$/gal of ethanol.

Emissions factor values for $CH_4$ and $N_2O$ are from the 2006 IPCC guidelines (IPCC, 2006b).

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at: http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_1c_fuel_combustion_in_industrial_commercial_residential_agricultural_and_other_sectors.pdf

## 4. Changes in Estimates

In previous editions of ARB's GHG inventory, this section included an "Unspecified" category for the natural gas and LPG that could not be attributed to a specific economic sector. In the current edition, staff has been able to eliminate that "unspecified" category after obtaining sufficient data to categorize all fuel use into one of the economic sectors.

In this edition of the inventory, gasoline and ethanol are listed as separate fuels. In the 1990-2004 edition, gasoline-ethanol blends were listed under the generic term of "gasoline". This change, which allows for gasoline and ethanol to be analyzed separately, had a small effect on the emissions estimates.

Data on fuel use by petroleum refineries in 2009, and cement plants in 2008 and 2009, were summarized from values reported to ARB's Mandatory Reporting Program.

These changes and the data revisions made by data providers resulted in limited adjustments in emissions estimates for the categories included in this section: -6.3 percent on average over the years 2000 to 2004 when compared with the estimates in the first edition of ARB's GHG inventory.

## 5. Future Improvements

Future estimates will continue to make use of the data reported under the GHG Mandatory Reporting Program for petroleum refining and cement production.

## D. Transport (IPCC 1A3)

### 1. Background

Emissions from the transportation sector include emissions from civil aviation (IPCC category 1A3a); road transportation, also referred to as "on-road" or "highway" vehicles (category 1A3b); railways (category 1A3c); and water-borne navigation (category 1A3d).

The Intergovernmental Panel on Climate Change (IPCC) guidelines recommend separating international from domestic aviation emissions. In the case of a state-level rather than a national inventory, this raises the question of how to treat emissions from interstate flights. Based upon jurisdictional interpretation of IPCC protocols, ARB staff opted to estimate, but not include, the emissions resulting from aviation fuel purchased in California but used for interstate flights. Intrastate aviation was defined as those flights with both origin and destination in California. The aviation fuel purchased in California was apportioned to intrastate and interstate aviation according to miles flown and typical aircraft fuel consumption. Emissions resulting from international flights were also excluded in accordance with international convention, and appear as an "excluded line item" in the inventory.

The railways portion of the inventory quantifies emissions based exclusively on fuel purchased in California.

Emissions from on-road vehicles include emissions from passenger cars; light duty trucks (pick-ups, SUVs, and medium-duty vehicles with a gross weight of 8500 lbs or less); heavy-duty vehicles (trucks over 8500 lbs., buses, and motor-homes); and motorcycles. The State of California defines these vehicle classes by type and/or weight during the vehicle certification process. Emissions from each category were based upon total fuel use as reported by government agencies and apportioned based on vehicle miles traveled and vehicle fuel consumption.

California's water-borne navigation emissions include emissions from shipping activities which occur in California or within 24 nautical miles of the coast (harbor craft, in-port, and transit emissions). All emissions from shipping activities occurring further than 24 nautical miles from California's coast are excluded regardless of trip origin or destination (in accordance with ARB's pre-existing regulatory purview for criteria pollutants). Emissions from international bunker fuels used for navigation (in excess of the amount that was combusted within 24 nautical miles from the coast) were estimated but excluded from the inventory in accordance with international convention.

### 2. Methodology

Staff used two different methodologies to estimate transport emissions. The first is based on the amount of fuel combusted and emission factors and is consistent with the tier 2 IPCC methodology. The other methodology uses an emission model based on tail pipe measurements and is consistent with the tier 3 IPCC methodology. The model-based methodology was used for estimating methane and nitrous oxide emissions from on-road gasoline and diesel vehicles. The simpler methodology was used for other on-road vehicles emissions and all other transportation categories.

### 2.1 On-road Gasoline & Diesel Vehicles (based on EMFAC model)

To quantify GHG emissions from on-road gasoline and diesel emissions, staff used outputs from the 2007 EMission FACtors model (ARB, 2007c). ARB staff chose to use EMFAC in part because it allows for apportioning fuel use data (for gasoline and distillate) among different categories of vehicles, and thus for calculating emissions for each of the classes of vehicles. Also, EMFAC has a rigorous scientific foundation (i.e., tailpipe measurements) and multiple versions have been vetted through various stakeholder reviews. Furthermore, the Air Resources Board State Implementation Plan (SIP) relies on EMFAC outputs for determining transportation emissions and helping to develop mitigation strategies for criteria pollutants. For the greenhouse gas inventory, staff used EMFAC modeled outputs for the amount of fuel combusted, and CH4, and NOx emissions. EMFAC outputs were scaled so that EMFAC fuel combustion numbers would match fuel use numbers obtained from the California Board of Equalization (BOE) and the Federal highway administration (FHWA).

The EMFAC model is a transportation emissions model developed by the ARB to quantify on-road vehicle emissions (THC, $CH_4$, CO, NOx, particulate matter, lead, SOx, etc.). The two primary information sources that feed into the EMFAC model are: 1) activity data (e.g., vehicle miles traveled - VMT) from local and regional transportation surveys and models, and 2) tailpipe emissions tests data from representative vehicle types. EMFAC reports emissions by: a) vehicle type (as listed in Section I.D.1 above), and b) fuel-specific emission control technology. For example, EMFAC has outputs for non-catalyzed gasoline passenger cars, catalyzed gasoline passenger cars, and diesel passenger cars. Diesel vehicles currently in use typically do not have catalysts so there is no catalyzed/non-catalyzed differentiation for that type of vehicles.

EMFAC uses a bottom-up approach (local-level data aggregated to the state level) and, therefore, the total fuel consumption computed by EMFAC differs somewhat from the values in top-down fuel inventories based on reported fuel sales. As mentioned above, staff decided to scale EMFAC outputs to match the fuel use numbers reported by the California Board of Equalization (BOE), Federal Highway Administration (FHWA), and California Energy Commission (CEC) in order to maintain a consistent state-level energy balance. This was done by scaling EMFAC model outputs using the ratio of the reported fuel use over the modeled EMFAC fuel consumption. That way, emission estimates do remain consistent with EMFAC outputs (in terms of emissions per gallon combusted for each vehicle type) but the total emissions match the amount of fuel reported by BOE and FHWA.

Also, in both the EMFAC fuel consumption data and the BOE and FHWA fuel use data, “gasoline” is in fact a blend of gasoline and ethanol. The proportions of ethanol and pure gasoline in this blend have changed from year to year. In this version of the inventory, to allow for gasoline and ethanol to be analyzed separately, staff used data from the FHWA and CEC to compute the proportion of ethanol in the blend for each year. Reporting gasoline and ethanol separately led staff to change the method of estimation of $CO_2$ emissions from on-road vehicles. Since EMFAC does not model the two components of the gasoline-ethanol separately, staff opted to use the emission factors approach to estimate $CO_2$ emissions. The derivation of the pure gasoline heat content and the choice of appropriate emission factors are discussed in Section I.C.3 above.

Estimation of the on-road gasoline and diesel vehicles emissions involved the following steps:

(a) Converting EMFAC outputs per weekday to outputs per year

EMFAC emissions outputs are in short tons per weekday (note that some raw EMFAC outputs are in thousand units, such as gallons, and VMT). In order to convert from EMFAC’s average weekday (i.e., any day of the week other than Saturday or Sunday) outputs to an average day, staff divided EMFAC outputs by a conversion factor (1.05 for gasoline, and 1.12 for diesel). Once an average number of “tons per day” was calculated, we multiplied it by 365.25 to get tons per year, and then by 0.90718474 to convert from short tons (2000 pounds) to metric tonnes (1000 kilograms).

*Equation 17: Conversion of emissions per weekday to emissions per year*

$$\boxed{Y = \frac{W}{C_{fuel}} \bullet 365.25 \bullet 0.90718474}$$

Where,

Y = Emission value in tonnes per year
W = Emission value in short tons per weekday
$C_{fuel}$ = factor to convert from average weekday value to average day value for a given fuel (1.05 for gasoline, and 1.12 for diesel).
0.90718474 = factor to convert short tons to metric tonnes, and
365.25 = average number of days in a year

(b) Scaling EMFAC outputs to match reported fuel use

Staff accounted for differences between EMFAC fuel consumption and reported fuel use values by calculating fuel-specific ratios for each year of the inventory, as follows:

*Equation 18: Ratio of EMFAC fuel combustion to reported fuel use*

$$R_{\text{fuel, year}} = \frac{S_{\text{fuel, year}}}{M_{\text{fuel, year}}}$$

Where,

$R_{\text{fuel, year}}$ = Ratio of reported fuel use to EMFAC modeled fuel combustion for a given fuel in a given year

$S_{\text{fuel, year}}$ = reported fuel use of the given fuel in the given year (gallons)

$M_{\text{fuel, year}}$ = modeled fuel consumption of the given fuel in the given year (gallons)

With,

Fuel = [Gasoline-ethanol blend, Distillate]

Year = [2000 – 2009]

*Table 22: Ratio of EMFAC modeled fuel combustion to reported fuel use*

| **Year** | **Fuel** | **Source** | **Reported (gal)** | **EMFAC (gal)** | **Ratio** |
|---|---|---|---|---|---|
| 2000 | Gasoline-ethanol blend | FHWA | 14,378,254,190 | 14,355,311,175 | 1.001598225 |
| 2001 | Gasoline-ethanol blend | FHWA | 14,691,753,000 | 15,205,782,538 | 0.966195128 |
| 2002 | Gasoline-ethanol blend | FHWA | 15,385,840,000 | 15,370,520,071 | 1.000996709 |
| 2003 | Gasoline-ethanol blend | FHWA | 15,358,354,000 | 15,883,526,958 | 0.966935999 |
| 2004 | Gasoline-ethanol blend | FHWA | 15,579,476,000 | 16,491,022,064 | 0.944724708 |
| 2005 | Gasoline-ethanol blend | FHWA | 15,614,464,000 | 16,695,911,660 | 0.935226798 |
| 2006 | Gasoline-ethanol blend | FHWA | 15,509,940,000 | 16,336,928,307 | 0.949379204 |
| 2007 | Gasoline-ethanol blend | FHWA | 15,402,164,000 | 16,102,023,204 | 0.956535946 |
| 2008 | Gasoline-ethanol blend | FHWA | 14,787,997,000 | 16,181,977,299 | 0.913855997 |
| 2009 | Gasoline-ethanol blend | FHWA | 14,575,079,000 | 16,323,754,522 | 0.892875409 |
| 2000 | Distillate | BOE | 2,632,760,061 | 2,381,859,604 | 1.105338055 |
| 2001 | Distillate | BOE | 2,671,500,229 | 2,485,518,206 | 1.074826257 |
| 2002 | Distillate | BOE | 2,700,122,539 | 2,484,187,217 | 1.086923933 |
| 2003 | Distillate | BOE | 2,667,933,636 | 2,798,919,446 | 0.953201293 |
| 2004 | Distillate | BOE | 2,842,332,046 | 2,707,620,861 | 1.049752603 |
| 2005 | Distillate | BOE | 2,963,733,672 | 3,042,196,448 | 0.974208511 |
| 2006 | Distillate | BOE | 2,994,049,134 | 3,385,552,037 | 0.88436069 |
| 2007 | Distillate | BOE | 3,082,740,281 | 3,228,602,808 | 0.95482178 |
| 2008 | Distillate | BOE | 2,827,526,205 | 3,232,961,892 | 0.874593113 |
| 2009 | Distillate | BOE | 2,580,139,949 | 3,275,287,410 | 0.787759859 |

EMFAC outputs can then be scaled to the reported fuel use by using the ratios from Table 22 and the following equation:

*Equation 19: Scaling of EMFAC outputs to reported fuel use*

$$Z_{type, fuel, year} = Y_{\text{type, fuel, year}} \bullet R_{fuel, year}$$

Where,

$Z_{\text{type, fuel, year}}$ = Scaled EMFAC output value for a particular vehicle type using a given fuel in a given year

$Y_{\text{type, fuel, year}}$ = Modeled output value for a particular vehicle type using a given fuel in a given year

$R_{\text{fuel, year}}$ = Ratio of reported fuel use to EMFAC modeled fuel combustion for a given fuel in a given year

With,
Type = [passenger cars, light duty trucks, heavy-duty vehicles, motorcycles]
Fuel = [Gasoline-ethanol blend, Distillate]
Year = [2000 – 2009]

(c) Proportions of gasoline and ethanol in the gasoline-ethanol blend

In the case of "gasoline", both the EMFAC modeled fuel use and the FHWA reported fuel use data are in fact amounts of an unspecified gasoline-ethanol blend. To allow for the separate analysis of pure gasoline and ethanol, staff calculated the yearly proportions of pure ethanol in the blend in section I.C above (see Table 20) and the proportion of gasoline by difference.

*Equation 20: Proportion of gasoline in the gasoline-ethanol blend*

$$\boxed{P_{Gasoline,\ year} = 1 - P_{Ethanol,\ year}}$$

Where,
$P_{\text{Gasoline, year}}$ = Proportion of gasoline in the gasoline-ethanol blend for a given fuel in a given year
$P_{\text{Ethanol, year}}$ = Proportion of ethanol in the gasoline-ethanol blend for a given fuel in a given year (from Table 20)

With,
Year = [2000 – 2009]

The gasoline and ethanol contributions to emissions of the gasoline ethanol blend can be un-mixed using their respective proportions in the blend.

*Equation 21: Un-mixing of scaled EMFAC output values to each component of a fuel blend*

$$\boxed{U_{type,\ fuel,\ year} = Z_{\text{type, blend, year}} \bullet P_{fuel,\ year}}$$

Where,
$U_{\text{fuel, year}}$ = Un-mixed value for a particular vehicle type using the given fuel in a given year
$Z_{\text{type, blend, year}}$ = Scaled EMFAC output value for a particular vehicle type using gasoline-ethanol blend in a given year (from Equation 19)
$P_{\text{fuel, year}}$ = Proportion of fuel in the blend (from Table 20 and Equation 20)

With,
Type = [passenger cars, light duty trucks, heavy-duty vehicles, motorcycles]
Blend = [Gasoline-ethanol]
Fuel = [Gasoline, Ethanol]
Year = [2000 – 2009]

## (d) Calculating $CO_2$ emissions

Emissions of $CO_2$ are estimated with the emissions factors method. The case of vehicles combusting a blend of gasoline and ethanol involves one extra factor to separate the emissions of each of these two fuels.

*Equation 22: $CO_2$ emissions from on road transport (diesel vehicles)*

$$\boxed{E_{type,\,fuel,year} = (V_{type,\,fuel,year} \bullet R_{fuel,year}) \bullet HC_{fuel} \bullet EF_{fuel}}$$

Where,

$E_{\text{type, fuel, year}}$ = $CO_2$ emissions of a particular vehicle type using the given fuel in the given year (g of $CO_2$)
$V_{\text{type, fuel, year}}$ = Amount of fuel combusted by the particular type of vehicle in a given year (gallons) as modeled with EMFAC
$R_{\text{fuel, year}}$ = Scaling factor for the given fuel in the given year (from Table 22)
$HC_{\text{fuel}}$ = Heat content of the given fuel (BTU / unit)
$EF_{\text{GHG, fuel}}$ = $CO_2$ emission factor for given fuel (g GHG / BTU)

With,

Type = [passenger cars, light duty trucks, heavy-duty vehicles]
Fuel = [distillate]
Year = [2000 – 2009]

*Equation 23: $CO_2$ emissions from on road transport (gasoline-ethanol vehicles)*

$$\boxed{E_{type,\,fuel,year} = (V_{type,blend,year} \bullet R_{blend,year}) \bullet P_{fuel,year} \bullet HC_{fuel} \bullet EF_{fuel}}$$

Where,

$E_{\text{type, fuel, year}}$ = $CO_2$ emissions of a particular vehicle type using the given fuel in the given year (g of $CO_2$)
$V_{\text{type, blend, year}}$ = Amount of gasoline-ethanol blend combusted by the particular type of vehicle in a given year (gallons) as modeled with EMFAC
$R_{\text{blend, year}}$ = Scaling factor for the gasoline-ethanol blend in the given year (from Table 22)
$P_{\text{fuel, year}}$ = Proportion of the given fuel in the blend (from Table 20 and Equation 20)
$HC_{\text{fuel}}$ = Heat content of the given fuel (BTU / unit)
$EF_{\text{GHG, fuel}}$ = $CO_2$ emission factor for given fuel (g GHG / BTU)

With,

Type = [passenger cars, light duty trucks, heavy-duty vehicles, motorcycles]
Blend = [gasoline-ethanol]
Fuel = [ethanol, gasoline]
Year = [2000 – 2009]

## (e) Calculating $CH_4$ emissions

The amount of $CH_4$ emitted is the EMFAC modeled output of $CH_4$ for a particular vehicle class scaled to the reported fuel use with Equation 19. In the case of diesel vehicles this is the only step.

In the case of gasoline-ethanol powered vehicles, the yearly proportions of gasoline and ethanol in the gasoline-ethanol blend are then used to separate the respective share of emissions from gasoline and ethanol (using Equation 21).

### (f) Calculating $N_2O$ emissions

We calculated $N_2O$ emissions from gasoline vehicles using a linear regression correlating $NO_x$ with $N_2O$ based on ARB tailpipe test data. That is:

*Equation 24: Regression correlating $N_2O$ emissions to $NO_x$ emissions (gasoline vehicles)*

$$\boxed{E_{N2O} = D \bullet (0.0167 + \frac{0.0318 \bullet O_{NOx}}{D})}$$

Where,

$E_{N2O}$ = $N_2O$ emissions of a class of gasoline vehicles (grams)
D = Distance travelled by the vehicles (miles)
0.0167 = a constant, the intercept of the linear regression
0.0318 = a multiplier, the slope of the linear regression
$O_{NOx}$ = scaled EMFAC output for $NO_x$ emitted by that category of vehicles (grams)

Equation 24 was calculated for each vehicle type and each year after scaling the distance travelled and $NO_x$ emissions values to reported fuel use using Equation 19. Then the respective share of $N_2O$ emissions of gasoline and ethanol were estimated for each vehicle type using Equation 21.

Based on ongoing ARB-supervised diesel tailpipe research, staff determined that the $N_2O$ emission factor for diesel vehicles was 0.3316 grams of $N_2O$ per gallon. Diesel vehicles $N_2O$ emissions are thus computed by multiplying the emission factor by BOE diesel fuel sales, for each category of vehicles:

*Equation 25: Transportation - on road $N_2O$ emissions (diesel vehicles)*

$$\boxed{E_{N2O} = V \bullet EF_{N2O}}$$

Where,

$E_{N2O}$ = $N_2O$ emissions of a type of diesel vehicles (grams)
V = Fuel consumption of that type of diesel vehicles (gallons) scaled to reported fuel use with Equation 19
$EF_{N2O}$ = Emission factor for diesel vehicles (0.3316 grams per gallon)

The emissions calculation methodologies for on-road vehicles running on natural gas are based on emission factors and are discussed in the following section alongside airplanes, trains, and ships due to methodological similarities.

## *2.2 Other on-road vehicles, Airplanes, Trains, Ships*

To estimate the emissions from other on-road vehicles (those using natural gas as a fuel), airplanes, trains, ships and from a few unspecified uses of fuel combustion for transportation, staff used the simpler methodology based on the amount of fuel combusted and emission factors, consistent with the tier 2

IPCC methodology. IPCC assumes a combustion efficiency of 100 percent, and the following equations reflect that assumption. Note: staff did not estimate indirect emissions resulting from the energy consumed by electric vehicles in the transportation sector because those emissions occur upstream (during electricity generation) and are discussed under Section I.A above.

### (a) Apportionment of aviation fuel data

For the reasons discussed in section I.D.1 above, staff apportioned aviation fuel use among intrastate, interstate and international flights. Statistics from the US Department of Transportation are available for all commercial airlines' flights taking off and/or landing in California which allows for distinguishing intrastate flights from interstate and international ones. Such statistics were not available for military flights and general aviation flights. General aviation flights are private and commercial flights other than military, scheduled airline or regular cargo flights. This led staff to focus on the apportionment of jet fuel used by scheduled airlines which, as estimated in section I.D.2.2(a.i) below, constitutes almost 90 percent of the jet fuel sold in California.

ARB staff retrieved data for aviation fuel sold within California from the Energy Information Administration (EIA, 2011d). Typically, aircrafts do not carry significant extra fuel, or fuel for a continuing flight, since that would add to the weight being transported, and thus to the fuel consumed and the costs incurred. Thus, the amount of aviation fuel sold within California should approximate the amount of fuel consumed on all flights originating in California.

#### *(a.i) Commercial airlines versus general aviation and military aircrafts*

The first step was to distribute the jet fuel sold in California between general aviation, military activity, and scheduled commercial flights. Faced with a lack of California specific statistics, staff assumed that the proportion of jet fuel used for general aviation would be the same in California as it is nationwide and used national data to estimate the amount of fuel used within California for general aviation. The share of fuel used nationwide for general aviation can be found in the USEPA annual greenhouse gas inventory (Table A-86 in USEPA, 2011a). Staff then estimated the amount of jet fuel used for military activity in California by assuming that the amount (300,468,000 gallons) obtained for 2004 from PIIRA (O'Brien, 2010) fluctuated in proportion with the amount of fuel consumed by military aviation nationwide. The amount of fuel used nationwide for military activity is reported in the USEPA annual greenhouse gas inventory (USEPA, 2011a). Staff then assigned the remainder of the aviation fuel to commercial airlines activity (Table 23).

*Table 23: Estimation of California commercial jet fuel use (gallons)*

| Year | Total CA Jet Fuel (from EIA) | USA General Aviation % | CA General Aviation | USA Military Jet Fuel | CA Military jet fuel (scaled to USA military jet fuel) | CA commercial airlines jet fuel (by difference) |
|---|---|---|---|---|---|---|
| 2000 | 3,634,451,000 | 3.583% | 130,213,763 | 2,647,100,000 | 296,469,675 | 3,207,767,562 |
| 2001 | 3,583,716,000 | 3.528% | 126,426,271 | 2,882,600,000 | 322,845,183 | 3,134,444,546 |
| 2002 | 3,771,399,000 | 3.699% | 139,506,883 | 2,592,500,000 | 290,354,588 | 3,341,537,529 |
| 2003 | 3,474,800,000 | 3.761% | 130,703,679 | 2,596,200,000 | 290,768,981 | 3,053,327,340 |
| 2004 | 3,694,603,000 | 4.791% | 177,025,120 | 2,682,800,000 | 300,468,000 | 3,217,109,880 |
| 2005 | 3,827,755,000 | 5.799% | 221,988,823 | 2,322,500,000 | 260,115,152 | 3,345,651,025 |
| 2006 | 3,768,990,000 | 6.418% | 241,880,007 | 2,078,500,000 | 232,787,661 | 3,294,322,331 |
| 2007 | 4,023,796,500 | 5.839% | 234,948,672 | 2,066,300,000 | 231,421,287 | 3,557,426,541 |
| 2008 | 3,720,481,500 | 7.048% | 262,219,448 | 2,052,800,000 | 229,909,315 | 3,228,352,737 |
| 2009 | 3,900,171,000 | 6.236% | 243,220,292 | 1,817,900,000 | 203,601,005 | 3,453,349,703 |

### (a.ii) Intrastate versus Interstate and International

In a second step, commercial airlines fuel consumption was subdivided among intrastate, interstate, and international flights. First, staff downloaded data regarding flight activity from the USDOT's Air Carrier Statistics database (USDOT, 2010). Based on the airports of departure and arrival, these flights were subdivided into five categories:

- (1) Flights originating and ending in California (intrastate)
- (2) Flights originating in California but ending in another state (interstate from CA)
- (3) Flights originating in another state but ending in California (intrastate to CA)
- (4) Flights originating in California but ending in another country (international from CA)
- (5) Flights originating in another country and ending in California (international to CA)

The flights in categories 1, 2, and 4 should all consume fuel purchased in CA —thus contributing to the amounts in the last column of Table 23. For example, in 2007, the database indicated that 402,758 intrastate flights occurred in California; 583,247 interstate flights originated in California; and 88,510 international flights originated in CA.

For each flight, the USDOT Air Carrier Statistics database also provides information on the type of aircraft and the length of the flight in miles. In the 2000-2004 edition of ARB's GHG Inventory staff had used distance to apportion fuel use into interstate, intrastate and international amounts.

However, this approach introduces a bias because it does not account for the impact of the size of the airplane on fuel consumption and, since smaller airplanes are used on shorter distances, they are used for a higher proportion of intrastate flights than of interstate or international ones. In 2007, eighty five different types of airplanes were used by airlines operating in California with a wide range of maximum takeoff weight: from the 3.3 tonnes of the Cessna 208 Caravan to the 365 tonnes of the Airbus A340-600 and 405 tonnes of the Antonov 124 (a cargo plane).

For each of these aircrafts, ARB staff estimated a fuel consumption factor that could be applied to each flight as a function of distance. These fuel consumption factors were based on data from the European Environment Agency (EAA) 2007 EMEP/CORINAIR Air Pollutant Emissions Inventory Guidebook (EAA, 2007). The Guidebook contains fuel consumption, as a function of flight distance, for 26 main aircraft types. For each aircraft type, the fuel consumption is subdivided into the fuel associated with the landing/takeoff phase of the flight and the fuel consumed during the other phases (Figure 2). An example of the data from the Guidebook is shown in Table 24.

*Figure 2: Standard flying cycles (from EMEP/CORINAIR Guidebook)*

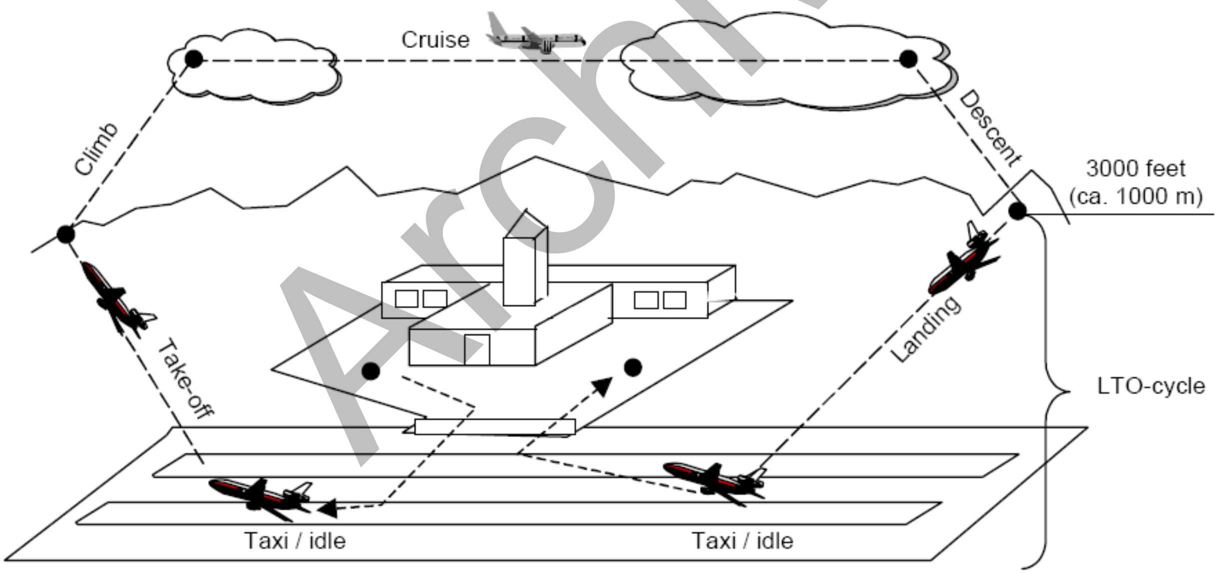


*Table 24: Example of typical fuel consumption (from EMEP/CORINAIR Guidebook)*

| ***Aircraft Type: Boeing 737-400*** | | | | | | | |
|---|---|---|---|---|---|---|---|
| ***Standard flight distances (nautical miles)*** [1 nautical mile = 1.15078 statute mile] | | | | | | | |
| Climb / Cruise / Descent | 125 | 250 | 500 | 750 | 1000 | 1500 | 2000 |
| ***Corresponding fuel use (kilograms)*** | | | | | | | |
| Landing & Take Off (LTO) | 825.4 | 825.4 | 825.4 | 825.4 | 825.4 | 825.4 | 825.4 |
| Climb / Cruise / Descent | 777.7 | 1442.6 | 2787.4 | 4134.9 | 5477.2 | 8362.3 | 11342.2 |
| Flight total | 1603.1 | 2268 | 3612.8 | 4960.3 | 6302.6 | 9187.7 | 12167.6 |

ARB staff used the EMEP/CORINAIR fuel consumption data to construct a linear formula that would estimate fuel consumption as a function of distance for each of the 26 aircraft. The coefficients for the resultant formulae are shown in Table 25.

*Table 25: Fuel consumption factors estimated for aircraft listed in the EMEP EEA Inventory.*

| Aircraft IATA code | Aircraft | Engine type | LTO Fuel (kg) | Cruise Fuel (kg/mi) | Max Takeoff Weight (kg) |
|---|---|---|---|---|---|
| 405 | Beech 1900 A/B/C/D | Turboprop | 59.9 | 0.78 | 7,688 |
| 416 | Cessna 208 Caravan | Turboprop | 28.8 | 0.49 | 3,310 |
| 442 | Aerospatiale/Aeritalia Atr-72 | Turboprop | 135.9 | 1.49 | 22,000 |
| 449 | Dornier 328 | Turboprop | 123.9 | 1.20 | 13,990 |
| 450 | Fokker Friendship F-27/Fairchild F-27/A/B/F/J | Turboprop | 158.2 | 1.58 | 20,410 |
| 456 | Saab-Fairchild 340/B | Turboprop | 74.9 | 1.19 | 13,155 |
| 482 | Dehavilland Dhc8-400 Dash-8 | Turboprop | 180.9 | 2.64 | 27,330 |
| 556 | Lockheed L100-30/L-382e | Turboprop | 272.0 | 5.96 | 70,310 |
| 602 | Fokker F28-4000/6000 Fellowship | Turbofan | 666.1 | 3.89 | 33,110 |
| 603 | Fokker 100 | Turbofan | 744.4 | 4.12 | 43,090 |
| 617 | Boeing 737-400 | Turbofan | 825.4 | 4.87 | 62,820 |
| 620 | Boeing 737-100/200 | Turbofan | 919.7 | 4.58 | 52,390 |
| 622 | Boeing 757-200 | Turbofan | 1,253.0 | 6.19 | 108,860 |
| 626 | Boeing 767-300/300er | Turbofan | 1,617.1 | 8.49 | 181,890 |
| 627 | Boeing 777-200/200lr/233lr | Turbofan | 2,562.8 | 12.30 | 286,897 |
| 640 | Mcdonnell Douglas Dc-9-30 | Turbofan | 876.1 | 4.95 | 64,885 |
| 656 | Mcdonnell Douglas Md-90 | Turbofan | 1,003.1 | 5.59 | 67,800 |
| 692 | Airbus Industrie A310-200c/F | Turbofan | 1,540.5 | 7.81 | 150,000 |
| 694 | Airbus Industrie A320-100/200 | Turbofan | 802.3 | 4.42 | 77,000 |
| 696 | Airbus Industrie A330-200 | Turbofan | 2,231.5 | 10.43 | 230,000 |
| 715 | Boeing 727-200/231a | Turbofan | 1,412.8 | 7.17 | 95,030 |
| 730 | Mcdonnell Douglas Dc-10-10 | Turbofan | 2,381.2 | 14.48 | 263,085 |
| 816 | Boeing 747-100 | Turbofan | 3,413.9 | 19.20 | 340,195 |
| 819 | Boeing 747-400 | Turbofan | 3,402.2 | 17.51 | 362,875 |
| 867 | British Aerospace Bae-146-200 | Turbofan | 569.5 | 4.44 | 42,185 |
| 873 | Airbus Industrie A340-200 | Turbofan | 2,019.9 | 11.34 | 260,000 |

For each aircraft, the fuel consumption is subdivided into the fuel associated with the landing/takeoff (LTO) of the aircraft and the fuel consumed during the climb, cruise and descent (“cruise”) phase. The fuel consumed during the landing and takeoff is assumed independent of the flight distance for all aircrafts. In EMEP/CORINAIR tables, the fuel consumed during the landing and takeoff of smaller aircraft is somewhat affected by flight distance – presumably because smaller aircraft travel at different elevations and project from the ground at different angles depending on flight distance. This factor was considered negligible in the context of the overall inventory and ignored for simplification sake. The EMEP/CORINAIR fuel consumptions associated with the cruise phase were linear for most aircraft and thus assumed linear for all aircrafts for estimation purposes.

For example, using Table 25, the fuel consumed during a 2,850 mile flight by a Boeing 737-400 would be approximated as 825 kg of fuel during the landing/takeoff phase and 4.87 kg of fuel for each mile flown between takeoff and landing (i.e. 825 + 4.87*2850) for a total of 14,704 kg of fuel. A 600-mile flight of a de Havilland Dhc8-400 Dash-8 would consume approximately (181 + 2.64*600 =) 1,765 kg of fuel.

In addition to the 26 aircraft types listed in the EMEP/CORINAIR guidebook, the flight activity originating in California between 2000 and 2008 comported approximately 80 other aircraft types. To estimate the fuel consumption associated with these aircraft, staff assumed that the fuel consumed by an aircraft during its flight cycle is largely proportional to its size. Because the exact size of an aircraft can vary between flights due to its payload, staff used the aircraft's maximum takeoff weight as representative of its size.

The equations to estimate fuel consumption of aircrafts based on their takeoff weight were fitted by least-square regression using the maximum takeoff weight values for each of the 26 EMEP aircraft types (shown in Table 25). Staff separated the aircrafts in 2 groups based on engine type (turboprop vs. turbofan) because doing so yielded better fitting equations. The equations are as follow:

*Equation 26: Fuel consumption regressions for turboprop aircrafts*

$$\boxed{\begin{aligned} F_{LTO} &= 0.58 + 0.0082 \bullet W - 6.2 \bullet 10^{-8} \bullet W^{2}) \\ F_{Cruise} &= 0.064 + 8.325 \bullet 10^{-5} \bullet W \end{aligned}}$$

Where,

$F_{LTO}$ = Amount of fuel consumed in the Landing and Take-off phase of the flight (kg)

$F_{Cruise}$ = Amount of fuel consumed during the climb/cruise/descent phase of the flight (kg/mile)

W = Maximum takeoff weight (kg)

*Equation 27: Fuel consumption regressions for turbofan aircrafts*

$$\boxed{\begin{aligned} F_{LTO} &= 546.49 + 0.0047 \bullet W - 8.86 \bullet 10^{-9} \bullet W^{2}) \\ F_{Cruise} &= 3.61 + 1.6 \bullet 10^{-5} \bullet W + 6.94 \bullet 10^{-11} \bullet W^{2} \end{aligned}}$$

Where,

$F_{LTO}$ = Amount of fuel consumed in the Landing and Take-off phase of the flight (kg)

$F_{Cruise}$ = Amount of fuel consumed during the climb/cruise/descent phase of the flight (kg/mile)

W = Maximum takeoff weight (kg)

The fuel consumption factors estimated with the regression model are shown in Table 26.

*Table 26: Fuel consumption factors estimated for aircraft not listed in the EMEP EEA Inventory.*

| Aircraft Type | Aircraft | LTO Fuel (kg) | Cruise fuel (kg/mile) | Max Takeoff Weight (kg) |
|---|---|---|---|---|
| 79 | Piper Pa-32 (Cherokee 6) | 13.86 | 0.20 | 1,633 |
| 110 | Beechcraft Beech 18 C-185 | 36.29 | 0.44 | 4,490 |
| 125 | Cessna C-402/402a | 25.56 | 0.32 | 3,107 |
| 194 | Piper Pa-31 (Navajo)/T-1020 | 25.50 | 0.32 | 3,100 |
| 430 | Convair Cv-580 | 174.43 | 2.26 | 26,371 |
| 461 | Embraer Emb-120 Brasilia | 87.03 | 1.02 | 11,500 |
| 483 | de Havilland Dhc8-100 Dash-8 | 114.19 | 1.37 | 15,650 |
| 485 | de Havilland Twin Otter Dhc-6 | 38.38 | 0.46 | 4,763 |
| 491 | de Havilland Dhc8-200q Dash-8 | 119.27 | 1.43 | 16,465 |
| 507 | Antonov 12 | 271.38 | 5.14 | 61,000 |
| 550 | Lockheed L-188a/C Electra | 261.67 | 4.45 | 52,664 |
| 555 | Lockheed L100-20 Hercules | 272.01 | 5.92 | 70,310 |
| 560 | Shorts Belfast Freighter-Sh5 | 208.60 | 2.89 | 34,000 |
| 608 | Boeing 717-200 | 818.98 | 4.64 | 52,390 |
| 612 | Boeing 737-700/700lr | 864.52 | 4.83 | 60,330 |
| 614 | Boeing 737-800 | 924.69 | 5.09 | 70,535 |
| 616 | Boeing 737-500 | 818.98 | 4.64 | 52,390 |
| 619 | Boeing 737-300 | 843.79 | 4.74 | 56,740 |
| 621 | Boeing 737-200c | 818.98 | 4.64 | 52,390 |
| 623 | Boeing 757-300 | 1,259.50 | 6.61 | 122,470 |
| 624 | Boeing 767-400/Er | 1,882.47 | 9.77 | 204,120 |
| 625 | Boeing 767-200/Er/Em | 1,650.98 | 8.56 | 175,540 |
| 628 | Canadair Rj-100/Rj-100er | 652.55 | 3.99 | 21,523 |
| 629 | Canadair Rj-200er /Rj-440 | 665.49 | 4.04 | 24,040 |
| 631 | Canadair Rj-700 | 711.85 | 4.21 | 32,885 |
| 633 | Boeing 737-600 | 840.95 | 4.73 | 56,245 |
| 634 | Boeing 737-900 | 950.63 | 5.20 | 74,840 |
| 635 | Mcdonnell Douglas Dc-9-15f | 989.18 | 5.37 | 81,140 |
| 636 | Cessna Citation Ii | 579.36 | 3.73 | 6,850 |
| 637 | Boeing 777-300/300er/333er | 2,405.74 | 12.63 | 263,080 |
| 638 | Canadair Crj 900 | 731.27 | 4.29 | 36,514 |
| 639 | Cessna Citationjet/Cj1/Cj2/Cj3 | 569.49 | 3.69 | 4,812 |
| 644 | Airbus Industrie A-318 | 909.58 | 5.02 | 68,000 |
| 645 | Mcdonnell Douglas Dc-9-40 | 833.17 | 4.70 | 54,885 |
| 646 | Cessna Citation X Model 650/550b/550xl/560xl | 626.44 | 3.89 | 16,375 |
| 647 | Cessna Citation X Model Ce750 X | 626.44 | 3.89 | 16,375 |
| 650 | Mcdonnell Douglas Dc-9-50 | 833.17 | 4.70 | 54,885 |
| 654 | Mcdonnell Douglas Dc9 Super 87 | 883.05 | 4.91 | 63,505 |
| 655 | Mcdonnell Douglas Dc9 Super 80/Md81/2/3/7/8 | 883.05 | 4.91 | 63,505 |
| 657 | Bombardier Crj 705 | 731.22 | 4.29 | 36,504 |

| ***Aircraft Type*** | ***Aircraft*** | ***LTO Fuel (kg)*** | ***Cruise fuel (kg/mile)*** | ***Max Takeoff Weight (kg)*** |
|---|---|---|---|---|
| 658 | Bombardier Bd-700 Global Express | 767.07 | 4.43 | 43,091 |
| 667 | Gulfstream V/ G-V Exec/ G-5/550 | 752.17 | 4.37 | 40,370 |
| 669 | Bombardier Challenger 604 | 654.31 | 4.00 | 21,865 |
| 671 | Gulfstream G450 | 715.23 | 4.23 | 33,520 |
| 674 | Embraer-135 | 639.70 | 3.94 | 19,000 |
| 675 | Embraer-145 | 647.84 | 3.97 | 20,600 |
| 676 | Embraer-140 | 650.39 | 3.98 | 21,100 |
| 677 | Embraer 170 | 725.56 | 4.27 | 35,450 |
| 678 | Embraer 190 | 788.65 | 4.52 | 46,990 |
| 681 | Dassault-Breguet Mystere-Falcon | 588.65 | 3.76 | 8,755 |
| 690 | Airbus Industrie A300b/C/F-100/200 | 1,018.83 | 5.50 | 85,910 |
| 691 | Airbus Industrie A300-600/R/Cf/Rcf | 1,611.65 | 8.36 | 170,500 |
| 693 | Airbus Industrie A310-300 | 1,456.35 | 7.58 | 150,000 |
| 698 | Airbus Industrie A319 | 885.95 | 4.92 | 64,000 |
| 699 | Airbus Industrie A321 | 1,038.26 | 5.59 | 89,000 |
| 710 | Boeing 727-100 | 936.91 | 5.14 | 72,570 |
| 711 | Boeing 727-100c/Qc | 936.91 | 5.14 | 72,570 |
| 732 | Mcdonnell Douglas Dc-10-30 | 2,405.79 | 12.63 | 263,085 |
| 733 | Mcdonnell Douglas Dc-10-40 | 2,371.74 | 12.44 | 259,450 |
| 735 | Mcdonnell Douglas Dc-10-30cf | 2,405.79 | 12.63 | 263,085 |
| 740 | Mcdonnell Douglas Md-11 | 2,502.84 | 13.17 | 273,314 |
| 760 | Lockheed L-1011-1/100/200 | 1,943.53 | 10.10 | 211,375 |
| 765 | Lockheed L-1011-500 Tristar | 2,116.30 | 11.03 | 231,330 |
| 770 | Dassault Falcon 900 | 648.04 | 3.97 | 20,640 |
| 817 | Boeing 747-200/300 | 3,306.27 | 17.82 | 351,535 |
| 818 | Boeing 747c | 3,431.74 | 18.56 | 362,875 |
| 820 | Boeing 747f | 3,431.74 | 18.56 | 362,875 |
| 822 | Boeing 747sp | 2,943.52 | 15.69 | 317,515 |
| 851 | Mcdonnell Douglas Dc-8-61 | 1,437.29 | 7.48 | 147,415 |
| 852 | Mcdonnell Douglas Dc-8-63f | 1,521.80 | 7.90 | 158,760 |
| 854 | Mcdonnell Douglas Dc-8-62 | 1,470.80 | 7.65 | 151,950 |
| 856 | Mcdonnell Douglas Dc-8-63 | 1,521.80 | 7.90 | 158,760 |
| 860 | Mcdonnell Douglas Dc-8-71 | 1,546.55 | 8.03 | 162,025 |
| 864 | Mcdonnell Douglas Dc-8-73 | 1,546.55 | 8.03 | 162,025 |
| 865 | Mcdonnell Douglas Dc-8-73f | 1,546.55 | 8.03 | 162,025 |
| 868 | British Aerospace Bae-146-300 | 773.32 | 4.46 | 44,225 |
| 870 | Lockheed Jetstar | 643.98 | 3.96 | 19,844 |
| 871 | Airbus Industrie A340-300 | 2,376.88 | 12.47 | 260,000 |
| 872 | Airbus Industrie A340-500 | 3,455.51 | 18.70 | 365,000 |
| 874 | Airbus Industrie A340-600 | 3,455.51 | 18.70 | 365,000 |
| 877 | Ilyushin 76/Td | 1,607.78 | 8.34 | 170,000 |
| 879 | Ilyushin 96 | 2,284.34 | 11.95 | 250,000 |
| 880 | Antonov 124 | 3,917.78 | 21.48 | 405,000 |

Staff then multiplied these aircraft-specific fuel consumption factors by the total number of flights and the total flight distance travelled by each aircraft type in each of the three categories of flights originating in California (intrastate, interstate, international) to estimate the total fuel consumed for flights originating in California. Table 27 shows examples of these estimates for three common aircraft types.

*Table 27: Fuel consumption in flights originating in California for three common aircrafts in 2007*

| Aircraft Type | Aircraft | Flight Category | Number of flights originating in CA | Total Distance Travelled (miles) | LTO Fuel (kg) | Cruise Fuel (kg) |
|---|---|---|---|---|---|---|
| 612 | Boeing 737-700/700lr | International | 4,680 | 5,918,964 | 4,045,971 | 28,595,314 |
| 612 | Boeing 737-700/700lr | Interstate | 81,757 | 75,399,452 | 70,680,869 | 364,264,933 |
| 612 | Boeing 737-700/700lr | Intrastate | 71,646 | 26,739,509 | 61,939,670 | 129,182,178 |
| 819 | Boeing 747-400 | International | 18,573 | 115,324,611 | 63,188,306 | 2,019,197,081 |
| 819 | Boeing 747-400 | Interstate | 1,453 | 4,817,124 | 4,943,338 | 84,342,125 |
| 819 | Boeing 747-400 | Intrastate | 677 | 228,003 | 2,303,262 | 3,992,062 |
| 627 | Boeing 777-200/200lr/233lr | International | 7,301 | 42,494,441 | 18,711,295 | 522,883,132 |
| 627 | Boeing 777-200/200lr/233lr | Interstate | 3,322 | 6,417,767 | 8,513,754 | 78,968,967 |
| 627 | Boeing 777-200/200lr/233lr | Intrastate | 3 | 1,011 | 7,689 | 12,440 |

Staff then calculated the cumulative fuel consumption in each flight category (intrastate, interstate, and international) for each calendar year between 2000 and 2008 (Table 28). These bottom-up, activity-based, fuel consumption estimates – assuming a fuel density of three kilograms per gallon – differ from the estimated sales in Table 23 by about 10 percent.

*Table 28: Estimates of fuel consumed by flight category between 2000 and 2008 (kg)*

| Year | International | Interstate | Intrastate | Grand Total |
|---|---|---|---|---|
| 2000 | 3,970,515,165 | 4,348,656,663 | 592,615,268 | 8,911,787,095 |
| 2001 | 3,811,323,532 | 4,355,672,197 | 572,392,450 | 8,739,388,180 |
| 2002 | 3,449,773,656 | 4,267,524,343 | 535,596,603 | 8,252,894,603 |
| 2003 | 3,430,750,495 | 4,537,372,535 | 588,282,082 | 8,556,405,111 |
| 2004 | 3,701,872,041 | 4,786,102,753 | 619,833,811 | 9,107,808,604 |
| 2005 | 3,839,943,473 | 4,662,405,012 | 618,534,181 | 9,120,882,665 |
| 2006 | 3,965,364,142 | 4,703,307,605 | 640,734,551 | 9,309,406,298 |
| 2007 | 4,020,346,444 | 4,789,034,047 | 685,004,491 | 9,494,384,982 |
| 2008 | 4,023,481,679 | 4,408,021,121 | 647,502,031 | 9,079,004,831 |

The share of total jet fuel consumption of each flight category within each calendar year is shown in Table 29.

*Table 29: Share of total jet fuel consumption of each flight category.*

| Year | International | Interstate | Intrastate | Grand Total |
|---|---|---|---|---|
| 2000 | 44.6% | 48.8% | 6.6% | 100% |
| 2001 | 43.6% | 49.8% | 6.5% | 100% |
| 2002 | 41.8% | 51.7% | 6.5% | 100% |

| Year | International | Interstate | Intrastate | Grand Total |
|---|---|---|---|---|
| 2003 | 40.1% | 53.0% | 6.9% | 100% |
| 2004 | 40.6% | 52.5% | 6.8% | 100% |
| 2005 | 42.1% | 51.1% | 6.8% | 100% |
| 2006 | 42.6% | 50.5% | 6.9% | 100% |
| 2007 | 42.3% | 50.4% | 7.2% | 100% |
| 2008 | 44.3% | 48.6% | 7.1% | 100% |

Note: Staff assumed that the share of each category in 2009 remained the same as in 2008.

Staff then applied the distribution of estimated fuel consumption in Table 29 to the estimated jet fuel sales to commercial airlines in California (last column of Table 23) to allocate California jet fuel sales to each of the three flight categories (Table 30).

*Table 30: Apportionment of California's commercial aviation fuel sales, 2000-2009 (gallons)*

| Year | Intrastate | Interstate | International | Total |
|---|---|---|---|---|
| 2000 | 213,309,857 | 1,565,284,228 | 1,429,173,477 | 3,207,767,562 |
| 2001 | 205,292,677 | 1,562,193,220 | 1,366,958,649 | 3,134,444,546 |
| 2002 | 216,859,204 | 1,727,889,842 | 1,396,788,484 | 3,341,537,529 |
| 2003 | 209,926,685 | 1,619,147,695 | 1,224,252,960 | 3,053,327,340 |
| 2004 | 218,941,083 | 1,690,573,344 | 1,307,595,453 | 3,217,109,880 |
| 2005 | 226,885,883 | 1,710,227,034 | 1,408,538,108 | 3,345,651,025 |
| 2006 | 226,736,923 | 1,664,360,839 | 1,403,224,569 | 3,294,322,331 |
| 2007 | 256,662,560 | 1,794,390,775 | 1,506,373,206 | 3,557,426,541 |
| 2008 | 230,241,639 | 1,567,423,668 | 1,430,687,431 | 3,228,352,737 |
| 2009* | 246,288,111 | 1,676,663,765 | 1,530,397,827 | 3,453,349,703 |

* Staff assumed that the share of each category in 2009 remained the same as in 2008.

In the final inventory allocation, staff assumed that all of California's general aviation jet fuel was consumed in the state and added it to the intrastate commercial jet fuel. Thus, the results from Table 23 and Table 30 can be combined to calculate the final apportionment of total jet fuel sales for California. Table 31 presents these results.

*Table 31: Apportionment of California's jet fuel sales, summary for 2000 to 2008 (gallons)*

| Year | Intrastate (commercial + general aviation flights) | Interstate commercial flights | International commercial flights | CA Military flights | Total CA fuel sales (from EIA) |
|---|---|---|---|---|---|
| 2000 | 343,523,620 | 1,565,284,228 | 1,429,173,477 | 296,469,675 | 3,634,451,000 |
| 2001 | 331,718,948 | 1,562,193,220 | 1,366,958,649 | 322,845,183 | 3,583,716,000 |
| 2002 | 356,366,086 | 1,727,889,842 | 1,396,788,484 | 290,354,588 | 3,771,399,000 |
| 2003 | 340,630,365 | 1,619,147,695 | 1,224,252,960 | 290,768,981 | 3,474,800,000 |
| 2004 | 395,966,203 | 1,690,573,344 | 1,307,595,453 | 300,468,000 | 3,694,603,000 |
| 2005 | 448,874,705 | 1,710,227,034 | 1,408,538,108 | 260,115,152 | 3,827,755,000 |
| 2006 | 468,616,930 | 1,664,360,839 | 1,403,224,569 | 232,787,661 | 3,768,990,000 |
| 2007 | 491,611,233 | 1,794,390,775 | 1,506,373,206 | 231,421,287 | 4,023,796,500 |

| Year | Intrastate (commercial + general aviation flights) | Interstate commercial flights | International commercial flights | CA Military flights | Total CA fuel sales (from EIA) |
|---|---|---|---|---|---|
| 2008 | 492,461,087 | 1,567,423,668 | 1,430,687,431 | 229,909,315 | 3,720,481,500 |
| 2009 | 489,508,403 | 1,676,663,765 | 1,530,397,827 | 203,601,005 | 3,900,171,000 |

(b) Apportionment of marine vessel fuel

Staff apportioned distillate and residual fuel oil used by marine vessels for port activities, harbor craft, transit (within 24 nautical miles from California's coast) and travel outside of California waters among intrastate, interstate and international activities using an ARB model based on geographically specific shipping activity data which was developed for the Goods Movement Plan (ARB, 2007a; ARB, 2007b).

(c) Emission calculations

All $CO_2$ emissions and the $CH_4$ and $N_2O$ emissions from LPG and natural gas where estimated using the fuel combustion equation based on heat content:

*Equation 28: Emissions from mobile source combustion (case 1)*

$$E_{GHG,\,fuel} = Q_{fuel} \bullet HC_{fuel} \bullet EF_{GHG,\,fuel}$$

Where,

$E_{GHG,\,fuel}$ = Emissions of the given GHG for the type of fuel (g of GHG)
$Q_{fuel}$ = Amount of fuel combusted (in units of gallons for liquid fuels or standard cubic feet for gaseous fuels)
$HC_{fuel}$ = Heat content of the type of fuel (BTU / unit)
$EF_{GHG,\,fuel}$ = Emission factor of the given GHG by the type of fuel (g GHG / BTU)

With,

(1) GHG = [$CO_2$] and Fuel = [aviation gasoline, distillate, jet fuel, LPG, natural gas, residual fuel oil]
(2) GHG = [$CH_4$, $N_2O$] and Fuel = [LPG, Natural Gas]

A slightly different equation was used for estimating $CH_4$ and $N_2O$ emissions from aviation gasoline, distillate, jet fuel and residual fuel oil, because the country specific emissions factors available were expressed by mass of fuel rather than by volume.

*Equation 29: Emissions from mobile source combustion (case 2)*

$$E_{GHG,\,fuel} = Q_{fuel} \bullet D_{fuel} \bullet EF_{GHG,\,fuel}$$

Where,

$E_{GHG,\,fuel}$ = Emissions of the given GHG for the type of fuel (g of GHG)
$Q_{fuel}$ = Amount of fuel combusted (in units of gallons for liquid fuels or standard cubic feet for gaseous fuels)
$D_{fuel}$ = Density of the type of fuel (kg / unit)
$EF_{GHG,\,fuel}$ = Emission factor of the given GHG by the type of fuel (g GHG / kg fuel)

With,
GHG = [$CH_4$, $N_2O$]
Fuel = [aviation gasoline, distillate, jet fuel, residual fuel oil]

## 3. Data Sources

On-road gasoline, on-road diesel, and aviation gasoline fuel sales numbers are from the Board of Equalization (BOE, 2011). These numbers are also referenced in the Federal Highway Administration (FHWA) Highway Statistics annual reports (FHWA, various years). Data for jet fuel sold within California came from the Energy Information Administration (EIA, 2011d). Data regarding fuel use for railroad activity (locomotives) were obtained from from the Energy Information Administration (Walzer, 2011).

Heat content values for ethanol are from EIA (EIA, 2011b) and those for gasoline are derived in Section I.C.3. Heat content of natural gas came from the EIA SEDS database (EIA, 2011e) and values for aviation gasoline, distillate, jet fuel, residual fuel oil and LPG from USEPA (USEPA, 2007d).

$CO_2$ emission factor values are for gasoline and ethanol were calculated from their carbon content in Section I.C.3. Other $CO_2$ emissions factors were from USEPA (USEPA, 2007d) for natural gas, aviation gasoline, and distillate and residual fuel oil used in international shipping; and from ARB's Goods Movement Plan (ARB, 2007a; ARB, 2007b) for distillate and residual fuel oil used by ships within California waters.

$CH_4$ and $N_2O$ emission factors values are from IPCC guidelines (IPCC, 2006b) for natural gas and LPG; from USEPA (USEPA, 2007c) for aviation gasoline, jet fuel, and distillate and residual fuel oil used in international shipping; and from ARB's Goods Movement Plan (ARB, 2007a; ARB, 2007b) for distillate and residual fuel oil used by ships within California waters.

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at:
http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_1d_transport.pdf

## 4. Changes in Estimates

In this edition of the inventory, on-road, rail and water-borne transportation received only minor updates such as updating fuel numbers to match the latest reported fuel data. The main change in estimates is that gasoline and ethanol are now listed as separate fuels, whereas in the 1990-2004 edition, gasoline-ethanol blends were listed under the generic term of "gasoline". This change, which allows for gasoline and ethanol to be analyzed separately, had a small effect on the emissions estimates. This change and the data revisions made by data providers had almost no impact on emissions estimates for on road transport: -0.2 percent on average over the years 2000 to 2004 when compared with the estimates in the first edition of ARB's GHG inventory for on road transport, and a small impact (+0.16 percent on average) for rail and water-borne transport.

Two changes were made to the estimation of emissions from aviation. First, California jet fuel sales data were obtained from the Energy Information Administration (EIA, 2011d), while in the 1990-2004 edition they were from the California Energy Balance (Murtishaw et al. 2005). Second, the methods used for the apportionment of aviation jet fuel among general aviation, military aircrafts and intrastate, interstate and international commercial flights were much improved. In this edition, the use of airplane type specific fuel consumptions rather than simply mileage to do some of the apportionment resulted in more realistic estimates of the share of jet fuel sales to allocate to intrastate flights versus interstate and international ones. These changes resulted in a substantial change in emission estimates: -15.6 percent on average over the years 2000 to 2004 when compared with the estimates in the first edition of ARB's GHG inventory for aviation in general, and +7.8 percent on average for intrastate flights only.

### 5. Future Improvements

ARB is currently investigating the feasibility of updating EMFAC to directly calculate emission outputs for on-road vehicles' $N_2O$ emissions and to better characterize $CO_2$ and $CH_4$ emissions. Train and ship emissions will be updated as improved activity and emissions data become available.

## E. Oil and Gas Production (IPCC 1A1cii)

### 1. Background

This section discusses combustion emissions arising from the energy-producing industries own (on-site) energy use for oil and gas extraction, the processing and upgrading of natural gas, and the transport in pipelines. The fuels used for these processes may be produced on site (crude oil, associated gas, natural gas) or may have gone through a refinery (distillate, residual fuel oil). Crude oil combustion occurred in California in the early 1990's but has since been discontinued.

When crude oil is first brought to the surface, it may contain a mixture of associated gas, produced fluids such as salt water, and both dissolved and suspended solids. Water (which can constitute more than 90 percent of the fluid extracted in older wells) is separated out, as are solids and any associated gas. The crude oil is then prepared for shipment to storage facilities and ultimately to refineries. The separated associated gas consists predominantly of methane and carbon dioxide, but ethane, propane, and butane are also significant components. The heavier components, including propane and butane, liquefy when cooled and compressed; these are often separated and processed as natural gas liquids. Associated gas is typically consumed on site as an energy source for steam generation. When consumed in this way, this gas is also called lease fuel.

Natural gas is produced from dry gas wells that produce no oil, and is typically sent to natural gas processing plants for distribution and sale through natural gas pipelines. Natural gas is composed of methane, ethane and other combustible hydrocarbons, but it may also contain water vapor, hydrogen sulfide, carbon dioxide, nitrogen, and helium. During processing, many of these components are removed to improve the quality of the natural gas or to make it easier to move the gas over great distances through pipelines. The resulting processed natural gas contains mostly methane and ethane, although there is no such thing as a "typical" natural gas. Emissions from fuel combusted in pipelines compressor stations are included in this section, but the fugitive emissions from pipelines are reported in section I.F.

## 2. Methodology

The method for estimating emissions follows IPCC 2006 guidelines for stationary combustion (IPCC, 2006a). California or US-specific emission factors and heat content values were used when available.

*Equation 30: Emissions from oil and gas production*

$$\boxed{E_{GHG,\,fuel} = Q_{fuel} \bullet HC_{fuel} \bullet EF_{GHG,\,fuel}}$$

Where,

$E_{\text{GHG, fuel}}$ = Emissions of the given GHG for the type of fuel (g of GHG)

$Q_{\text{fuel}}$ = Amount of fuel combusted (in units of gallons for liquid fuels or standard cubic feet for gaseous fuels)

$HC_{\text{fuel}}$ = Heat content of the type of fuel (BTU / unit)

$EF_{\text{GHG, fuel}}$ = Emission factor of the given GHG by the type of fuel (g GHG / BTU)

With,

GHG = [$CO_2$, $CH_4$, $N_2O$]

Fuel = [Associated gas, Distillate, Natural Gas, Residual fuel oil]

## 3. Data Sources

The data sources for estimating emissions include the California Energy Commission's Quarterly Fuels and Energy Report (QFER), the CA Department of Conservation Division of Oil, Gas & Geothermal Resources (DOGGR), the Energy Information Administration (EIA), the US Environmental Protection Agency, the Intergovernmental Panel on Climate Change (IPCC), and the Western States Petroleum Association (WSPA).

Distillate and residual fuel oil use are from EIA (EIA, 2011d). The QFER (Gough, 2011) provided natural fuel use. The DOGGR (Kustic, 2011) provided data on associated gas fuel use.

Natural gas heat content values are from EIA SEDS (EIA, 2011e), associated gas values from WSPA (Wang, 2007) and other heat content values from USEPA (USEPA, 2007b).

Emission factor values for $CO_2$ are from WSPA (Wang, 2007) for associated gas and from USEPA (USEPA, 2007b) for other fuels. Emissions factor values for $CH_4$ and $N_2O$ are from the 2006 IPCC guidelines (IPCC, 2006a).

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at: http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_1e_oil_and_gas_production.pdf

### 4. Changes in Estimates

Data from the 2005 California Energy Balance (CALEB, Murtishaw et al. 2005) is no longer used in the current edition of the inventory; all estimates are now derived from data from direct sources.

In compiling the first edition of ARB's GHG inventory, staff had mistakenly concluded that the CEC's QFER dataset contained data on associated gas use. To avoid double counting, staff had then reconciled QFER data with the DOGGR dataset on associated gas and this resulted in a reduction in the amount of gas and thus of GHG emissions. Having discovered this error, staff used the full DOGGR dataset for associated gas for this edition of the inventory.

In previous editions, staff used CEC's QFER data to estimate emissions from natural gas pipeline compressor stations. However, it was later discovered that QFER did not receive a comprehensive reporting of fuel use in this particular subsector. The current edition uses a complete data set of fuel use by pipeline compressor stations from the EIA, resulting in an increase in emissions estimates over the previous editions.

These changes and the data revisions made by data providers resulted in substantial changes in emissions estimates for the categories included in this section: + 22.2 percent on average over the years 2000 to 2004 when compared with the estimates in the 1990-2004 edition of ARB's GHG inventory.

### 5. Future Improvements

Only a fraction of emissions in this category must be reported to ARB's Mandatory Reporting Program, the rest being emitted by facilities under the current emissions threshold of 25,000 tonnes of $CO_2$. Thus, the data sources currently in use provide the best comprehensive estimate of emissions from this sector. Future improvements may, however, come from better data on the composition and heating value of associated gas.

## F. Fugitive Emissions from Fuels and Energy Production (IPCC 1B1, 1B2, and 1B4)

### 1. Background

This section discusses various emissions associated with fuels and energy production, other than combustion emissions, in several industrial sectors.

Methane emissions occur due to leaks arising from the pumping/pressurization of pipelines used to transport crude oil, refined petroleum products, natural gas liquids and natural or associated gases, and with their storage in tanks. These emissions are associated with oil and gas extraction, petroleum refining and marketing activities; and a variety of manufacturing activities such as construction, chemicals, plastics and rubber, electric and electronic equipment, food products, etc. Fugitive emissions of methane also occur from the natural off-gassing of methane from petroleum gas seeps and coal storage piles.

Carbon dioxide emissions are generated by some processes used to control and eliminate acid gases in the exhaust of power plants. For example, limestone or lime is injected to react with acid gases and result in the release of carbon dioxide as a byproduct of the reaction.

Emissions of both methane and carbon dioxide arise from certain processes occurring in petroleum refineries. These emissions result from the purposeful venting of exhaust gases, rather than an unintended leakage from pipes or tanks. Sources of these process emissions include: catalyst regeneration (but not emissions associated with the consumption of catalyst coke), asphalt blowing, coke drum vents, hydrogen production pressure swing absorption gas, and sulfur recovery units.

Flaring at petroleum refineries is a process that burns various waste products for which a more useful purpose cannot be found. The composition of these waste streams can vary greatly and are usually not monitored in such a way as to allow a breakdown into their component parts. They are grouped here with the fugitive and process emissions even though they are a type of combustion emission. Flaring produces the usual gases associated with combustion: carbon dioxide, methane and nitrous oxide.

## 2. Methodology

For some of the categories, staff queried ARB's California Emission Inventory Development and Reporting System (CEIDARS) database for total organic gases (TOG) emissions and then speciated the results to estimate fugitive emissions of $CH_4$. In the CEIDARS database, total organic gases include emissions of compounds of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate. The ARB maintains and updates estimates of the chemical composition and size fractions of particulate matter (PM) and the chemical composition and reactive fractions of total organic gases (TOG) in CEIDARS, for a variety of emission source categories. These speciation profiles provide estimates of the chemical composition of the emissions, and are used in the emission inventory and air quality models. For more information see: http://arb.ca.gov/ei/speciate/speciate.htm

Year 2009 data from ARB's Mandatory Reporting Program were used for some categories. Estimates for fugitive emissions from pipes, storage tanks and process losses in the petroleum refining and cement manufacturing sectors were based on CEIDARS for 2000-2008 and on Mandatory Reporting data for 2009. New sources of fugitive and process emissions were identified in the Mandatory Reporting data including: flaring in refineries ($CO_2$, $CH_4$ and $N_2O$), acid gas control devices ($CO_2$), refinery process such as catalyst regeneration emissions ($CO_2$, $CH_4$), and fugitives from coal storage piles ($CH_4$). For these new categories, reported emissions for 2009 were obtained from the Mandatory Reporting database, and then scaled back in time —proportionally to the relevant level of activity— to estimate values for 2000-2008.

*Equation 31: Scaling of some fugitive emissions back in time*

$$\boxed{E_{year} = \frac{E_{2009} \bullet H_{year}}{H_{2009}}}$$

Where,

$E_{year}$ = GHG emission estimate for a given economic subsector in a particular year (g of GHG)
$E_{2009}$ = GHG emission reported by the given economic subsector in 2009 (g of GHG)
$H_{2009}$ = Total amount of heat used by the facilities in the given subsector in 2009 (btu)
$H_{year}$ = Total amount of heat used by the facilities in the given subsector in the particular year (btu)

With

Year = [2000 to 2008]

The scaling used PIIRA data on the total heat used by refineries to scale emissions from flaring, refinery process emissions and the refinery portion of acid gas control. Total fuel heat from coal used by the electricity sector was used to scale methane emissions from coal storage piles. Total fuel heat from coal, petroleum coke, biomass and MSW from the electricity sector was used to scale the electricity sector portion of the emissions resulting from acid gas control.

## 3. Data Sources

The California Air Resources Board (ARB) has collected information on emissions from air pollution sources since 1969. Data are gathered on an ongoing basis and stored in the California Emission Inventory Development and Reporting System (CEIDARS) database. See: http://www.arb.ca.gov/ei/general.htm

Data from ARB’s Mandatory Reporting Program (ARB, 2011b) were used instead of CEIDARS data for some categories in 2009 (e.g. fugitive emissions from refineries process losses and storage tanks). Data from the PIIRA database (O’Brien, 2010) and from EIA databases published online (EIA, 2011a) were used to scale 2009 emissions found only in the Mandatory Reporting database back in time to cover 2000-2008 (e.g. emissions from coal piles, flaring, or acid gas control devices).

### 4. Changes in Estimates

In this edition of the GHG inventory, new categories were added to this section and changes were made to the methodology used for estimating emissions from some of the other categories. The use of Mandatory Reporting data, combined with the updates and data revisions in the CEIDARS database resulted in a substantial increase in emissions estimates for the categories included in this section: + 23.5 percent on average over the years 2000 to 2004 when compared with the estimates in the first edition of ARB’s GHG inventory.

### 5. Future Improvements

ARB staff will continue to use of Mandatory Reporting data for future editions of the GHG inventory. Staff is also considering the potential use of more comprehensive data on fugitive emissions from tanks and pipelines now being collected through year specific surveys of the Oil & Gas industry.

## *G. Carbon Dioxide from Geothermal Energy Production (IPCC 1B3)*

### 1. Background

Geothermal power plants use high-pressure hot water and steam from deep inside the earth crust to turn turbine generators to produce electricity. The geothermal wells and gathering systems collect and convey the deep geothermal fluid to the power plants. Geothermal fluids contain minerals leached from the reservoir rock and variable quantities of gas, mainly carbon dioxide and a smaller amount of hydrogen sulfide ($H_2S$). The quantity and composition of dissolved gases depend on the local geological conditions. When the steam cools it turns back into water and is re-injected back into the reservoir, with most of its mineral content and some of the gases. Most of the non-condensable gases are released to the environment. Some plants remove the $H_2S$ in a gas treatment process before releasing the $CO_2$ to the environment.

### 2. Methodology

#### *2.1 Years 2000 to 2008*

To estimate the $CO_2$ emissions resulting from the exploitation of geothermal power, staff obtained data from the EIA for the amount of geothermal heat used by power plants and applied the $CO_2$ emission factor used by USEPA in the national inventory.

*Equation 32: $CO_2$ emissions from geothermal power*

$$\boxed{E = GH \bullet EF}$$

Where,
E = $CO_2$ emissions by geothermal plants (g of $CO_2$)
GH = Amount of geothermal heat used by the plants (btu)
EF = $CO_2$ emission factor (g of $CO_2$ per btu)

### *2.2 Year 2009*

Emissions data reported by individual power plants under ARB's Mandatory Reporting Program were used for 2009. However, small plants emitting less than the Mandatory Reporting threshold of 2,500 metric tons of $CO_2$ do not report their emissions. For those plants staff used the same methodology as for years 2000 to 2008, see Equation 32 above.

## 3. Data Sources

Geothermal heat data was obtained from the U.S. Energy Information Administration (EIA). Data for 2000 was obtained through personal correspondence with Robert Schnapp of U.S. Energy Information Administration (Schnapp, 2008). Data for 2001-2008 data was downloaded from U.S. Energy Information Administration databases published online (EIA, 2011a). The emission factor comes from USEPA 1990-2005 inventory annex 2.1 (USEPA, 2007b). ARB's Mandatory Reporting data (ARB, 2011b) was used for 2009 for plants emitting more than the reporting threshold of 2,500 metric tons of $CO_2e$.

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at: http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_1g_carbon_dioxide_from_geothermal_power.pdf

## 4. Changes in Estimates

The only change made to the methodology used for estimating emissions from categories in this section was the use of Mandatory Reporting data for 2009.

While working on the 2000-2008 edition of the inventory, staff learned of specified imports from a geothermal plant: Caithness Dixie Valley Plant in Nevada. This plant was not included in previous editions of the inventory. Its addition raises total emission estimates in this section by an average of 3.7 percent over the years 2000 to 2004 when compared with the estimates in the 1990-2004 edition of ARB's GHG inventory.

## 5. Future Improvements

ARB's GHG Mandatory Reporting data for geothermal plants will continue to be included in future editions of the GHG inventory.

# II. Industrial Processes and Product Use

## A. Cement Production (IPCC 2A1)

### 1. Background

In cement manufacturing, $CO_2$ emissions occur during the production of clinker, an intermediate product that is the main component of hydraulic (usually portland) cements.

To produce clinker, limestone (predominantly made up of calcium carbonate $CaCO_3$) is heated at high temperature in a kiln to produce lime (CaO), and $CO_2$. This process is called calcination. The CaO then reacts with silica ($SiO_2$), alumina ($Al_2O_3$), and iron oxide ($Fe_2O_3$) in the raw materials to make the clinker minerals (chiefly calcium silicates). During the making of clinker some cement kiln dust (CKD) may leave the kiln system. Since that CKD is made up of partially calcined carbonates, cement manufacture emission estimates should also account for the $CO_2$ emissions associated with the CKD.

Masonry cement is produced by adding lime or ground limestone to portland cement. Since the emissions associated with the lime is already accounted for under the lime production section of the ARB statewide GHG inventory, the production of masonry cement does not lead to additional emissions in this section. Similarly, the emissions resulting from the combustion of fuels to heat the kiln are accounted for in another section of the inventory.

### 2. Methodology

This GHG inventory for the cement industrial sector presents two calculation methods including a Tier 2 approach for years 2000 to 2007, followed by Tier 3 approach —based on facility level measurements— for years 2008 and 2009.

### 2.1 Methodology for years 2000 through 2007

Staff estimated the cement manufacture $CO_2$ emissions using Tier 2 methodology from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006a). These guidelines recommend using the following two equations.

*Equation 33: $CO_2$ emissions from cement production (equation 2.2 of the guidelines)*

$$\boxed{E_K = M_{cl} \bullet EF_{cl} \bullet CF_{ckd}}$$

Where,

$E_K$ = emissions of $CO_2$ from cement production in the clinker process (tonnes)
$M_{cl}$ = weight (mass) of clinker produced (tonnes)
$EF_{cl}$ = emission factor for clinker (tonnes CO2/tonne clinker). This clinker emission factor ($EF_{cl}$) is not corrected for CKD.
$CF_{ckd}$ = emissions correction factor for CKD, (dimensionless, see Equation 34)

*Equation 34: Emission correction factor for CKD (equation 2.5 of the guidelines)*

$$\boxed{CF_{ckd} = 1 + \left(\frac{M_d}{M_{cl}}\right) \bullet C_d \bullet F_d \bullet \left(\frac{EF_c}{EF_{cl}}\right)}$$

Where,

$CF_{ckd}$ = emissions correction factor for CKD (dimensionless)
$M_d$ = weight of CKD not recycled to the kiln (tonnes)
$M_{cl}$ = weight of clinker produced (tonnes)
$C_d$ = fraction of original carbonate in the CKD (i.e., before calcination) (fraction)
$F_d$ = fraction calcination of the original carbonate in the CKD (fraction)
$EF_c$ = emission factor for the carbonate (tonnes $CO_2$/tonne carbonate)
$EF_{cl}$ = emission factor for clinker uncorrected for CKD (tonnes $CO_2$/tonne clinker)

Substituting the expression for $CF_{ckd}$ from Equation 34 into Equation 33, one gets Equation 35.

*Equation 35: Substituting for $CF_{ckd}$ into Equation 33*

$$\boxed{E_K = (M_{cl} \bullet EF_{cl}) + (M_d \bullet C_d \bullet F_d \bullet EF_c)}$$

And considering that $(C_d \bullet F_d \bullet EF_c)$ constitutes $EF_d$ the emission factor of the CKD, Equation 35 can be simply written as:

*Equation 36: $CO_2$ emissions from cement production*

$$\boxed{E = (M_{cl} \bullet EF_{cl}) + (M_d \bullet EF_d)}$$

## 2.2 Methodology for years 2008 and 2009

Years 2008 and 2009 $CO_2$ emissions were quantified by each cement manufacturing plant in California using the calculation methodology specified by the ARB GHG Mandatory Reporting regulation (ARB, 2007d). This is a clinker-based method using the volume and composition of clinker produced and the amount of CKD discarded. A plant-specific clinker $CO_2$ emission factor and a CKD emission factor for $CO_2$ are also determined. The clinker emission factor is based on the actual percentage of lime (CaO) and magnesium oxide (MgO) content of the clinker. For any CKD which is not recycled back into the kiln, a plant-specific CKD calcination rate is determined. Further, each cement plant calculates the process related emissions resulting from the total organic carbon (TOC) content of the raw materials such as limestone, shale, or fly ash. This additional TOC factor was not included in the methodology used for years 2000 to 2007.

The plant-specific clinker emission factor is determined using the following equation:

*Equation 37: Clinker emission factor*

$$\boxed{EF_{cl} = (F_{CaO} \bullet 0.785) + (F_{MgO} \bullet 1.092)}$$

Where,

$EF_{cl}$ = emission factor for clinker (tonnes $CO_2$/tonne clinker). This clinker emission factor is not corrected for CKD.

$F_{CaO}$ = fraction content of CaO in the clinker by weight minus non-carbonate CaO in the clinker by weight (fraction)

0.785 = molecular weight ratio of $CO_2$/CaO (44g/56g), (dimensionless)

$F_{MgO}$ = fraction content of MgO in the clinker by weight minus non-carbonate MgO in the clinker by weight (fraction)

1.092 = molecular weight ratio of $CO_2$/MgO (44g/40g), (dimensionless)

The plant-specific CKD emission factor is quantified for cement plants that generate CKD which is not recycled back to the kiln as follows:

*Equation 38: Clinker kiln dust emission factor*

$$\boxed{EF_{CKD} = \frac{\dfrac{EF_{cl}}{1+EF_{cl}} \bullet d}{1 - \dfrac{EF_{cl}}{1+EF_{cl}} \bullet d}}$$

Where,

$EF_{CKD}$ = emission factor for CKD (tonnes $CO_2$/tonne CKD)

$EF_{cl}$ = emission factor for clinker (tonnes $CO_2$/tonne clinker). This clinker emission factor is not corrected for CKD.

d = plant-specific CKD calcination rate (dimensionless, see Equation 39)

*Equation 39: Plant specific clinker kiln dust calcination rate*

$$\boxed{d = 1 - \frac{C_d \bullet (1 - C_{RM})}{(1 - C_d) \bullet C_{RM}}}$$

Where,

d = plant-specific CKD calcination rate (dimensionless)

$C_d$ = fraction of original carbonate in the CKD (fraction)

$C_{RM}$ = fraction of original carbonate in the raw material (fraction)

The $CO_2$ emissions from the clinker process for each cement plant are calculated using the following equation:

*Equation 40: CO2 emissions from clinker production*

$$\boxed{E_{cl} = (M_{cl} \bullet EF_{cl}) + (M_{CKD} \bullet EF_{CKD})}$$

Where,

$E_{cl}$ = emissions of $CO_2$ from clinker calcination process (tonnes)

$M_{cl}$ = amount of clinker produced (tonnes)

$EF_{cl}$ = emission factor for clinker (tonnes $CO_2$/tonne clinker).
$M_{CKD}$ = amount of CKD not recycled to the kiln (tonnes)
$EF_{CKD}$ = emission factor for CKD (tonnes $CO_2$/tonne CKD)

The estimation of $CO_2$ emissions from the combustion of the total organic carbon (TOC) in raw materials is calculated as follows (with a default value of 0.2 percent organic carbon):

*Equation 31: $CO_2$ emissions from combustion of organic carbon in raw materials*

$$\boxed{E_{TOC} = TOC \bullet C_{RM} \bullet 3.664}$$

Where,
$E_{TOC}$ = emissions of $CO_2$ from the combustion of organic carbon (TOC) content in raw materials (tonnes)
TOC = total organic carbon content of raw material, default value = 0.002 (fraction)
$C_{RM}$ = fraction of original carbonate in the raw material (fraction)
3.664 = molecular weight ratio of $CO_2$/C (44g/12g), (dimensionless)

The total $CO_2$ emissions from the calcination process for each plant are finally determined using the next equation; by summing the emissions from the clinker process and the emissions from the combustion of organic carbon in raw materials described above.

*Equation 32: Total $CO_2$ emissions from cement production process*

$$\boxed{E_{total} = E_{cl} + E_{TOC}}$$

Where,
$E_{total}$ = total process emissions of $CO_2$ from cement production (tonnes)
$E_{cl}$ = emissions of $CO_2$ from the clinker calcination process (tonnes)
$E_{TOC}$ = emissions of $CO_2$ from the combustion of organic carbon in raw materials (tonnes)

Note that to satisfy the ARB GHG Mandatory Reporting regulation, cement plant operators also have the option to determine $CO_2$ emissions from installed Continuous Emission Monitoring Systems (CEMS) which comply with federal performance standards. The cement sector total in California is obtained by summation of all cement plants' emissions. Emissions for 2007 were determined by interpolation between 2006 and 2008 estimates.

## 3. Data Sources

The Portland Cement Association (PCA) provided clinker production data ($M_{cl}$) for all California Portland cement plants for years 2000 and 2005 (O'Hare, 2007). The PCA also provided the amount of cement kiln dust and bypass dust leaving the kiln system ($M_d$) for the same set of years. ARB staff used interpolation to estimate the values for $M_{cl}$ and $M_d$ for the missing intervening years.

In 2008, ARB conducted a survey of California cement plants to obtain the 2006 annual production data which was utilized by ARB to calculate the 2006 $CO_2$ emissions (ARB, 2008). Cement plant emissions for 2007 were determined through interpolation of clinker production and CKD discarded amounts between the ARB survey for 2006 and the 2008 cement production reports submitted by facilities to ARB under the ARB GHG Mandatory Reporting regulation.

For years 2000 to 2007, the default emission factor values from the 2006 IPCC guidelines (IPCC, 2006a) were used for $CO_2$ emissions calculations, that is:

- The emission factor of clinker ($EF_{cl}$) assumes that the clinker is 65 percent CaO, that this CaO is 100 percent derived from $CaCO_3$ and that the kiln achieves 100 percent calcination. Since 1 tonne of clinker contains 0.65 tonnes CaO and $CaCO_3$ is 56.03 percent CaO and 43.97 percent $CO_2$ by weight, the amount of $CaCO_3$ needed to yield 1 tonne of clinker is: 0.65/0.5603 = 1.1601 tonnes of $CaCO_3$. The amount of $CO_2$ released by calcining this $CaCO_3$ = 1.1601 • 0.4397 = 0.5101 tonne $CO_2$ (unrounded). Thus $EF_{cl}$ = 0.51 tonne of $CO_2$ per tonne of clinker.
- The emission factor of CKD ($EF_d$) assumes that the fraction of original carbonate in the CKD ($C_d$) = 0.85, that the fraction calcination of the original carbonate in the CKD ($F_d$) = 0.50, and that the original carbonate in CKD is all $CaCO_3$ (hence $EF_c$ = 0.4397 tonne $CO_2$/tonne carbonate). Thus $EF_d$ = 0.85 x 0.50 x 0.4397 = 0.19 tonne of $CO_2$ per tonne of CKD.

The 2008 and 2009 $CO_2$ emissions were calculated for all California cement manufacturing plants using the data reported by plant operators as required by the ARB GHG Mandatory Reporting regulation (ARB, 2011b). Plant-specific emission factors for clinker and CKD are determined and then used to calculate $CO_2$ emissions per facility which are summed to present the total statewide GHG emissions for this industrial sector.

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at:
http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_2a_cement_production.pdf

## 4. Changes in Estimates

For the 2008 and 2009 emissions calculations, staff utilized data collected under the ARB GHG Mandatory Reporting regulation. This calculation methodology uses plant-specific data to determine emission factors, and also includes the $CO_2$ emissions from the combustion of the organic content of the raw materials such as limestone and shale. These plant-specific emission factors incorporate data on the mass and composition of calcium and magnesium carbonates. Further, the fraction of non-carbonate sources (e.g. steel slag, calcium silicates, or fly ash) is subtracted from the total amount of the CaO and MgO content of the clinker. The additional estimation of $CO_2$

emissions from the combustion of organic carbon contained in raw materials was not included for years 2000 through 2007.

### 5. Future Improvements

ARB plans to continue to utilize plant-specific data submitted under the requirements of the ARB GHG Mandatory Reporting program for future state emission inventory calculations. This approach is considered to be Tier 3 in the IPCC 2006 guidelines and produces a more precise emissions estimate.

## B. Lime Production (IPCC 2A2)

### 1. Background

Lime production involves three key stages: stone preparation, calcination, and hydration. This section focuses on the $CO_2$ emitted during the calcination process, when limestone (mostly $CaCO_3$) or dolomitic limestone (higher Mg concentration) is heated in a kiln to produce lime (CaO), $CO_2$ emissions and lime kiln dust (LKD) as a by-product.

*Equation 41: Calcination processes*

$$\boxed{\begin{array}{l} \mathrm{CaCO_3 + Heat \rightarrow CaO + CO_2} \\ \mathrm{MgCO_3 + Heat \rightarrow MgO + CO_2} \end{array}}$$

Lime is used in a variety of industrial applications, such as in steelmaking, water and sewage treatment, and paper manufacturing.

### 2. Methodology

There are two types of lime material: high-calcium lime and dolomitic lime. Quicklime is the product which results from the calcination of limestone material. High-calcium quicklime is derived from limestone material containing less than 5 percent magnesium carbonate ($MgCO_3$). Dolomitic quicklime is produced from limestone material containing 35 to 46 percent $MgCO_3$. A plant-specific $CO_2$ emission factor for limestone calcination in a kiln can be developed through laboratory analysis of the actual percent CaO and percent magnesium oxide (MgO) in the input limestone material. Then, multiplying the quantity of lime produced annually at a plant by the derived $CO_2$ emission factor will provide the annual $CO_2$ emissions. This methodology is consistent with emission estimation methodology used by the USEPA Emission Inventory Improvement Program guidance (USEPA, 2004a), and with the Tier 3 method of the 2006 IPCC guidelines (IPCC, 2006a).

*Equation 42: $CO_2$ emissions from lime calcination*

$$\boxed{E_l = W_l \bullet (P_{CaO,l} \bullet 0.7848 + P_{MgO,l} \bullet 1.0918)}$$

Where,

$E_l$ = $CO_2$ emissions from lime calcination process (tonnes)
$W_l$ = Weight (mass) of lime produced (tonnes)
$P_{CaO,l}$ = Proportion of CaO in lime (fraction)
0.7848 = Molecular weight ratio of $CO_2$ to CaO (44g/56g), (dimensionless)
$P_{MgO,l}$ = Proportion of MgO in lime (fraction)
1.0918 = Molecular weight ratio of $CO_2$ to MgO (44g/40g), (dimensionless)

*Equation 43: $CO_2$ emissions from LKD by-product*

$$\boxed{E_{LKD} = W_{LKD} \bullet (P_{CaO,LKD} \bullet 0.7848 + P_{MgO,LKD} \bullet 1.0918)}$$

Where,

$E_{LKD}$ = $CO_2$ emissions from LKD calcined by-product generation (tonnes)
$W_{LKD}$ = Weight (mass) of LKD generated (tonnes)
$P_{CaO,LKD}$ = Proportion of CaO in LKD (fraction)
0.7848 = Molecular weight ratio of $CO_2$ to CaO (44g/56g), (dimensionless)
$P_{MgO,LKD}$ = Proportion of MgO in LKD (fraction)
1.0918 = Molecular weight ratio of $CO_2$ to MgO (44g/40g), (dimensionless)

*Equation 44: Total CO2 emissions from lime production*

$$\boxed{E_{total} = E_l + E_{LKD}}$$

Where,

$E_{total}$ = total process emissions of $CO_2$ from lime production (tonnes)
$E_l$ = $CO_2$ emissions from lime production (tonnes)
$E_{LKD}$ = $CO_2$ emissions from LKD calcined by-product generation (tonnes)

## 3. Data Sources

The National Lime Association (NLA) provided $CO_2$ emission estimates from lime production operations in California using plant-specific $CO_2$ emission factors and actual material throughput for both limestone calcination and LKD by-product generation (Lime Producers, 2011). The limestone material is generally mined on-site and mineral characteristics for CaO and MgO concentrations are determined monthly by laboratory analysis. The molecular weight ratio of $CO_2$ to CaO (0.7848) and $CO_2$ to MgO (1.0918) are derived from molecular weight data published by the International Union of Pure and Applied Chemistry (IUPAC, 2006).

The NLA provided $CO_2$ emission estimates for California lime plants for years 2002 to 2009 (rounded to the nearest thousand tonne). Material throughput amounts presented in the inventory were back-calculated for 2000 and 2001, based on the 2002 to 2008 $CO_2$ emissions and using the data for lime material composition and LKD ratios provided for 2007. GHG emissions data for 2000 and 2001 were determined through extrapolation from the values for years 2002 to 2008.

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at:
http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_2b_lime_production.pdf

### 4. Changes in Estimates

The1990-2004 edition of the California GHG inventory used annual material production data provided by the California Department of Conservation. This previous inventory calculation method assumed a $CO_2$ emission factor for high-calcium lime only and did not account for $CO_2$ emissions from LKD by-product generation. This edition of the GHG inventory relies upon industry calculations based on plant-specific emission factors and including the $CO_2$ emissions from LKD by-product generation.

The current estimates should be more accurate and have resulted in significantly lower GHG emissions for this category: minus 50 percent on average over years 2000 to 2004 when compared with the estimates in the first edition of ARB's GHG inventory.

### 5. Future Improvements

ARB staff will attempt to obtain complete data for lime production, lime material composition and LKD ratios for future inventories.

## *C. Non-energy Uses of Fossil Fuels (IPCC 2B, 2D)*

### 1. Background

Some fossil fuels are also consumed for non-energy uses. These non-energy uses include use as feedstock for the chemical industry (IPCC category 2B) for the manufacture of plastics, rubber, synthetic fibers and other materials. Other consumptive uses of fossil fuels involve non-energy products such as lubricants, waxes, asphalt, and the evaporation of solvents (category 2D). The fuels used for these purposes include natural gas, liquefied petroleum gases (LPG), asphalt, naphtha, petroleum coke and other petroleum products.

Non-energy uses of fossil fuels often do generate some $CO_2$ emissions. Emissions may occur during the manufacture of various products from fuel-derived feedstock or they may occur during the product's lifetime, for instance some of the lubricant in motors will end up being burned and evaporated solvents are eventually oxidized in the atmosphere. However, emissions from lubricants, solvents and materials made from fossil fuels that are combusted after the end of the useful life are not accounted in this section but under the appropriate fuel combustion category in Section I above.

In California, the only known activities of this kind are the consumption of lubricants and evaporation of solvents. Hydrogen production which also consumes fuels, is discussed in a later section (IPCC 2H3)

## 2. Methodology

### 2.1 Consumption of lubricants

Staff used a simple methodology consistent with that used by USEPA for the national GHG inventory (USEPA, 2011a). The proportion of the carbon that is stored in the derived product and thus not oxidized is used to modify the carbon oxidation formula used for fuel combustion. The proportion of carbon stored can vary from 1 (all of the fuel's carbon is stored) as in the case of asphalt used for pavement, to 0 (none of the carbon is stored) as in the case of natural gas or naphtha used for hydrogen production.

Staff determined that, in the case of California, only lubricants consumed incidentally in internal combustion engines make up this category, as no data could be found for consumptive use of other fossil fuels resulting in their partial oxidation.

*Equation 45: $CO_2$ emissions from non-energy uses of fossil fuels*

$$\boxed{E_{fuel} = Q_{fuel} \bullet HC_{fuel} \bullet EF_{fuel} \bullet (1 - CS_{fuel})}$$

Where,

$E_{fuel}$ = $CO_2$ emissions for the particular fuel used as feedstock or other non-energy use (g)

$Q_{fuel}$ = Amount of fuel used as feedstock or other non-energy use (in units of gallons for liquid fuels or standard cubic feet for gaseous fuels)

$HC_{fuel}$ = Heat content of the type of fuel (BTU / unit)

$EF_{fuel}$ = $CO_2$ emission factor for the type of fuel (g / BTU)

$CS_{fuel}$ = Proportion of carbon that is stored in the derived product (unitless)

With,

fuel = [lubricants]

### 2.2 Solvent evaporation

Solvent evaporation data was retrieved from ARB's CEIDARS database. Emissions of Reactive Organic Compounds (ROG), which do not include methane, are converted into the amount of $CO_2$ that would result from the oxidation of all carbon atoms in the ROG compounds into $CO_2$. To do that, staff assumed that each ROG compound can be approximated as a hydrocarbon, where each carbon is bonded to 2 other carbon atoms and to 2 hydrogen atoms.

*Equation 46: Assumed oxidation of reactive organic compounds*

$$\boxed{C_nH_{2n+2} + \frac{3n+1}{2}O_2 \rightarrow nCO_2 + (n+1)H_2O}$$

Thus each $CH_2$ chain in the ROG molecules is converted into a molecule of $CO_2$. $CH_2$ has an approximate molar mass of 14 grams/mole, while $CO_2$ has a molar mass of approximately 44 grams/mole. Thus, multiplying by 44/14 converts the amount of evaporated ROG the resulting amount of $CO_2$ emissions.

### 3. Data sources

Lubricant consumption data came from EIA SEDS (EIA, 2011e). Heat content, the proportion of carbon stored, and the $CO_2$ emission factors came from USEPA inventory annex 2 (USEPA, 2007b). Solvent evaporation data comes from the CEIDARS database (ARB, 2011a).

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at: http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_2c_non-energy_uses_of_fossil_fuels.pdf

### 4. Changes in Estimates

The first edition of ARB's GHG inventory used fuel consumption data from the California Energy Balance (CALEB, Murtishaw et al. 2005). CALEB listed amounts of several fuels (asphalt, LPG, naphtha, natural gas, petroleum feedstocks, other petroleum products, waxes) as being used for non-energy purposes. However, further investigation has led staff to make the following assumptions: (1) the totality of carbon in asphalt and waxes ends up being stored; (2) emissions from lubricants, solvents and materials made from fossil fuels that are combusted for energy after the end of the useful life are already accounted for under the fuel combustion category in Section I above; (3) emissions from hydrogen production which consumes natural gas, refinery gas, and petroleum feedstock, are discussed later in section II.K below. And thus, in California, the only known activities resulting in emissions fitting this section are the consumption of lubricants and evaporation of solvents.

Staff introduced emission estimates for an IPCC category (2D3 - Solvent use) that is part of this section. This addition resulted in small increases in total emissions discussed in this section.

Together these changes resulted in a substantial reduction emissions estimates for the categories included in this section: -19.1 percent on average over the years 2000 to 2004 when compared with the estimates in the first edition of ARB's GHG inventory.

### 5. Future Improvements

ARB staff will seek to obtain more detailed data about the non-energy use of fuel in California, to determine if any other fuel use as feedstock should be included in this section.

## D. Nitric Acid Production (IPCC 2B2)

### 1. Background

The main use of nitric acid ($HNO_3$) is for the manufacture of nitrogen fertilizer. It is also used in the production of adipic acid and explosives (e.g., dynamite), for metal etching and in the processing of ferrous metals. During the production of nitric acid, $N_2O$ is generated as an unintended by-product of the high temperature catalytic oxidation of ammonia ($NH_3$), and is released into the atmosphere. The amount of $N_2O$ formed varies with the process conditions (pressure, temperature), catalyst composition and age, etc. Some nitric acid manufacturing plants have emissions control devices that reduce the amount of $N_2O$ released to the atmosphere.

### 2. Methodology

ARB staff did not have access to annual $HNO_3$ production data for California and continued to employ the estimation method suggested by USEPA Emission Inventory Improvement Program guidance (USEPA, 2004a). This approach estimates California production by scaling the national production of nitric acid by the ratio of California's nitric acid production capacity to the national production capacity.

*Equation 47: California nitric acid production*

$$\boxed{P_{CA} = P_{US} \bullet \left(\frac{C_{CA}}{C_{US}}\right)}$$

Where,
$P_{CA}$ = California nitric acid production (g)
$P_{US}$ = US nitric acid production (g)
$C_{CA}$ = California nitric acid production capacity (tonnes)
$C_{US}$ = US nitric acid production capacity (tonnes)

Then, the emissions of N2O are estimated in a manner consistent with the Tier 1 method of the 2006 IPCC guidelines.

*Equation 48: $N_2O$ emissions from nitric acid production*

$$\boxed{E = P_{CA} \bullet EF}$$

Where,
E = $N_2O$ emissions from nitric acid production (g)
$P_{CA}$ = California nitric acid production (g)
EF = $N_2O$ emission factor (g / g)

### 3. Data sources

Data for US nitric acid production and US nitric acid production capacity are from the USEPA national GHG inventory (Desai, 2011). $N_2O$ emission factors are from the USEPA Emission Inventory Improvement Program guidance (USEPA, 2004a). Data for California nitric acid production capacity are from the annual reference produced by SRI Consulting entitled “Directory of Chemical Producers – United States” (SRI, 2007;SRI, 2008). The Directory of Chemical Producers is a comprehensive annual survey of the international chemical industry covering 90 countries in nine separate regions.

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at: http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_2d_nitric_acid_production.pdf

### 4. Changes in Estimates

Staff learned that all nitric acid plants in California are using non-selective catalytic reduction (NSCR) air pollution abatement devices since the 1980s (Toledo, 2011). The $N_2O$ emission factor for nitric acid plants with NSCR is 2 kg $N_2O$/tonne $HNO_3$ while plants with only selective catalytic reduction (SCR) release 9.5 kg $N_2O$/tonne $HNO_3$ produced (USEPA, 2004a). In the 1990-2004 edition of the Inventory staff had used a weighted average $N_2O$ emission factor of 8 kg $N_2O$/tonne $HNO_3$ from the USEPA Emission Inventory Improvement Program guidance (USEPA, 2004b) which is based on a national survey of abatement devices on nitric acid manufacturing facilities that found that 80 percent of US plants had SCR technology while 20 percent had NSCR installations. Adjustment of the $N_2O$ emission factor and other revisions in data by data providers resulted in a large reduction in emissions: -73.4 percent on average over the years 2000 to 2004 when compared with the estimates in the first edition of ARB’s GHG inventory.

### 5. Future Improvements

ARB staff will try to obtain California production data to determine $N_2O$ emissions from California nitric acid manufacturing rather than using California and national plant capacities to estimate the share of national production that occurs in California.

## E. Semiconductor Manufacturing (IPCC 2E)

### 1. Background

Manufacturers of semiconductors use fluorinated greenhouse gases in plasma etching and plasma enhanced chemical vapor deposition processes. Plasma etching of dielectric films creates the pattern of pathways connecting individual circuit components in semiconductors. Vapor deposition chambers are used for depositing the dielectric films, and are cleaned periodically using fluorinated gases. Fluorinated gases are converted to fluorine atoms in plasma, which etches away dielectric material or cleans the chamber walls and hardware. Un-dissociated fluorinated gases and other products end up in the waste streams and, unless captured by abatement systems, into the atmosphere. Some fluorinated compounds can also be transformed in the plasma processes into other compounds (e.g., $CF_4$ generated from $C_2F_6$). If they are not captured by emission control systems, then the process-generated gases will also be released into the atmosphere.

## 2. Methodology

The USEPA has developed estimates of the national GHG emissions from semiconductor manufacture based in part upon information reported by participants in its PFC Reduction/Climate Partnership for the Semiconductor Industry. ARB staff estimated California's emissions by apportioning USEPA's estimates of U.S. semiconductor manufacture emissions using the ratio of California to U.S. semiconductor shipments. This approach is consistent with USEPA's Emission Inventory Improvement Program guidance of 2004 (USEPA, 2004a). ARB staff assumed that emissions of individual fluorinated gas from semiconductor manufacturing facilities in California were proportional to emissions of these gases at the national level. The fluorinated gases included in the USEPA GHG inventory are: $CF_4$, $C_2F_6$, $C_3F_8$, $C_4F_8$, HFC-23 ($CHF_3$), $SF_6$, and $NF_3$.

*Equation 49: Emissions from semiconductor manufacturing*

$$\boxed{E_{CA,GHG} = E_{US,GHG} \bullet \left(\frac{SS_{CA}}{SS_{US}}\right)}$$

Where,

$E_{CA,GHG}$ = Emissions of a particular fluorinated gas from semiconductor manufacturing in California (g)

$E_{US,GHG}$ = Emissions of the particular fluorinated gas from semiconductor manufacturing in the entire US (g)

$SS_{CA}$ = Value of California semiconductor shipments (thousand dollars)

$SS_{US}$ = Value of US semiconductor shipments (thousand dollars)

GHG = [$CF_4$, $C_2F_6$, $C_3F_8$, $C_4F_8$, HFC-23 ($CHF_3$), $SF_6$, $NF_3$]

## 3. Data Sources

Estimates of emissions for years 2000 through 2009 from semiconductor manufacturing for the United States are from the US Environmental Protection Agency (USEPA, 2011h). Semiconductor shipment data for the United States and California are from the US Census Bureau economic data surveys (USCB, various years b). National and state level economic data compiled by the US Census Bureau is updated periodically. The most recent national update was completed in 2009, and the most recent state level economic information for this sector was published in 2007 and therefore 2007 data were used for this inventory.

For a list of parameter values used in the equations, please consult the online documentation annex at: http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_2e_semiconductor_manufacturing.pdf

### 4. Changes in Estimates

In this edition of the inventory for the semiconductor manufacturing sector, emissions are now speciated by gas (including $NF_3$) instead of a single emission value for all halogenated compounds, expressed in $CO_2$ equivalent. Nitrogen trifluoride ($NF_3$) was introduced as a new GHG compound by the IPCC 4th Assessment report with a Global Warming Potential (GWP) value of 17,200. In 2009, California Senate Bill 104 amended the California Health & Safety code (Section 38505) to include $NF_3$ as a defined GHG. The USEPA presents $NF_3$ emissions from semiconductor manufacturing in their annual national inventory; however, they do not include it in the aggregated total of halogenated compounds for this sector since $NF_3$ is not a specified Kyoto gas and is therefore not reported under UNFCCC guidelines. It is anticipated that $NF_3$ will be added to future UNFCCC standards.

Despite the addition of emissions from a new GHG, revisions made by the USEPA to its semiconductor emission rates resulted in a decrease in emissions: -16.6 percent on average over the years 2000 to 2004 when compared with the estimates published in the 1990-2004 edition of ARB's GHG inventory.

### 5. Future Improvements

Staff will seek data from industry associations to obtain facility-specific semiconductor manufacturing and emission data to implement a bottom-up inventory.

## F. Use of ODS Substitutes (IPCC 2F)

### 1. Background

Ozone-depleting substances (ODS) are being phased out under the terms of the Montreal Protocol, and the Clean Air Act Amendments of 1990. Many of the substances approved to replace them, including hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs), are greenhouse gases. Historically, ozone-depleting substances (chlorofluorocarbons (CFCs), halons, carbon tetrachloride, hydrochlorofluorocarbons (HCFCs), and methyl chloroform) have been used in applications such as refrigeration and air conditioning equipment, solvent cleaning, foam production, sterilization, fire extinguishing, and aerosols. HFCs and PFCs are now replacing them in most of these applications and, as a result of that switch, emissions of ODS substitutes have been steadily increasing since 1990.

## 2. Methodology

Emissions of ODS substitutes occur when they are released into the atmosphere (e.g., from fire extinguishers or aerosol cans) or when they leak out of equipment such as refrigerators and air conditioning units. Estimating these emissions is difficult because the sources are diffuse and the emissions occur over the lifetime of equipment. The USEPA has implemented a detailed "vintaging" model of ODS-containing equipment and products that can be used to estimate the actual (versus potential) emissions of various ODS substitutes, including HFCs and PFCs (USEPA, 2011a). The model tracks the use and emissions of various compounds for the annual "vintages" of new equipment that enter service in each end-use, and estimates emissions by applying annual leak rates and release profiles over time.

ARB staff estimated California's share of ODS substitute emissions by apportioning national emissions numbers on the basis of population. This approach is consistent with USEPA's Emission Inventory Improvement Program guidance of 2004 (USEPA, 2004a).

*Equation 50: Emissions of ODS substitutes*

$$\boxed{E_{CA,GHG} = E_{US,GHG} \bullet Rpop}$$

Where,

| | |
|---|---|
| $E_{CA,\ GHG}$ | = Estimate of the given GHG (ODS substitute) emissions in California (g) |
| $E_{US,\ GHG}$ | = Estimate of the given GHG (ODS substitute) emissions in the entire US (g) |
| Rpop | = Ratio of the population of California to the population of the entire US (dimensionless) |

With,

GHG = [$CF_4$, HFC-125, HFC-134a, HFC-143a, HFC-23, HFC-236fa, HFC-32, other ODS substitutes]

Note: other ODS substitutes include HFC-152a, HFC-227ea, HFC-245fa, HFC-4310mee, $C_4F_{10}$ and PFC/PFPEs (various PFCs and perfluoropolyethers (PFPEs) employed for solvent applications). The GWP value used for PFC/PFPEs was based upon that of $C_6F_{14}$.

## 3. Data Sources

Estimates of emissions of ODS substitutes for the United States were provided by the US Environmental Protection Agency (Godwin, 2009 and USEPA, 2011e). Population estimates for the United States and California were from the US Census Bureau (USCB, various years a) and from the California Department of Finance (CDOF, 2011).

For a list of parameter values used in the equations, please consult the online documentation annex at: http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_2f_use_of_ods_substitutes.pdf

### 4. Changes in Estimates

Since the publication of the 1990-2004 edition of California's GHG inventory, USEPA modified its Vintaging Model to incorporate changes in the assumptions used for a variety of refrigeration and air conditioning end uses (such as chillers). These revised assumptions are based on input from industry and updated research. Other revisions included changes to mobile vehicle air conditioning end uses in order to disaggregate vehicles from light-duty trucks. These Vintaging Model updates resulted in a decrease of California's current estimates of emissions of ODS substitute compounds: -15.2 percent on average over the years 2000 to 2004 when compared with the estimates in the 1990-2004 edition of ARB's GHG inventory.

### 5. Future Improvements

ARB Staff will track further updates of USEPA Vintaging Model information and will use California surveys to partition the emission estimates by end-use or type of product.

## G. Sulfur Hexafluoride from Use of Electrical Equipment (IPCC 2G1b)

### 1. Background

Sulfur hexafluoride gas ($SF_6$) is used by the electric power industry in gas-insulated substations, circuit breakers, and other switchgear because of its dielectric strength and arc-quenching characteristics. Fugitive emissions of $SF_6$ are the result of leaks through seals of gas-insulated substations and switch gear. $SF_6$ can also be released during equipment installation and servicing.

### 2. Methodology

The USEPA has developed estimates of the national $SF_6$ emissions from use of electrical equipment based in part upon information reported by participants in its $SF_6$ Emission Reduction Partnership for Electric Power Systems (USEPA, 2008c). ARB staff estimated $SF_6$ emissions in California by apportioning U.S. emissions using the ratio of the sum of the power generated and imported in California to the national power generation. This approach is consistent with USEPA's – EIIP guidance of 2004 (USEPA, 2004a).

*Equation 51: $SF_6$ emissions from use of electrical equipment*

$$\boxed{E_{CA} = E_{US} \bullet \frac{(G_{CA} + G_{IMP})}{G_{US}}}$$

Where,

$E_{CA}$ = California $SF_6$ emissions (grams)
$E_{US}$ = National $SF_6$ emissions (grams)
$G_{CA}$ = California in-state electricity generation (watt-hours)
$G_{IMP}$ = Electricity generation imported into California (watt-hours)

$G_{US}$ = National electricity generation (watt-hours)

*Table 32: $SF_6$ emissions ($TgCO_2e$)*

| Year | National $SF_6$ (Tg $CO_2$e) | National generation (GWh) | CA In-State Generation (GWh) | CA Imported Generation (GWh) | CA SF6 emissions - In-State (Tg CO2e) | CA SF6 emissions - Imports (Tg CO2e) |
|---|---|---|---|---|---|---|
| **2000** | 16.0 | 3,802,100 | 215,428 | 79,841 | 0.909 | 0.337 |
| **2001** | 16.3 | 3,736,600 | 198,596 | 86,255 | 0.867 | 0.376 |
| **2002** | 15.6 | 3,858,500 | 184,210 | 101,760 | 0.744 | 0.411 |
| **2003** | 15.1 | 3,883,200 | 192,789 | 98,839 | 0.751 | 0.385 |
| **2004** | 15.1 | 3,970,600 | 194,780 | 103,906 | 0.738 | 0.394 |
| **2005** | 15.1 | 4,055,400 | 200,293 | 100,286 | 0.748 | 0.374 |
| **2006** | 14.1 | 4,064,700 | 216,799 | 91,644 | 0.751 | 0.317 |
| **2007** | 13.2 | 4,156,700 | 210,848 | 105,732 | 0.671 | 0.337 |
| **2008** | 13.3 | 4,119,400 | 207,984 | 111,498 | 0.674 | 0.361 |
| **2009** | 12.8 | 3,953,100 | 208,104 | 108,554 | 0.675 | 0.352 |

## 3. Data sources

Estimates of the national $SF_6$ emissions are from the USEPA greenhouse gas inventory (USEPA, 2011a), national and California electricity generation data are from the Energy Information administration. California in-state electricity generation is from data discussed in section I.A. California electricity generation imports are from data discussed in section I.B.

## 4. Changes in Estimates

No changes were made to the methodology used to estimate emissions from these categories. However updates in the sources of the data have resulted in an increase of California's current estimates of emissions from this category: +9.8 percent on average over the years 2000 to 2004 when compared with the estimates in the 1990-2004 edition of ARB's GHG inventory.

## 5. Future Improvements

$SF_6$ emissions estimates could be improved by using California specific data from ARB's Mandatory GHG Reporting Program. Staff will continue to evaluate the use of reported data for inventory purposes.

## H. Carbon Dioxide Consumption (IPCC 2G4a)

### 1. Background

Carbon dioxide ($CO_2$) is used in chemical production, food processing, carbonated beverages, refrigeration, and for enhanced oil recovery (EOR) in petroleum production. Except in the case of EOR (where $CO_2$ is injected in underground reservoirs), the $CO_2$ used in these applications is eventually released in the atmosphere.

The $CO_2$ used for these applications is either produced as a by-product from energy production (fossil fuel combustion) and industrial processes (e.g., ethanol production), as a by-product from the extraction of crude oil and natural gas, or from naturally occurring $CO_2$ reservoirs. However, $CO_2$ originating from biogenic sources (e.g., ethanol production plants) is not included in the inventory, so it is not considered here. $CO_2$ captured from crude oil and gas production is used in EOR applications and should be reported in the energy section. $CO_2$ from fuel combustion or other industrial process is already accounted for in the appropriate fossil fuel combustion or industry section of the inventory where it is assumed to have been emitted to the atmosphere. This leaves only the $CO_2$ extracted from naturally occurring $CO_2$ reservoirs to be accounted for in this section.

### 2. Methodology

ARB staff did not find any source of data to assess California's $CO_2$ consumption. USEPA publishes $CO_2$ consumption emission estimates for the entire US. California emissions were estimated by scaling the national emissions from $CO_2$ consumption by the ratio of California population to the US population.

*Equation 52: Emissions from $CO_2$ consumption*

$$\boxed{E_{CA} = E_{US} \bullet Rpop}$$

Where,

$E_{CA}$ = California emissions from $CO_2$ consumption (g)

$E_{US}$ = US emissions from $CO_2$ consumption (g)

Rpop = Ratio of the population of California to the population of the entire US (dimensionless)

### 3. Data sources

Data for US emissions from $CO_2$ consumption are from the USEPA national GHG inventory (USEPA, 2011g). Data for California and US population estimates were from the California Department of Finance (CDOF, 2011) and from the US Census Bureau (USCB, various years a).

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at:

http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_2h_carbon_dioxide_consumption.pdf

### 4. Changes in Estimates

Staff changed the ratio used to estimate California emissions by scaling down national emissions. In the 1990-2004 edition of the inventory, the ratio of California's $CO_2$ production capacity to US $CO_2$ production capacity was used instead of the ratio of population. Staff decided to change from production to population because $CO_2$ is widely used throughout society —in chemical production, food processing, carbonated beverages, refrigeration— and emissions occur wherever it is released to the atmosphere. Moreover, since only the $CO_2$ extracted from naturally occurring $CO_2$ reservoirs is to be accounted for in this section (see Background section above) using the ratio of state to national production has very little relevance.

These changes and the data revisions made by USEPA resulted in a significant increase in emissions estimates for this category: + 42.25 percent on average over the years 2000 to 2004 when compared with the estimates in the 1990-2004 edition of ARB's GHG inventory.

### 5. Future Improvements

ARB staff will seek to obtain more specific data about California $CO_2$ consumption for future inventories.

## I. Limestone and Dolomite Consumption (IPCC 2G4b)

### 1. Background

Limestone ($CaCO_3$) and dolomite ($CaCO_3MgCO_3$) are used by a wide variety of industries such as construction, agriculture, chemical and glass manufacture, metallurgy, and environmental pollution control. In some of these applications, limestone (or dolomite) is heated to a high temperature during the process and generates $CO_2$ as a by-product.

This section accounts for uses of limestone and dolomite resulting in $CO_2$ emissions in the following applications: flux stone (metallurgical furnaces), glass manufacturing, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining.

### 2. Methodology

The USEPA has developed estimates of the national GHG emissions from limestone and dolomite consumption based upon information from the US Geological Survey (USGS, various years a). ARB staff estimated emissions from limestone and dolomite consumption in California by apportioning U.S. emissions using the ratio of California to U.S. consumption of limestone and dolomite. This approach is consistent with USEPA's – Emission Inventory Improvement Program guidance of 2004 (USEPA, 2004a).

*Equation 53: $CO_2$ emissions from limestone and dolomite consumption*

$$E_{CA} = E_{US} \bullet \left( \frac{C_{CA}}{C_{US}} \right)$$

Where,

$E_{CA}$ = California emissions from limestone and dolomite consumption (g)
$E_{US}$ = US emissions from limestone and dolomite consumption (g)
$C_{CA}$ = California limestone and dolomite consumption (tonnes)
$C_{US}$ = US limestone and dolomite consumption (tonnes)

### 3. Data sources

Data for US emissions from limestone and dolomite consumption are from the USEPA national GHG inventory (USEPA, 2011f). Data for California's consumption of limestone and dolomite is from the US Geological Survey (USGS, various years a), and national consumption data came from the US Geological Survey (USGS, various years b).

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at: [http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_2i_limestone_and_dolomite_consumption.pdf](http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_2i_limestone_and_dolomite_consumption.pdf)

### 4. Changes in Estimates

The US Geological Survey revised some of their estimates of limestone and dolomite consumption. In addition, USEPA revised their estimates of national CO2 emissions from limestone and dolomite consumption for the entire time series based on changes for the subcategory of "unspecified uses" identified by US Geological Survey. These changes resulted in somewhat lower emissions for this sector: -12.4 percent on average over the years 2000 to 2004 when compared with the estimates in the 1990-2004 edition of ARB's GHG inventory.

## J. Soda Ash Consumption (IPCC 2G4c)

### 1. Background

Sodium carbonate ($Na_2CO_3$), also called soda ash, is a strongly alkaline chemical used in a variety of industrial processes. The most important use of soda ash is in glass production, but it also enters in the fabrication of many common products such as soap and detergents, paper, textiles and processed food. As soda ash is consumed for these purposes, $CO_2$ is usually emitted. It is assumed that one mole of C is released for every mole of soda ash used.

Note that some soda ash manufacturing processes also generate $CO_2$ emissions. However, according to the USEPA, in California soda ash is manufactured using sodium carbonate-bearing brines instead of trona ore. These complex brines are first treated with $CO_2$ in carbonation towers to convert the sodium carbonate into sodium bicarbonate, which then precipitates from the brine solution. The precipitated sodium bicarbonate is then calcined back into sodium carbonate. Although $CO_2$ is generated as a by-product, the $CO_2$ is recovered and recycled for use in the carbonation stage and is not emitted (USEPA, 2009). For this reason, there is no “Soda ash production” section (IPCC category 2B7) in the California GHG inventory.

## 2. Methodology

ARB staff did not have access to soda ash consumption numbers for California and used the estimation method recommended by the USEPA Emission Inventory Improvement Program guidance (USEPA, 2004a). This approach first estimates California’s consumption by scaling the national consumption by the ratio of California population to that of the entire United States.

*Equation 54: California soda ash consumption*

$$\boxed{C_{CA} = C_{US} \bullet Rpop}$$

Where,

$C_{CA}$ = California soda ash consumption (g)
$C_{US}$ = US soda ash consumption (g)
Rpop = Ratio of the population of California to the population of the entire US (unitless)

Then, the emissions of $CO_2$ are estimated using the emission factor from IPCC 2006 Guidelines (IPCC, 2006c).

*Equation 55: $CO_2$ emissions from soda ash consumption*

$$\boxed{E = C_{CA} \bullet EF}$$

Where,

E = $CO_2$ emissions from soda ash consumption (g)
$C_{CA}$ = California soda ash consumption (g)
EF = $CO_2$ emission factor (g / g)

## 3. Data sources

Data for the US soda ash consumption are from the US Geological Survey (USGS, various years c), and population estimates for the United States and California come from the US Census Bureau (USCB, various years a) and from the California Department of Finance (CDOF, 2011). The emission factor for soda ash consumption is from the 2006 IPCC Guidelines (IPCC, 2006c).

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at:
http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_2j_soda_ash_consumption.pdf

### 4. Changes in Estimates

There were no changes for this category.

## K. Fuel Consumption as Feedstock for Hydrogen Production (IPCC 2H3)

### 1. Background

In California, hydrogen ($H_2$) production by and for refineries generates substantial amounts of $CO_2$ because the most common processes use carbon-based feedstock inputs (e.g., methane from natural gas) as a source of hydrogen and emit the carbon as $CO_2$. Hydrogen production is not a direct part of the petroleum refining process but it provides the hydrogen gas needed to upgrade heavier fractions into lighter, more valuable products.

### 2. Methodology

### 2.1 $CO_2$ emissions

(a) Years 2000 to 2008

Yearly hydrogen production data from the Oil and Gas Journal's "Historical Worldwide Refinery Survey" database were provided to staff by the Western States Petroleum Association (Shires, 2009). This database indicates that two basic types of $H_2$ production processes are used by California refineries: steam-methane reforming and partial-oxidation. Staff assumed that steam-methane reforming used either natural gas or refinery gas as the methane feedstock source and that partial-oxidation used various hydrocarbons as feedstocks. In the Oil and Gas Journal’s database hydrogen gas production rates were reported in million cubic feet per day (MMCFd), and staff converted these production rates into million cubic feet per year (MMCF) by multiplying the original value by 365 days per year. Staff assumed that these were standard cubic feet measured at 60° F and 1 atmosphere of pressure. In the absence of yearly data on the respective amounts of refinery gas and natural gas used as feedstock, staff assumed that the proportions reported to ARB’s Mandatory Reporting Program in 2009 (42.1 percent refinery gas and 57.9 percent natural gas) applied to previous years.

To estimate the $CO_2$ emissions from the amount of $H_2$ produced, staff made stoichiometric assumptions for each process type as described below.

The methane reforming process was assumed to generate 1 mole of $CO_2$ for every 4 moles of $H_2$ produced:

*Equation 56: Methane reforming process stoichiometric assumption*

$$\boxed{CH_4 + 2H_2O \rightarrow CO_2 + 4H_2}$$

The partial oxidation method was assumed to generate 1 mole of $CO_2$ for every 3 moles of $H_2$ produced. This molar ratio is based on the assumption that each carbon in the longer chain carbon molecules was bonded to 2 hydrogen atoms on average, since the other 2 carbon bonds (normally bonded to another 2 hydrogen atoms in methane for a total of 4 hydrogen atoms for each methane carbon) would be most often attached to another carbon atom in the chain.

*Equation 57: Partial oxidation stoichiometric assumption*

$$\boxed{CH_2 + 2H_2O \rightarrow CO_2 + 3H_2}$$

Based on these assumptions, $CO_2$ emissions can be derived from the volume of hydrogen produced in a given year:

*Equation 58: $CO_2$ emissions from hydrogen production*

$$\boxed{E_{process} = V_{process} \bullet 1{,}195{,}250 \bullet R_{process} \bullet 44}$$

Where,

$E_{process}$ = Emissions of $CO_2$ from hydrogen production with a given process (grams)

$V_{process}$ = Volume of hydrogen produced with a given process (million cubic feet)

1,195,250 = Moles of $H_2$ per million cubic feet (at 60° F and 1 atmosphere of pressure)

$R_{process}$ = stoichiometric molar ratio of $CO_2$ to $H_2$ for the given process = 1/4 for steam-methane and 1/3 for partial oxidation

44 = molecular weight of $CO_2$ (grams per mole)

With,

Process = [steam-methane, partial oxidation]

(b) <u>Year 2009</u>

Staff used facility level production and emissions data from ARB's Mandatory Reporting Program (ARB, 2011b).

### *2.2 Fuel consumed as feedstock*

(a) <u>Years 2000 to 2008</u>

Staff estimated the amount of fuel consumed as feedstock by the hydrogen production processes using their heat content and combustion emission factor. Input fuels were assumed to be natural gas and refinery gas for methane-steam reforming, and various petroleum feedstocks for partial oxidation.

*Equation 59: Amount of fuel consumed as feedstock for hydrogen production*

$$Q_{fuel} = \frac{E_{process}}{(HC_{fuel} \bullet EF_{fuel})}$$

Where,

$Q_{fuel}$ = amount of the corresponding fuel consumed by a given hydrogen production process (in units of gallons for liquid fuels or standard cubic feet for gaseous fuels)
$E_{process}$ = Emissions of $CO_2$ from hydrogen production with a given process (grams)
$HC_{fuel}$ = Heat content of the fuel (BTU per unit)
$EF_{fuel}$ = $CO_2$ emission factor of the fuel (grams per BTU)

With,

Process = [steam-methane, partial oxidation]
Fuel = [natural gas, refinery gas, petroleum feedstock]

(b) Year 2009

Staff used facility level production and emissions data from ARB's Mandatory Reporting Program (ARB, 2011b).

## 3. Data Sources

For years 2000 to 2008, data on hydrogen production from the Oil and Gas Journal's "Historical Worldwide Refinery Survey" database were provided to staff by the Western States Petroleum Association (Shires, 2009). Estimates of the respective amounts of refinery gas and natural gas used in the steam-methane reforming process were made using data from the Mandatory Reporting Program (ARB, 2011b).

Years 2000 to 2008 heat content data came from the U.S. Energy Information Administration (Schnapp, 2008; EIA, 2011a). $CO_2$ Emissions factors are from USEPA 1990-2005 greenhouse gas inventory (USEPA, 2007b).

All data for 2009 came directly from ARB's Mandatory Reporting Program.

## 4. Changes in Estimates

In the 1990-2004 edition of ARB's GHG Inventory staff assumed that a 50 percent-50 percent mix of natural gas and refinery gas was used for methane-steam reforming. In this edition staff used other data to estimate the proportion of natural gas and refinery gas for each year (Mandatory Reporting). The overall methodology used to calculate emissions estimates remained the same, with the exception of the direct use of Mandatory Reporting data for 2009.

These changes and the data revisions made by data providers resulted in limited changes in emissions estimates for the categories included in this section: + 4.6 percent on average over the years 2000 to 2004 when compared with the estimates in the 1990-2004 edition of ARB's GHG inventory.

### 5. Future Improvements

ARB's GHG Mandatory Reporting data for hydrogen plants will continue to be included in future editions of the GHG inventory.

# III. Agriculture Forestry and Other Land Use

## *A. Enteric Fermentation (IPCC 3A1)*

### 1. Background

The microbial fermentation that occurs in the digestive system of some animals is called enteric fermentation. It is a normal digestive process during which microbes break down indigestible carbohydrates (e.g., cellulose, hemi-cellulose) and reprocess them into nutrients that can be absorbed by the animal. This microbial fermentation process produces $CH_4$ as a by-product, which is then exhaled, eructated or passed out as gas by the animal. The amount of $CH_4$ produced and emitted by an animal depends on its anatomy and the amount and type of feed it consumes.

Among domesticated animal species, ruminants (e.g., cattle, buffalo, sheep, and goats) are the main emitters of $CH_4$. Ruminants have a large "fore-stomach" with four chambers in which microbial fermentation breaks down the feed they consume into products that can be absorbed and metabolized in the stomach and intestines. This fermentation-based digestive system enables ruminants to live on a diet of coarse plant material. Some non-ruminant domesticated animals (e.g., swine, horses, and mules) also rely on microbial fermentation as part of their digestive system although this microbial fermentation occurs in the caecum and the large intestine. Individuals of these species also emit $CH_4$ but less than ruminants of similar sizes because the capacity of their fermentation chambers is lower.

Aside from the type of digestive system, the quantity and quality of feed ingested by the animal also affects $CH_4$ emissions. The amount of food an animal consumes is a function of its size, its growth rate and production (e.g., milk production, wool growth, pregnancy, or work in the case of draft animals), and as the amount ingested increases so does the $CH_4$ production. As for the quality of the feed, coarser, more fibrous feed (i.e., straw, hay) generally also leads to higher $CH_4$ emissions than more concentrated feed such as grains.

### 2. Methodology

The USEPA has developed methods based on the 2006 IPCC guidelines to estimate the greenhouse gas emissions from enteric fermentation for the national GHG inventory (USEPA, 2011a). For California's GHG inventory, ARB staff extracted California specific information from a detailed set of inventory data and model results obtained from the USEPA's Climate Change Division (Wirth, 2011).

USEPA used two different methodologies to estimate enteric fermentation emissions: one for cattle and another for other livestock. For complete detail on these methodologies, see Annex 3.9 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2009 (USEPA, 2011d).

### *2.1 Methane emissions from cattle*

Because of their large population, large size, and the fact that they are ruminants, cattle are responsible for the majority of $CH_4$ emissions from enteric fermentation in the United States. Therefore, USEPA developed a more detailed methodology for cattle, the Cattle Enteric Fermentation Model (CEFM), which tracks cattle sub-populations at different growth and production stages. The methane production is then derived from the gross energy contained in each sub-population's feed intake and the methane conversion rate associated with its diet composition.

The CEFM is an implementation of the Tier 2 methodology of the IPCC guidelines, with the added refinement that cattle sub-populations are modeled on a monthly basis instead of a yearly basis. Calves and bulls are not modeled in the CEFM. The IPCC recommends assuming zero methane emissions from calves, because they consume mainly milk. Emissions from bulls are estimated using a Tier 1 approach based on published population statistics and national average emission factors because the variation in their diets and within-year population changes are minimal.

The steps involved in the CEFM are as follows:

#### (a) Characterization of cattle populations

The amount of methane emitted by cattle at different stages of their lifecycle varies greatly because of changes in size, growth rate or lactation. Also, while the emissions are reported on a yearly basis, some of these stages may last less than a year (e.g., calves become stockers; stockers enter a feedlot, etc.). USEPA uses a population transition matrix to simulate each stage of the cattle lifecycle on a per month basis to estimate the number of individuals in each cattle sub-population from birth to slaughter. The model disaggregates dairy and beef cattle populations into the categories of Table 33, based upon cattle population data from the U.S. Department of Agriculture statistics (USDA, 2011a), calving rates, average weights and weight gains, feedlot placement statistics, pregnancy and lactation, and death rates.

*Table 33: Cattle population categories based on life-cycle*

| ***Dairy cattle*** | ***Beef cattle*** |
|---:|---:|
| Dairy cows | Beef cows |
| Bulls* | Bulls* |
| Dairy replacements (0-12 months) | Beef replacements (7-11 months) |

| ***Dairy cattle*** | ***Beef cattle*** |
|---|---|
| Dairy replacements (12-23 months) | Beef replacements (12-23 months)<br>Heifer stockers<br>Steer stockers<br>Feedlot heifers<br>Feedlot steers |

*Bulls for dairy and beef cattle are combined in a single category

The cattle population numbers from this monthly lifecycle modeling may differ from the annual livestock population data published by the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS). The reason being that USDA NASS population numbers are point estimates for a specific date (e.g., January 1 or July 1), whereas the Population transition matrix outputs represent an annual average based on the estimated monthly fluctuations.

### (b) Characterization of cattle diets

To determine the digestible energy (DE, the percent of gross energy intake digested by the animal) and $CH_4$ conversion rates ($Y_m$, the fraction of gross energy converted to $CH_4$) for each of the cattle categories, the USEPA collected data on diets considered representative of different regions (California was one of these regions). Data from state livestock specialists for each of the diets were used to estimate feed chemical composition, DE and $Y_m$ for each animal type.

DE values for dairy cows were estimated from results of a literature search. Ym values for dairy cows were estimated using mechanistic models of the digestive processes occurring in cattle: AAMOLLY (Donovan and Baldwin, 1999) and COWPOLL described in Kebreab et al. (2008). For grazing beef cattle, USEPA used diet descriptions to calculate weighted DE values for a combination of forage and supplemental diets. Ym values for all grazing beef cattle were set at 6.5 percent. For feedlot animals, DE and Ym values for 1990 were taken from the literature. DE and Ym values for 2000 onwards were estimated using the MOLLY model as described in Kebreab et al (2008). Values for 1991 through 1999 were linearly extrapolated based on values for 1990 and 2000.

### (c) Calculation of gross energy intake

Gross Energy is derived based on several net energy (NE) estimates and feed characteristics. Net energy equations are provided in the IPCC Guidelines (IPCC, 2006d). The general form of these equations is:

*Equation 60: Gross energy intake*

$$GE = \frac{\left(\dfrac{NE_m + NE_{mobilized} + NE_a + NE_l + NE_p}{\dfrac{NE_{ma}}{DE}}\right) + \left(\dfrac{NE_g}{\dfrac{NE_{ga}}{DE}}\right)}{\dfrac{DE\%}{100}}$$

Where,

$GE$ = Gross energy (MJ/day)

$NE_m$ = Net energy required by the animal for maintenance (MJ/day)

$NE_{mobilized}$ = Net energy due to weight loss –mobilization of fat reserves– (MJ/day)

$NE_a$ = Net energy for animal activity (MJ/day)

$NE_l$ = Net energy for lactation (MJ/day)

$NE_p$ = Net energy required for pregnancy (MJ/day)

$NE_{ma}$ = Net energy available in a diet for maintenance (MJ/Day)

$DE$ = Digestible energy consumed (MJ/day)

$NE_g$ = Net energy needed for growth (MJ/day)

$NE_{ga}$ = Net energy available for growth in a diet (MJ/Day)

$DE\%$ = Digestibility of the diet (digestible energy content in percent)

## (d) Calculation of daily emissions

The daily emission factors for each category are computed from the gross energy value and the methane conversion factor, as follows:

*Equation 61: Daily $CH_4$ emission factor for a cattle population category*

$$EF = \frac{GE \bullet Y_m}{55.65}$$

Where,

$EF$ = Emission factor (kg $CH_4$ per head per day)

$GE$ = Gross energy intake (MJ per head per day)

$Y_m$ = $CH_4$ conversion rate, which is the fraction of gross energy in feed converted to $CH_4$ (unitless)

55.65 = the energy content of methane (MJ per kg)

## (e) Estimation of yearly emissions

Emissions are then summed for each month for each population category using the daily emission factor for a representative animal and the number of animals in the category, as shown in the following equation:

*Equation 62: Yearly $CH_4$ emissions of a cattle population category*

$$E = \sum_{month} EF \bullet D_{month} \bullet N_{month}$$

Where,

E = Yearly $CH_4$ emissions of a cattle population category (kg)
EF = Emission factor for the population category (kg $CH_4$ per head per day)
$D_{month}$ = number of days in the month
$N_{month}$ = number of animals in the population category during the month

With,
Month = each month of the given year.

This yields the estimated yearly methane emissions for the cattle population category for the given year.

### 2.2 Methane emissions from other livestock

Following USEPA, ARB staff used the simpler Tier 1 IPCC method to estimate enteric fermentation emissions from bulls and other livestock.

*Equation 63: $CH_4$ emissions of bulls and other livestock*

$$\boxed{E = N \bullet EF}$$

Where,
E = $CH_4$ emissions of a type of other livestock
N = Number of individuals of the type of livestock (animals)
EF = Methane emission factor for the type of livestock (kg per animal per year)

Other livestock population data, except for horses, come from the USDA NASS (USDA, 2011a) or California Department of Food and Agriculture (CDFA 2011). California horse population numbers are derived from the United Nations' Food and Agriculture Organization (FAO) FAOSTAT database (FAO, 2011) and from an American Horse Council Report (AHC, 2005). California's horse population is estimated as follows:

*Equation 64: Estimation of California's horse population*

$$\boxed{H_{CA,year} = H_{US,year} \bullet R}$$

Where,
$H_{CA,\ year}$ = California's horse population for a given year (head)
$H_{US,\ year}$ = National horse population for a given year (head) from FAOSTAT
R = Ratio of California horse population to US horse population from AHC

Default methane emission factors for bulls and other livestock, shown in Table 34 below, are from IPCC Guidelines (IPCC, 2006d).

*Table 34: Methane emission factors for bulls and other livestock (kg/animal/year)*

| ***Livestock Type*** | ***Emission Factor*** |
|---:|---:|
| Bulls | 53 |
| Horses | 18 |
| Sheep | 8 |
| Goats | 5 |
| Swine | 1.5 |

## 3. Data Sources

All data used by ARB staff were from a detailed set of data and model results obtained from the USEPA Climate Change Division (Wirth, 2011), from the California Department of Food and Agriculture annual directories (CDFA 2011), the U.S. Department of Agriculture (USDA, 2011a), the United Nations Food and Agriculture Organization (FAO, 2011), the American Horse Council (AHC, 2005) and from the IPCC guidelines (IPCC, 2006d).

For a list of livestock population numbers and parameter values used in the estimates, please consult the online documentation annex at: http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_3a_enteric_fermentation.pdf

## 4. Changes in Estimates

The major changes in data and methods used in the current estimation of enteric fermentation emissions when compared with those used for the 1990-2004 edition of GHG Inventory are:

- Adjustments to heifer and steer stocker populations and placements in feedlots.
- Adjustments to the weights of calves at weaning, mature weight of beef cows, mature weight for dairy cows was adjusted to 1,550 for all years, and beef and dairy replacement weight at 15 and 24 months.
- Monthly weight gain for stockers was increased starting in 2000.
- The USDA published revised population estimates that affected historical emissions estimated for swine, sheep and for certain beef and dairy populations.
- Four models to predict methane production from cattle (two mechanistic, and two empirical) were evaluated to determine appropriate Ym and DE values for use in the analysis. The results are described in Kebreab et al. (2008). In addition to the model evaluation, separate research was conducted to update the assumptions used for cattle diet components for feedlot and dairy cattle. An extensive literature review was performed on dairy diets and nearly 250 diets were analyzed to derive the current DE and Ym estimates for dairy. In addition, feedlot diets were updated based on current survey data.
- Bull populations are based solely on January estimates.
- Swine population categories were modified so that the categories "<60 pounds" and "60-119 pounds" were replaced with "<50 pounds" and "50-119" pounds.
- The method to estimate California's share of national horse population was updated.

All together these methodology changes and updates to data sources resulted in substantial adjustments in emissions estimates for the categories included in this section: +22.4 percent on average over the years 2000 to 2004 when compared with the estimates in the first edition of ARB's GHG inventory.

## *B. Manure Management (IPCC 3A2)*

### 1. Background

Anthropogenic $CH_4$ and $N_2O$ emissions can result from manure management operations. $CH_4$ is produced by the anaerobic decomposition of manure. $N_2O$ is produced as part of the nitrogen cycle through the nitrification and denitrification of nitrogen in livestock manure and urine.

When livestock or poultry manure is stored or treated in systems that promote anaerobic conditions (such as liquid/slurry, lagoons, tanks, ponds or pits), the decomposition of organic material by methanogenic bacteria produces $CH_4$ emissions. Manure stored as a solid (e.g., in stacks or drylots) or deposited on pasture, range, or paddock lands, tends to decompose aerobically and produce little or no $CH_4$. Temperature, moisture, residency time are factors that affect the amount of $CH_4$ produced by bacteria. The quality of the feed also plays a role; manure from animals eating higher energy content feed has greater potential for $CH_4$ emissions.

Manure and urine composition, the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system influence the amount of $N_2O$ emissions. Overall only a small portion of the excreted nitrogen is converted to $N_2O$ during manure management operations.

Note that $N_2O$ emissions from livestock manure and urine deposited on pasture, range, or paddock lands, and emissions from manure and urine spread onto fields either directly as “daily spread” or after it is removed from manure management systems are discussed and estimated in Section III.F.

### 2. Methodology

The USEPA developed methods to estimate the $CH_4$ and $N_2O$ emissions from manure management for the national GHG inventory (USEPA, 2011a). ARB staff extracted California specific information from a detailed set of data and parameters obtained from the USEPA Climate Change Division (Wirth, 2011) and computed emissions for California’s GHG inventory using USEPA’s methodology.

USEPA methods are consistent with the Tier 2 methodology of the IPCC Guidelines (IPCC, 2006a). For complete detail on these methodologies, see Annex 3.10 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2009 (USEPA, 2011c).

The estimation of $CH_4$ and $N_2O$ emissions involves the following steps:

#### *2.1 Characterization of livestock populations*

First, animal population data are compiled into livestock groups reflecting differences in diet, size and animal management systems (Table 35). Annual animal population data for cattle are from USEPA’s Cattle Enteric Fermentation

Model (CEFM) population transition matrix (see section III.A.2.1(a)). Other species population data are from the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) (USDA, 2011a) except for horses. Horse population data were derived from the FAOSTAT database (FAO, 2011) and an American Horse Council Report (AHC, 2005) as described in section III.A.2.2. Goat population data were obtained from the Census of Agriculture. Additional data sources and personal communications with experts used to make adjustments to these data are described in the USEPA inventory report (USEPA, 2011c).

*Table 35: Livestock groups used for manure management emissions estimates*

| **Dairy Cattle** | **Beef Cattle** | **Swine** | **Poultry** | **Others** |
|---|---|---|---|---|
| ▪ Dairy Cows<br>▪ Dairy Heifers | ▪ Beef Cows<br>▪ Bulls >500 lbs<br>▪ Calves <500 lbs<br>▪ Heifers >500 lbs<br>▪ Steers >500 lbs<br>▪ Feedlot Heifers<br>▪ Feedlot Steers | ▪ Breeding<br>▪ Market <50 lbs<br>▪ Market 50-119 lbs<br>▪ Market 120-179 lbs<br>▪ Market 180+ lbs | ▪ Layer Hens >1 yr<br>▪ Layers – Pullets<br>▪ Layers – Chickens<br>▪ Broilers<br>▪ Turkeys | ▪ Sheep<br>▪ Goats<br>▪ Horses |

### 2.2 Characterization of animal waste

Methane and nitrous oxide emissions estimates are based on the following animal characteristics for each of the relevant livestock groups:

- Typical animal mass (TAM), in kg per animal
- Volatile solids excretion rate (VS) in kg per year. Excreted volatile solids are the portion of organic matter in the diet that was not digested by the animal and is thus available for use by methanogenic bacteria. For cattle, it is calculated by the enteric fermentation model of Section III.A above. For other species values are based on measurements from the literature and are adjusted for the typical animal mass of animals in the group.
- Maximum methane producing capacity ($B_0$) of excreted volatile solids ($m^3$ of $CH_4$ per kg of VS). This is a characteristic of the volatile solids found in a particular livestock group's manure.
- Nitrogen excretion rate (Nex). This is the amount of Kjeldahl nitrogen excreted per animal per year (g of N per year). For cattle, it is calculated by the enteric fermentation model of Section III.A above. The values used for other species are based on measurements made on manure of each of the livestock groups.

For further information about how to calculate VS for cattle, swine and poultry, as well as the sources of data for the VS, TAM and $B_0$ parameters see USEPA, 2011c.

### 2.3 Compilation of waste management system usage Data

USEPA compiled data on the distribution of the manure of the various livestock groups among waste management systems, by state and by year.

Table 36 and Table 37 show the distribution of livestock manure among waste management systems in California. Note that the manure that is directly deposited on pasture, range or paddocks, or spread daily does not actually enter a "waste management system". This un-managed manure is listed here for completeness of the animal waste distribution. Estimates of nitrogen inputs from both managed and un-managed manure will be used in the Nitrous Oxide from Agricultural Soil Management Section of the inventory (see III.F below).

*Table 36: Waste distribution of cattle, goats, horses and sheep manure in California*

| ***Waste System*** | ***Beef cattle (not on feed)*** | ***Feedlot heifers and steers*** | ***Dairy Cows*** | ***Dairy Heifers*** | ***Goats*** | ***Horses*** | ***Sheep*** |
|---|---|---|---|---|---|---|---|
| Anaerobic digester | | | ✓ | | | | |
| Anaerobic lagoon | | | ✓ | | | | |
| Daily spread* | | | ✓ | ✓ | | | |
| Deep pit | | | ✓ | | | | |
| Dry lot | | ✓ | | ✓ | ✓ | ✓ | ✓ |
| Liquid / slurry | | ✓ | ✓ | ✓ | | | |
| Pasture* | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ |
| Solid Storage | | | ✓ | | | | |

* Un-managed manure: manure that is directly deposited on pasture, rangeland, or paddock, or is spread daily on agricultural land.

*Table 37: Waste distribution of swine and poultry manure in California*

| ***Waste System*** | ***Poultry - Layers*** | ***Poultry - Pullets*** | ***Poultry - Chickens*** | ***Poultry - Broilers*** | ***Poultry - Turkeys*** | ***Swine - Market*** | ***Swine - Breeding*** |
|---|---|---|---|---|---|---|---|
| Anaerobic digester | | | | | | ✓ | ✓ |
| Anaerobic lagoon | ✓ | ✓ | ✓ | | | ✓ | ✓ |
| Deep pit | | | | | | ✓ | ✓ |
| Liquid / slurry | ✓ | ✓ | ✓ | | | ✓ | ✓ |
| Pasture* | | | | ✓ | ✓ | ✓ | ✓ |
| Poultry with bedding | | | | ✓ | ✓ | | |
| Poultry without bedding | ✓ | ✓ | ✓ | | | | |
| Solid Storage | ✓ | ✓ | ✓ | | | ✓ | ✓ |

* Un-managed manure: manure that is directly deposited on pasture, rangeland, or paddock.

## *2.4 Calculation of Methane Conversion Factors (MCF)*

The methane conversion factor (MCF) is the portion of the maximum methane producing capacity of the manure that is achieved in given conditions. It varies with the waste management system and with temperature. Climate-based default values from the 2006 IPCC Guidelines (IPCC, 2006d) are used for all dry systems. For lagoons and liquid systems, USEPA developed a country-specific methodology using the van't Hoff-Arrhenius equation to estimate MCFs that reflects the seasonal changes in temperatures, and also accounts for long-term retention time. State-specific MCF values are derived using monthly weighted-average temperatures for the state, calculated using the population estimates and average monthly temperature in each county. For lagoon systems MCF values also account for a variety of factors that may affect methane production in lagoon systems.

In the particular case of anaerobic digesters, the MCF reflects the proportion of methane actually released to the atmosphere. To estimate it, USEPA assumed that anaerobic digester systems produce 90 percent of the maximum $CH_4$ producing capacity; have a collection efficiency of 75 percent in the case of covered lagoon systems and 99 percent for complete mix and plug flow systems; and that the methane destruction efficiency from flaring or burning in an engine was 98 percent.

### 2.5 Estimation of methane emissions

Methane emissions of each combination of the livestock group and waste management system are then calculated using the following equations:

*Equation 65: $CH_4$ emissions in in each animal group and manure management system*

$$\boxed{E_{group,system} = P_{group} \bullet WMS_{group,system} \bullet VS_{group} \bullet MCF_{group,system} \bullet B_{0,group} \bullet 662}$$

Where,

$E_{group,\ system}$ = $CH_4$ emissions of the given livestock group in the particular waste management system (grams per year)

$P_{group}$ = Number of animals in the livestock group (heads)

$WMS_{group,\ system}$ = Proportion of animals in the group whose manure is managed in the particular waste management system (fraction)

$VS_{group}$ = Volatile Solids Production rate of livestock group (kg per head per year)

$MCF_{group,\ system}$ = Methane conversion factor for the given group in the particular waste management system (fraction )

$B_{o,\ group}$ = Maximum methane producing capacity of the VS in manure of the given animal group ($m^3$ per kg)

662 = Density of methane ($g / m^3$), at 22ºC and 1 atm.

With,

Group = livestock group from Table 35

System = waste management system from Table 36 and Table 39.

*Equation 66: Total $CH_4$ emissions from manure management*

$$\boxed{E = \sum_{group,system} E_{group,system}}$$

Where,

E = $CH_4$ emissions from manure management (grams per year)

$E_{group,\ system}$ = $CH_4$ emissions of the given livestock group in the particular waste management system (grams per year)

With,

Group = livestock group from Table 35

System = waste management system from Table 36 and Table 39.

### 2.6 Nitrous oxide emission factors

Direct $N_2O$ emission factors for manure management systems (g $N_2O$-N/g excreted N) were taken from the most recent default IPCC factors (IPCC, 2006d) and are presented below.

*Table 38: Direct N2O emission factors*

| Management system | Direct N as $N_2O$ EF |
|---:|---:|
| Anaerobic digester | 0 |
| Anaerobic lagoon | 0 |
| Daily spread | 0 |
| Deep pit | 0.002 |
| Dry lot | 0.02 |
| Liquid/slurry | 0.005 |
| Pasture | 0 |
| Poultry with bedding | 0.001 |
| Poultry without bedding | 0.001 |
| Solid storage | 0.005 |

Indirect N2O emission factors account for two fractions of nitrogen losses: volatilization of ammonia ($NH_3$) and $NO_X$ (volatilized fraction) and runoff/leaching (runoff fraction). IPCC default indirect $N_2O$ emission factors were used. These factors are 0.010 g $N_2O$-N/g N for volatilization and 0.0075 g $N_2O$-N/g N for runoff and leaching.

USEPA has developed region-specific estimates of nitrogen losses for the volatilized fraction and the runoff/leaching fraction for the U.S using available data. Nitrogen losses from leaching are believed to be small in comparison to the runoff losses; therefore, the runoff/leaching fraction was set equal to the runoff loss factor. Values for individual combinations of animal group and waste management system are available in the online annexes to this document and in USEPA, 2011c.

### 2.7 Estimation of nitrous oxide emissions

Nitrous oxide emissions of each combination of livestock group and waste management system are then calculated using the following equation:

*Equation 67: $N_2O$ emissions in each animal group and manure management system*

$$E_{group,system} =$$
$$P_{group} \bullet WMS_{group,system} \bullet NER_{group} \bullet \left[DEF_{system} + (VF_{group,system} \bullet VEF) + (RF_{group,system} \bullet REF)\right] \bullet 1.5711$$

Where,

$E_{group,\ system}$ = $N_2O$ emissions of the given livestock group in the particular management system (grams)
$P_{group}$ = Number of animals in the livestock group (heads)
$WMS_{group,\ system}$ = Proportion of animals in the group whose manure is managed in the particular waste management system (fraction)
$NER_{group}$ = Nitrogen excretion rate of animals in the group (g per year)

$DEF_{system}$ = Direct N as $N_2O$ emission factor for the particular management system (g $N_2O$-N per g N)
$VF_{group,\ system}$ = Volatilization fraction of N for the given animal group in the particular management system (fraction)
VEF = Indirect N as $N_2O$ emission factor for re-deposited volatilized N (g $N_2O$-N per g N)
$RF_{group,\ system}$ = Runoff fraction of N for the given animal group in the particular management system (fraction)
REF = Indirect N as $N_2O$ emission factor for runoff N (g $N_2O$-N per g N)
1.5711 = Molecular weight ratio of $N_2O$ to $N_2$

With,
Group = livestock group from Table 35
System = waste management system from Table 36 and Table 39.

*Equation 68: Total $N_2O$ emissions from manure management*

$$\boxed{E = \sum_{group,system} E_{group,system}}$$

Where,
E = $N_2O$ emissions from manure management (grams per year)
$E_{group,\ system}$ = $N_2O$ emissions of the given livestock group in the particular waste management system (grams per year)

With,
Group = livestock group from Table 35
System = waste management system from Table 36 and Table 39.

## 3. Data Sources

All data used by ARB staff were from a detailed set of data and parameters obtained from the USEPA Climate Change Division (Wirth, 2011), and from the IPCC guidelines (IPCC, 2006d).

For a complete list of livestock population numbers and parameter values used in the estimates, please consult the online documentation annex at: http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_3b_manure_management.pdf

## 4. Changes in Estimates

The major changes in data and methods used in the current estimation of emissions from manure management when compared with those used for the 1990-2004 edition of GHG Inventory are:

- Anaerobic digester systems were added to the list of waste management system using the existing WMS distributions and USEPA AgSTAR data. Emissions for anaerobic digestion systems calculated using assumptions about their $CH_4$ production rate, collection efficiency, and combustion efficiency.

- The WMS distribution for sheep was updated using newer data from USDA.
- USEPA Cattle Enteric Fermentation Model (CEFM) team implemented methodological changes to the VS estimation. The VS production rates from the CEFM are used for $CH_4$ emissions estimates.
- Cattle population data and N excretion rates from the CEFM were incorporated in the manure management calculations, increasing the methodological consistency with the enteric fermentation modeling.
- The VS production rates and N excretion rates for other animal types were updated using data from USDA's 2008 Agricultural Waste Management Field Handbook. Data from both the previous Handbook and the updated Handbook were used to create a time series across inventory years for all animals.
- The USDA published revised population estimates that affected historical emissions estimated for swine, sheep and for certain beef and dairy populations.
- Swine population categories were modified so that the categories "<60 pounds" and "60-119 pounds" were replaced with "<50 pounds" and "50-119" pounds.
- Emissions of $CH_4$ and $N_2O$ are now reported by animal group *and* by manure management system. This last change does not alter total emissions but it allows for comparisons of the relative GHG intensity of the various systems used in California.

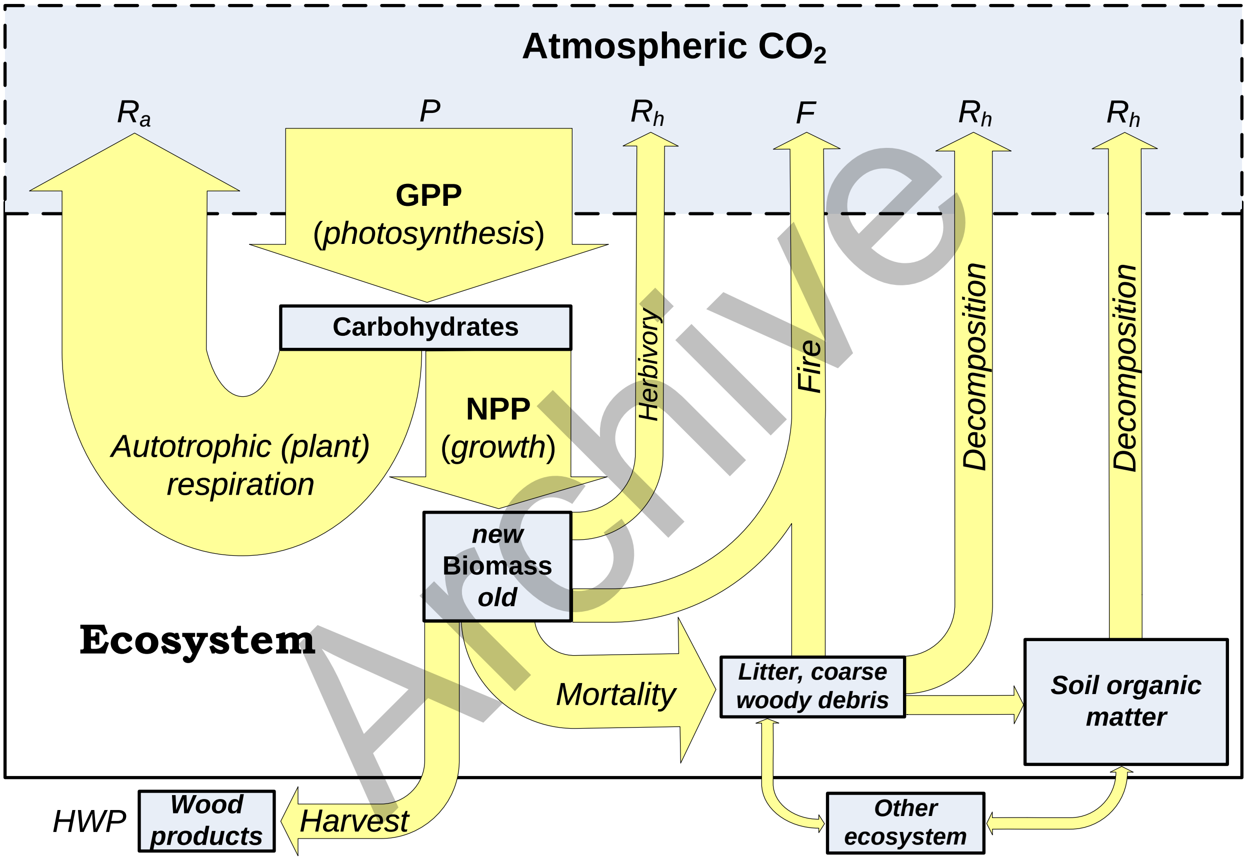
All together these methodology changes and updates to data sources resulted in sizable adjustments in emissions estimates for the categories included in this section: +28.5 percent on average over the years 2000 to 2004 when compared with the estimates in the first edition of ARB's GHG inventory.

## C. Land - Forests and Rangelands (IPCC 3B)

### 1. Background

Trees and other green plants can remove $CO_2$ from the atmosphere via photosynthesis. Light energy is captured by chlorophyll in plant cells and used to convert water, carbon dioxide, and minerals into oxygen and energy-rich organic compounds (carbohydrates). Nearly all life on Earth either directly or indirectly depends on this process as a source of energy. The total amount of energy stored into carbohydrates through photosynthesis is called *Gross Primary Production* (GPP), see Figure 3. GPP is generally expressed as a mass of carbon per unit area per unit of time. Plants use some of their carbohydrates for energy through cellular respiration, and that process releases carbon back to the atmosphere as $CO_2$. About half of GPP is respired by plants, the remaining carbohydrates being used to build plant tissues (e.g., roots, stalks, leaves, seeds). These tissues constitute the plant biomass and, as they die, dead biomass. GPP minus respiration is called *Net Primary Production* (NPP), the amount of production of living and dead biomass per unit area per unit of time. The carbon tied in carbohydrates in plant tissues is sequestered away from the atmosphere for a period of time. However, it will eventually be released back into the atmosphere: rapidly through combustion by fire, or slowly via decomposition. NPP minus the losses from the decomposition of organic matter in dead wood, litter and soils is called *Net Ecosystem Production* (NEP). Changes in NEP are used to estimate atmospheric $CO_2$ removals, and emissions due to disturbance (fire, harvest, etc.) in this section of the GHG inventory called Land –Forests and Rangelands.

*Figure 3: Carbon fluxes of terrestrial ecosystems (after Schulze et al., 2000 and Lovett et al., 2006)*



**Carbon Fluxes of Terrestrial Ecosystems**
- ► Gross Primary Production (GPP) = Carbon assimilation by photosynthesis (*P*)
- ► Net Primary Production (NPP) = GPP – Autotrophic respiration ($R_a$)
- ► Net Ecosystem Production (NEP) = NPP – Heterotrophic respiration ($R_h$)
- ► Organic Carbon accumulation ($\Delta C_{org}$) = NEP + Carbon imports form other ecosystems – Fire (*F*) – Harvested wood products (*HWP*) – Carbon exports to other ecosystems

The concept of distinct reservoirs or pools is useful to keep track of the fate of the carbon that has been removed from the atmosphere by plants. The United Nations Framework Convention on Climate Change (UNFCCC) defines reservoirs as “components of the climate system where a GHG or a precursor of a GHG is stored”. In forestry, these reservoirs are referred to as “pools.” The pools in a forested landscape include: the above and below ground live vegetation pools (trunks, stems, foliage, roots); the dead organic matter pools (standing or downed dead wood, litter); and the soil organic matter pool (living and non-living). Greenhouse gas inventories also include a forest biomass pool called Harvested Wood Products (HWP). Over time, carbon is transferred among these "reservoirs" or "pools". For instance, when a tree is harvested some of its carbon is transferred from the live tree pool to the harvested wood product pool; during a fire carbon may flow from the dead wood pool to the cinders pool.

Greenhouse gas fluxes in this section may be estimated using two main approaches (IPCC, 2003), either singly or in combination. The first, called the stock-change approach, estimates the net change in carbon over all reservoirs in the system. The second, called the atmospheric flow approach, directly estimates gas fluxes between each of the reservoirs and the atmosphere. ARB staff has used the atmospheric flow approach (Figure 5) to estimate the net flux of $CO_2$ for the forested lands and wood products pools in California. This net $CO_2$ flux is reported under IPCC category 3B.

Ecosystems also emit $N_2O$ and $CH_4$ through soil microbial processes and the combustion of organic matter. Estimates of $CH_4$ and $N_2O$ emissions from fire and other disturbances are reported under IPCC Category 3B1.

The 2003 IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC, 2003) and the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006g) specify additional land-use categories for GHG flux estimation, including croplands, wetlands, and urban areas. This edition of California's GHG inventory does not include $CO_2$ fluxes from agricultural lands because of a lack of data and a need to adapt methodologies to reflect California's large set of crops. Non-$CO_2$ emissions from agriculture are reported under IPCC category 3C. Greenhouse gas emissions from fossil fuel use in forestry and agriculture are included in Section I.C above.

## 2. Methodology

### *2.1 Forest and range lands biomass*

Carbon dioxide removal from the atmosphere can be estimated from an increase in biomass (stock change) on a landscape over a time interval (i.e., years). Likewise, decreases in biomass may be used to estimate $CO_2$ emissions back to the atmosphere. However, not all of the gross decreases in biomass on a forest site result in an emission, because a fraction of the removed biomass carbon may be transferred to a product pool rather than released to the atmosphere. For example, live tree biomass removed from a forest to make a long-term wood product such as a house, represents a cessation of atmospheric $CO_2$ removal, and a transfer of carbon from the live tree pool to a wood product pool. The harvest event causes some $CO_2$ emissions through the decomposition (or combustion) of on-site harvest residues ("slash") and soil disturbance. The carbon in the wood product, on the other hand, will not be released to the atmosphere until the product reaches its end of use (e.g., when a wood pallet or a piece of furniture is discarded). To avoid over-estimating emissions it is necessary to account for all pool-to-pool transfers and determine the net biomass stock change.

Conventionally, forest biomass is estimated using statistically designed networks of on-the-ground sampling plots (or transects) and measurement protocols. Equations are used to estimate the biomass present in various pools from measured variables (such as tree diameter at breast height [4.5 ft or 1.37 m], or DBH). Additional equations are used to scale-up from plot scale (tens of square meters) to larger areas (hectares). Plots are re-sampled at annual or multi-year intervals in order to track biomass changes over time. Examples of landscape biomass monitoring networks include the USDA Forest Service Forest Inventory and Analysis (FIA) program. Emerging approaches to landscape biomass estimation include satellite or aircraft remote sensing coupled with ground sampling (e.g., Dong et al. 2003; Gonzalez et al. 2010; Hurtt et al. 2004; Potter et al. 2007a, 2007b; Treuhaft et al. 2003, 2004; Zhang and Kondragunta 2006).

For this version of California’s GHG inventory, ARB staff used data and analyses results from a project, “Baseline Greenhouse Gas Emissions for Forest, Range and Agricultural Lands in California”, carried out for the California Energy Commission (CEC, 2004). In this work, Winrock International, a non-profit research organization, used a methodology combining satellite-based forest change detection with ground-based data, and derived empirical relationships between tree canopy cover and biomass for various forest types. Their methods were consistent with IPCC Tier 3 approaches (IPCC, 2006g), as they employed “regional data, models, and measurement systems repeated over time using comprehensive field sampling and/or GIS-based systems.” These methods are not discussed here in detail: particulars can be found in the California Energy Commission (CEC) project report (CEC, 2004). Instead, a general description is presented here together with a worked example.

Researchers estimated the biomass of forests and wooded range lands in 1994 and 2000 in three northern California project areas representing 84 percent of forest lands and 42 percent of range lands in the state (CEC, 2004). The year 1994 represented “time zero” or initial condition stocks. Biomass estimates were based on empirical relationships between tree canopy cover and biomass for five forest types, and determined for each cell of a grid (with 100 m x 100 m = 1 hectare grid cell size) covering the regions. Gross stock changes between 1994 and 2000 were used to estimate atmospheric $CO_2$ removals, and net stock changes were used to estimate $CO_2$ emissions and emissions of other GHGs over the interval. Changes in forest canopy cover detected by satellite were attributed to events or “change agents” (such as growth, fire, harvest, etc.) using ground survey data. For each type of disturbance event (fire, harvest, etc.), specified amounts of biomass carbon were allocated through various pathways to destination pools. Pre- and post-event biomass pools were used to estimate gross and net stock change.

### 2.2 Fire

Fire events were categorized into low, middle, or high intensities depending on the relative change in tree canopy cover detected by satellite. Fire causes biomass carbon to be redistributed through various pathways (Figure 4). A fraction of the carbon is volatilized, while other fractions become soot, charcoal, dead wood or survive as vegetation. The proportion of carbon volatilized versus surviving as vegetation varies with the fire intensity (Table 39). For example, following intense fires 60 percent of the affected carbon volatilizes, 11 percent survives as vegetation, and 29 percent remains as charcoal, soot, and dead wood. A greater fraction of vegetation survives in low intensity fires, and a smaller fraction of the affected carbon volatilizes. Regardless of fire intensity, a decay rate of 0.05 $yr^{-1}$ is applied to the dead wood fraction for two years post-fire.

*Figure 4: Flow diagram of carbon fate after fire. Adapted from Figure 1-5 in CEC (2004).*

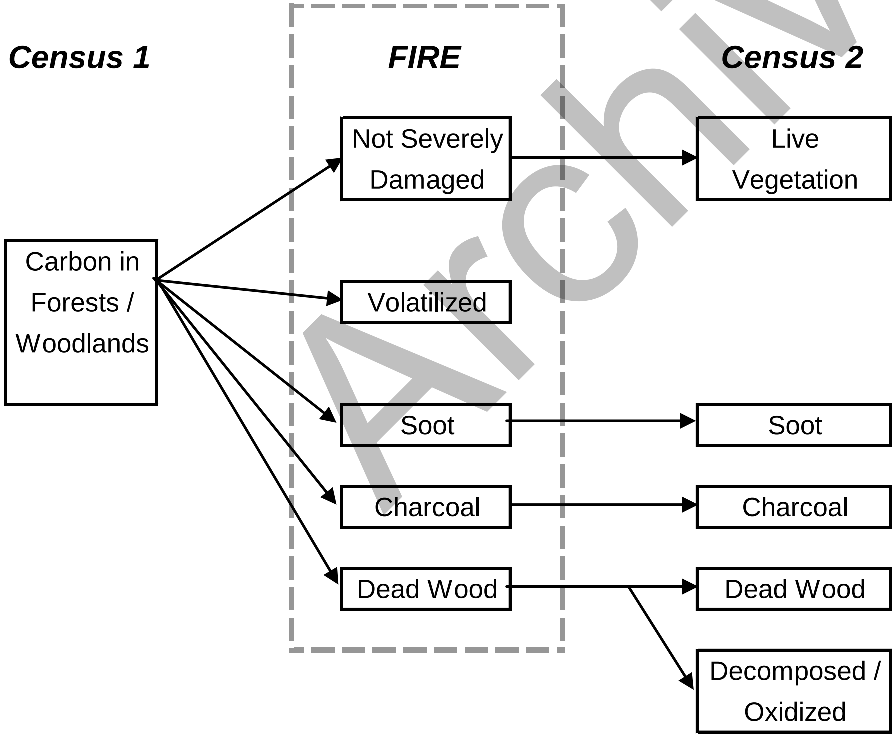


*Table 39: Carbon fate assumptions after decreases in canopy cover caused by fire (percent).*

| **Carbon fate** | **High Intensity Fire** | **Medium Intensity Fire** | **Low Intensity Fire** |
|---|---|---|---|
| Fraction volatilized | 60 | 40 | 20 |
| Fraction not volatilized | 29.4 | 27.3 | 28.6 |
| ▪ Charcoal | 6.5 | 5.8 | 6.4 |

| Carbon fate | High Intensity Fire | Medium Intensity Fire | Low Intensity Fire |
|---|---|---|---|
| ▪ Soot | 13.3 | 12.4 | 12.9 |
| ▪ Dead wood | 9.6 | 9.1 | 9.3 |
| Surviving vegetation | 10.6 | 32.7 | 51.4 |
| Total | 100 | 100 | 100 |

Based on data in the CEC report by Winrock International (CEC, 2004).

The following example lists the stock changes and resultant emissions inferred for a large decrease in tree canopy cover resulting from intense fire in a dense-canopied Douglas-fir forest:

- Region: North Coast
- Forest Type: Douglas-fir
- Pre-fire canopy cover: Dense (>= 60 percent)
- Fire Intensity: High
- Affected area: 390 hectares
- Pre-Fire Biomass: 152875.7 tonnes
- Post-Fire Biomass: 67696.5 tonnes
- Gross Stock Change: -85179.2 tonnes
- Post-Fire Charcoal: (Pre-Fire Biomass – Post-Fire Biomass) x 0.065 = 5536.6 tonnes
- Post-Fire Soot: (Pre-Fire Biomass – Post-Fire Biomass) x 0.133 = 11328.8 tonnes
- Post-Fire Dead Wood after 2-year decomposition: (Pre-Fire Biomass – Post-Fire Biomass) x 0.096 x 0.95 x 0.95 = 7379.9 tonnes
- Post-Fire Biomass, Charcoal, Soot, Dead Wood: 91941.9 tonnes
- Net Stock Change: (Post-Fire Biomass, Charcoal, Soot, Dead Wood) – (Pre-Fire Biomass) =
    - Biomass: -60933.8 tonnes
    - Carbon released: 30466.9 tonnes of C, or
    - $CO_2$ emissions: 111712 tonnes of $CO_2$

By convention, minus signs denote stock decreases, while reported emissions to the atmosphere are denoted with a positive sign. To further estimate the stock changes and resultant emissions from fire for the Douglas-fir forest type, the approach is performed for other pre-fire canopy cover classes (Moderate, Open, etc.) and fire intensity categories (moderate, light). The process is repeated for fires in other forest types (Fir-Spruce, Hardwood, etc.) in the region. Results for the North Coast region are listed in Table 1-9 of the report (CEC, 2004).

Methane and nitrous oxide emissions from fire are estimated from the mass of carbon released, using the default IPCC approach (IPCC, 2003):

*Equation 69: $CH_4$ emissions from fires*

$$\boxed{E_{CH4} = M_c \bullet 0.012 \bullet 1.3357}$$

Where,

$E_{CH4}$ = $CH_4$ emissions from fire (tonnes)
$M_C$ = Mass of carbon released (tonnes)
0.012 = Proportion of carbon emitted as methane
1.3357 = Molecular weight ratio of $CH_4$ to C

*Equation 70: $N_2O$ emissions from fires*

$$\boxed{E_{N2O} = M_C \bullet 0.01 \bullet 0.007 \bullet 1.5711}$$

Where,

$E_{N2O}$ = $N_2O$ emissions from fire (tonnes)
$M_C$ = Mass of carbon released (tonnes)
0.01 = Nitrogen to carbon ratio in biomass
0.007 = Proportion of nitrogen emitted as nitrous oxide
1.5711 = Molecular weight ratio of $N_2O$ to $N_2$

### 2.3 Harvest

Tree harvests transfer a fraction of tree carbon from live biomass to wood products pools. A portion of the wood products are long-lasting and do not generate $CO_2$ emissions in the short term. Emissions from such products occur after end of use and disposal, and are discussed in the Wood Products Section (III.C.2.7 below), and in the Landfills Section (IV.A below).

Emissions associated with harvest events for softwood and hardwood forests were estimated in a manner similar to disturbance by fire, accounting for net changes in biomass resulting from the transfer of carbon from trees to products. Pre- and post-harvest biomass was estimated on a grid with a one hectare cell size from satellite imagery for various forest types and canopy cover classes. For harvested softwood forests, the wood product fraction was 44 percent of the extracted biomass, where extracted biomass was defined as 75 percent of the gross stock change. For harvested hardwood forests, 23 percent of the extracted biomass became product, where the extracted fraction was defined as 73 percent of the gross stock change. For softwood forests the on-site residue (slash) fraction was defined as 25 percent of the gross stock change. For hardwood forests, the slash fraction was defined as 27 percent of the gross stock change. A 0.05 $yr^{-1}$ decomposition rate was applied to all slash for two years. Net stock change was estimated by the difference between pre-harvest stock and post-harvest stock, plus persistent slash and wood product. The net stock change was converted from biomass to carbon and reported as $CO_2$. Post-harvest methane emissions were estimated using a default rate (0.94 kg/ha/yr).

### 2.4 Other disturbances

Emissions associated with stock changes inferred from forest canopy cover declines due to land use change (development) or other forces are described in the Winrock report (CEC, 2004).

### 2.5 Scaling to state-wide estimates

Average annual rates of $CO_2$ removals and GHG emissions for forests and range lands were derived from the estimates made over the three northern California study regions over the 1994 to 2000 time interval (CEC, 2004). Then, these average annual rates were scaled-up to the entire state of California using factors based on the fraction of statewide forests (0.84) and range lands (0.42) represented in the study (CEC, 2006). Scaling the regional results to statewide estimates was necessary because satellite-based change detection data for central and southern California were not available at the time of the study.

### 2.6 Forecasting to 2008

State-wide $CO_2$ removals and GHG emissions estimates for 1994 to 2000 were extrapolated to cover the 2000 to 2008 GHG inventory period (CEC, 2006). To do this, estimates were forecast using factors based on forest land area trends reported in a publication of the USDA-Forest Service (Alig and Butler 2004). The forecast factor was a 0.0755 percent per year decline in forest land area projected for 1997 to 2050.

### 2.7 Wood products

Because carbon stored in wood can persist for long periods of time, the fate of wood products is an important element in GHG inventories. California uses a wide range of (mostly imported) wood products and, once discarded, these wood products arrive at a variety of destinations, such as landfills, recycling, and composting facilities. ARB staff estimated the emissions from the statewide use and disposal of wood products in landfills and composting operations for years 2000 to 2008. To do this, a time series of statewide wood products (paper, lumber, etc.) use and disposal was developed from output of the WOODCARB model (Skog and Nicholson 1998, Skog et al. 2004) provided by the USDA-Forest Service Forest Products Laboratory and from waste characterization data from the Department of Resources Recycling and Recovery (CalRecycle) —previously known as California Integrated Waste Management Board (CIWMB). For landfilled wood product waste, a first-order decay model (IPCC, 2006f) was applied to estimate $CO_2$ and $CH_4$ emissions for years 2000 through 2008. The model estimates the fraction of carbon eventually released to the atmosphere and the fraction that persists in landfills. For composted wood products, CalRecycle staff recommended assuming that 15 percent of their dry mass is released as $CO_2$ in one year (Oliver, 2007). According to CalRecycle staff, 10 million short tons of composting are currently permitted under CalRecycle's authority each year. This amount does not include any composting of agricultural products, which is appropriate for the current GHG inventory since it considers only forest sector biomass and assumes that agriculture biomass production and decay balances out to a net zero $CO_2$ emission, pending further study. Details of these methodologies are given in the Landfills Section (IV.A below) of this report.

### *2.8 Net $CO_2$ fluxes*

ARB staff used the Atmospheric Flow Approach (IPCC, 2006g) to inventory the fluxes of $CO_2$ to and from the atmosphere for the forested lands and wood products pools within the state (Table 40). This table focuses on forested lands and $CO_2$ removals and emissions from (non-woody) crop lands are not included, pending further study. The Atmospheric Flow Approach explicitly delineates land-atmosphere $CO_2$ fluxes and emissions from decomposing wood products (Figure 5). Details on wood product stock changes in landfills and associated emissions are given in Section IV.A. The 2006 edition of the CEC GHG inventory reported forest and range land $CO_2$, $CH_4$, and $N_2O$ emissions as a combined single $CO_2$-equivalent value. Table 40 reports individual $CO_2$ emissions by process (e.g., fire, harvest). Non-$CO_2$ emissions are reported separately elsewhere in the inventory. ARB staff estimated the net $CO_2$ flux for forests and rangelands by summing the $CO_2$ removals from the atmosphere and $CO_2$ emissions to the atmosphere for these lands and for the wood products pool (Table 40). Forest and range land $CO_2$ removals and emissions reported for the years 1994 through 2000 are constant because they were derived as annual averages over the period.

## 3. <u>Data Sources</u>

### *3.1 Forest and range lands*

The inventory of $CO_2$ removals and GHG emissions by forest and range lands for years 1994 to 2000 is based upon prior work performed under the auspices of the CEC Public Interest Energy Research (PIER) program (CEC, 2004). Data sources used in that project included peer-reviewed scientific publications on forest biomass (principally Birdsey and Lewis 2003, and Smith et al. 2003), satellite remote sensing and GIS products from the Fire and Resource Assessment Program (FRAP) of the California Department of Forestry and Fire Protection (CDF, now CalFire), and FIA data from the USDA-FS.

### *3.2 Wood products*

Estimates of national wood product use and disposal (landfill, recycling, composting, etc.) generated by the USDA-FS WOODCARB model were provided by the Forest Service and scaled to California based on population. The composition of the wood product waste stream entering landfills in California was derived from data provided by CalRecycle. Wood products decay rates were from data published by USEPA (RTI, 2004).

## 4. Changes in Estimates

The methods used to estimate forest and range land $CO_2$ removals and GHG emissions did not change since the 1990-2004 edition of California's GHG Inventory. Estimates for recent years employ extrapolation, using land area trend factors as a proxy. Data for emission estimates for decomposing wood and paper products in landfills were updated since then. These changes resulted in a minor decrease in size of the overall $CO_2$ sink from forests and rangelands: -6.5 percent on average over the years 2000 to 2004 when compared with the estimates in the 1990-2004 edition of ARB's GHG inventory.

## 5. Future Improvements

### *5.1 Forest and range lands*

The USDA-Forest Service uses FIA data and models to estimate biomass and track carbon transfers among forest and product pools, and to estimate forest land GHG fluxes for the USEPA national inventory. The FIA network is designed to statistically sample conditions over large forested areas. Forest inventories derived from FIA data and protocols are designed to be accurate within plus or minus 3 percent at the 67 percent confidence interval per million acres (USEPA 2006). California has approximately 31 million acres of forested land (CDF, 2003) and over 9,000 FIA plots. The current statewide forest and range land GHG inventory was developed from exploratory methods applied to a region of the state and with limited use of FIA. As data on forest and range land growth and disturbance processes accrue, it will eliminate the need to use extrapolated GHG values for specific years. In partnership with state and federal land management agencies and the academic community, ARB will seek to improve the statewide forest and range lands GHG inventory through improvements in biomass and flux estimation, based on FIA and other relevant products and methods.

Soil organic carbon (SOC) is a significant carbon reservoir on forest and range lands and is included in the national GHG inventory (USEPA 2006). The current ARB edition of the GHG inventory does not include GHG fluxes due to changes in SOC. Future editions of the sector inventory may include soil fluxes of $CO_2$ and other greenhouse gases.

### *5.2 Other land use types*

IPCC guidance specifies additional land use types for inclusion in the Land category of GHG inventories, such as agricultural lands, wetlands, and urban areas. ARB staff plans to improve California's GHG inventory by including $CO_2$ fluxes associated with these land use categories in the future.

Agriculture uses 11 percent of the land in the state, while 31 percent is used by forests (CDF, 2003). Farming management practices such as tillage, fertilization and irrigation affect soil organic carbon dynamics and GHG emissions. Soil organic carbon (SOC) constitutes a large reservoir of carbon;

changes to SOC content are currently reported in the national GHG inventory (USEPA 2006). Staff will assess available methods and data sources from which to estimate fluxes of $CO_2$ in and out of agricultural soils for future editions of the inventory.

Changes in live and dead biomass pools on crop lands also correspond to atmospheric $CO_2$ removals and emissions. They are not included in this edition of the inventory due to data limitations. For annual crops, it is unclear whether the annual cycling of biomass through growth, harvest, and the disposition of post-harvest residue results in significant net $CO_2$ fluxes. In the case of woody crops (e.g., vineyards and orchards), carbon removed from the atmosphere may persist in woody tissue for decades, although emissions occur from the combustion of prunings and other dead biomass, and/or their decomposition. Changes in woody crops biomass are likely to result in significant net $CO_2$ fluxes.

Urban areas comprise 5 percent of land use in the state (CDF, 2003) and exhibit about 13 percent tree canopy cover (Nowak and Crane, 2002). California's urban forests account for a small but growing fraction of the state atmospheric $CO_2$ removals, and emissions by urban forests are included in the national GHG inventory. Soil organic carbon (SOC) is also a significant carbon pool in urban green space (Jo and McPherson, 1995). The current GHG inventory does not include atmospheric $CO_2$ fluxes from urban forests, but methods and state-specific data exist from which to develop an inventory of $CO_2$ removals and GHG emissions from the state's urban forests for future editions of this inventory.

*Table 40: Forested Lands and Wood Products Biodegradable Carbon Emissions & Sinks (MMTCO$_2$)*

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |
| **Forested Lands Removals** | | | | | | | | | | | |
| ▪ *Forest woody biomass growth* | *-13.052* | *-13.042* | *-13.032* | *-13.022* | *-13.012* | *-13.002* | *-12.993* | *-12.983* | *-12.973* | *-12.963* | *Winrock* |
| ▪ *Rangeland woody biomass growth* | *-1.097* | *-1.096* | *-1.095* | *-1.094* | *-1.093* | *-1.093* | *-1.092* | *-1.091* | *-1.090* | *-1.089* | *Winrock* |
| **Total Sinks** | **-14.148** | **-14.137** | **-14.127** | **-14.116** | **-14.105** | **-14.095** | **-14.084** | **-14.074** | **-14.063** | **-14.052** | |
| | | | | | | | | | | | |
| **Forested Lands Emissions** | | | | | | | | | | | |
| ▪ *Forest and rangeland fires* | *2.018* | *2.017* | *2.015* | *2.014* | *2.012* | *2.010* | *2.009* | *2.007* | *2.006* | *2.004* | *Winrock* |
| ▪ *Other disturbances (such as insect pests damage)* | *1.200* | *1.199* | *1.198* | *1.197* | *1.196* | *1.195* | *1.194* | *1.193* | *1.192* | *1.192* | *Winrock* |
| ▪ *Development of forest or range lands (Landuse change)* | *0.021* | *0.021* | *0.021* | *0.021* | *0.021* | *0.021* | *0.021* | *0.021* | *0.021* | *0.021* | *Winrock* |
| ▪ *Timber harvest slash* | *0.155* | *0.155* | *0.155* | *0.155* | *0.155* | *0.155* | *0.155* | *0.155* | *0.154* | *0.154* | *Winrock* |
| **Wood Products Emissions** | | | | | | | | | | | |
| ▪ *Fuel wood* | *1.521* | *1.520* | *1.519* | *1.518* | *1.517* | *1.515* | *1.514* | *1.513* | *1.512* | *1.511* | *Winrock* |
| ▪ *Wood Waste Dumps* | *0.000* | *0.000* | *0.000* | *0.000* | *0.000* | *0.000* | *0.000* | *0.000* | *0.000* | *0.000* | *CalRecycle* |
| ▪ *Discarded wood and paper in landfills* | *4.004* | *4.184* | *4.315* | *4.251* | *4.239* | *4.367* | *4.511* | *4.435* | *4.523* | *4.556* | *ARB Model* |
| ▪ *Composting of wood waste materials* | *0.743* | *0.743* | *0.745* | *0.800* | *0.803* | *0.805* | *0.808* | *0.811* | *0.814* | *0.816* | *CalRecycle/ USEPA* |
| **Total Emissions** | **9.662** | **9.839** | **9.969** | **9.955** | **9.943** | **10.070** | **10.213** | **10.135** | **10.223** | **10.254** | |
| **Net CO$_2$ Flux (million tonnes of CO$_2$)** | | | | | | | | | | | |
| **Sinks + Emissions** | **-4.486** | **-4.298** | **-4.158** | **-4.161** | **-4.163** | **-4.025** | **-3.871** | **-3.938** | **-3.840** | **-3.798** | |

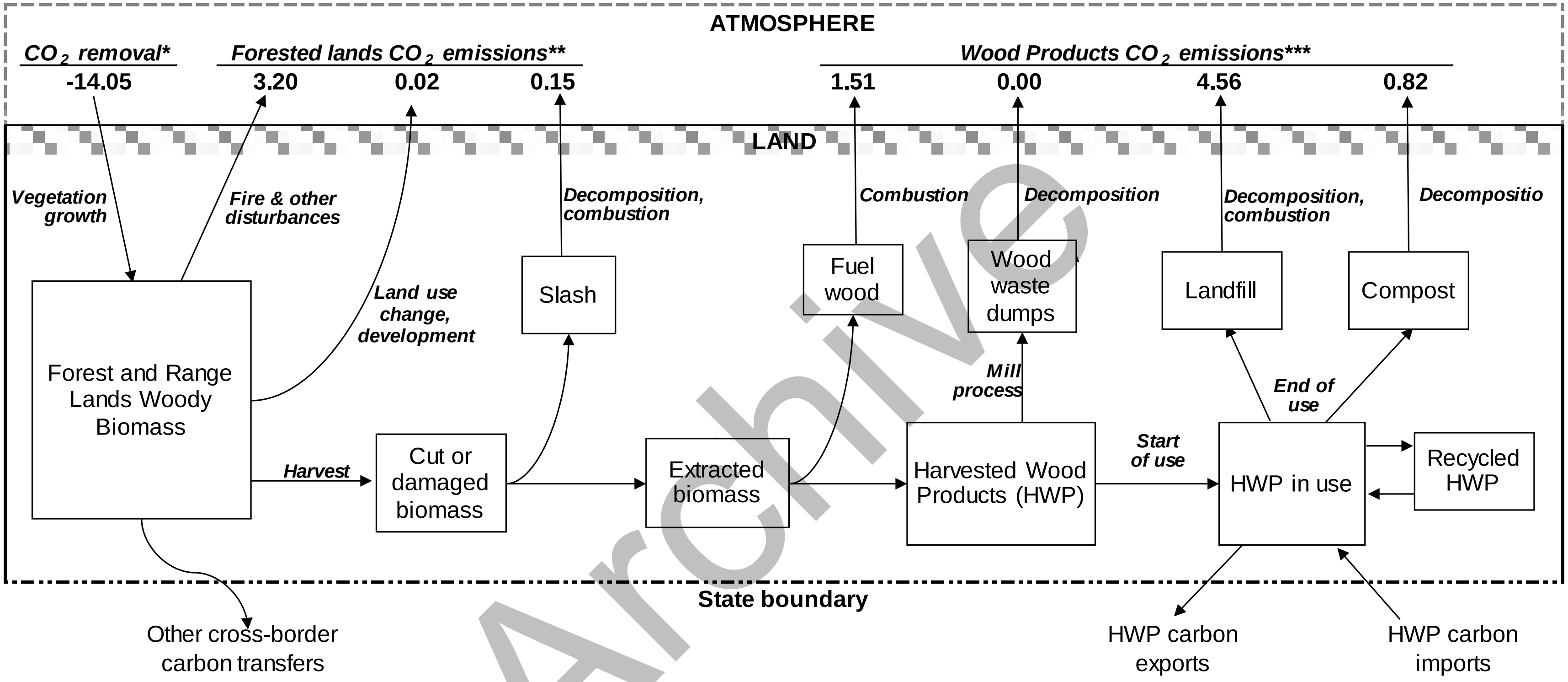
**Data sources:**

- **Winrock:** CEC (2004). Baseline Greenhouse Gas Emissions for Forest, Range, and Agricultural Lands in California. CEC PIER final report CEC-500-04-069F. Annual average forest and range land CO2 removal and emission rates for period 1994 - 2000 in Table 1-21, CEC (2004) scaled to state-wide in CEC (2006): Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004. Publication CEC-600-2006-013-SF. Emissions and removals are back-cast to 1990 from 1994 using 0.1707% per year forest land area trend from 1953 to 1994, from p. 14 in Shih (1998): The Land Base of California's Forests. Fire and Resource Assessment Program, California Dept. of Forestry and Fire Protection. Emissions and removals forecasted from 2000 using 4% forest land area decline predicted for 1997 to 2050 in the Pacific Coast Region, from p. 53 in: Area Changes for Forest Cover Types in the United States, 1952 to 1997, with projections to 2050. (2004) USDA Forest Service, Pacific Northwest Research Station, publication PNW-GTR-61
- **CalRecycle/USEPA:** Department of Resources Recycling and Recovery SWIS waste-in-place and landfill survey data, USEPA Harvested Wood Products use data provided by Kenneth Skog (Forest Products Laboratory, USDA Forest Service, Madison, WI), scaled to state based on population.
- **ARB Model:** From IPCC Mathematically Exact First-Order Decay Model, with CalRecycle SWIS waste-in-place and landfill survey data.

*Figure 5: Diagram of the Atmospheric Flow Approach to forested lands and wood products carbon accounting for the California GHG inventory.*

**2009 Net CO2 Flux = Sinks + Emissions = -14.05 + 10.25 = -3.80**

*Values for 2009 in million tonnes of CO$_2$ (Biodegradable carbon only, no fossil fuel CO$_2$)*



*** CO2 removals** from the atmosphere include vegetation biomass growth in forests and wooded range lands.

**** Forested lands CO$_2$ emissions** to the atmosphere include biomass oxidation resulting from forest and range lands fires and other disturbances such as insect pest damage, forest and range land use change (development), decomposition/combustion of slash after tree harvest.

***** Wood Products CO$_2$ emissions** to the atmosphere include: fuel wood combustion, decomposition of wood mill waste and discarded wood products in landfills and composting facilities.

**Adapted from:**

1) Figure 12.A.2. System boundary of the Atmospheric Flow Approach. In: Chapter 12, Harvested Wood Products. Volume 4, Agriculture, Forestry, and Other Land Use (AFOLU). 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IPCC National Greenhouse Gas Inventories Programme.

2) Figure 1-6. Flow diagram illustrating the various destinations of pre-harvest carbon after commercial harvest. In: Baseline Greenhouse Gas Emissions for Forest, Range, and Agricultural Lands in California. (2004) California Energy Commission PIER final report 500-04-069F.

## D. Agricultural Residue Burning (IPCC 3C1b)

### 1. Background

Open burning of agricultural biomass is a common practice in California and a source of nitrogen oxide ($N_2O$) and methane ($CH_4$) emissions. Carbon dioxide ($CO_2$) emissions from agricultural biomass burning is not considered a net source of emissions because the carbon released to the atmosphere as $CO_2$ from the combustion of agricultural biomass is assumed to have been absorbed during the previous (or a recent) growing season. Therefore, emissions from $CO_2$ are estimated but not included in California's GHG inventory total.

### 2. Methodology

The methodology for estimating greenhouse gas emissions from agricultural residue burning of agricultural biomass is consistent with the IPCC Tier 2 approach as it uses California specific emission factors. Researchers at University of California, Davis developed emission factors for six crops including, almond, walnut, wheat, barley, corn and rice (Jenkins et al. 1996). These six crops account for a majority of the orchard and field biomass burned in California. Emissions are calculated as follows:

*Equation 71: GHG emissions from residue burning*

$$\boxed{E_{GHG,crop} = A_{crop} \bullet 0.404685642 \bullet FB_{crop} \bullet MR_{crop} \bullet EF_{GHG,crop}}$$

Where,

$E_{GHG,\,crop}$ = Emissions of the given GHG from the given crop residue burning (g)
$A_{crop}$ = Harvested area of the given crop (acres)
0.404685642 = Acres to hectares conversion factor
$FB_{crop}$ = Fraction of harvested area on which crop residues are burned (unitless)
$MR_{crop}$ = Mass of the given crop's residue (g dry matter per ha)
$EF_{GHG,\,crop}$ = Emission factor for the given GHG and crop (unit mass of GHG per unit mass of residue dry matter)

With,

GHG = [$CO_2$, $CH_4$, $N_2O$]
Crop = [Almond, Barley, Corn, Rice, Walnut, Wheat]

### 3. Data Sources

Areas harvested of a particular crop were obtained from the crop production summary reports published by the U.S. Department of Agriculture's National Agricultural Statistics Service (USDA, 2011b; USDA, 2011c). The fractions of crop acreage on which residues are burned, and the mass of residue burned are taken from survey data gathered and published by B.M. Jenkins (Jenkins et al. 1992) and assumed to have remained constant since, except for rice. The

1991 rice straw burning phase-down law required the incremental reduction of rice straw burning in the Sacramento Valley. Rice straw burning decreased over a period of ten years, with progressively fewer acres of rice fields burned each year. An ARB progress report (ARB, 2003) on the phase down of rice straw burning provided the percent of acres planted that were actually burned per year until 2002. For later years, the percent of rice acres burned came from data compiled by USEPA (USEPA, 2008a and USEPA, 2010a). Emissions factors are taken from a study report by UC researchers (Jenkins et al. 1996).

For a list of parameter values used in the equations, please consult the online documentation annex at: http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_3d_agricultural_residue_burning.pdf

## 4. Changes in Estimates

The major change made to the estimation of emissions from this category concerned the crop data. In the 1990-2004 version of the inventory staff had used the planted area reported by USDA, in this version we have used the harvested area from the same USDA surveys. The difference between planted and harvested area is especially large in the case of corn because the planted area includes both corn used for grain and used for silage. When harvested for silage the entire corn plant is harvested and there are no residues left in the field to burn. Since a large majority of acres planted in corn in California is used for silage, this change resulted in a decrease in emissions from corn residue burning of -68 percent on average over the period 2000-2004. Other crops with a significant difference between planted and harvested areas are barley and wheat. These cereals are often planted in the fall in California in areas that cannot be irrigated (dry farming). If the winter rainfall is abundant then these acres can be harvested for grain, if not they are typically harvested for forage. On the other hand, rice planted and harvested numbers are very close.

All together these changes resulted in substantial adjustments in emissions estimates for the categories included in this section: -19.6 percent on average over the years 2000 to 2004 when compared with the estimates in the first edition of ARB's GHG inventory.

## 5. Future Improvements

ARB staff is seeking more specific data on the number of acres burned by crop to improve yearly estimates.

## E. Carbon Dioxide from Liming (IPCC 3C2)

### 1. Background

Liming is used to reduce soil acidity and thus improve plant growth in agricultural fields and managed forests. Adding carbonates to soils in the form of “lime” (e.g., calcic limestone ($CaCO_3$), or dolomite ($CaMg(CO_3)_2$) leads to $CO_2$ emissions as the carbonate in limes dissolve and release bicarbonate ($2HCO_3^-$), which evolves into $CO_2$ and water ($H_2O$).

### 2. Methodology

ARB staff used methods consistent with the Tier 1 methodology of the 2006 IPCC Guidelines (IPCC, 2006a). Total $CO_2$ emissions from liming are estimated as follows:

*Equation 72: $CO_2$ emissions from liming*

$$\boxed{E = [(M_L \bullet EF_L) + (M_D \bullet EF_D)] \bullet 3.6642}$$

Where,

E = $CO_2$ emissions from liming (g)
$M_L$ = Mass of limestone applied to soils (g)
$EF_L$ = Limestone C emissions factor (0.12 g C per g limestone)
$M_D$ = Mass of dolomite applied to soils (g)
$EF_D$ = Dolomite C emissions factor (0.13 g C per g dolomite)
3.6642 = Molecular weight ratio of $CO_2$ to C

To estimate the mass of limestone and dolomite applied to soils from reported amount of “lime” (not distinguishing between limestone and dolomite) applied to agricultural soils, staff used the following equations:

*Equation 73: Mass of limestone applied to soils*

$$\boxed{M_L = L_{AG} \bullet \frac{T_L}{(T_L + T_D)}}$$

*Equation 74: Mass of dolomite applied to soils*

$$\boxed{M_D = L_{AG} \bullet \frac{T_D}{(T_L + T_D)}}$$

Where,

$M_L$ = Mass of limestone applied to soils (g)
$M_D$ = Mass of dolomite applied to soils (g)
$L_{AG}$ = Total “lime” applied to agricultural soils in California (g)
$T_L$ = Total limestone sold or used in California (g)
$T_D$ = Total dolomite sold or used in California (g)

### 3. Data Sources

Data for the mass of "lime" applied to agricultural soils are from yearly editions of the *Fertilizing Materials Tonnage Report* published by the California Department of Food and Agriculture (CDFA, various years). Limestone and dolomite sold or used in California are reported in the *Minerals Yearbook* by the U.S. Geological Survey (USGS, various years a). Limestone and dolomite emission factors are from the 2006 IPCC Guidelines (IPCC, 2006e).

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at: http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_3e_carbon_dioxide_from_liming.pdf

### 4. Changes in Estimates

No change was made to the methods or data used for these estimates.

## F. Nitrous Oxide from Agricultural Soil Management (IPCC 3C4 & 3C5)

### 1. Background

Modern agriculture is characterized by the intensive use of fertilizers, especially synthetic nitrogen fertilizers. The large scale input of nitrogen into agricultural soils has greatly increased the nitrogen availability for microbial processes such as nitrification and denitrification. Nitrous oxide is an intermediate gaseous product of denitrification and a by-product of nitrification that leaks from microbial cells into the soil and ultimately into the atmosphere. There are many sources of nitrogen input into agricultural soils aside from synthetic fertilizers: application of organic fertilizers, manure and sewage sludge; decomposition of crop residues; and mineralization of N in soil organic matter following drainage of organic soils (histosols). All these human activities increase the supply of mineral nitrogen, and therefore $N_2O$ emissions from agricultural soils. These emissions are called *direct emissions* because they occur directly from the soils to which N is applied, and are reported under IPCC category 3C4.

In addition to the direct emissions of $N_2O$ from managed soils, emissions of $N_2O$ also take place through two indirect pathways. The first indirect pathway is the volatilization of a portion of the applied nitrogen as $NH_3$ and oxides of N ($NO_x$). Eventually, this volatilized N is deposited onto soils and the surface of lakes and other waters where nitrification and denitrification processes cause $N_2O$ emissions. The second pathway is the leaching and runoff from land of N from synthetic and organic fertilizer additions, crop residues, mineralization of N in soil organic matter following drainage of organic soils, and urine and dung deposition from grazing animals. This nitrogen ends up in the groundwater below the land to which the N was applied, in riparian zones receiving drain or runoff water, or in the ditches, streams, rivers and estuaries (and their sediments) into which the land drainage water eventually flows. There, it is subject to the nitrification and denitrification processes that produces $N_2O$ emissions. These *indirect emissions* are reported under IPCC category 3C5.

## 2. Methodology

ARB staff used emission factor equations, which are based on the USEPA Emission Inventory Improvement Program (EIIP) guidance (USEPA, 2004b) and the Tier 1 methodology of the 2006 IPCC guidelines (IPCC, 2006e).

### *2.1 Emission Estimation*

$N_2O$ emissions are estimated separately for direct emissions and indirect emissions. The following equations describe the IPCC methods and steps in calculating $N_2O$ emissions from managed soils.

(a) Direct $N_2O$ emissions (IPCC category 3C4)

Direct $N_2O$ emissions are calculated with the following equation:

*Equation 75: Direct $N_2O$ emissions from managed soils*

$$E_{direct} = \left\{ \begin{array}{l} \left[ N_{SF} + N_{OF} + N_{MM} + N_{CR} \right] \bullet EF_1 \\ + N_{UM,CPP} \bullet EF_{2,CPP} + N_{UM,SGH} \bullet EF_{2,SGH} \\ + A_{OS} \bullet EF_3 \end{array} \right\} \bullet 1.5711$$

Where,

$E_{direct}$ = Direct $N_2O$ emissions from managed soils (kg $N_2O$)
$N_{SF}$ = Amount of N from synthetic fertilizers applied to soils (kg N)
$N_{OF}$ = Amount of N from organic fertilizers applied to soils (kg N)
$N_{MM}$ = Amount of N from managed manure spread on soils (kg N)
$N_{CR}$ = Amount of N in crop residues that is returned to soils (kg N)
$N_{UM, CPP}$ = Amount of N from un-managed manure from grazing cattle, poultry and pigs (kg N)
$N_{UM, SGH}$ = Amount of N from the un-managed manure from grazing sheep, goats and horses (kg N)
$A_{OS}$ = Area of drained organic soil (histosols) (ha)
$EF_1$ = Emission factor: proportion of N applied to agricultural soils that is emitted as $N_2O$
$EF_{2, CPP}$ = Emission factor: proportion of N from cattle, poultry and pigs un-managed manure that is emitted as $N_2O$
$EF_{2, SGH}$ = Emission factor: proportion of N from sheep, goats and horses un-managed manure that is emitted as $N_2O$
$EF_3$ = Emission factor: N emitted as $N_2O$ per unit area of cultivated of organic soils (kg N per ha)
1.5711 = Molecular weight ratio of $N_2O$ to $N_2$

### (b) Indirect $N_2O$ emissions (IPCC category 3C5)

Indirect $N_2O$ emissions are calculated with the following equations:

*Equation 76: Indirect $N_2O$ emissions from managed soils*

$$\boxed{E_{indirect} = E_V + E_{LR}}$$

Where,

$E_{indirect}$ = Indirect $N_2O$ emissions from managed soils (kg $N_2O$)
$E_V$ = Indirect $N_2O$ emissions through nitrogen volatilization (kg $N_2O$)
$E_{LR}$ = Indirect $N_2O$ emissions through nitrogen leaching and runoff (kg $N_2O$)

### *(b.i) Emissions from volatilization ($E_V$)*

Indirect emissions from volatilized N are estimated as follows:

*Equation 77: Indirect $N_2O$ emissions from volatilization*

$$\boxed{E_V = \left[N_{SF} \bullet V_1 + (N_{OF} + N_{MM} + N_{UM}) \bullet V_2\right] \bullet EF_4 \bullet 1.5711}$$

Where,

$E_V$ = Emissions of $N_2O$ from volatilization (kg)
$N_{SF}$ = Amount of N from synthetic fertilizers applied to soils (kg N)
$N_{OF}$ = Amount of N from organic fertilizers applied to soils (kg N)
$N_{MM}$ = Amount of N from managed manure applied to soils (kg N)
$N_{UM}$ = Amount of N from un-managed manure [$N_{UM,\ CPP}$ + $N_{UM,\ SGH}$] (kg N)
$V_1$ = Fraction of synthetic fertilizer N that volatilizes (unitless)
$V_2$ = Fraction of organic fertilizer and manure N that volatilizes (unitless)
$EF_4$ = Emission factor: proportion of N volatilized and re-deposited on soils that is emitted as $N_2O$

### *(b.ii) Emissions from leaching and runoff ($E_{LR}$)*

Indirect emissions from N lost to leaching and runoff are estimated as:

*Equation 78: Indirect $N_2O$ emissions from N lost to leaching and runoff*

$$\boxed{E_{LR} = \left[N_{SF} + N_{OF} + N_{MM} + N_{UM}\right] \bullet L \bullet EF_5 \bullet 1.5711}$$

Where,

$E_{LR}$ = Emissions of $N_2O$ from leaching and run-off (kg)
$N_{SF}$ = Amount of N from synthetic fertilizers applied to soils (kg N)
$N_{OF}$ = Amount of N from organic fertilizers applied to soils (kg N)
$N_{MM}$ = Amount of N from managed manure applied to soils (kg N)
$N_{UM}$ = Amount of N from un-managed manure [$N_{UM,\ CPP}$ + $N_{UM,\ SGH}$] (kg N)
L = Leaching factor: proportion of N lost by leaching and runoff for regions where the soil water-holding capacity is exceeded as a result of rainfall and/or irrigation.
$EF_5$ = Emission factor: Proportion of N lost to leaching and runoff that is emitted as $N_2O$

The values for the emission, volatilization and leaching-runoff factors are given in Table 41.

*Table 41: Factors for the estimation of $N_2O$ emissions from agricultural soil management*

| Emission factor | Description | Default Value |
|---|---|---|
| $EF_1$ | Proportion of N applied to agricultural soils that is emitted as $N_2O$ | 0.01 |
| $EF_{2,\ CPP}$ | proportion of N deposited on pastures, rangelands, and paddocks by cattle, poultry and pigs [PRP–CPP] that is emitted as $N_2O$ | 0.02 |
| $EF_{2,\ SGH}$ | proportion of N deposited on pastures, rangelands, and paddocks by sheep, goats, horses [PRP–SGH] that is emitted as $N_2O$ | 0.01 |
| $EF_3$ | N emitted as $N_2O$ per unit area of drained organic soils (kg N per ha) | 8 |
| $EF_4$ | Proportion of N volatilized and re-deposited on soils that is emitted as $N_2O$ | 0.01 |
| $EF_5$ | Proportion of N lost to leaching and runoff that is emitted as $N_2O$ | 0.0075 |
| $V_1$ | Fraction of synthetic fertilizer N that volatilizes | 0.1 |
| $V_2$ | Fraction of organic fertilizer and manure N that volatilizes | 0.2 |
| $L$ | Leaching rate: fraction of N lost by leaching and runoff for regions where the soil water-holding capacity is exceeded as a result of rainfall and/or irrigation | 0.3 |

Source: IPCC 2006 guidelines.

### 2.2 Calculation of nitrogen inputs from various sources

To limit the number of subcategories in the inventory, staff compiled the nitrogen inputs from fertilizers, animal manure, crop residues, and aggregated them into the following categories.

(a) Synthetic and organic fertilizers nitrogen

The amount of nitrogen in synthetic fertilizers ($N_{SF}$) and organic fertilizers ($N_{OF}$) applied to soils were compiled from the data published in California Department of Food and Agriculture *Fertilizing Materials Tonnage Reports* (CDFA, various years)

(b) Animal manure nitrogen

The amount of nitrogen in animal manure is estimated in the manure management section (see III.B above). The amount of N in managed manure ($N_{MM}$) is calculated as the total N excreted by animal groups in manure management systems minus the amount of nitrogen lost to volatilization, runoff and direct $N_2O$ emissions during the manure management phase. The amount of N in un-managed manure is equal to the total N excreted by animal groups depositing their urine and dung directly on the land (i.e. pasture, rangeland and paddocks) and animal groups whose manure is spread daily.

Unmanaged manure N is grouped in two categories: manure N from cattle, poultry and pigs ($N_{UM, CPP}$); and that from sheep, goats and horses ($N_{UM, SGH}$) (see Table 35 and Table 36).

(c) Crop residues nitrogen

The amount of nitrogen from crop residues ($N_{CR}$) comprises above-ground and below-ground residues N and includes N-fixing crops. The nitrogen is returned to the soil as the crop is renewed. Crops are generally renewed on an annual basis, with some exceptions such as alfalfa which is typically renewed every four years. Since the combustion of residue causes most of its nitrogen to be volatilized, an adjustment must be made for burning of crop residue. $N_{CR}$ is calculated using the following equations, the variables and regression parameters used in the equations are from the IPCC guidelines (Table 11.2 in IPCC, 2006e) unless the source is noted otherwise:

*Equation 79: Amount of nitrogen input from crop residues*

$$\boxed{N_{CR} = \sum_{crop} \left( N_{AGR,crop} + N_{BGR,crop} \right)}$$

Where,

$N_{CR}$ = Amount of N in crop residues that is returned to soils (kg)
$N_{AGR, crop}$ = Amount of N in the above-ground residues of the given crop (kg)
$N_{BGR, crop}$ = Amount of N in the below-ground residues of the given crop (kg)

With,

Crop = crops listed in Table 43.

The amount of nitrogen in the above-ground residues of a given crop ($N_{AGR, crop}$) is calculated as follows:

*Equation 80: Amount of nitrogen in the above-ground residues of a crop*

$$\boxed{N_{AGR,crop} = A_{NBR,crop} \bullet M_{AGR,crop} \bullet NC_{AGR,crop}}$$

Where,

$N_{AGR, crop}$ = Amount of N in a given crop above-ground residues that is returned to soils (kg)
$A_{NBR, crop}$ = Area of the given crop that is not burned after harvest and is renewed (kg)
$M_{AGR, crop}$ = Mass of above-ground residue left after harvest of the given crop (kg dry matter per ha)
$NC_{AGR, crop}$ = Nitrogen content of above-ground residues of the given crop (fraction)

With,

Crop = crops listed in Table 43.

The amount of above-ground residue of a given crop ($M_{AGR,\ crop}$) can be estimated from its harvested yield using:

*Equation 81: Amount above-ground residues of a crop*

$$\boxed{M_{AGR,crop} = \beta_{0,crop} + \beta_{1,crop} \bullet M_{Yield,crop}}$$

Where,

$M_{AGR,\ crop}$ = Mass of above-ground residue left after harvest of the given crop (kg dry matter per ha)
$\beta_{0,crop}$ = Intercept of linear regression of the given crop's above-ground residue on its yield
$M_{Yield,\ crop}$ = Mass harvested yield of the given crop (kg dry matter per ha)
$\beta_{1,\ crop}$ = Slope of linear regression of the given crop's above-ground residue on its yield

With,

Crop = crops listed in Table 43.

The amount of nitrogen in the below-ground residues of a given crop ($N_{BGR,\ crop}$) is calculated as follows:

*Equation 82: Amount of nitrogen in the below-ground residues of a crop*

$$\boxed{N_{BGR,crop} = A_{NBR,crop} \bullet \left(M_{Yield,crop} + M_{AGR,crop}\right) \bullet R_{BA,crop} \bullet NC_{BGR,crop}}$$

Where,

$N_{BGR,\ crop}$ = Amount of N in a given crop below-ground residues that is returned to soils (kg)
$A_{NBR,\ crop}$ = Area of the given crop that is not burned after harvest and is renewed (ha)
$M_{Yield,\ crop}$ = Mass of harvested yield of the given crop (kg dry matter per ha)
$M_{AGR,\ crop}$ = Mass of above-ground residue left after harvest of the given crop (kg dry matter per ha)
$R_{BA,\ crop}$ = Ratio of below-ground residue to above-ground biomass of the given crop
$NC_{BGR,\ crop}$ = Nitrogen content of below-ground residues of the given crop (fraction)

With,

Crop = crops listed in Table 43.

The area of a given crop that is not burned in the given year and is renewed ($A_{NBR,\ crop}$) is calculated as follows:

*Equation 83: Area of the given crop that is not burned and is renewed*

$$\boxed{A_{NBR,crop} = A_{H,crop} \bullet \left(1 - (F_{AB,crop} \bullet F_{RC,crop}\right) \bullet F_{AR,crop}}$$

Where,

$A_{NBR,\ crop}$ = Area of the given crop that is not burned after harvest and is renewed (ha)

$A_{H,\ crop}$ = Area of the given crop that is harvested (ha)

$F_{AB,\ crop}$ = Fraction of the given crop harvested area on which residues are burned (see Agricultural Residue Burning section III.D)

$F_{RC,\ crop}$ = Fraction of the residue combusted when crop residues are burned

$F_{AR,\ crop}$ = Fraction of the given crop area that is renewed each year

With,

Crop = crops listed in Table 43.

*Table 42: Fraction of crop area renewed each year ($F_{AR,\ crop}$) and fraction of residue combusted when crop residues are burned ($F_{RC,\ crop}$)*

| **Crop** | $F_{AR,\ crop}$ | $F_{RC,\ crop}$ |
|---:|---:|---:|
| Alfalfa hay | 0.25 | 0 |
| Other hay | 0.5 | 0 |
| Corn for grain | 1 | 0.8 |
| Corn for silage | 1 | 0 |
| Wheat winter | 1 | 0.9 |
| Wheat durum | 1 | 0.9 |
| Barley | 1 | 0.9 |
| Sorghum for grain | 1 | 0 |
| Sorghum for silage | 1 | 0 |
| Oats | 1 | 0 |
| Rice | 1 | 0.8 |
| Potatoes | 1 | 0 |
| Dry Edible Beans | 1 | 0 |

Crop renewal data from cost studies of the UC Davis Agricultural Economics department, and assuming half of non-legume hay crop is annual; residue combusted data from IPCC 2006 Volume 4 Chapter 2 Table 2.6 and assuming Barley same as wheat.

The nitrogen input to soils from crop residues ($N_{CR,\ crop}$) are shown in Table 43.

*Table 43: Amount of nitrogen input to soils from crop residues (metric tons)*

| **Crop** | **2000** | **2001** | **2002** | **2003** | **2004** | **2005** | **2006** | **2007** | **2008** | **2009** |
|---:|---:|---:|---:|---:|---:|---:|---:|---:|---:|---:|
| Alfalfa hay | 25,700 | 25,448 | 28,810 | 27,463 | 26,456 | 25,829 | 26,923 | 25,656 | 26,456 | 26,067 |
| Other hay | 6,150 | 7,201 | 7,476 | 7,835 | 7,898 | 8,574 | 9,123 | 9,689 | 9,309 | 7,071 |
| Corn for grain | 7,368 | 5,750 | 5,391 | 4,751 | 5,541 | 4,728 | 3,843 | 7,589 | 6,963 | 6,071 |
| Corn for silage | 6,765 | 6,458 | 7,995 | 7,893 | 7,893 | 8,713 | 8,622 | 9,474 | 9,953 | 7,893 |
| Wheat winter | 9,433 | 9,191 | 7,848 | 8,704 | 9,318 | 7,454 | 5,061 | 6,594 | 14,277 | 11,236 |
| Wheat durum | 3,216 | 2,813 | 2,984 | 3,812 | 300 | 2,178 | 2,134 | 2,368 | 4,120 | 4,561 |
| Barley | 1,732 | 1,618 | 1,419 | 1,006 | 1,228 | 1,023 | 988 | 655 | 912 | 825 |
| Sorghum for | 153 | 154 | 221 | 221 | 265 | 221 | 250 | 243 | 207 | 207 |

| **Crop** | **2000** | **2001** | **2002** | **2003** | **2004** | **2005** | **2006** | **2007** | **2008** | **2009** |
|---|---|---|---|---|---|---|---|---|---|---|
| grain | | | | | | | | | | |
| Sorghum for silage | 46 | 46 | 78 | 110 | 184 | 221 | 321 | 300 | 495 | 495 |
| Oats | 315 | 267 | 430 | 462 | 346 | 252 | 280 | 297 | 330 | 491 |
| Rice | 15,639 | 15,427 | 17,558 | 16,002 | 20,852 | 15,780 | 17,034 | 17,382 | 17,802 | 19,651 |
| Potatoes | 1,242 | 990 | 1,255 | 1,261 | 1,300 | 1,154 | 1,152 | 1,139 | 1,090 | 1,078 |
| Dry Edible Beans | 887 | 656 | 736 | 594 | 477 | 562 | 518 | 496 | 412 | 604 |
| Total ($N_{CR}$) | 78,645 | 76,021 | 82,201 | 80,116 | 82,059 | 76,689 | 76,248 | 81,882 | 92,326 | 86,251 |

### (d) Area of drained organic soil ($A_{OS}$)

In California, the Sacramento-San Joaquin Delta was once a 540 square mile tidal marsh where peat soils (termed organic soils or histosols) accreted for thousands of years. Peat is made of partially decayed organic matter that accumulates under waterlogged —and thus anaerobic— conditions. The layer of peat in the Delta is up to 50 feet thick. In the late 1800's Delta land was "reclaimed" with levees and since then it has been drained and used for crops and as pasture land. Drainage exposes peat to oxygen and triggers rapid microbial oxidation which results in the continuous release of large amounts of the stored carbon to the atmosphere as $CO_2$. Peat oxidation is the principal cause of land subsidence in the Delta, some "islands" are now down to 25 feet below mean sea level. Subsidence continues at a rate of 1 to 3 inches per year. As organic soils oxidize, the N-rich organic matter mineralizes thereby increasing $N_2O$ emissions from these soils.

The area of drained organic soils in the Sacramento-San Joaquin Delta was determined with a Geographic Information System (GIS) using the following steps:

- Download the Soil Survey Geographic (SSURGO) database from U.S. Department of Agriculture, Natural Resources Conservation Service website for counties comprising the Delta (Contra Costa, Sacramento, San Joaquin, Solano and Yolo).
- Use the NRCS soil classification and attributes to identify all organic soils.
- Overlay the organic soils with the 2001 National Land Cover Data (NLCD 2001) downloaded from the USGS website to identify all areas of organic soils that are drained (i.e. developed, grassland/pasture, cultivated).
- Calculate the sum of area in ha of drained organic soils.

## 3. Data Sources

Fertilizer use data was obtained from *Fertilizing Materials Tonnage Reports*, published by the California Department of Food and Agriculture (CDFA, various years). Crop yield and acreage harvested data were taken from CDFA

Agriculture Resources Directories (CDFA 2011). The amount of manure returned to soils as fertilizer is estimated in section III.B above. Variables and regression parameters for the crop residues estimates are from the IPCC guidelines (Table 11.2 in IPCC, 2006e). The data for the fraction of crop area renewed each year are from cost studies of the UC Davis Agricultural Economics department, and assume half of non-legume hay crop is annual. The fraction of crop harvested area on which residues are burned is discussed in the Agricultural Residue Burning section (III.D). Residue combusted data are from IPCC 2006 Guidelines Volume 4 Chapter 2 Table 2.6 and assume barley values are the same as wheat's values. Drained organic soils area was estimated based on the Soil Survey Geographic (SSURGO) database from U.S. Department of Agriculture, Natural Resources Conservation Service and the 2001 National Land Cover Data (NLCD 2001) downloaded from the USGS website. The emission factors and conversion factors were from IPCC guidelines (IPCC, 2006a).

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at: http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_3f_nitrous_oxide_from_agricultural_soil_management.pdf

### 4. Changes in Estimates

The main changes in data and methods used in the current estimation of emissions of $N_2O$ from agricultural soil management, when compared with those used for the 1990-2004 edition of GHG Inventory, are:

- Calculations of the amount of N input to soils from N-fixing crops (i.e., plants that convert atmospheric $N_2$ to biologically available N) have changed following the 2006 IPCC recommendations. Biological nitrogen fixation has been removed as a direct source of $N_2O$ because of the lack of evidence of significant emissions arising from the fixation process itself. However, the above-ground and below-ground nitrogen inputs from crop/forage residue remain in the estimates (see IPCC, 2006a).
- A differentiation is made between the amount of N in un-managed manure from cattle, poultry and pigs [UM–CPP]; and from sheep, goats and horse [UM–SGH] following the 2006 IPCC guidelines. The direct emission factor for the nitrogen from UM-SGH was reduced by half.
- The amount of nitrogen in animal manure that is applied to soils is estimated in the manure management section (see III.B above) rather than by an independent accounting in this section. This change increases the consistency of estimates across emissions categories.
- The estimation of the amount of N returned to soils by crop residues has been updated from a method based on older IPCC guidelines (IPCC, 1997) to an improved method based on the 2006 IPCC guidelines (IPCC, 2006a).

- The estimate of the area of drained organic soils has been updated to an objective method using GIS analysis of detailed spatial datasets.

All together these changes resulted in limited adjustments in emissions estimates for the categories included in this section: +12.6 percent on average over the years 2000 to 2004 when compared with the estimates in the first edition of ARB's GHG inventory.

### 5. Future Improvements

Simple emission factor models can not reflect variations in emissions due to the many factors (such as climate, soil, cropping systems and agricultural practices) that affect $N_2O$ emissions. Process based models can be constructed to quantify the physical, chemical, biological and physiological processes associated with nitrification and denitrification in managed soils. A modeling approach to estimating emissions is generally considered to be more accurate, but it also requires more extensive data. USEPA started using the DAYCENT model in 2005 to calculate $N_2O$ emissions from major agricultural crops (USEPA, 2007a). The ARB has sponsored a study to explore the possibility of using the DNDC model to estimate GHG emissions from California agricultural systems. The data necessary to parameterize and validate such models for agricultural crops grown in California is currently being developed.

## *G. Rice Cultivations (3C7)*

### 1. Background

Methane is produced by the anaerobic decomposition of organic material in flooded rice fields. It escapes to the atmosphere mostly through the rice plants aerenchyma system. The amount of $CH_4$ emitted annually per unit area is a function of: the number and duration of crops grown, the flooding regime before and during the cultivation period, the amount of organic and inorganic soil amendments, the soil type and temperature, and the rice cultivar.

### 2. Methodology

The methodology used for estimating $CH_4$ emissions from rice cultivation follows the revised 1996 IPCC guidelines (IPCC, 1997). The computation is:

*Equation 84: $CH_4$ emissions from rice cultivation*

$$\boxed{E = A \bullet EF}$$

Where,
E = Amount of $CH_4$ emitted by rice cultivation (g)
A = Harvested rice area (ha)
EF = California specific $CH_4$ emission factor (g/ha)

### 3. Data Sources

Harvested rice area data are from the crop production summary reports published by the U.S. Department of Agriculture's National Agricultural Statistics Service (USDA, 2011b). The California-specific emission factor is from CEC's 2002 GHG inventory report (CEC, 2002). This factor was computed at the time from values taken from four papers reporting California specific measurements. Measured seasonal $CH_4$ emissions were averaged to represent the wide range of rice cultivation conditions that exist in California. Experiments on fields with and without added nitrogen fertilizer, with and without winter flooding, and with all variations of rice straw management (incorporated, rolled, or burned) were included.

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at: http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_3g_rice_cultivations.pdf

### 4. Changes in Estimates

No change was made to the estimates.

### 5. Future Improvements

The current IPCC guidelines (IPCC, 2006a), recognizing that the natural conditions and agricultural management of rice production may be highly variable, advise that it is good practice to account for this variability by disaggregating the total harvested area into sub-units (e.g., different water regimes, amendments). Then, the harvested area for each sub-unit is multiplied by the respective cultivation period and emission factor that is representative of the conditions that define the sub-unit. The total annual emissions are equal to the sum of emissions from each sub-unit of harvested area. ARB staff will be seeking the information necessary to apply this updated methodology in future editions of the GHG inventory.

# IV. Waste

## *A. Landfills (IPCC 4A1)*

### 1. Background

Landfills are sites for solid waste disposal in which refuse is buried between layers of dirt so as to fill in or reclaim low-lying ground or excavated pits; they are the oldest form of waste treatment. There are numerous types of landfills accepting different types of waste. The GHG inventory is concerned only with landfills that contain and/or receive biodegradable, carbon-bearing waste. The Department of Resources Recycling and Recovery (CalRecycle) —previously known as California Integrated Waste Management Board or CIWMB— has identified 372 such landfills in the State. Most of the waste contained in these landfills (95 percent) is currently under a control system that reduces the emissions of methane, the principal GHG pollutant generated by landfills, by combustion of the gas.

Landfilled carbon-bearing waste degrades mainly through anaerobic biodegradation. In an anaerobic environment (i.e., without oxygen from the air), water ($H_2O$) is the source of oxygen (O) for oxidation and becomes the limiting reactant for biodegradation. The water content of a landfill determines how fast the waste degrades. If water is not available, the waste does not degrade. This anaerobic biodegradation process generates approximately equal amounts of $CO_2$ and $CH_4$ gas as a byproduct:

*Equation 85: Anaerobic biodegradation process*

$$\boxed{2C + 2H_2O \rightarrow CO_2 + CH_4}$$

A large fraction (49 percent to 62 percent) of the carbon in the waste will not degrade under these anaerobic conditions and is effectively sequestered. This carbon will remain sequestered as long as the landfill's anaerobic conditions persist.

The various gases produced as the waste degrades are collectively called "landfill gas". Landfill gas is an odor nuisance, a source of air toxics and may even be a physical danger to those living near a landfill because the methane it contains is combustible. For these reasons, most landfills in the State (holding about 95 percent of the waste) are equipped with a gas collection system. However, although those collection systems are designed to collect landfill gas, it is known that a portion of the gas does escape into the atmosphere.

Once collected, landfill gas can simply be vented to the air if the only reason for the collection was to address offsite gas migration issues. Alternatively, the collected landfill gas may be stripped of its non-methane components via carbon adsorption, of which the main purpose is to reduce odors and/or volatile organic compounds (VOC) and toxics. Carbon adsorption allows most (99 percent) of the $CH_4$ to escape. Most commonly, the collected landfill gas is combusted, either in a flare (to destroy odors and VOC and toxic components in the gas), or in an engine or turbine to generate electricity.

## 2. Methodology

ARB staff requested site-specific landfill gas collection data through landfill surveys, but received answers for only certain years and for about half of the landfilled waste (e.g., approximately 52 percent in 2006, the latest data year reported in the surveys to ARB). Therefore, staff opted to use a model to estimate landfill emissions for all sites, and used the survey data to supplement these predictions where available.

Staff used the Mathematically Exact First-Order Decay (FOD) model from the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines (IPCC, 2006f). In summary, this model assumes that a fixed fraction of the waste available at any moment will degrade. The amount that degrades over a given amount of time is determined by a factor (*k*), which is tied to the moisture content in the landfill. The *k* values used in the model were obtained from USEPA and are a function of the annual precipitation occurring at each landfill; rainfall being used as a surrogate for landfill moisture content. The model assumes that the waste carbon is biodegraded into equal amounts of $CO_2$ and $CH_4$ (see Equation 85).

### 2.1 Model Equations

The inputs to the model are the amount of anaerobically degradable organic carbon (ANDOC), the delay in months before waste begins to decay anaerobically (*M*), the rate at which waste decays (*k*), and the fraction of degraded carbon that is converted into $CH_4$ ($F_{CH4}$). Of these four inputs, three are set by using default values: a six month default for *M*, a 50 percent default for $F_{CH4}$ and USEPA defaults based on rainfall levels for *k*. Only *ANDOC* requires a more detailed method of derivation, which is the focus of Equation 86 below. The inputs for calculating *ANDOC* are therefore important determinants of landfill emissions estimates.

(a) Anaerobically Degradable Organic Carbon (*ANDOC*)

*Equation 86: Anaerobically degradable organic carbon*

$$ANDOC = WIP \bullet 0.9072 \bullet \sum_{component} (FW_{component} \bullet DOC_{component} \bullet DANF_{component})$$

Where,

ANDOC = Anaerobically Degradable Organic Carbon: the amount of waste carbon that is biodegradable in an anaerobic environment (Mg (i.e., $10^6$ grams) of carbon)
WIP = Waste-in-Place: the landfilled waste (wet weight) as reported to the California Integrated Waste Management Board (tons)
0.9072 = Short ton to Mg (a.k.a. tonne or metric ton) conversion
$FW_{component}$ = Fraction of a given waste component in the landfilled waste
$DOC_{component}$ = Degradable Organic Carbon (DOC) content of the given waste component.
$DANF_{component}$ = Decomposable Anaerobic Fraction (DANF) of the given waste component.

With,

Component = [Newspaper, Office Paper, Corrugated Boxes, Coated Paper, Food, Grass, Leaves, Branches, Lumber, Textiles, Diapers, Construction/Demolition, Medical Waste, Sludge/Manure]

### *(a.i) Waste-In-Place (WIP)*

The Department of Resources Recycling and Recovery (CalRecycle) staff provided ARB staff with Waste-in-Place (*WIP*) data in two basic forms: 1) the cumulative amount of waste deposited, by landfill, up to the year 1990 and, 2) the amounts deposited, by landfill, each year from 1991 to 2009 for those landfills still receiving waste after 1990. CalRecycle staff also furnished the amounts of green waste and sludge used as daily cover by each landfill from 1995 to 2009. CalRecycle staff provided data on 372 landfills known to contain waste that is biodegradable. Landfills containing only inert waste, like ash and masonry from demolition sites, were excluded. ARB staff also received survey data from 48 of these landfills (comprising 52.4 percent of the 2006 WIP, the last year reported by the surveys) and used them to update the CalRecycle data. In most cases, however, these updates were modest.

Yearly amounts of deposited waste are necessary inputs for the IPCC FOD model to work properly. Yearly data were not available before 1990, however, only the cumulative WIP totals in 1990 were known. This led staff to estimate how much of these cumulative amounts were deposited each year from the landfills' opening year to 1990 (or up to their closure year if they closed before 1990). This estimation was made as follows. First, ARB staff inquired about the opening and closure dates for all landfills. CalRecycle staff had closure dates for all 372 landfills of interest, but did not have a complete list of opening dates, so an estimate was made for those cases where the opening date was missing. Once these dates were established, the cumulative total of WIP in each landfill was distributed over the pre-1990 years (from opening to 1990, or opening to closure if before 1990) in a manner commensurate to the trend in California's population over those years. As a result, a larger proportion of the waste in place was distributed in the later years of this range than in the earlier ones, since the population kept growing over the time period.

### *(a.ii) Components of the Waste-in-Place*

To determine its DOC and DANF, the WIP must first be disaggregated into its component parts. Disaggregation was done on the basis of waste characterization studies from CalRecycle and the USEPA. The CalRecycle studies were conducted in 1999, 2004 and 2008; the 1999 study was used to characterize waste for 1996 to 2002, the 2004 study for 2003 to 2006 and the 2008 study for 2007 and beyond, as suggested by CalRecycle's staff. For years prior to 1995, staff used the USEPA study that best applied to a given year. The USEPA did waste characterization studies in 1960, 1970, 1980, 1990 and 1995. Staff used the waste profiles from those studies as follows: up to 1964

(1960 survey), 1965-1974 (1970 survey), 1975-1984 (1980 survey), 1985-1992 (1990 survey) and 1993-1995 (1995 survey). Applying these profiles allowed disaggregating the waste deposited each year into its component parts. The components of interest to estimate TDOC (i.e., those containing biodegradable carbon content) are listed in Table 44.

*Table 44: Waste characterization – Percentage of each component in the overall waste in place*

| ***Waste Component*** | ***Up to 1964*** | ***1965 - 1974*** | ***1975 - 1984*** | ***1985 - 1992*** | ***1993 - 1995*** | ***1996 - 2002*** | ***2003 - 2006*** | ***2007 +*** |
|---:|---:|---:|---:|---:|---:|---:|---:|---:|
| Newspaper | 6.4% | 6.4% | 5.9% | 4.8% | 3.9% | 4.3% | 2.2% | 1.7% |
| Office Paper | 10.7% | 11.3% | 12.0% | 13.1% | 15.0% | 4.4% | 2.0% | 1.8% |
| Corrugated Boxes | 10.8% | 13.5% | 11.5% | 10.5% | 10.3% | 4.6% | 5.7% | 4.8% |
| Coated Paper | 2.2% | 2.0% | 2.4% | 2.1% | 1.8% | 16.9% | 11.1% | 9.0% |
| Food | 14.8% | 11.3% | 9.5% | 12.1% | 13.4% | 15.7% | 14.6% | 15.5% |
| Grass | 12.1% | 10.3% | 10.1% | 9.0% | 6.6% | 5.3% | 2.8% | 1.9% |
| Leaves | 6.1% | 5.1% | 5.0% | 4.5% | 3.3% | 2.6% | 1.4% | 3.2% |
| Branches | 6.1% | 5.1% | 5.0% | 4.5% | 3.3% | 2.4% | 2.6% | 2.0% |
| Lumber | 3.7% | 3.3% | 5.1% | 7.0% | 7.3% | 4.9% | 9.6% | 14.5% |
| Textiles | 2.1% | 1.8% | 1.7% | 3.3% | 4.5% | 2.1% | 4.4% | 5.5% |
| Diapers | 0.1% | 0.3% | 1.4% | 1.6% | 1.9% | 6.9% | 4.4% | 4.3% |
| Construction/Demolition | 2.6% | 2.5% | 3.5% | 3.9% | 4.5% | 6.7% | 12.1% | 5.5% |
| Medical Waste | - | - | - | - | - | 0.0% | 0.0% | 0.0% |
| Sludge/Manure | - | - | - | - | - | 0.1% | 0.1% | 0.1% |

* Dash indicates no data available; percentage assumed to be zero.

The amounts of green waste and sludge used as daily cover were included with the landfill WIP. According to CalRecycle staff, most of the daily cover is green waste, thus ARB staff assumed that 10 percent of the daily cover amounts were sludge and 90 percent green waste. Green waste was further split based on USEPA studies (Table 45).

*Table 45: Waste characterization of daily green waste cover material*

| ***Daily Cover Waste Component*** | ***Assumed Content Percentage*** |
|---:|---:|
| Grass | 50% |
| Leaves | 25% |
| Branches | 25% |

### *(a.iii) Degradable Organic Carbon (DOC) content*

Staff obtained values for the Degradable Organic Carbon (DOC) content of solid waste components from USEPA (Newspaper, Office Paper, Corrugated Boxes, Coated Paper, Food, Grass, Leaves, Branches) and from the 2006 IPCC Guidelines (Lumber, Textiles, Diapers, Construction/Demolition, Medical Waste, Sludge/Manure). These values are summarized in Table 46.

*Table 46: Degradable Organic Carbon (DOC) content of different MSW components*

| ***Waste Component*** | ***DOC Fraction (Mg DOC / Mg wet waste)*** | ***Source*** |
|---:|---:|:---:|
| Newspaper | 0.471 | USEPA |
| Office Paper | 0.385 | USEPA |
| Corrugated Boxes | 0.448 | USEPA |
| Coated Paper | 0.330 | USEPA |
| Food | 0.148 | USEPA |
| Grass | 0.133 | USEPA |
| Leaves | 0.291 | USEPA |
| Branches | 0.442 | USEPA |
| Lumber | 0.430 | CEC |
| Textiles | 0.240 | IPCC |
| Diapers | 0.240 | IPCC |
| Construction/Demolition | 0.040 | IPCC |
| Medical Waste | 0.150 | IPCC |
| Sludge/Manure | 0.050 | IPCC |

### *(a.iv) Decomposable Anaerobic Fraction (DANF)*

Theoretically, all biodegradable carbon-bearing waste can degrade, but only a portion actually degrades in the special anaerobic environment of landfills. The carbon in the waste that does not decompose remains sequestered.

Values for the DANF of different MSW components came from USEPA (Newspaper, Office Paper, Corrugated Boxes, Coated Paper, Food, Grass, Leaves, and Branches), the CEC (lumber) and the IPCC guidelines (default of 50 percent anaerobic decomposition for Textiles, Diapers, Construction/Demolition, Medical Waste, and Sludge/Manure).

*Table 47: Decomposable anaerobic fraction (DANF) of the DOC of different MSW components*

| ***Waste Component*** | ***Decomposable Anaerobic Fraction*** | ***Source*** |
|---:|---:|---:|
| Newspaper | 0.150 | USEPA |
| Office Paper | 0.870 | USEPA |
| Corrugated Boxes | 0.442 | USEPA |
| Coated Paper | 0.243 | USEPA |
| Food | 0.865 | USEPA |
| Grass | 0.474 | USEPA |
| Leaves | 0.073 | USEPA |
| Branches | 0.231 | USEPA |
| Lumber | 0.233 | CEC |
| Textiles | 0.500 | IPCC |
| Diapers | 0.500 | IPCC |
| Construction/Demolition | 0.500 | IPCC |
| Medical Waste | 0.500 | IPCC |

| **Waste Component** | **Decomposable Anaerobic Fraction** | **Source** |
|---:|---:|---:|
| Sludge/Manure | 0.500 | IPCC |

### (a.v) Overall waste profile and estimate of landfilled carbon sequestration

With the data described above, staff calculated the overall waste profile for California (Table 48). Staff also estimated the amount of non-decomposable organic carbon in landfills, that is, the carbon which is expected to remain sequestered until removed from the anaerobic conditions present in landfills (Table 49).

*Table 48: Overall waste profile for California - Percentage of each component in the overall waste in place*

| **Waste Type** | **Up to 1964** | **1965 - 1974** | **1975 - 1984** | **1985 - 1992** | **1993 - 1995** | **1996 - 2002** | **2003 - 2006** | **2007 +** |
|---|---:|---:|---:|---:|---:|---:|---:|---:|
| 1. Biodegradable Carbon | 23.16% | 22.90% | 22.86% | 23.32% | 22.95% | 20.77% | 18.87% | 19.78% |
| a. Decomposable | 10.45% | 10.44% | 10.34% | 11.02% | 11.62% | 8.42% | 7.45% | 7.52% |
| b. Sequestered | 12.71% | 12.46% | 12.52% | 12.30% | 11.33% | 12.35% | 11.42% | 12.25% |
| 2. Other Materials | 76.84% | 77.10% | 77.14% | 76.68% | 77.05% | 79.23% | 81.13% | 80.22% |

Most of the waste in landfills is non-biodegradable. Of that portion that is biodegradable (19 percent to 23 percent) most (49 percent to 62 percent) will not decompose in a landfill environment and instead will remain permanently sequestered.

*Table 49: Estimate of carbon sequestration in landfills (million metric tonnes of carbon)*

| **Waste Component** | **2000** | **2001** | **2002** | **2003** | **2004** | **2005** | **2006** | **2007** | **2008** | **2009** |
|---:|---:|---:|---:|---:|---:|---:|---:|---:|---:|---:|
| Newspaper | 0.572 | 0.582 | 0.581 | 0.316 | 0.320 | 0.338 | 0.327 | 0.230 | 0.208 | 0.183 |
| Office Paper | 0.074 | 0.075 | 0.075 | 0.035 | 0.035 | 0.037 | 0.036 | 0.032 | 0.029 | 0.026 |
| Corrugated Boxes | 0.383 | 0.390 | 0.389 | 0.514 | 0.522 | 0.551 | 0.533 | 0.418 | 0.378 | 0.333 |
| Coated Paper | 1.414 | 1.438 | 1.434 | 0.992 | 1.007 | 1.064 | 1.029 | 0.782 | 0.707 | 0.623 |
| Food | 0.105 | 0.107 | 0.107 | 0.104 | 0.106 | 0.112 | 0.108 | 0.108 | 0.098 | 0.086 |
| Grass | 0.178 | 0.189 | 0.196 | 0.148 | 0.157 | 0.172 | 0.162 | 0.120 | 0.115 | 0.096 |
| Leaves | 0.342 | 0.365 | 0.378 | 0.285 | 0.302 | 0.332 | 0.312 | 0.447 | 0.416 | 0.357 |
| Branches | 0.401 | 0.429 | 0.446 | 0.502 | 0.526 | 0.573 | 0.542 | 0.411 | 0.386 | 0.329 |
| Lumber | 0.542 | 0.551 | 0.550 | 1.140 | 1.156 | 1.222 | 1.182 | 1.668 | 1.509 | 1.330 |
| Textiles | 0.084 | 0.086 | 0.086 | 0.191 | 0.193 | 0.204 | 0.198 | 0.229 | 0.207 | 0.182 |
| Diapers | 0.277 | 0.282 | 0.281 | 0.187 | 0.190 | 0.201 | 0.194 | 0.181 | 0.164 | 0.144 |
| Construction/ Demolition | 0.044 | 0.045 | 0.045 | 0.086 | 0.088 | 0.093 | 0.090 | 0.038 | 0.034 | 0.030 |
| Medical Waste | 0.000 | 0.000 | 0.000 | 0.001 | 0.001 | 0.001 | 0.001 | 0.000 | 0.000 | 0.000 |
| Sludge/ | 0.007 | 0.005 | 0.005 | 0.007 | 0.009 | 0.009 | 0.009 | 0.010 | 0.008 | 0.010 |

| **Waste Component** | **2000** | **2001** | **2002** | **2003** | **2004** | **2005** | **2006** | **2007** | **2008** | **2009** |
|---|---|---|---|---|---|---|---|---|---|---|
| Manure | | | | | | | | | | |
| **TOTAL** | **4.425** | **4.544** | **4.573** | **4.508** | **4.611** | **4.909** | **4.722** | **4.675** | **4.257** | **3.731** |

(b) Change in ANDOC

Next, staff used the IPCC FOD model to calculate the change in ANDOC over time, determining how much of the anaerobically degradable organic carbon remains at the end of each year:

*Equation 87: Change in anaerobically degradable organic carbon in landfills*

$$ANDOCstock_{Year(i+1)} = \left\{ \begin{array}{l} ANDOCstock_{year(i)} \bullet e^{-k} \\ + ANDOCadded_{year(i-1)} \bullet [\frac{1}{k} \bullet (e^{-k \bullet [1-\frac{M}{12}]} - e^{-k}) - \frac{M}{12} \bullet e^{-k}] \\ + ANDOCadded_{year(i)} \bullet [\frac{1}{k} \bullet (1 - e^{-k \bullet [1-\frac{M}{12}]}) + \frac{M}{12}] \end{array} \right\}$$

Where,

$ANDOCstock_{Year(i+1)}$ = stock of ANDOC remaining un-decomposed at the end of inventory year i, and thus present in the landfill at the beginning of the next year (year i+1), (g)

$ANDOCstock_{Year(i)}$ = stock of ANDOC present in the landfill at the beginning of inventory year i, i.e., remaining un-decomposed at the end of the previous year (i-1), (g)

$ANDOCadded_{Year(i-1)}$ = ANDOC added during the previous inventory year (year i-1), (g)

$ANDOCadded_{Year(i)}$ = ANDOC added during inventory year i, (g)

M = Assumed delay before newly deposited waste begins to undergo anaerobic decomposition (months), default value = 6 months

k = Assumed rate constant for anaerobic decomposition; k = ln2/half-life (years); the half-life being the number of years required for half of the original mass of carbon to degrade (Table 50).

This calculation is performed iteratively for all subsequent years, starting with the landfill opening year and ending with the inventory year of interest.

*Table 50: Assumed rate constant values for anaerobic decomposition (k)*

| **Average Rainfall (Inches/Year)** | **k value** |
|---|---|
| <20 | 0.02 |
| 20-40 | 0.038 |
| >40 | 0.057 |

Source: USEPA

(c) Methane Generation

*Equation 88: Methane generation in landfills*

$$G_{CH4} = F_{CH4} \bullet \left\{ \begin{array}{l} ANDOCstock_{year(i)} \bullet (1 - e^{-k}) \\ + ANDOCadded_{year(i-1)} \bullet [\frac{1}{k} \bullet (e^{-k\bullet[1-\frac{M}{12}]} - e^{-k}) - \frac{M}{12} \bullet e^{-k}] \\ + ANDOCadded_{year(i)} \bullet [1 - \frac{M}{12} - \frac{1}{k} \bullet (1 - e^{-k\bullet[1-\frac{M}{12}]})] \end{array} \right\}$$

Where,

$G_{CH4}$ = $CH_4$ generated during inventory year i (g)

$F_{CH4}$ = Fraction of decomposing carbon that is converted into $CH_4$, default value = 0.5

$ANDOCstock_{Year(i)}$ = Stock of ANDOC present in the landfill at the beginning of inventory year i (g)

$ANDOCadded_{Year(i-1)}$ = ANDOC added during the previous inventory year (year i-1)

$ANDOCadded_{Year(i)}$ = ANDOC added during inventory year i (g)

M = Assumed delay before newly deposited waste begins to undergo anaerobic decomposition (months), default value = 6 months

k = Assumed rate constant for anaerobic decomposition; k = ln2/half-life (years); the half-life being the number of years required for half of the original mass of carbon to degrade (Table 50).

(d) Emissions Estimates

*Equation 89: $CH_4$ emissions from landfills*

$$E_{CH4} = G_{CH4} \bullet CE_{LFG} \bullet (1 - DE_{LFG}) + G_{CH4} \bullet (1 - CE_{LFG}) \bullet (1 - O_{CH4})$$

Where,

$E_{CH4}$ = Emissions of $CH_4$ from landfill (g)

$G_{CH4}$ = Amount of $CH_4$ generated by the landfill during the inventory year (g)

$CE_{LFG}$ = Landfill Gas Collection Efficiency, the fraction of generated landfill gas captured by the collection system (default value = 0.75)

$DE_{LFG}$ = Landfill Gas Destruction Efficiency, the fraction of $CH_4$ in the captured landfill gas oxidized to $CO_2$ (default values = 0.99 for combustion/thermal oxidation, and 0.01 for carbon filtration)

$O_{CH4}$ = Fraction of uncollected $CH_4$ that is oxidized to $CO_2$ in the landfill cover (default value = 0.1)

CalRecycle staff provided information about which landfills have gas collection systems and what control method they use, if any. Responses to an ARB survey allowed staff to update a portion of the CalRecycle numbers. For years where CalRecycle data was lacking on the year of collection system installation (primarily years 1991 - 2003), staff used existing regulatory requirements to help estimate the installation dates. Staff intends to improve the accuracy of collection system installation dates in the future.

Staff assumed that a landfill gained the full benefits of gas collection beginning with the year in which the system was first installed. In the future, as the exact month of installation and start-up operation becomes available, it will be factored in and the collection efficiency for that year may be prorated.

CalRecycle staff also provided the type of control landfills are using, including: simple venting to the atmosphere, carbon adsorption, or combustion (flaring, engines, thermal oxidizers, etc.). In the case of combustion, ARB staff assumed that 99 percent of the $CH_4$ was converted into $CO_2$ and 1 percent escaped as $CH_4$. For carbon adsorption, 1 percent of the $CH_4$ was assumed captured and 99 percent released. For venting 100 percent of the $CH_4$ was assumed released.

Each site with a gas collection system was assigned a default of 75 percent collection efficiency and a default of 10 percent oxidation for the uncollected landfill gas as it migrates through the landfill cover into the air. Using these default values (75 percent for collection efficiency and 10 percent for oxidation fraction) has been the object of some debate. Staff recognizes that many values can be found for these factors in the literature and that some site-specific measurements and local estimates do exist. However, given the current lack of rigorous, scientifically-based measurement data, staff chose to use the default values established by USEPA. As better data become available through current and future research, staff will update the collection efficiency and oxidation factors for estimating landfill gas emissions.

### *(d.i) Use of site specific survey data*

Using the First Order Decay model from the IPCC guidelines, staff estimated the amount of carbon sequestered and the amount of $CH_4$ emitted by each of the 372 landfills of interest in California.

ARB staff also surveyed landfill operators and some landfills provided site-specific landfill gas collection data for certain years of operations (48 of the 372 landfills submitted site specific survey data). These data were used either to replace or to improve the model's estimates for that landfill.

When staff received landfill survey data for a particular year, it used the survey information in place of the model estimate. However, survey data included only the amount of gas collected, and not the amount generated since landfill operators only know what is measured at the point of collection. To estimate the amount of gas generated, a default collection efficiency of 75 percent was used and the amount of collected gas was divided by 0.75 to obtain an estimate of the generated gas. Then, the estimate of gas generated—

based on the amount of gas collected—was used to replace the model estimate for that year.

When an actual value for the $CH_4$ fraction in landfill gas was reported in the survey, staff used it instead of the general default landfill gas composition assumption of 50 percent $CH_4$ and 50 percent $CO_2$. However, because $CO_2$ specific fractions were not obtained from the site specific survey data (only $CH_4$ fractions were obtained), it was assumed that whatever was not reported as $CH_4$ was $CO_2$. Staff recognizes that $N_2$ gas and small amounts of $O_2$ are expected to be present, and therefore not all of the remaining gas (i.e., the fraction that is not $CH_4$) is $CO_2$. Nevertheless, the amounts of these other gases were considered to be negligible for the purpose of estimating the $CO_2$ emissions from landfills. As data improves, this conservative assumption may be revisited.

When landfill survey data was provided for some of the years and not others, staff used the provided years to improve the model estimates for the missing years by interpolating or extrapolating using the model predicted trend for that landfill. For example, if the years 1990-1993 were missing from a set of survey data for a particular landfill, but the year 1994 was available, then the years 1990-1993 were extrapolated from this 1994 data point by following the trend the model showed for that landfill. So if the model indicated that the $CH_4$ generation in 1993 was 3 percent lower than the 1994 predicted value, the available 1994 value from the survey was multiplied by 97 percent to estimate the 1993 point, and so on. This method of filling missing data preserves a consistent trend that smoothly joins the survey data. The same methodology was used to estimate $CO_2$ emissions when missing survey data were encountered.

An exception was made to these procedures in the case of survey-reported first years of operation of a collection system. These reported values were not used as a substitute for model estimates, as it was not known if the indicated first year represented a full year of operation. Staff assumed that the second year of reported data was a complete year and used that year as the starting point, ignoring data from the first year. For surveys with collection system data dating back to 1990, staff assumed that the 1990 value represented a full year of operations and always made use of it. Staff made this assumption since data was not available to indicate if 1990 was the first year of operation and no survey data was available for 1989.

### *(d.ii) Emissions from landfill gas combustion*

Emissions of N2O from the combustion of landfill gas are included in the inventory. These emissions are a function of the BTU content of the landfill gas being burned. The amount of landfill gas burned (LFG) is determined from model output for the amount of gas collected and from CalRecycle data indicating which landfills burn their captured gas.

*Equation 90: $N_2O$ emissions from landfill gas combustion*

$$\boxed{E_{N2O} = LFG \bullet F_{CH4} \bullet HC_{CH4} \bullet EF_{CH4}}$$

Where,

$E_{N2O}$ = $N_2O$ emissions from landfill gas combustion (grams)
LFG = Landfill gas captured and burned (standard cubic feet)
$F_{CH4}$ = $CH_4$ fraction of landfill gas (unitless)
$HC_{CH4}$ = Heat content of $CH_4$ (BTU / standard cubic foot)
$EF_{CH4}$ = $N_2O$ emission factor of $CH_4$ (grams per BTU)

## 3. Data Sources

The First order decay model is from the 2006 IPCC guidelines (IPCC, 2006a). Waste characterization data was obtained from studies made by the Department of Resources Recycling and Recovery (CalRecycle, 2009) and by the USEPA (USEPA, 2007e). Degradable Organic Carbon (DOC) content and values for Decomposable Anaerobic Fraction (DANF) were taken from USEPA (USEPA, 2010b). DANF data for lumber comes from the California Energy Commission (CEC, 2006). Default values used for DANF and DOC content of waste in place, and $CH_4$ combustion emission factors were taken from the 2006 IPCC Guidelines (IPCC, 2006a). Default collection capture efficiency and $CH_4$ oxidation factor values were obtained from the USEPA through personal correspondence (Weitz, 2007). Landfill gas collection, geographic coordinates and control data for California landfills were provided by CalRecycle staff through personal communication (Walker, 2007). Average precipitation data for the landfills was extracted from a map published by the NRCS (NRCS, 2007). Methane and nitrous oxide emissions factors are from IPCC Guidelines (IPCC, 2006b).

For a list of yearly activity and parameter values used in the equations, please consult the online documentation annex at: http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_4a_landfills.pdf

## 4. Changes in Estimates

Since the publication of the 1990-2004 edition of the GHG Inventory, staff obtained new survey data, updated information on landfill controls and obtained a new waste characterization study from CalRecycle (2008 study). While the model remained the same, inclusion of these new pieces of information resulted in a limited change in emission estimates: +9.3 percent on average over the years 2000 to 2004 when compared with the estimates in the 1990-2004 edition of ARB's GHG inventory.

### 5. Future Improvements

Staff will continue to follow ongoing research and data developments susceptible to help improve estimates of landfill gas emissions. ARB's Landfill Methane Control Measure will provide more comprehensive, California-specific data on landfill gas collection and composition, as well as information on the types of cover used by landfills. A study of the seasonal variability of GHG emissions from various cover materials (e.g. fresh refuse, daily, intermediate, and final cover materials) at two California landfills was recently published (Bogner et al., 2011). The authors of that study have released CALMIM, a new landfill methane inventory model focusing on individual landfill emissions.

## B. Composting of Organic Waste (IPCC 4B)

### 1. Background

Composting of organic waste such as food scraps, yard trimmings, branches, leaves, grass and organic municipal solid waste, is common in California as a way to divert such waste from landfills. Over the last 20 years, the amount of organic waste composted in California has increased over 3-fold (CalRecycle, various years). Composting is a controlled decomposition process that destroys pathogens in the waste material, reduces its volume greatly and yields a stable organic-rich soil-like mixture called compost. This section is concerned with emissions from industrial-scale composting facilities and does not include small-scale backyard composting. These industrial facilities predominantly use a process called windrow composting in which large amounts of organic waste undergo decomposition in long rows. The windrows are actively managed (e.g. shredding, aeration, watering, etc.) to maximize the aerobic decomposition of the organic feedstock. During the composting process a large fraction of the degradable organic carbon (DOC) in the waste material is converted into carbon dioxide. However, studies have indicated that some anaerobic pockets occur in the piles where methanogenic bacteria produce some methane, and some nitrous oxide is emitted as the byproduct of nitrifying or denitrifying bacteria (ARB, 2010).

### 2. Methodology

The methodology staff used to calculate the $CH_4$ and $N_2O$ emissions from industrial composting is similar to that used for the Inventory of U.S Greenhouse Gas Emissions and Sinks (USEPA, 2010a). These methodologies are consistent with Tier-1 and Tier-2 methods of the IPCC Guidelines (IPCC, 2006h), and incorporates California-specific data when available.

### *2.1 Methane Emissions*

Emissions of $CH_4$ and $N_2O$ were estimated by multiplying the amount of composting feedstock processed in California by an appropriate emission factor.

*Equation 91: GHG emissions from composting*

$$\boxed{E_{GHG} = Q * EF_{GHG} * 907.2}$$

Where,

$E_{GHG}$ = emissions of the given GHG during the composting process (g)
Q = amount of organic waste feedstock composted (ton)
$EF_{GHG}$ = emission factor for methane emissions during the composting process (g/kg)
907.2 = factor to convert tons into kilograms (kg/ton)

With,

GHG = [$CH_4$, $N_2O$]

The amount of composting feedstock processed in California was obtained from CalRecycle's *California Compost -and Mulch- Producing Infrastructure Studies* (CalRecycle, various years). These reports published in 2001, 2004 and 2010 estimated amount of composting feedstock that was processed in California during the years 2000, 2003 and 2008 respectively. Using these three data points for 2000, 2003 and 2008, a linear regression was calculated ($R^2 = 0.998$). The best fit equation was used to generate feedstock tonnages for each of the years 1990 to 2009.

Staff used a methane emission factor of 4.1 g/kg and a nitrous oxide emission factor of 0.09 g/kg which are based on the studies used to determine IPCC and USEPA emissions factors as well as more up-to-date compost emission studies. (ARB, 2010).

## 3. Data Sources

The estimates for composting feedstock were obtained from three CalRecycle reports (CalRecycle, various years). The emission factors for methane and nitrous oxide were obtained from a study that was used to support the generation of a lifecycle compost emission factor (ARB, 2010).

For a list of yearly activity and parameter values used in the equations, please consult the online documentation annex at: http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_4b_composting_of_organic_waste.pdf

## 4. Changes in Estimates

This category of emissions was not estimated in previous editions of California's GHG Inventory. The need to add these emission sources to the current edition arose from stakeholder interest and the increased prevalence of industrial composting operations in California.

### 5. Future Improvements

In the future, the composting fugitive emission factors for both methane and nitrous oxide need to be improved. The current factors are more representative of a global average (and consistent with IPCC and USEPA values); however, future emission factors would ideally be California-specific.

## *C. Wastewater Treatment and Discharge (IPCC 4D)*

### 1. Background

Wastewater from households, commercial activities, and industrial production contains soluble organic matter, suspended particles, pathogenic organisms, and chemical contaminants. In California, a large percentage of wastewater is collected and processed in centralized wastewater treatment plants. Methane is emitted from wastewater when it is treated in anaerobic conditions. Nitrous oxide is emitted as the result of the nitrification and denitrification processes, which take place at wastewater treatment plants, but also in the water bodies where effluent is discharged.

The magnitude of $CH_4$ emissions is determined by the amount of degradable organic component in the wastewater, the temperature, and the type of treatment system. The more organic material and the higher the temperature of the wastewater, the more $CH_4$ will be generated. The degradable organic material content in wastewater is quantified by its Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD). The BOD measures the amount of biodegradable organic material present in wastewater, while the COD measures all organic materials both biodegradable and non-biodegradable.

$N_2O$ emissions are associated with the degradation of nitrogen compounds present in the wastewater. $N_2O$ is generated during the nitrification and denitrification processes, which occur at wastewater treatment plants and in water bodies that receive discharges of wastewater or treatment plant effluent. Emissions of $N_2O$ at wastewater treatment plants are generally small compared to the emissions from effluent discharged into aquatic environments.

### 2. Methodology

Most $CH_4$ and all $N_2O$ emissions from wastewater treatment and discharge were estimated using methodologies and updated parameter values from the Inventory of U.S Greenhouse Gas Emissions and Sinks: 1990-2009 (USEPA, 2011b). These methodologies are consistent with Tier-1 and Tier-2 methods of the IPCC Guidelines (IPCC, 2006a), and incorporates some USEPA improvements and California-specific data when available.

### 2.1 Methane Emissions

Methane emissions from wastewater are estimated from the volume of wastewater generated, organic loading in wastewater (measured in BOD or COD), and percentage of wastewater that is centrally treated (aerobic or anaerobic systems), anaerobically digested or treated in septic systems. The volume of wastewater discharged into municipal sewage system is estimated from the state population. The volume of wastewater generated from a particular industrial sector is estimated from the quantity of product it manufactured or processed.

(a) Methane emissions from domestic wastewater

Methane emissions from the treatment of domestic wastewater are estimated using the following equations:

*Equation 92: Total $CH_4$ emissions from domestic wastewater treatment*

$$\boxed{E_{Domestic,CH4} = E_{Septic,CH4} + E_{Aerobic,CH4} + E_{Anaerobic,CH4} + E_{Digester,CH4}}$$

*Equation 93: $CH_4$ emissions from Septic Systems*

$$\boxed{E_{Septic,CH4} = P \bullet R_{BOD5} \bullet 365.2425 \bullet f_{Septic} \bullet B_o \bullet MCF_{Septic}}$$

*Equation 94: $CH_4$ emissions from Centrally Treated Aerobic Systems*

$$\boxed{E_{Aerobic,CH4} = \begin{Bmatrix} P \bullet R_{BOD5} \bullet 365.2425 \bullet f_{central} \bullet f_{aerobic} \bullet \\ (f_{aerobic,woPT} + (f_{aerobic,wPT} \bullet (1 - f_{BOD}))) \bullet f_{NWM} \bullet B_o \bullet MCF_{aerobic,NWM} \end{Bmatrix}}$$

*Equation 95:$CH_4$ emission from Centrally Treated Anaerobic Systems*

$$\boxed{E_{Anaerobic,CH4} = \begin{Bmatrix} P \bullet R_{BOD5} \bullet 365.2425 \bullet f_{central} \bullet f_{anaerobic} \bullet \\ (f_{anaerobic,woPT} + (f_{anaerobic,wPT} \bullet (1 - f_{BOD}))) \bullet B_o \bullet MCF_{anaerobic} \end{Bmatrix}}$$

*Equation 96:$CH_4$ emissions from Anaerobic Digesters*

$$\boxed{E_{Digester,CH4} = V_{biogas} \bullet f_{CH4} \bullet 0.02831 \bullet 662 \bullet (1 - D_{CH4})}$$

*Equation 97: Volume of biogas produced in anaerobic digesters*

$$V_{biogas} = W_{Digester} \bullet \frac{R_{biogas}}{R_{wastewater}} \bullet 365.2425$$

Where,

$E_{Domestic,\ CH4}$ = Emissions of methane from domestic wastewater treatment (gram)
$E_{Septic,\ CH4}$ = Emissions of methane from Septic Systems (gram)
$E_{Aerobic,\ CH4}$ = Emissions of methane from Centrally Treated Aerobic Systems (gram)
$E_{Anaerobic,\ CH4}$ = Emissions of methane from Centrally Treated Anaerobic Systems (gram)
$E_{Digester,\ CH4}$ = Emissions from Anaerobic Digesters (gram)
$P$ = California population (person)
$R_{BOD5}$ = Rate of per capita biological organic demand ($BOD_5$) production (gram / person / day)
0.02831 = Average number of days per year (day)
$f_{septic}$ = Fraction of California wastewater treated in septic systems (unitless)
$B_o$ = Maximum methane production capacity (g $CH_4$/g $BOD_5$)
$MCF_{septic}$ = Methane correction factor for septic systems (unitless)
$f_{central}$ = Fraction of wastewater centrally treated in California (unitless)
$f_{aerobic}$ = Fraction of wastewater treated aerobically in California (unitless)
$f_{aerobic,\ woPT}$ = Fraction of aerobic systems that do not employ primary treatment (unitless)
$f_{aerobic,\ wPT}$ = Fraction of aerobic systems that employ primary treatment (unitless)
$f_{BOD}$ = Fraction of BOD removed during primary treatment (unitless)
$f_{NWM}$ = Fraction of aerobic systems that are not well managed and in which some anaerobic degradation occurs (unitless). *Currently, it is assumed that all aerobic systems are well managed and produce no $CH_4$.*
$MCF_{aerobic,\ NWM}$ = Methane correction factor for aerobic systems that are not well managed (unitless)
$f_{anaerobic}$ = Fraction of wastewater treated anaerobically in California (unitless)
$f_{anaerobic,\ woPT}$ = Fraction of anaerobic systems that do not employ primary treatment (unitless)
$f_{anaerobic,\ wPT}$ = Fraction of anaerobic systems that employ primary treatment
$MCF_{anaerobic}$ = Methane correction factor for anaerobic systems
$V_{biogas}$ = Volume of biogas produced ($ft^3$)
$f_{CH4}$ = Fraction of methane in biogas (unitless)
0.02831 = Factor used to convert between $m^3$ and $ft^3$ ($m^3/ft^3$)
662 = Density of methane ($g/m^3$)
$D_{CH4}$ = Methane destruction efficiency from flaring or burning in engine (unitless)
$W_{Digester}$ = Total wastewater flow to treatment plants that have anaerobic digesters (gal)
$R_{biogas}$ = Rate of per capita digester gas production ($ft^3$/person/day)
$R_{wastewater}$ = Rate of per capita wastewater production (gal/person/day)

(b) Methane emissions from industrial wastewater

### *(b.i) Processing of pulp and paper, fruits, vegetables, red meat and poultry*

For each of the type of product processed in industrial wastewater treatment plants, the $CH_4$ emissions are estimated using the following equation:

*Equation 98: $CH_4$ emissions from industrial wastewater treatment*

$$\boxed{E_{CH4,product} = Q_{product} \bullet W_{product} \bullet COD_{product} \bullet f_{COD,product} \bullet B_o \bullet MCF}$$

Where,

$E_{CH4,\ product}$ = Emissions of methane from the treatment of wastewater associated with processing the given product (gram)
$Q_{product}$ = Quantity of the given product processed (tonne)
$W_{product}$ = Wastewater outflow associated with processing the given product (liter / tonne)
$COD_{product}$ = Chemical Oxygen Demand (COD) of the wastewater associated with the processing of the given product (gram / liter)
$f_{COD,\ product}$ = Proportion of COD anaerobically degraded by the treatment of the wastewater associated with the processing of the given product (unitless)
$B_o$ = Maximum methane producing potential of industrial wastewater (g $CH_4$/ g COD)
MCF = Methane correction factor, indicating the extent to which the organic content (measured as COD) degrades anaerobically (unitless)

With,

Product = [Pulp and Paper, Red meat, Poultry, Potatoes, Other vegetables, Apples, Citrus Fruits, Non-citrus fruits, and Wine grapes]

### *(b.ii) Petroleum refining*

For petroleum refining emissions associated with wastewater treatment systems, the following equation was used:

*Equation 99:$CH_4$ Emissions from petroleum refineries wastewater treatment systems*

$$\boxed{E_{CH4} = W \bullet COD \bullet B_o \bullet MCF}$$

*Equation 100: Wastewater flow from petroleum refineries*

$$\boxed{W = V \bullet 35}$$

Where,

$E_{CH4}$ = Methane emissions from wastewater treatment systems at petroleum refining facilities (gram)
W = Wastewater flow ($m^3$)
COD = COD loading in wastewater entering anaerobic treatment system ($g/m^3$)
$B_o$ = Maximum methane production capacity (g $CH_4$/ g COD)
MCF = Methane conversion factor (unitless)

V = Volume of petroleum finished product produced by California's refineries (barrel)
35 = wastewater flow generation rate of petroleum refineries (gal/barrel)

### 2.2 Nitrous Oxide Emissions

Neither the IPCC nor USEPA has a separate category for $N_2O$ emissions from industrial wastewater. The methodologies for estimating $N_2O$ emissions from wastewater focus on emissions from municipal wastewater treatment plants and estimate the amount of nitrogen in wastewater on the basis of human protein consumption. In the USEPA methodology, the nitrogen from industrial wastewater is factored into the estimation by applying a coefficient to account for industrial and commercial co-discharge into municipal sewage treatment plants (estimated at 25 percent).

Emissions of nitrous oxide occur from wastewater in treatment plants and from effluents discharged into surface waters, thus:

*Equation 101: $N_2O$ emissions from wastewater treatment*

$$\boxed{E_{N2O} = E_{N2O,Plant} + E_{N2O,Effluent}}$$

Where,

$E_{N2O}$ = Total N2O emissions from wastewater treatment (gram)
$E_{N2O,\ plant}$ = N2O emissions from centralized wastewater treatment plants (gram)
$E_{N2O,\ effluent}$ = N2O emissions from wastewater effluent discharged into aquatic environments (gram)

(a) Emissions at the wastewater treatment plants

Plant emissions ($E_{N2O,\ plant}$) are estimated with the following equations:

*Equation 102: $N_2O$ emissions at the water treatment plant*

$$\boxed{E_{N2O,plant} = E_{N2O,wNDN} + E_{N2O,woNDN}}$$

*Equation 103: $N_2O$ emissions from centralized wastewater treatment plant with nitrification/denitrification*

$$\boxed{E_{N2O,wNDN} = P_{NDN} \bullet EF_{wNDN} \bullet F_{IC}}$$

*Equation 104: $N_2O$ emissions from centralized wastewater treatment plant without nitrification/denitrification*

$$\boxed{E_{N2O,woNDN} = \left[(P \bullet f_{central}) - P_{ND}\right] \bullet EF_{woNDN} \bullet F_{IC}}$$

Where,

$E_{N2O,\ plant}$ = Total $N_2O$ emissions from centralized wastewater treatment plants (gram)

$E_{N2O,\ wNDN}$ = $N_2O$ emissions from centralized wastewater treatment plants with nitrification/denitrification (gram)
$E_{N2O,\ woNDN}$ = $N_2O$ emissions from centralized wastewater treatment plants without nitrification/denitrification (gram)
$P_{NDN}$ = California population served by biological denitrification (person)
$EF_{wNDN}$ = Emission factor for with nitrification/denitrification (gram/person)
$F_{IC}$ = Factor for industrial and commercial co-discharged nitrogen into the sewer system (unitless)
$P$ = California population (person)
$F_{central}$ = Fraction of population using centralized wastewater treatments plants as opposed to septic systems (unitless)
$EF_{woNDN}$ = Emission factor for without nitrification/denitrification (gram/person)

(b) Emissions from nitrogen-containing effluent discharged into water bodies

Effluent emissions ($E_{N2O,\ Effluent}$) are estimated using the following equation:

*Equation 105: $N_2O$ emissions from wastewater effluent*

$$\boxed{E_{N2O,Effluent} = \{[(P-(P_{NDN} \bullet 0.9)) \bullet R_{protein} \bullet f_N \bullet F_{NCN} \bullet F_{IC}] - N_{sludge}\} \bullet EF_{effluent} \bullet 1.5711}$$

Where,

$E_{N2O,\ Effluent}$ = Effluent $N_2O$ emissions (gram)
$P$ = California population (person)
$P_{NDN}$ = California population served by biological denitrification (person)
0.9 = Factor to scale the population served by biological denitrification to reflect the amount of N removed by denitrification (unitless)
$R_{protein}$ = Rate of per capita protein consumption (gram/person/year)
$f_N$ = fraction of N in protein (gram N/gram protein)
$F_{NCN}$ = Factor for non-consumed protein added to wastewater (unitless)
$F_{IC}$ = Factor for industrial and commercial codischarged protein into the sewer system (unitless)
$N_{sludge}$ = Sewage sludge N not entering aquatic environment (gram N/year)
$EF_{Effluent}$ = Emission factor for effluent water (g $N_2O$-N/ gram sewage N produced)
1.5711 = Molecular weight ratio of $N_2O$ to $N_2$ (unitless)

## 3. Data Sources

State population numbers came from the California Department of Finance (CDOF, 2011). The fraction of Californians using centrally treated facilities and septic systems was obtained from the California Wastewater Training and Research Center (CWTRC, 2003). The proportions of wastewater treated aerobically or anaerobically, and with or without primary treatment are derived from USEPA's Clean Watershed Needs Surveys (USEPA, various years). The production data for fruits and vegetables, red meat, and poultry are from the California Department of Food and Agriculture (CDFA) and USDA National Agriculture Statistics Services (USDA, 2011a). The volume of petroleum finished product produced by California's refineries was obtained from the CEC Weekly Fuel Watch Reports (CEC, various years). The rate of wastewater flow of refineries was determined to be 35 gallons per barrel of petroleum finished product based on a CEC report (CEC, 2005b) and on a study of water use and wastewater treatment alternatives for oil refineries in New Mexico (Timm, 1985). Other factors used in the equations are from USEPA 1990-2009 GHG Inventory (USEPA, 2011b). The fraction of California's population served by biological denitrification was estimated to the same as that of the US population.

*Table 51: California population served by biological denitrification.*

| Year | US Population served by biological denitrification (from USEPA inventory) | CA to US population ratio | CA population served by biological denitrification |
|---|---|---|---|
| 2000 | 2,600,000 | 0.120044126 | 312,114 |
| 2001 | 2,600,000 | 0.12077586 | 314,017 |
| 2002 | 2,600,000 | 0.121832808 | 316,765 |
| 2003 | 2,600,000 | 0.122802121 | 319,285 |
| 2004 | 2,400,000 | 0.123527959 | 296,467 |
| 2005 | 2,400,000 | 0.12401197 | 297,628 |
| 2006 | 2,400,000 | 0.124205787 | 298,093 |
| 2007 | 2,400,000 | 0.124224491 | 298,138 |
| 2008 | 2,400,000 | 0.124423912 | 298,617 |
| 2009 | 2,400,000 | 0.124608117 | 299,059 |

For a list of yearly activity and parameter values used in the equations, please consult the online documentation annex at: http://www.arb.ca.gov/cc/inventory/doc/methods_00-09/annex_4c_wastewater_treatment_and_discharge.pdf

## 4. Changes in Estimates

Extensive changes to both the domestic and industrial wastewater emission equations occurred since the publication of the 1990-2004 edition of the GHG Inventory.

### 4.1 Domestic wastewater

ARB staff adopted the method refinements introduced by the USEPA for their 1990-2007 GHG inventory (USEPA, 2009). Instead of using a single general equation to estimate $CH_4$ emissions, four wastewater treatment options were considered each with a separate equation: septic systems, centrally treated aerobic systems, centrally treated anaerobic systems and anaerobic digesters.

The estimation of $N_2O$ emissions was also improved by distinguishing the contributions of plants with nitrification/denitrification and plants without nitrification/denitrification. Additionally, the per capita protein consumption factor was modified to include only the amount of protein consumed, not the total protein available for consumption (USEPA, 2009). Finally, the population component of Equation 105 was modified to subtract out the population served by biological denitrification.

### *4.2 Industrial wastewater*

The methane emissions from the pulp and paper manufacturing industries are now included in the industrial wastewater emissions section and is calculated by population-weighting the pulp and paper production data compiled by the United States Environmental Protection Agency (USEPA, 2011b). The estimation of $CH_4$ emissions from wastewater treatment facilities of petroleum refineries is now based on Equation 99. The new equation for petroleum refining is more consistent with ARB's Greenhouse Gas Mandatory Reporting Program. In addition, the industrial fruits processing data was modified by subtracting out the influence of nut production.

The modifications to methods used for this sector have resulted in a significant reduction in emission estimates: -29.6 percent on average over the years 2000 to 2004 when compared with the estimates in the 1990-2004 edition of ARB's GHG inventory.

## 5. Future Improvements

ARB staff is working on obtaining data to include wastewater treatment emissions from ethanol production facilities. Currently, the data set is incomplete, making it difficult for staff to estimate the emissions. Additionally, staff is working with USEPA to obtain a California-specific assessment for the fraction of centralized wastewater facilities that use aerobic or anaerobic treatment. Staff anticipates being able to include these distinctions in future inventories.

## DATA STORAGE AND MANAGEMENT

Greenhouse gas inventories involve a wide range of human activities. Estimating the amount of greenhouse gases generated by these activities requires using a multiplicity of data sources and a diverse set of methodologies. Storing, cataloging and documenting such a multifaceted set of information is challenging.

ARB staff has designed a custom relational database to hold California's greenhouse gas inventory information and created a set of web pages to disseminate it.

### 1. Inventory Database

We implemented the GHG inventory database using Microsoft Access software. Two main types of GHG estimation methodologies are stored in this database, using different amounts of detailed information.

#### *1.1 Methodologies involving simple algebraic formulas. (e.g., fuel combustion, clinker production, etc.)*

In this case the formulas are stored as text strings in the database with the values for activity level and all other parameters involved in the formulas. The GHG estimates are recomputed in the database by a set of Visual Basic routines that parse the formula and query the database for the necessary data. The references for the origin of the formulas and the source of all data values are also stored in the database. Cases where data were not available and their values were estimated through interpolation, extrapolation or other methods are also documented in the data tables.

#### *1.2 Methodologies requiring a complex model (e.g., land-use and forestry models, EMission FACtors (EMFAC) model, cattle enteric fermentation model, landfill emission model).*

In this case, only the values for activity level and greenhouse gases estimates (model output) are stored in the database. The references for the origin of the models and the source of data values are also stored in the database. Cases where model input data were not available and their values were estimated through interpolation, extrapolation or other methods are not documented in the data tables (that information is available through the model reference however).

#### *1.3 Cataloguing attributes*

The various activities and their GHG estimates are catalogued using:

- Their IPCC category of emissions and removal (IPCC, 2006a). For instance, *1A3aii* : "Energy - Fuel Combustion Activities - Transport - Civil Aviation -

Domestic Aviation”; or *2B2* : “Industrial Processes and Product Use - Chemical Industry - Nitric Acid Production”
- The activity name (e.g., fuel combustion, livestock population)
- The activity subset, if applicable, such as fuel type (e.g., coal, natural gas, gasoline) or livestock category (e.g., dairy cow, dairy heifer, market swine > 180 lbs)
- Up to four levels of economic sector information. For instance, “Electricity Generation (In State) -Utility Owned - Geothermal -“ or, Industrial - Manufacturing - Metal Durables - Industrial Machinery & Equipment”

## 2. Inventory Web Pages

Information is extracted and summarized from the database to produce Inventory tables and documentation pages for dissemination through ARB’s Climate Change web site.

### 2.1 Inventory tables

A set of queries and reports is used to summarize and tabulate the GHG estimates by categories defined in the scoping plan, by IPCC category of emission and removal, by economic sector, by greenhouse gas and by year. The amounts of greenhouse gas are expressed in millions of metric tonnes of $CO_2$ equivalent. The $CO_2$ equivalence calculations are based upon the IPCC Second Assessment Report’s (IPCC, 1996) global warming potentials. Detailed inventory tables are publicly available as PDF documents and as MS Excel spreadsheets by following the corresponding links on the GHG Inventory and Documentation website at: http://www.arb.ca.gov/cc/inventory/inventory.htm. Other, simplified, inventory tables are generated in similar fashion, summarizing the inventory by categories and by year. These summary tables are also available through the GHG Inventory web site. An interactive query tool is also available to select a subset of the inventory in a table, view it or download it to your computer, find out how each of the emissions values was estimated, and plot the data (http://www.arb.ca.gov/app/ghg/2000_2009/ghg_sector.php).

### 2.2 Documentation pages

Each of the emission values contained in the detailed inventory table discussed above has its own html documentation page. The goal of these pages is summarize all the information that was used by ARB staff to produce the particular emission value. With this information, members of the public may assess the methodology used to derive the GHG estimates and independently verify the estimates.

These pages are created by an automated set of queries extracting information from the GHG inventory database. Each of the html documentation pages features the following items:

- The date on which the page was last updated.
- The identification of the estimate: its IPCC category of emission and removal, economic sector classification, the greenhouse gas estimated and the year of the estimate.
- The estimated amount of emission or removal (both the mass of gas and its $CO_2$ equivalent), the units it is expressed in, the basis of the estimate (the algebraic formula or the name of the mathematical model), and the reference for the origin of the model or formula.
- The amount of activity that resulted in the GHG emission or removal (if applicable), the basis of the amount (data point, compilation of statistics, result from a calculation, mathematical model) and the reference for the source of the amount. In the case where the amount of activity is itself the result of a calculation, the formula and its source are given.
- The parameters and constants used in the calculation of the GHG estimate and/or the amount of activity. The value and units of these parameters and constants and the reference for their source is also listed.
- The calculated amount of greenhouse gas emitted per unit of activity.

The html documentation pages are publicly available on ARB's Climate Change website (http://www.arb.ca.gov/cc/inventory/doc/doc.htm) through a hierarchical index based on the same categorization as the detailed inventory table discussed above: IPCC category of emission and removal, economic sector, greenhouse gas and year. This index is located at: http://www.arb.ca.gov/cc/inventory/doc/doc_index.php. The documentation pages are also available within the interactive query tool by clicking on emissions values in the query result table.

## REFERENCES

AHC, 2005 American Horse Council. National Economic Impact of the U.S. Horse Industry. Report available at: http://horsecouncil.org/

Alig, R.J. and B.J. Butler. 2004. Area changes for forest cover types in the United States, 1952 to 1997, with projections to 2050. USDA-Forest Service, Pacific Northwest Research Station General Technical Report PNW-GTR-613. Available on-line at http://www.fs.fed.us/pnw/pubs/pnw_gtr613.pdf

Alvarado, 2007. Personal communication between Larry Hunsaker of the CA Air Resources Board and Al Alvarado of the California Energy Commission. Summer 2007.

ARB, 2003. 2003 Progress Report on Phase-Down of Rice Straw Burning in the Sacramento Valley Air Basin, California Air Resources Board, December 2003. Available online at: http://www.arb.ca.gov/smp/rice/phsdown/phsdown.htm

ARB, 2007a. Technical Support Document to the Proposed Regulations to Reduce Emissions from Diesel Engines on Commercial Harbor Craft Operated Within California Waters (October 25, 2007). Appendix B: Emissions Estimation Methodology for Commercial Harbor Craft Operating in California. CA Air Resources Board. Available online at: http://www.arb.ca.gov/regact/2007/chc07/appb.pdf

ARB, 2007b. Technical Support Document to the Proposed Regulations to Reduce Emissions from Diesel Auxiliary Engines on Ocean-Going Vessels While At Berth at a California Port (December 6, 2007). Appendix B: Hotelling Emissions Estimation Methodology for Ship Auxiliary Engines in California. CA Air Resources Board. Available online at: http://www.arb.ca.gov/regact/2007/shorepwr07/appb.pdf

ARB, 2007c. The California Air Resources Board's EMission FACtors (EMFAC) model was used to calculate emission rates from all motor vehicles, such as passenger cars to heavy-duty trucks, operating on highways, freeways and local roads in California. Model and documentation available online at: http://www.arb.ca.gov/msei/onroad/latest_version.htm

ARB, 2007d. Regulation for the Mandatory Reporting of Greenhouse Gas Emissions. Subchapter 10, Article 2, sections 95100 to 95133, title 17, California Code of Regulations. Available online at: http://www.arb.ca.gov/regact/2007/ghg2007/frofinoal.pdf

ARB, 2008. Unpublished Survey of Cement Manufacturers for 2006. California Air Resources Board, Stationary Source Division, April 2008.

ARB, 2010 Proposed Method for Estimating Greenhouse Gas Emission Reductions from Compost from Commercial Organic Waste, California Air

Resources Board, Planning and Technical Support Division. Available online at: http://www.calrecycle.ca.gov/Actions/PublicNoticeDetail.aspx?id=248&aiid=248

ARB, 2011a. California Emission Inventory Development and Reporting System Database (CEIDARS). CA Air Resources Board Staff queried CEIDARS for Total Organic Gases (TOG) emissions, and then speciated the results into $CH_4$. California Air Resources Board. June 2011. More information at: http://www.arb.ca.gov/ei/general.htm

ARB, 2011b. Summary of data from California's Greenhouse Gas Mandatory Reporting Program. Reported emissions are available at: http://www.arb.ca.gov/cc/reporting/ghg-rep/ghg-rep.htm

Birdsey, R.A. and G.M. Lewis, 2001. "Carbon Stock Changes in California's Forests, 1987-1997," working paper sent via email by R.A. Birdsey, USDA Forest Service, October 9, 2001.

Birdsey, R.A. and G.M. Lewis. 2003. Carbon in U.S. forests and wood products, 1987-1997: State-by-state estimates. USDA Forest Service, Northeastern Research Station General Technical Report GTR-NE-310. Available on-line at http://www.fs.fed.us/ne/newtown_square/publications/technical_reports/pdfs/2003/gtrne310.pdf

BOE, 2011. California State Board of Equalization. Fuel Taxes Division Statistics & Reports - Motor Vehicle Fuel. Accessed online at: http://www.boe.ca.gov/sptaxprog/spftrpts.htm

Bogner, Spokas, K.A., Chanton, J. 2011. Seasonal greenhouse gas emissions (methane, carbon dioxide, nitrous oxide) from engineered landfills: Daily, intermediate, and final California cover soils. Journal of Environmental Quality. 40(3):1010-1020.

CalRecycle, 2009. Solid Waste Characterization Database, California Department of Resources Recycling and Recovery, Sacramento. Accessed online, fall 2009, at: http://www.calrecycle.ca.gov/WasteChar/

CalRecycle, various years. CalRecycle (2010, 2003, 2001) Assessment of California's Compost and Mulch-Producing Infrastructure - Management Practices and Market Conditions. Infrastructure Surveys, 1st, 2nd and 3rd versions. CalRecycle. Sacramento. CA. Accessed online at: http://www.calrecycle.ca.gov/Organics/Processors/

CDF, 2003. The Changing California: Forest and Range 2003 Assessment. Fire and Resource Assessment Program, California Department of Forestry and Fire Protection. Sacramento, CA. Available on-line at http://www.frap.cdf.ca.gov/assessment2003/

CDFA 2011. California Agricultural Resource Directory 2010-2011, California Department of Food and Agriculture, Sacramento. http://www.cdfa.ca.gov/statistics/

CDFA, various years. Fertilizing Materials Tonnage Report, (published bi-annually). California Department of Food and Agriculture, Sacramento. http://www.cdfa.ca.gov/is/ffldrs/Fertilizer_Tonnage.html

CDOF, 2010. California Department of Finance, California Statistical Abstract, Table J-11 — Electrical Energy Generation: Total Production by Resource Type, California. Accessed online at: http://www.dof.ca.gov/HTML/FS_DATA/STAT-ABS/documents/J11.xls

CDOF, 2011. State of California, Department of Finance, E-4 Population Estimates for Cities, Counties and the State, 2001-2010, with 2000 & 2010 Census Counts. Sacramento, California, September 2011. http://www.dof.ca.gov/research/demographic/reports/estimates/e-4/2001-10/view.php

CEC, 1990. 1988 Inventory of California Greenhouse Gas Emissions, Final Staff Report, October 1990. California Energy Commission, Sacramento, CA.

CEC, 1997. California's Greenhouse Gas Emissions Inventory 1990. Publication P500-97-004, March 1997. California Energy Commission, Sacramento, CA.

CEC, 1998. 1997 Global Climate Change Report: Greenhouse Gas Emissions Reduction Strategies for California. Appendix A – Historical and Forecasted Greenhouse Gas Emissions Inventories for California. Publication # 500-98-001V3, January 1998. California Energy Commission, Sacramento, CA. Available online at: http://www.energyarchive.ca.gov/global_climate_change/1997_ghg_report/P500-98-001V3.PDF

CEC, 2000. 1999 Net System Power Calculation, (1999 California Power Mix). Adopted by the full Commission at the April 5, 2000 Business Meeting. California Energy Commission publication # 300-00-004. Available online at: http://www.energy.ca.gov/sb1305/documents/

CEC, 2002. {CEC 2002} Inventory of California Greenhouse Gas Emissions and Sinks: 1990-1999. Publication #600-02-001F. November 2002. California Energy Commission, Sacramento. http://www.energy.ca.gov//reports/600-02-001F/2002-09-14_600-02-001F.PDF

CEC, 2002-08. Net System Power Reports, 2002 to 2008 editions, California Energy Commission. Accessed online, summer 2011, at: http://energyalmanac.ca.gov/electricity/system_power/

CEC, 2004. Baseline Greenhouse Gas Emissions for Forest, Range, and Agricultural Lands in California. PIER Final Project Report CEC-500-04-

069F. California Energy Commission. http://www.energy.ca.gov/pier/project_reports/500-04-069.html

CEC, 2005a. Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2002 Update. CEC Publication CEC-600-2005-025. Available online at http://www.energy.ca.gov/2005publications/CEC-600-2005-025/CEC-600-2005-025.PDF

CEC, 2005b. Petroleum Infrastructure Environmental Performance Report, California Energy Commission, CEC-700-2005-012, June 2005. Available online at www.energy.ca.gov/2005publications/CEC-700-2005-012/CEC-700-2005-012.PDF

CEC, 2006. Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004. CEC Publication CEC-600-2006-013-SF. Available online: http://www.energy.ca.gov/2006publications/CEC-600-2006-013/CEC-600-2006-013-SF.PDF

CEC, various years. Weekly Fuel Watch Reports. Yearly compilations of weekly refinery production and stocks levels in California. California Energy Commission. Available online in tabular form at http://energyalmanac.ca.gov/petroleum/fuels_watch/index.php

CWTRC, 2003. Status Report: Onsite Wastewater Treatment Systems in California. Jointly presented by: California Wastewater Training & Research Center, California State University Chico and USEPA Region 9 Ground Water Office. August 2003. http://www.csuchico.edu/cwtrc/Pages/InfoandReoprtspage.htm

Desai, 2011. Personal communication between CA Air Resources Board Staff and Mausami Desai of the US Environmental Protection Agency. Washington DC. Spring 2011.

Dong, J., Kaufmann, R., Myneni, R., Tucker, C., Kauppi, P., Liski, J., Buermann, W., Alexeyev, V., and M. Hughes. 2003. Remote sensing estimates of boreal and temperate forest woody biomass: carbon pools, sources, and sinks. Remote Sensing of Environment 84, 393-410.

Donovan and Baldwin, 1999. Donovan, K. and L. Baldwin (1999). Results of the AAMOLLY model runs for the Enteric Fermentation Model. University of California, Davis.

EAA, 2007. EMEP/CORINAIR Air Pollutant Emissions Inventory Guidebook – 2007. European Environment Agency Technical report No 16/2007. Available online at: http://www.eea.europa.eu/publications/EMEPCORINAIR5

EIA, 2011a. Energy Information Administration. Form EIA-906/920/923: Monthly Utility Power Plant Database. Accessed online in June 2011 at: http://www.eia.gov/cneaf/electricity/page/eia906_920.html

EIA, 2011b. Energy Information Administration. Monthly Energy Review, Renewable Energy, Table 10.3 - Fuel Ethanol Overview. Accessed online at: http://www.eia.gov/totalenergy/data/monthly/#renewable

EIA, 2011c. Energy Information Administration. Natural Gas Navigator. Natural Gas Consumption by End Use. Accessed online at: http://tonto.eia.doe.gov/dnav/ng/ng_cons_sum_dcu_SCA_a.htm

EIA, 2011d. Energy Information Administration. Petroleum Navigator. Topics for Petroleum Consumption/Sales. Accessed online at: http://tonto.eia.doe.gov/dnav/pet/pet_cons_top.asp

EIA, 2011e. Energy Information Administration. State Energy Data System (SEDS). Available online at: http://www.eia.gov/state/seds/seds-states.cfm?q_state_a=CA&q_state=California

EIA, 2011f. Energy Information Administration. Annual Energy Review (AER), Renewable Energy, Table 10.3. Available online at: http://www.eia.gov/emeu/aer/renew.html

EIA, 2011g. Energy Information Administration. Total Energy. Appendices. Table A3. Approximate Heat Content of Petroleum Consumption and Biofuels Production. Available online at: http://www.eia.gov/totalenergy/data/monthly/#appendices

FAO, 2011. FAOSTAT Statistical Database. Food and Agriculture Organization of the United Nations. Available online at http://faostat.fao.org/

FHWA, various years. US Department of Transportation, Federal Highway Administration - Highway Statistics Series. Motor Fuel. Data accessed online at: http://www.fhwa.dot.gov/policy/ohpi/qffuel.cfm

Godwin, 2009. Personal communication between Karen Lutter of CA Air Resources Board and Dave Godwin, Stratospheric Protection Division Source Lead, US Environmental Protection Agency, Summer 2009.

Gonzalez, P., Asner, G., Battles, J., Lefsky, M., Waring, K. and Palace, M. (2010) Forest carbon densities and uncertainties from LIDAR, QuickBird, and field measurements in California. Remote Sensing of Environment 114: 1561-1575.

Gough, 2011. Personal communication (data from the CEC's Quarterly Fuels and Energy Report) between Larry Hunsaker of the CA Air Resources Board and Andrea Gough of the California Energy Commission. June 2011.

Griffin, 2007. Personal communication between Larry Hunsaker of the CA Air Resources Board and Karen Griffin of the California Energy Commission. Summer 2007.

Hahn, 2007. Personal communication (source test data) between Larry Hunsaker of the CA Air Resources Board and Jeffrey L. Hahn, environmental director of Covanta Energy. Summer 2007.

Hurtt, G., Dubayah, R., Drake, J., Moorcroft, P., Pacala, S., Blair, J., and M. Fearon. 2004. Beyond potential vegetation: combining LIDAR data and a height-structured model for carbon studies. Ecological Applications 14, 873-883.

IPCC, 1996. Second Assessment Report. Climate Change 1995: WG I - The Science of Climate Change. Intergovernmental Panel on Climate Change; J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.); Cambridge University Press. Cambridge, U.K.

IPCC, 1997. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (Revised Guidelines). Intergovernmental Panel on Climate Change. Published: IGES, Japan. http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm

IPCC, 2000. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. Penman J., Kruger D., Galbally I., Hiraishi T., Nyenzi B., Emmanuel S., Buendia L., Hoppaus R., Martinsen T., Meijer J., Miwa K., and Tanabe K. (Eds). IPCC/OECD/IEA/IGES, Hayama, Japan. Available online at http://www.ipcc-nggip.iges.or.jp/public/gp/english/index.html

IPCC, 2003. Good Practice Guidance for Land Use, Land-Use Change and Forestry. Intergovernmental Panel on Climate Change. IPCC National Greenhouse Gas Inventories Programme. IGES, Kanagawa, Japan. Available on-line at http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.html

IPCC, 2006a. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston HAS., Biennia L., Miwa K., Negara T. and Tanabe K. (eds). Published: IGES, Japan. http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.htm

IPCC, 2006b. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T., and Tanabe K. (eds). Volume 2, Chapter 2: Energy. http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf

IPCC, 2006c. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T., and Tanabe K. (eds). Volume 3, Chapter 2: Mineral Industries Emissions. Published: IGES, Japan. http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/3_Volume3/V3_2_Ch2_Mineral_Industry.pdf

IPCC, 2006d. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston HAS., Biennia L., Miwa K., Negara T. and Tanabe K. (eds). Volume 4, Chapter 10: Emissions from Livestock and Manure Management. Published: IGES, Japan. http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf

IPCC, 2006e. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston HAS., Biennia L., Miwa K., Negara T. and Tanabe K. (eds). Volume 4, Chapter 11: $N_2O$ Emissions from Managed Soils, And $CO_2$ Emissions from Lime and Urea Application. Published: IGES, Japan. http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_11_Ch11_N2O&CO2.pdf

IPCC, 2006f. IPCC (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Eggleston H.S., Buendia L., Miwa K., Ngara T., and Tanabe K. (eds). Vol.5, Chap. 3: Solid Waste Disposal. Published: IGES, Japan. http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_3_Ch3_SWDS.pdf

IPCC, 2006g. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston HAS., Biennia L., Miwa K., Negara T. and Tanabe K. (eds). Volume 4: Agriculture, Forestry and Other Land Use. Published: IGES, Kanagawa, Japan. http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html

IPCC, 2006h 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Eggleston H.S., Buendia L., Miwa K., Ngara T., and Tanabe K. (eds). Vol.5, Chap. 4: Biological Treatment of Solid Waste. Published: IGES, Japan. Accessed online at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_4_Ch4_Bio_Treat.pdf

IUPAC, 2006. Atomic Weights of the Elements 2005 (IUPAC Technical Report). Pure Appl. Chem., Vol. 78, No. 11, pp. 2051–2066, 2006.

Jenkins et al. 1992. Jenkins, B.M., Turn, S.Q., and Williams, R.B. (1992) Atmospheric Emissions from Agricultural Burning in California: Determination of Burn Fractions, Distribution Factors, and Crop-specific Contributions. Agriculture, Ecosystems and Environment, 38: 313-330.

Jenkins et al. 1996. Atmospheric Pollutant Emission Factors from Open Burning of Agricultural and Forest Biomass by Wind Tunnel Simulation. California Air Resources Board, A932-126, April 1996. (see in particular Tables 4.1.1 - 4.1.8). http://www.arb.ca.gov/research/single-project.php?row_id=55021

Jo, H-K and E.G. McPherson. 1995. Carbon storage and flux in urban residential greenspace. Journal of Environmental Management 45, 109-133.

Kebreab, E. and Johnson, KA and Archibeque, SL and Pape, D. and Wirth, T. 2008. Model for estimating enteric methane emissions from United States dairy and feedlot cattle. Journal of animal science 86(10): 2738.

Kustic, 2011 Personal communication between Larry Hunsaker of CA Air Resources Board and Tim Kustic of the CA Department of Conservation, Division of Oil, Gas & Geothermal Resources. Summer 2011. http://www.conservation.ca.gov/DOG/Pages/Index.aspx

Lime Producers, 2011. Personal communication between Karen Lutter of CA Air Resources Board and representatives of the Lime Producers of California, April 2011.

Long, 2007. Personal communication between Kevin Eslinger of CA Air Resources Board and Jeff Long, Air Resources Board Mobile Sources Assessment Branch, September 2007.

Lovett, G.M., Cole, J.J. and M.L. Pace. 2006. Is Net Ecosystem Production Equal to Ecosystem Carbon Accumulation? Ecosystems, 9: 1-4.

Mendez, 2009. Personal communication between Larry Hunsaker, CA Air Resources Board and Atoya Mendez, City of Riverside. Summer 2009.

Murtishaw et al. 2005. Murtishaw S., De La Rue du Can, S,. Price, L., Masanet, E., and Simcich, M. CALEB: California Energy Balance Database, September 12, 2005. Lawrence Berkeley National Laboratory, Berkeley, CA.

Nowak, D.J. and D.E. Crane. 2002. Carbon storage and sequestration by urban forests in the United States. Environmental Pollution 116(3), 381-389.

NRCS, 2007. Map of Average precipitation data for California, US Department of Agriculture National Resources Conservation Service's Geospatial Data Gateway. Accessed online, fall 2007, at: http://datagateway.nrcs.usda.gov/

Nyberg, 2009. Personal communication (data from the CEC's Quarterly Fuels and Energy Report) between Larry Hunsaker of the CA Air Resources Board and Michael Nyberg of the California Energy Commission. Fall 2009.

O'Brien, 2010. Personal communication (data from the Petroleum Industry Information Reporting Act [PIIRA] M-13 Survey Form and volumes of ethanol used in on-road gasoline in California) between Larry Hunsaker of the CA Air Resources Board and Keith O'Brien of the California Energy Commission. Fall 2010.

O'Hare, 2007. Personal communication between CA Air Resources Board Staff and Andrew T. O'Hare of the Portland Cement Association, Washington, DC. http://www.cement.org/

Oliver, 2007. Personal communication between CA Air Resources Board staff and Kitty Oliver, Climate and Technical Research Section, CA Integrated Waste Management Board. Summer 2007.

Parsons, 2009. Personal communication (EIA form 767 data submittal & Plant Specific Data Reports) between Larry Hunsaker of CA Air Resources Board and Cindy Parsons, Los Angeles Department of Water & Power. Summer 2009.

Potter, C., Gross, P., Genovese, V., and M.-L. Smith. 2007a. Net primary productivity of forest stands in New Hampshire estimated from Landsat and MODIS satellite data. Carbon Balance and Management 2:9, doi:10.1186/1750-0680-2-9.

Potter, C., Klooster, S., Huete, A., and V. Genovese. 2007b. Terrestrial carbon sinks for the United States predicted from MODIS satellite data and ecosystem modeling. Earth Interactions 11, 1-21.

RMA, 2007. Rubber Manufacturers Association website. Scrap tires characteristics. Accessed online at: http://www.rma.org/scrap_tires/scrap_tire_markets/scrap_tire_characteristics/

RTI, 2004. Changes to the methodology for the inventory of methane emissions from landfills. Research Triangle Institute. Research Triangle Park, NC. Cited in: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2004. United States Environmental Protection Agency. EPA 430-R-06-002. April 15, 2006. Washington DC. .

Schnapp, 2008. Personal communication (data submittal) between Larry Hunsaker of CA Air Resources Board and Robert Schnapp of the Energy Information Administration. Fall 2008.

Shih, Tian-Ting. 1998. The land base of California’s forests. Fire and Resource Assessment Program, California Department of Forestry and Fire Protection. Sacramento, CA.

Shires, 2009. Personal communication between Larry Hunsaker of CA Air Resources Board and Terri Shires of URS Corporation (Austin, TX) who provided printed excerpt from the Oil and Gas Journal's "Historical Worldwide Refinery Survey" (Prod No. E1181C) database, for refineries in California for the years 1990 to 2008.

Schulze, E.-D., Wirth C. and M. Heimann, 2000. Climate Change: Managing Forests after Kyoto. Science, 289(5407): 2058-2059.

Skog, K.E. and G.A. Nicholson. 1998. Carbon cycling through wood products: the role of wood and paper products in carbon sequestration. Forest Products Journal 48, 75–83.

Skog, K.E., Pingoud, K., and J.E. Smith. 2004. A method countries can use to estimate changes in carbon stored in harvested wood products and the uncertainty of such estimates. Environmental Management 33 (Suppl. 1), S65–S73.

Smith, J.E., Heath, L.S. and J.C. Jenkins. 2003. Forest volume-to-biomass models and estimates of mass for live and standing dead trees of U.S. forests. USDA Forest Service, Northeastern Research Station General Technical Report GTR-NE-298. Available on-line at http://www.fs.fed.us/ne/newtown_square/publications/technical_reports/pdfs/2003/gtrne298.pdf

SRI, 2007. 2007 Directory of Chemical Producers (DCP) -- United States. http://www.sriconsulting.com/DCP/Public/index.html

SRI, 2008 2008 Directory of Chemical Producers (DCP) -- United States. http://www.sriconsulting.com/DCP/Public/index.html

Timm, C.M., 1985. Water use, conservation and wastewater treatment alternatives for oil refineries in New Mexico. NMERDI-2-72-4628. NMERDI, Suite M., 457 Washington SE, Albuquerque, NM 87108

Toledo, 2011. Personal communication between CA Air Resources Board Staff and Rene Toledo of the Yolo-Solano Air Quality Management District. Davis, CA. Summer 2011.

Treuhaft, R.N., Asner, G.P. and B.E. Law. 2003. Structure-based forest biomass from fusion of radar and hyperspectral observations. Geophysical Research Letters 30(9), 1472, doi:10.1029/2002GL016857, 2003.

Treuhaft, R.N., Law, B.E. and G.P. Asner. 2004. Forest attributes from radar interferometric structure and its fusion with optical remote sensing. BioScience 54(6), 561-571.

USCB, various years a. U.S. Census Bureau, Population Estimates for the United States and California. Accessed online at: http://www.census.gov

USCB, various years b. U.S. Census Bureau's Economic Census data. Accessed online at: (Information is listed by NAICS Code Number, NAICS Code for Semiconductor Manufacturing = #334413). http://www.census.gov/econ/census02/

USDA, 2011a. U.S. Department of Agriculture, National Agriculture Statistics Service, California Statistics. Accessed June 2011. Available online at: http://www.nass.usda.gov/Statistics_by_State/California/index.asp

USDA, 2011b. U.S. Department of Agriculture, National Agricultural Statistics Service, Historical data. Field Crops. Field Crops. Accessed June 2011. Available online at: http://www.nass.usda.gov/Statistics_by_State/California/Publications/index.asp

USDA, 2011c. U.S. Department of Agriculture, National Agricultural Statistics Service, Historical data. Fruit and Nuts. Accessed June 2011. Available online at: http://www.nass.usda.gov/Statistics_by_State/California/Publications/index.asp

USDOT, 2010. U.S. Department of Transportation, Research and Innovative Technology Administration, Bureau of Transportation Statistics, Air Carrier Statistics database (T100 databank). Accessed online at: http://www.transtats.bts.gov/Fields.asp?Table_ID=293

USEPA, various years Clean Watershed Needs Surveys for 2000 and 2004. Data have been extrapolated for years not covered in the surveys. Accessed online at: http://www.epa.gov/cwns/

USEPA, 1995. State Workbook, Methodologies for Estimating Greenhouse Gas Emissions, January 1995. U.S. EPA, Office of Policy, Planning and Evaluation, State and Local Reach Program.

USEPA, 1999. Emission Inventory Improvement Program. Technical Report Series, Volume 8: Estimating Greenhouse Gas Emissions. October 1999. US Environmental Protection Agency. Washington DC.

USEPA, 2001. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1999. EPA 236-R-01-001, April 2001. U.S. Environmental Protection Agency. Washington DC.

USEPA, 2004a. Emission Inventory Improvement Program. Technical Report Series, Volume 8: Estimating Greenhouse Gas Emissions, Chapter 6: Industrial Processes. US Environmental Protection Agency. Washington DC. http://www.epa.gov/ttn/chief/eiip/techreport/volume08/index.html

USEPA, 2004b. Emission Inventory Improvement Program. Technical Report Series, Volume 8: Estimating Greenhouse Gas Emissions, Chapter 10: Agricultural Soil Management. US Environmental Protection Agency. Washington DC. http://www.epa.gov/ttn/chief/eiip/techreport/volume08/index.html

USEPA, 2007a. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005. United States Environmental Protection Agency. EPA 430-R-07-002. April 15, 2007. Washington DC. http://www.epa.gov/climatechange/emissions/usgginv_archive.html

USEPA, 2007b. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005. United States Environmental Protection Agency. EPA 430-R-07-002. and Annex 2.1 (Tables A-31, A-32, A-35, and A-36). April 15, 2007. Washington DC. http://www.epa.gov/climatechange/emissions/usgginv_archive.html

USEPA, 2007c. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005. United States Environmental Protection Agency. EPA 430-R-07-002. and Annex 3.2. Methodology for Estimating Emissions of $CH_4$, $N_2O$, and

Indirect Greenhouse Gases from Mobile Combustion. April 15, 2007. Washington DC. http://www.epa.gov/climatechange/emissions/usgginv_archive.html

USEPA, 2007d. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005. United States Environmental Protection Agency. EPA 430-R-07-002. Annex 6: Additional Information. April 15, 2007. Washington DC. http://www.epa.gov/climatechange/emissions/usgginv_archive.html

USEPA, 2007e. Municipal Solid Waste Characterization Reports (various years), US Environmental Protection Agency. Accessed online, fall 2007, at: http://www.epa.gov/epawaste/inforesources/pubs/municipal_sw.htm

USEPA, 2008a. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006. United States Environmental Protection Agency. EPA 430-R-08-005. Washington DC. http://www.epa.gov/climatechange/emissions/usgginv_archive.html

USEPA, 2008b. {USEPA wood HC} Climate Leaders Greenhouse Gas Inventory Protocol, Core Module Guidance. Direct Emissions from Stationary Combustion Sources. US Environmental Protection Agency. EPA 430-R-08-003. May 2008. (Tables B-1 and B-2). http://www.epa.gov/climateleaders/documents/resources/stationarycombustionguidance.pdf

USEPA, 2008c. $SF_6$ Emission Reduction Partnership for Electric Power Systems. 2007 Annual Report, December 2008. United States Environmental Protection Agency. Washington DC. http://www.epa.gov/electricpower-sf6/documents/sf6_2007_ann_report.pdf

USEPA, 2009. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2007. United States Environmental Protection Agency. EPA 430-R-09-004. April 15, 2009. Washington DC. http://www.epa.gov/climatechange/emissions/usgginv_archive.html

USEPA, 2010a {USEPA 2010} Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008. United States Environmental Protection Agency. EPA 430-R-10-006. April 15, 2010. Washington DC. http://www.epa.gov/climatechange/emissions/usgginv_archive.html

USEPA, 2010b. Solid Waste Management and Greenhouse Gases. Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM). Landfilling Chapter, exhibits 6 & 12. United States Environmental Protection Agency. October 28, 2010. http://www.epa.gov/climatechange/wycd/waste/SWMGHGreport.html

USEPA, 2011a. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2009. United States Environmental Protection Agency. EPA 430-R-10-006. http://www.epa.gov/climatechange/emissions/usinventoryreport.html

USEPA, 2011b. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2009. United States Environmental Protection Agency. EPA 430-R-10-006.

Chapter 8: Waste. April 15, 2011. Washington DC. http://www.epa.gov/climatechange/emissions/usinventoryreport.html

USEPA, 2011c Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2009. United States Environmental Protection Agency. EPA 430-R-11-005. Annex 3.10: Methodology for Estimating CH4 and N2O Emissions from Manure Management. April 15, 2011. Washington DC. http://www.epa.gov/climatechange/emissions/usinventoryreport.html

USEPA, 2011d Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2009. United States Environmental Protection Agency. EPA 430-R-11-005. Annex 3.10: Methodology for Estimating CH4 Emissions from Enteric Fermentation. April 15, 2011. Washington DC. http://www.epa.gov/climatechange/emissions/usinventoryreport.html

USEPA, 2011e Inventory of U.S. Greenhouse Gas Emissions and Sinks (April 2011), Table 4-85, U.S. Environmental Protection Agency EPA 430-R-11-005. http://www.epa.gov/climatechange/emissions/usinventoryreport.html

USEPA, 2011f Inventory of U.S. Greenhouse Gas Emissions and Sinks (April 2011), Table 4-11, U.S. Environmental Protection Agency EPA 430-R-11-005. http://www.epa.gov/climatechange/emissions/usinventoryreport.html

USEPA, 2011g Inventory of U.S. Greenhouse Gas Emissions and Sinks (April 2011), Table 4-41, U.S. Environmental Protection Agency EPA 430-R-11-005. http://www.epa.gov/climatechange/emissions/usinventoryreport.html

USEPA, 2011h Inventory of U.S. Greenhouse Gas Emissions and Sinks (April 2011), Table 4-88, U.S. Environmental Protection Agency EPA 430-R-11-005. http://www.epa.gov/climatechange/emissions/usinventoryreport.html

USGS, various years a. Minerals Yearbook: The Mineral Industry of California. California Dept. of Conservation, California Geological Survey/U.S. Geological Survey. (See: Crushed Stone). Accessed online at: http://minerals.usgs.gov/minerals/pubs/state/ca.html

USGS, various years b. U.S. Geological Survey, Crushed Stone Statistics and Information, Mineral Yearbooks (Various Years), Stone (Crushed) Accessed online at: http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/

USGS, various years c. U.S. Geological Survey, Mineral Industry Surveys, Soda Ash. Accessed online at: http://minerals.usgs.gov/minerals/pubs/commodity/soda_ash/

Walker, 2007. Personal communication (Collection, Lat/Lon, and Control Data for Landfills) between Larry Hunsaker of CA Air Resources Board and Scott Walker, California Integrated Waste Management Board. Fall 2007.

Walzer, 2011 Personal communication between Webster Tasat, CA Air Resources Board and Dan Walzer, U.S. Energy Information Administration. July 18, 2011.

Wang, 2007. Personal communication between Larry Hunsaker, CA Air Resources Board and Michael D. Wang, Senior Advisor, Western States Petroleum Association. Summer 2007.

WBCSD & WRI, 2005. WBCSD Cement Sustainability Initiative, $CO_2$ Emissions Inventory Protocol, Version 2.0. Published by The World Business Council for Sustainable Development and The World Resources Institute in 2005. Available online at: http://www.wbcsd.org/plugins/DocSearch/details.asp?type=DocDet&ObjectId=MTU5MjQ

WCI, 2011. Western Climate Initiative, 2006, 2007 and 2008 Default Emission Factor Calculators. Queried in June 2011. Available online at: http://www.westernclimateinitiative.org/document-archives/Electricity-Team-Documents/Default-Emission-Factor-Calculators/

Weitz, 2007. Personal communication between Larry Hunsaker of CA Air Resources Board and Melissa Weitz, US Environmental Protection Agency. Fall 2007.

Wirth, 2011. Personal communication between Marc Vayssières of CA Air Resources Board and Tom Wirth, Greenhouse Gas Inventory Source Lead, US Environmental Protection Agency, April 2011.

Zhang, X. and S. Kondragunta. 2006. Estimating forest biomass in the USA using generalized allometric models and MODIS land products. Geophysical Research Letters 33, L09402, doi:10.1029/2006GL025879.

## LIST OF TABLES & FIGURES

# LIST OF EQUATIONS

# LIST OF ACRONYMS

**A**

AB: Assembly Bill
AHC: American Horse Council
ANDOC: Anaerobically Degradable Organic Carbon
ARB: Air Resources Board
ASTM: American Society for Testing and Materials

**B**

BOD: Biochemical Oxygen Demand
BOE: California Board of Equalization
BTU: British Thermal Unit

**C**

CALEB: California Energy Balance
CalFire: California Department of Forestry and Fire Protection
CalRecycle: California Department of Resources Recycling and Recovery
CDFA: California Department of Food and Agriculture
CDOF: California Department of Finance
CEC: California Energy Commission
CEFM: Cattle Enteric Fermentation Model (USEPA)
CEIDARS: California Emission Inventory Development and Reporting System (ARB)
CEMS: Continuous Emission Monitoring System
$CH_4$: Methane
CHP: Combined Heat and Power
CKD: Cement Kiln Dust
CO: Carbon Monoxide
$CO_2$: Carbon Dioxide
COD: Chemical Oxygen Demand
CORINAIR: CORe INventory AIR emissions (EEA)

**D**

DANF: Decomposable Anaerobic Fraction
DBH: Diameter at Breast Height
DE: Digestible Energy
DOC: Degradable Organic Carbon
DOGGR: Division of Oil, Gas & Geothermal Resources (CA Department of Conservation)

**E**

EEA: European Environment Agency
EF: Emission Factor
EIA: Energy Information Administration
EIIP: Emission Inventory Improvement Program (USEPA)
EMEP: European Monitoring and Evaluation Programme (EEA)
EMFAC: EMission FACtors model (ARB).

EOR: Enhanced Oil Recovery

**F**

FAO: United Nations Food and Agriculture Organization
FAOSTAT: Statistics Division of the FAO
FHWA: Federal Highway Administration
FIA: Forest Inventory and Analysis program (USDA-FS)
FOD: First Order Decay model (IPCC)
FRAP: Fire and Resource Assessment Program (CalFire)

**G**

GE: Gross Energy
GHG: Greenhouse Gas
GIS: Geographic Information System
GPP: Gross Primary Production
GWP: Global Warming Potential

**H**

HC: Heat Content
HFC: Hydrofluorocarbon
HWP: Harvested Wood Products

**I**

IPCC: International Panel on Climate Change (UN)
IUPAC: International Union of Pure and Applied Chemistry

**L**

LADWP: Los Angeles Department of Water and Power
LFG: Landfill Gas
LKD: Lime Kiln Dust
LPG: Liquefied Petroleum Gas

**M**

MCF: Methane Conversion Factor
MSW: Municipal Solid Waste
MW: Mega Watt
MWh: Mega Watt hour

**N**

N: Nitrogen
$N_2O$: Nitrous Oxide
NASS: National Agricultural Statistics Service (USDA)
NE: Net Energy
NEP: Net Ecosystem Production
NLA: National Lime Association
NLCD: National Land Cover Data (USGS)
$NO_x$: Nitrogen oxides
NPP: Net Primary Production

NRCS: Natural Resources Conservation Service (USDA)
NSCR: Non-Selective Catalytic Reduction
NSP: Net System Power report (CEC)

**O**

ODS: Ozone Depleting Substance

**P**

PCA: Portland Cement Association
PFC: Perfluorocarbon
PFPE: Perfluoropolyether
PIER: Public Interest Energy Research (CEC)
PIIRA: Petroleum Industry Information Reporting Act (CEC)
PM: Particulate Matter
PNW: Pacific Northwest
PSW: Pacific Southwest

**Q**

QFER: Quarterly Fuels and Energy Report (CEC)

**R**

ROG: Reactive Organic Compound

**S**

SCR: Selective Catalytic Reduction
SEDS: State Energy Data System (EIA)
SIP: State Implementation Plan (USEPA)
SOC: Soil Organic Carbon
SSURGO: Soil Survey Geographic database (USDA-NRCS)

**T**

TDOC: Total Degradable Organic Carbon
THC: Total Hydrocarbon
TOC: Total Organic Carbon
TOG: Total Organic Gases

**U**

UC: University of California
UNFCCC: United Nations Framework Convention on Climate Change
USCB: United States Census Bureau
USDA: United States Department of Agriculture
USDA-FS: United States Department of Agriculture – Forest Service
USDOT: United States Department of Transportation
USEPA: United States Environmental Protection Agency
USGS: United States Geological Survey
UTO: Useful Thermal Output

**V**

VMT: Vehicle Miles Traveled
VS: Volatile Solids

**W**

WCI: Western Climate Initiative
WIP: Waste in Place
WMS: Waste Management System
WSPA: Western States Petroleum Association