California Environmental Protection Agency

Air Resources Board

California's 2000-2009 Greenhouse Gas Emissions Inventory

Technical Support Document

State of California
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Planning and Technical Support Division

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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.

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

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

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

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

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

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

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.

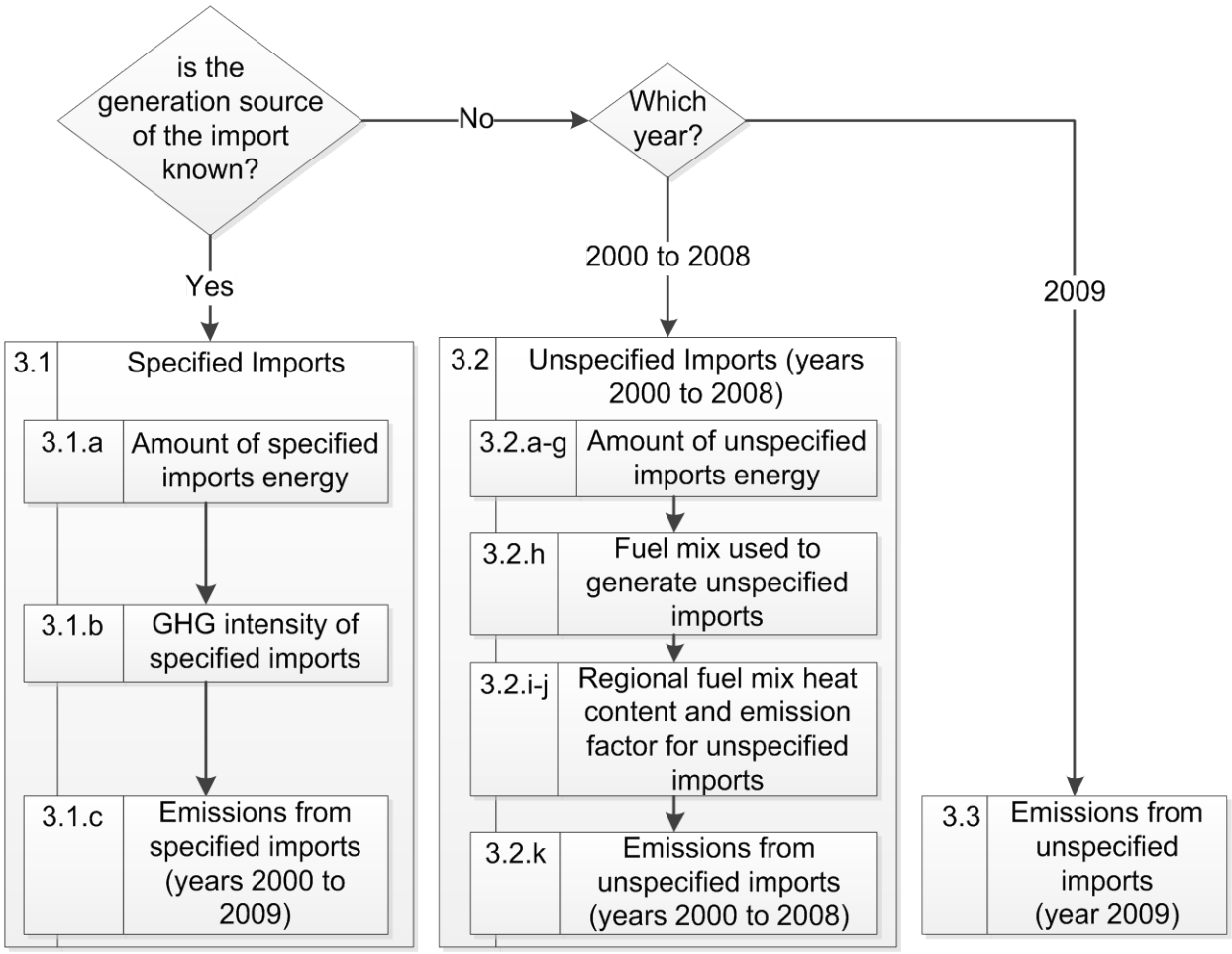
Fuel CO_2 Emissions factors are from USEPA 1990-2005 greenhouse gas inventory (USEPA, 2007b). Fuel CH_4 and N_2O emissions factors come from the IPCC 2006 guidelines for stationary combustion (IPCC, 2006b).

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) <u>Amount of specified imports energy</u>

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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,

$HC_{Gas, year}$ = Heat Content of the pure (unblended) gasoline (Btu / gal) for a particular year

$V_{Blend, year}$ = Volume of gasoline-ethanol blend consumed in the US in a particular year (gal)

$V_{Ethanol, year}$ = Volume of ethanol consumed in the US in a particular year (gal)

$HC_{Blend, year}$ = Heat Content of the gasoline-ethanol blend consumed in the US in a particular year (Btu / gal)

$V_{Ethanol, year}$ = 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

$$C_2H_5OH + 3O_2 \rightarrow 2CO_2 + 3H_2O$$

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

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

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

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

Where,

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

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

$M_{fuel,\ year}$ = 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,

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

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

$R_{fuel, year}$ = 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

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

Where,

$P_{Gasoline, year}$ = Proportion of gasoline in the gasoline-ethanol blend for a given fuel in a given year
$P_{Ethanol, year}$ = 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

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

Where,

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

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

Where,

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

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

Where,

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

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

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)

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

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)

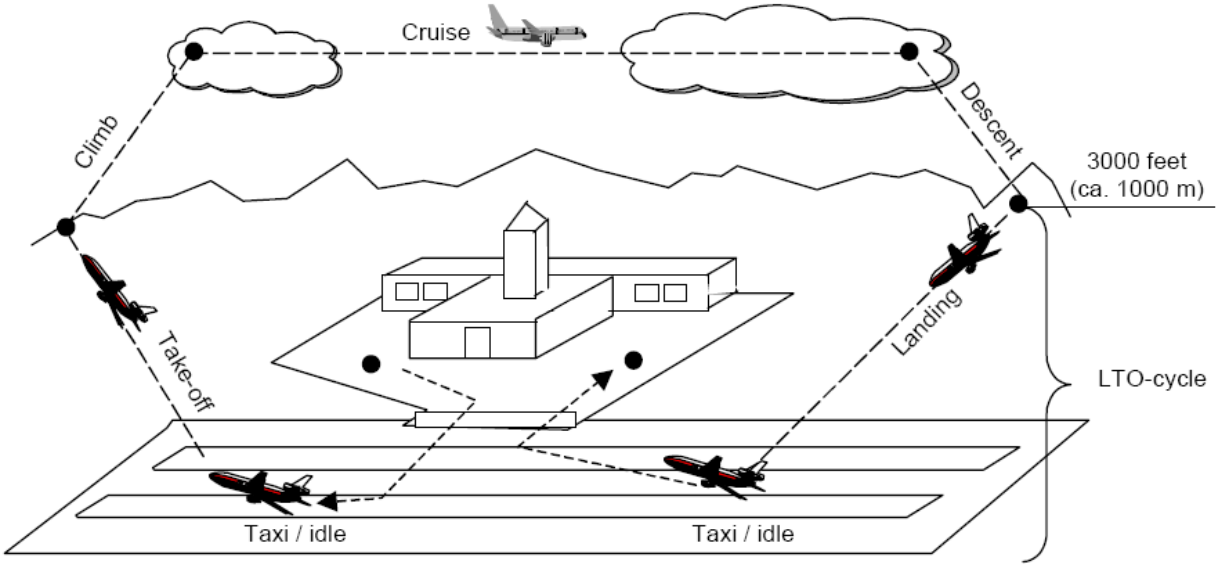


Table 24: Example of typical fuel consumption (from EMEP/CORINAIR Guidebook)

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

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

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

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

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

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

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,

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

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

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

$$E = GH \bullet EF$$

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)

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

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)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\boxed{\begin{aligned} &CaCO_3 + Heat \rightarrow CaO + CO_2 \\ &MgCO_3 + Heat \rightarrow MgO + CO_2 \end{aligned}}$$

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

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

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

$$E_{total} = E_I + E_{LKD}$$

Where,

E_{total}	= total process emissions of CO_2 from lime production (tonnes)
E_I	= 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

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

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

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

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

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

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

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

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

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

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

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

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

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

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_2e)	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

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

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

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

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

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

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

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

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$

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

$$CH_2 + 2H_2O \rightarrow CO_2 + 3H_2$$

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

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

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) Heifer stockers Steer stockers Feedlot heifers 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

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

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

$$E = N \bullet EF$$

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

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

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

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

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

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

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

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

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.

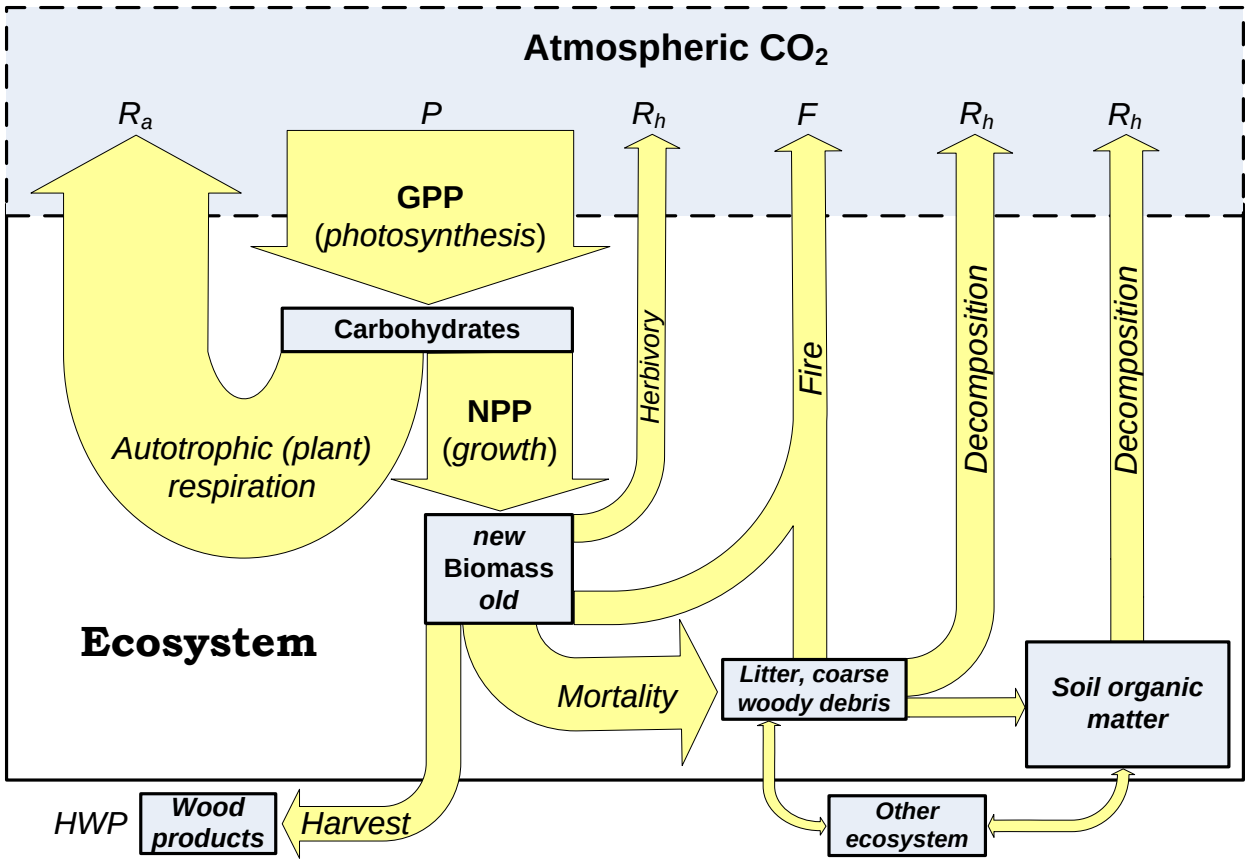
C. Land - Forests and Rangelands (IPCC 3B)

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 (ΔC_{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).

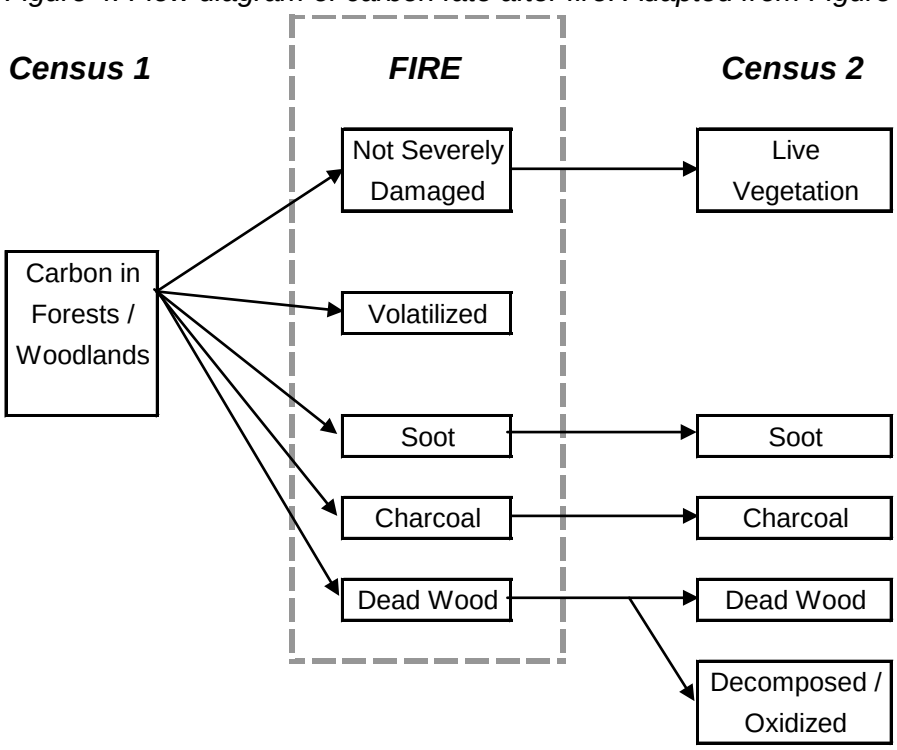


Table 39: Carbon fate assumptions after decreases in canopy cover caused by fire (percent).

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

$$E_{CH4} = M_c \bullet 0.012 \bullet 1.3357$$

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

$$E_{N2O} = M_C \bullet 0.01 \bullet 0.007 \bullet 1.5711$$

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. Data Sources

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 ($MMTCO_2$)

Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Data Source
Sinks (million tonnes of CO_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**	
Emissions (million tonnes of CO_2)											
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**	

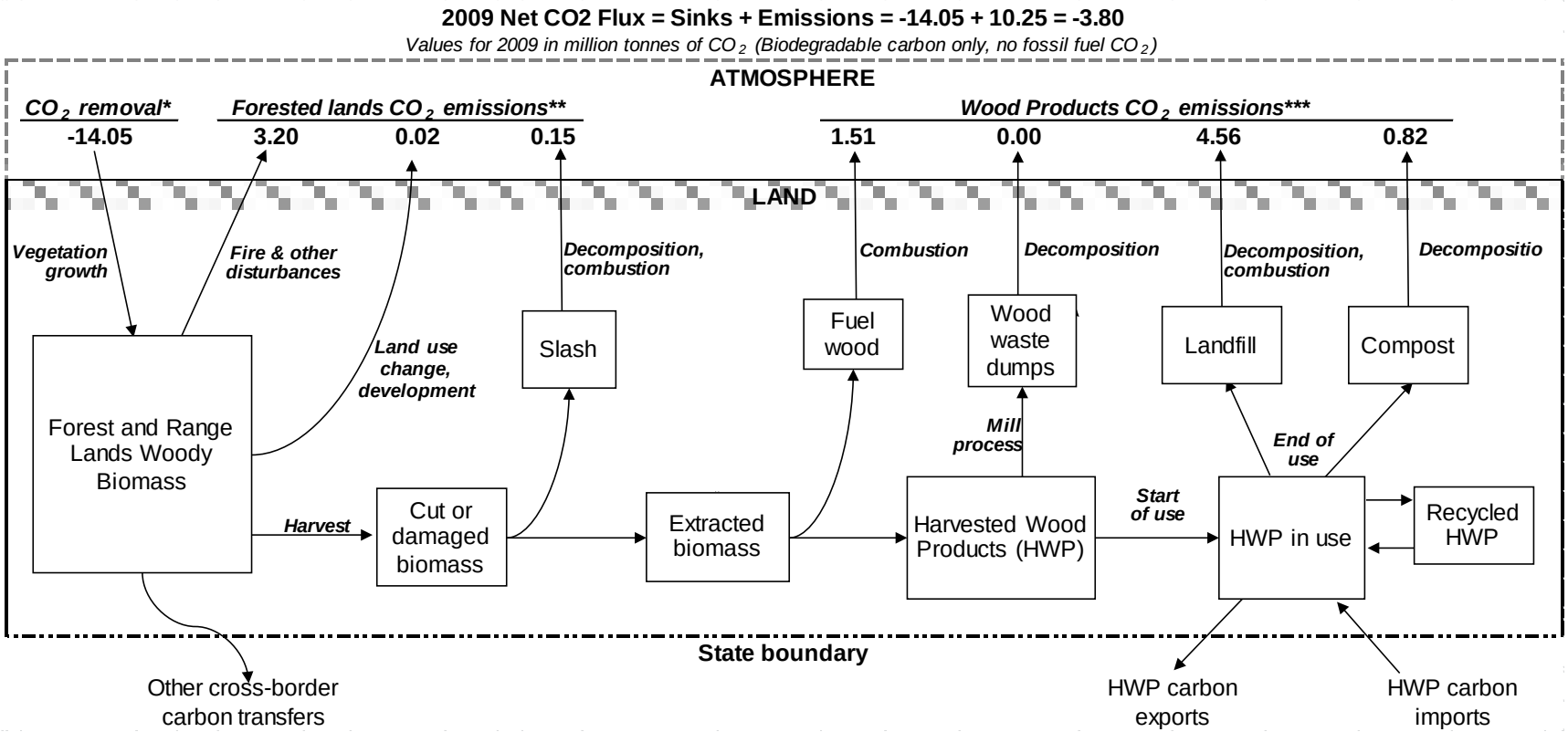
Data sources:

● **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.



*** 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

$$E_{GHG,crop} = A_{crop} \bullet 0.404685642 \bullet FB_{crop} \bullet MR_{crop} \bullet EF_{GHG,crop}$$

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

$$E = \left[\left(M_L \bullet EF_L\right) + \left(M_D \bullet EF_D\right)\right] \bullet 3.6642$$

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

$$M_L = L_{AG} \bullet \frac{T_L}{(T_L + T_D)}$$

Equation 74: Mass of dolomite applied to soils

$$M_D = L_{AG} \bullet \frac{T_D}{(T_L + T_D)}$$

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

$$E_{indirect} = E_V + E_{LR}$$

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

$$E_V = \left[N_{SF} \bullet V_1 + (N_{OF} + N_{MM} + N_{UM}) \bullet V_2\right] \bullet EF_4 \bullet 1.5711$$

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

$$E_{LR} = \left[N_{SF} + N_{OF} + N_{MM} + N_{UM}\right] \bullet L \bullet EF_5 \bullet 1.5711$$

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

$$N_{CR} = \sum_{crop} \left(N_{AGR,crop} + N_{BGR,crop} \right)$$

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

$$N_{AGR,crop} = A_{NBR,crop} \bullet M_{AGR,crop} \bullet NC_{AGR,crop}$$

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

$$M_{AGR,crop} = \beta_{0,crop} + \beta_{1,crop} \bullet M_{Yield,crop}$$

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

$$N_{BGR,crop} = A_{NBR,crop} \bullet \left(M_{Yield,crop} + M_{AGR,crop}\right) \bullet R_{BA,crop} \bullet NC_{BGR,crop}$$

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

$$A_{NBR,crop} = A_{H,crop} \bullet \left(1 - (F_{AB,crop} \bullet F_{RC,crop}\right) \bullet F_{AR,crop}$$

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

$$E = A \bullet EF$$

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) <u>Anaerobically Degradable Organic Carbon (*ANDOC*)</u>

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

$$E_{N2O} = LFG \bullet F_{CH4} \bullet HC_{CH4} \bullet EF_{CH4}$$

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

$$E_{GHG} = Q * EF_{GHG} * 907.2$$

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

$$E_{Domestic,CH4} = E_{Septic,CH4} + E_{Aerobic,CH4} + E_{Anaerobic,CH4} + E_{Digester,CH4}$$

Equation 93: CH_4 emissions from Septic Systems

$$E_{Septic,CH4} = P \bullet R_{BOD5} \bullet 365.2425 \bullet f_{Septic} \bullet B_o \bullet MCF_{Septic}$$

Equation 94: CH_4 emissions from Centrally Treated Aerobic Systems

$$E_{Aerobic,CH4} = \left\{ \begin{array}{l} P \bullet R_{BOD5} \bullet 365.2425 \bullet f_{central} \bullet f_{aerobic} \bullet \\ (f_{aerobic,woPT} + (f_{aerobic,wPT} \bullet (1 - f_{BOD}))) \bullet f_{NWM} \bullet B_o \bullet MCF_{aerobic,NWM} \end{array} \right\}$$

Equation 95:CH_4 emission from Centrally Treated Anaerobic Systems

$$E_{Anaerobic,CH4} = \left\{ \begin{array}{l} P \bullet R_{BOD5} \bullet 365.2425 \bullet f_{central} \bullet f_{anaerobic} \bullet \\ (f_{anaerobic,woPT} + (f_{anaerobic,wPT} \bullet (1 - f_{BOD}))) \bullet B_o \bullet MCF_{anaerobic} \end{array} \right\}$$

Equation 96:CH_4 emissions from Anaerobic Digesters

$$E_{Digester,CH4} = V_{biogas} \bullet f_{CH4} \bullet 0.02831 \bullet 662 \bullet (1 - D_{CH4})$$

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

$$E_{CH4,product} = Q_{product} \bullet W_{product} \bullet COD_{product} \bullet f_{COD,product} \bullet B_o \bullet MCF$$

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

$$E_{CH4} = W \bullet COD \bullet B_o \bullet MCF$$

Equation 100: Wastewater flow from petroleum refineries

$$W = V \bullet 35$$

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

$$E_{N2O} = E_{N2O,Plant} + E_{N2O,Effluent}$$

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) <u>Emissions at the wastewater treatment plants</u>

Plant emissions ($E_{N2O,\ plant}$) are estimated with the following equations:

Equation 102: N_2O emissions at the water treatment plant

$$E_{N2O,plant} = E_{N2O,wNDN} + E_{N2O,woNDN}$$

Equation 103: N_2O emissions from centralized wastewater treatment plant with nitrification/denitrification

$$E_{N2O,wNDN} = P_{NDN} \bullet EF_{wNDN} \bullet F_{IC}$$

Equation 104: N_2O emissions from centralized wastewater treatment plant without nitrification/denitrification

$$E_{N2O,woNDN} = \left[(P \bullet f_{central}) - P_{ND}\right] \bullet EF_{woNDN} \bullet F_{IC}$$

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) <u>Emissions from nitrogen-containing effluent discharged into water bodies</u>

Effluent emissions ($E_{N2O,\ Effluent}$) are estimated using the following equation:

Equation 105: N_2O emissions from wastewater effluent

$$E_{N2O,Effluent} = \left\{\left[(P - (P_{NDN} \bullet 0.9)) \bullet R_{protein} \bullet f_N \bullet F_{NCN} \bullet F_{IC}\right] - N_{sludge}\right\} \bullet EF_{effluent} \bullet 1.5711$$

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. <u>Data Sources</u>

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.

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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