PART II OVERVIEW

Energy, Industry, and Waste Management Activities: An Introduction to CO_2 Emissions from Fossil Fuels

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THE CONTEXT

Fossil fuels (coal, oil, and natural gas) are used primarily for their concentration of chemical energy, energy that is released as heat when the fuel is burned. Fossil fuels are composed primarily of compounds of hydrogen and carbon. When the fuels are burned, the hydrogen and carbon oxidize to water and CO_2, and heat is released. If the water and CO_2 are released to the atmosphere, the water will soon fall out as rain or snow. The CO_2, however, will increase the concentration of CO_2 in the atmosphere and join the active cycling of carbon that takes place among the atmosphere, biosphere, and hydrosphere. Since humans began taking advantage of fossil-fuel resources for energy, we have been releasing to the atmosphere, over a very short period of time, carbon that was stored deep in the Earth over millions of years. We have been introducing a large perturbation to the active cycling of carbon.

Estimates of fossil-fuel use globally show that there have been significant emissions of CO_2 dating back at least to 1750, and from North America back at least to 1785. However, this human perturbation of the active carbon cycle is largely a recent process, with the magnitude of the perturbation continuing to grow as population grows and demand for energy grows. Looking back from the end of 2005, fully half of the CO_2 released from fossil-fuel burning globally has occurred since 1980 (Figure 1).

Figure 1. Cumulative global emissions of CO_2 from fossil-fuel combustion and cement manufacture from 1751 to 2002.

Some CO_2 is also released to the atmosphere during the manufacture of cement. Limestone ($CaCO_3$) is heated to release CO_2 and produce the calcium oxide (CaO) used to manufacture cement. In North America, cement manufacturing now releases less than 1% of the CO_2 released by fossil-fuel combustion. However, cement manufacturing is the largest anthropogenic (of human origin) source of CO_2 after fossil-fuel use and the clearing and oxidation of forests and soils (see Part III of this report). The CO_2 emissions from cement manufacture are often included in the accounting of anthropogenic CO_2 emissions from fossil fuels.

Part II of this report addresses the magnitude and pattern of CO_2 emissions from fossil-fuel consumption and cement manufacturing in North America, and discusses some scenarios for emissions in the future. This introductory section addresses some general issues associated with CO_2 emissions and the annual and cumulative magnitude of total emissions. It looks at the temporal and spatial distribution of emissions and some other data likely to be of interest. The following four chapters delve into the sectoral details of emissions so that we can understand the forces that have driven the growth in emissions to date and the possibilities for the magnitude and pattern of emissions in the future. These chapters reveal that 38.4% of CO_2 emissions from North America come from enterprises whose primary business is to provide electricity and heat and another 30.8% come from the transport of passengers and freight. This introduction focuses on the total emissions from the use of fossil fuels, and the subsequent chapters provide insight into how these fuels are used and the economic and human processes motivating their use.

Estimating CO_2 Emissions

If we have estimates of the consumption of fossil fuels, it is relatively straightforward to estimate the amount of CO_2 released to the atmosphere when they are consumed. Because CO_2 is the equilibrium product of oxidizing the carbon in fossil fuels, we need to know only the amount of fuel used and its carbon content. For greater accuracy, we adjust this estimate to take into consideration the amount of carbon that is left as ash or soot and is not actually oxidized. We also consider the fraction of fossil fuels that is used for products such as highway asphalt, lubricants, waxes, solvents, and plastics and thus may not soon be converted to CO_2. Some of these long-lived carbon-containing products will release the carbon they contain to the atmosphere as CO_2 during use or during processing of the materials as waste. Other products will hold the carbon in use or in landfills for decades or longer. One of the differences among the various estimates of CO_2 emissions is the ways they deal with the carbon in these carbon-containing products.

Fossil-fuel consumption is often measured in mass or volume units and, in these terms, the carbon content of fossil fuels is quite variable. However, when we measure the amount of fuel consumed in terms of its energy content, we find that for each of the primary fuel types (coal, petroleum, and natural gas) there is a strong correlation between the energy content and the carbon content. The rate of CO_2 emitted per unit of useful energy released depends on the ratio of hydrogen to carbon and on the details of the organic compounds in the fuels; but, roughly speaking, the numerical conversion from energy released to carbon released as CO_2 is about 25 kg C per billion J for coal, 20 kg C per billion J for petroleum, and 15 kg C per billion J for natural gas. Figure 2 shows details of the correlation between energy content and carbon content for more than 1000 coal samples. Detailed analysis of the data suggests that hard coal contains 25.16 kg C per billion J of coal (measured on a net heating value basis[1]), with a standard error of the mean at 2.09%. The value is slightly higher for lignite and brown coals (26.23 kg C per billion J ±2.33%, also shown in Figure 1). Similar correlations exist for all fuels, and Table 1 shows some of the coefficients reported by the Intergovernmental Panel on Climate Change (IPCC) for estimating CO_2 emissions from measures of fossil-fuel use. The differences between the values in Table 1 and those in Figure 1 are small, but they begin to explain how different data compilations can end up with different estimates of CO_2 emissions.

Figure 2. The carbon content of coal varies with the heat content, shown here as the net heating value. To make them easier to distinguish, data for lignites and brown coals are shown on the left axis, and data for hard coals are offset by 20% and shown on the right axis. Heating value is plotted in the units at which it was originally reported, Btu/lb, where 1 Btu/lb = 2324 J/kg (from Marland *et al.*, 1995).

Table 1. A sample of the coefficients used for estimating CO_2 emissions from the amount of fuel burned (from IPCC, 1996).

Data on fossil-fuel production, trade, consumption, and so on are generally collected at the level of some political entity, such as a country, and over some time interval, typically a year. Estimates of national annual fuel consumption can be based on estimates of fuel production and trade, estimates of actual final consumption, data for fuel sales or some other activity that is clearly related to fuel use, or on estimates and models of the activities that consume fuel (such as vehicle miles driven). In the discussion that follows, some estimates of national annual CO_2 emissions are based on "apparent consumption" (defined as production + imports – exports ± changes in stocks), while others are based on more direct

[1]"Net heating value" is the heat release measured when fuel is burned at constant pressure so that the water is released as water vapor. This is distinguished from the "gross heating value," which is the heat release measured when the fuel is burned at constant volume so that the water is released as liquid water. The difference is essentially the heat of vaporization of the water and is related to the hydrogen content of the fuel.

estimates of fuel consumption. All of the emissions estimates in this chapter are in terms of the mass of carbon released.[2]

The uncertainty in estimates of CO_2 emissions will thus depend on the variability in the chemistry of the fuels, the quality of the data, or models of fuel consumption, and on uncertainties in the amount of carbon that is used for non-fuel purposes (such as asphalt and plastics) or is otherwise not burned. For countries like the United States—with good data on fuel production, trade, and consumption—the uncertainty in national emissions of CO_2 is probably on the order of ±5% or less. In fact, the U.S. Environmental Protection Agency (EPA) (2005) suggests its estimates of CO_2 emissions from energy use in the United States are accurate, at the 95% confidence level, within –1 to +6 %; and Environment Canada (2005) suggests its estimates for Canada are within –4 to 0 %. The Mexican National Report (Mexico, 2001) does not provide estimates of uncertainty, but our analyses using the Mexican data suggest that uncertainty is larger than for the United States and Canada. Emissions estimates for these same three countries as reported by the Carbon Dioxide Information Analysis Center (CDIAC) and the International Energy Agency (IEA) (see the following section) will have larger uncertainty because these groups are making estimates for all countries. Because they work with data from all countries, they are inclined to use global average values for things like the emissions coefficients, whereas agencies within the individual countries use values that are more specific to the particular country.

The Magnitude of National and Regional CO_2 Emissions

Figure 3 shows that from the beginning of the fossil-fuel era (1750 in these graphs) to the end of 2002, there were 93.5 Gt C released as CO_2 from fossil-fuel consumption (and cement manufacturing) in North America: 84.4 Gt C from the United States, 6.0 from Canada, and 3.1 from Mexico. All three countries of North America are major users of fossil fuels, and this 93.5 Gt C is 31.5 % of the global total. Among all countries, the United States, Canada, and Mexico rank as the first, eighth, and eleventh largest emitters of CO_2 from fossil-fuel consumption, respectively (for 2002) (Marland *et al.*, 2005). Figure 4 shows, for each of these countries and for the sum of the three, the annual total of emissions and the contributions from the different fossil fuels.

Figure 3. The cumulative total of CO_2 emissions from fossil-fuel consumption and cement manufacturing as a function of time, for the three countries of North America and for the sum of the

[2]The carbon is actually released to the atmosphere as CO_2, and it is accurate to report (as is often done) either the amount of CO_2 emitted or the amount of carbon in the CO_2. The numbers can be easily converted back and forth using the ratio of the molecular masses, i.e. (mass of carbon) × (44/12) = (mass of CO_2).

three. Figure 3a is for the United States, Figure 3b is for Canada, Figure 3c is for Mexico, and Figure 3d is for the sum of the three. Note that in order to illustrate the contributions of the different fuels, the four plots are not to the same vertical scale (from Marland *et al.*, 2005).

Figure 4. Annual emissions of CO_2 from fossil-fuel use by fuel type.

The long time series of emissions estimates illustrated in Figures 2 and 3 are from CDIAC (Marland *et al.*, 2005). These estimates are derived from the "apparent consumption" of fuels and are based on data from the UN Statistics Office back to 1950 and on data from a mixture of sources for the earlier years (Andres *et al.*, 1999). There are other published estimates (with shorter time series) of national annual CO_2 emissions. Most notably, IEA (2005) has reported estimates of emissions for many countries for all years back to 1971, and most countries have now provided some estimates of their own emissions as part of their national obligations under the United Nations Framework Convention on Climate Change (UNFCCC, http://unfccc.int). The latter two sets of estimates are based on data on actual fuel combustion and thus are able to provide details as to the sector of the economy where fuel use is taking place.[3]

Comparing the data from multiple sources can give us some insight into the reliability of the estimates generally. These different estimates of CO_2 emissions are not, of course, truly independent because they all rely ultimately on national data on fuel use. However, they do represent different manipulations of these primary data, and in many countries, there are multiple potential sources of energy data. Many developing countries do not collect or do not report all of the data necessary to precisely estimate CO_2 emissions. In these cases, differences can be introduced by how the various agencies derive the basic data on fuel production and use. Because of the way data are collected, there are statistical differences between "consumption" and "apparent consumption" as defined earlier.

To make comparisons of different estimates of CO_2 emissions, we would like to be sure that we are indeed comparing estimates of the same thing. For example, emissions from cement manufacturing are not available from all of the sources, so they are not included in the comparisons in Table 2. All of the estimates in Table 2, except those from the IEA, include emissions from flaring natural gas at oil production facilities. It is not easy to identify the exact reason the estimates differ, but the differences are generally small. The differences have mostly to do with the statistical difference between consumption and apparent consumption, the way a correction is made for non-fuel usage of fossil-fuel resources, the conversion from mass or volume to energy units, and/or the way estimates of carbon content are derived. Because the national estimates from CDIAC do not include emissions from the non-fuel uses of

[3]IEA provides estimates based on both the reference approach (estimates of apparent consumption) and the sectoral approach (estimates of actual consumption) as described by the IPCC (IPCC 1997). In the comparison here, we use the numbers that they believe to be the most accurate, those based on the sectoral approach.

petroleum products, we expect them to be slightly smaller than the other estimates shown here, all of which do include these emissions.[4] The comparisons in Table 2 reveal one number for which there is a notable difference among the multiple sources: the emissions from Mexico in 1990. Losey (2004) has suggested, based on other criteria, that there is an inaccuracy in the UN energy data set for Mexican natural gas for the three-year period 1990–1992; these kinds of analyses result in reexamination of some of the fundamental data.

Table 2. Estimates (in Mt C) of CO_2 emissions from fossil-fuel consumption for the United States, Canada, and Mexico.

IEA (2005, p. 1.4) has systematically compared its estimates with those reported to the UNFCCC by the different countries, and it finds that the differences for most developed countries are within 5%. IEA attributes most of the differences to the following:

- use of the IPCC Tier 1 method that does not take into account different technologies
- use of energy data that may have come from different "official" sources within a country
- use of average values for the net heating value of secondary oil products
- use of average emissions values
- use of incomplete data on non-fuel uses
- different treatment of military emissions
- a different split between what is identified as emissions from energy and emissions from industrial processes.

Emissions by Month and/or State

With interest increasing in the details and processes of the global carbon cycle, there is also increasing interest in knowing emissions at spatial and temporal scales finer than countries and years. For the United States, energy data have been collected for many years at the level of states and months, and thus estimates of CO_2 emissions can be made by state or by month. Figure 5 shows there is considerable variation in United States emissions by month, and preliminary analyses by Gurney *et al.* (2005) reveal that proper recognition of this variability can be very important in some exercises to model the details of the global carbon cycle.

[4]The CDIAC estimate of global total emissions does include estimates of emissions from oxidation from non-fuel use of hydrocarbons.

Figure 5. Emissions of CO_2 from fossil-fuel consumption in the United States, by month. Emissions from cement manufacturing are not included (from Blasing *et al.*, 2005a).

Because of differences in the way energy data are collected and aggregated, it is not obvious that an estimate of emissions from the United States will be identical to the sum of estimates for the 50 U.S. states. Figure 6 shows that estimates of total annual CO_2 emissions are slightly different if we use data directly from the U.S. Department of Energy (DOE) and sum the estimates for the 50 states, or if we sum the estimates for the 12 months of a given year, or if we take United States energy data as aggregated by the UN Statistics Office and calculate the annual total of CO_2 emissions directly. Again, the state and monthly emissions data are based on estimates of fuel consumption, while the national emissions estimates calculated using UN data result from estimates of "apparent consumption." There is a difference between annual values for consumption and annual values of "apparent consumption" (the IEA calls this difference simply "statistical difference") that is related to the way statistics are collected and aggregated. There are also differences in the way values for fuel chemistry and non-fuel usage are averaged at different spatial and temporal scales, but the differences in CO_2 estimates are seen to be within the error bounds generally expected.

Figure 6. A comparison of three different estimates of national annual emissions of CO_2 from fossil-fuel consumption in the United States.

Data from DOE permit us to estimate emissions by state or by month (Blasing *et al.*, 2005a and 2005b), but they do not permit us to estimate CO_2 emissions for each state by month directly from the published energy data. Nor do we have sufficiently complete data to estimate emissions from Canada and Mexico by month or province. Andres *et al.* (2005), Gregg (2005), and Losey (2004) have shown that we can disaggregate national total emissions by month or by some national subdivision (such as states or provinces) if we have data on some large fraction of fuel use. Because this approach relies on determining the fractional distribution of an otherwise-determined total, it can be done with incomplete data on fuel use. The estimates, will of course, improve as the fraction of the total fuel use is increased. Figure 7 is based on sales data for most fossil-fuel commodities and the CDIAC estimates of total national emissions. It shows how the CO_2 emissions from North America vary at a monthly time scale.

Figure 7. CO_2 emissions from fossil-fuel consumption in North America, by month. Monthly values are shown where estimates are justified by the availability of monthly data on fuel consumption or sales (from Andres *et al.*, 2005).

Emissions by Economic Sector

To understand how CO_2 emissions from fossil-fuel use enter and interact in the global and regional cycling of carbon, it is necessary to know the masses of emissions and their spatial and temporal patterns. We have tried to summarize this information in this brief discussion. To understand the trends and the driving forces behind the growth in fossil-fuel emissions, and the opportunities for controlling emissions, it is necessary to look in more detail at how the fuels are used and at the economic sectors in which the fuels are used and from which the CO_2 is emitted. This is the goal of the next four chapters of this volume.

Before looking at the details of how energy is used and where CO_2 emissions occur in the economies of North America, however, there are two indices of CO_2 emissions at the national level that provide additional perspective on the scale and distribution of emissions. These two indices are emissions per capita and emissions per unit of economic activity, the latter generally represented by CO_2 per unit of gross domestic product (GDP). Figure 8 shows the 1950–2002 record of CO_2 emissions per capita for the three countries of North America and, for perspective, includes the same data for the Earth as a whole. Similarly, Table 3 shows CO_2 emissions per unit of GDP for the three countries of North America and for the world total. These are, of course, very complex indices; and though they provide some insight, they say nothing about the details and the distributions within the means. The data on CO_2 per capita for the 50 U.S. states (Figure 9) show that values range over a full order of magnitude, differing in complex ways with the structure of the economies and probably with factors such as climate, population density, and access to resources (Blasing *et al.*, 2005b; Neumayer, 2004).

Chapters 6 through 9 of this volume discuss the patterns and trends of CO_2 emissions by sector and the driving forces behind the trends that are observed. Estimating emissions by sector brings special challenges in defining sectors and assembling the requisite data. Readers will find that there is consistency and coherence within the following chapters but will encounter difficulty in aggregating or summing numbers across chapters. Different experts use different sector boundaries, different data sources, different conversion factors, etc. Different analysts will find data for different base years and may treat electricity and biomass fuels differently. Despite numeric differences, however, the 4 chapters accurately characterize the patterns of emissions and the opportunities for controlling the growth in emissions. They reveal that there are major differences between the countries of North America where, for example, the United States derives 50% of its electricity from coal, Mexico gets 73% from petroleum and natural gas, and Canada gets 60% from hydroelectric stations. Partially as a reflection of this difference, 40% of United States CO_2 emissions are from enterprises whose primary business is to generate electricity and heat, while this number is only 31% in Mexico and 23% in Canada (for 2002, from IEA, 2004). Chapter 8 reveals that the sectors are not independent as, for example, a change from fuel burning to electricity in an industrial process will decrease emissions from the industrial sector but increase emissions in the electric power sector. The database of the International Energy Agency allows us to summarize CO_2 emissions for the 3 countries according to sectors that closely correspond to the sectoral division of chapters 6 through 9 (Table 4).

Figure 8. Per capita emissions of CO_2 from fossil-fuel consumption (and cement manufacturing) in the United States, Canada, and Mexico and for the global total of emissions (from Marland *et al.*, 2005).

Table 3. Emissions of CO_2 from fossil-fuel consumption (cement manufacturing and gas flaring are not included) per unit of GDP for the United States, Canada, and Mexico and worldwide.

Figure 9. Per capita emissions of CO_2 from fossil-fuel consumption for the 50 U.S. states in 2000. To demonstrate the range of values, values have been rounded to whole numbers of metric tons per capita. A large portion of the range for extreme values is related to the occurrence of coal resources and inter-state transfers of electricity (from Blasing *et al.*, 2005b).

CONCLUSION

There are a variety of reasons we want to know the emissions of CO_2 from fossil fuels, there are a variety of ways of coming up with the desired estimates, and there are a variety of ways of using the estimates. By the nature of the process of fossil-fuel combustion, and because of its economic importance, there are reasonably good data over long time intervals that we can use to make reasonably accurate estimates of CO_2 emissions to the atmosphere. In fact, it is the economic importance of fossil-fuel burning that has assured us of both good data on emissions and great challenges in altering the rate of emissions.

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Table 1. A sample of the coefficients used for estimating CO_2 emissions from the amount of fuel burned
(from IPCC, 1996)

Fuel	Emissions coefficient (kg carbon/10^9 J net heating value)
Lignite	27.6
Anthracite	26.8
Bituminous coal	25.8
Crude oil	20.0
Residual fuel oil	21.1
Diesel oil	20.2
Jet kerosene	19.5
Gasoline	18.9
Natural gas	15.3

Table 2. Estimates (in Mt C) of CO_2 emissions from fossil-fuel consumption for the United States, Canada, and Mexico

Country	1990		1998		2002	
United States	CDIAC	1305	CDIAC	1501	CDIAC	1580
	IEA	1320	IEA	1497	IEA	1545
	U.S. EPA	1316	U.S. EPA	1478	U.S. EPA	1534
Canada	CDIAC	112	CDIAC	119	CDIAC	139
	IEA	117	IEA	136	IEA	145
	U.S. EPA	117	U.S. EPA	133	U.S. EPA	144
Mexico	CDIAC	99	CDIAC	96	CDIAC	100
	IEA	80	IEA	96	IEA	100
	U.S. EPA	81	U.S. EPA	96	U.S. EPA	NA

Notes:
These data have been multiplied by 12/44 to get the mass of carbon for the comparison here.
Many of these data were published in terms of the mass of CO_2.
Values for the United States, Canada and Mexico represent consumption data as reported by CDIAC (Marland *et al.*, 2005), IEA (2005), and by the National Reports to the United Nations Framework Convention on Climate Change [United States (EPA, 2005), Canada (Environment Canada, 2005), and Mexico (2001)].
All data except CDIAC include oxidation of non-fuel hydrocarbons.
All data except IEA include flaring of gas at oil and gas processing facilities.

Table 3. Emissions of CO_2 from fossil-fuel consumption (cement manufacturing and gas flaring are not included) per unit of GDP for the United States, Canada, and Mexico and worldwide

Country	CO_2 emissions per unit of GDP[a]		
	Year		
	1990	1998	2002
United States	0.19	0.17	0.15
Canada	0.18	0.18	0.16
Mexico	0.13	0.12	0.11
Global total	0.17	0.15	0.14

[a]CO_2 is measured in kg carbon and GDP is reported in 2000 US$ purchasing power parity (from IEA, 2005).

Table 4. Percentage of CO_2 emissions by sector for 2002

Sector	United States	Canada	Mexico	North America
Energy extraction and conversion[a]	46.8	36.0	49.4	46.1
Transportation[b]	31.2	28.3	28.7	30.8
Industry[c]	11.0	16.8	13.2	11.6
Buildings[d]	11.0	18.9	8.8	11.6

[a]The sum of three IEA categories, “public electricity and heat production,” “unallocated autoproducers,” and “other energy industries.” (IEA, 2004)

[b]IEA category “transport.” (IEA, 2004)

[c]IEA category “manufacturing industries and construction.” (IEA, 2004)

[d]IEA category “other sectors.” (IEA, 2004)

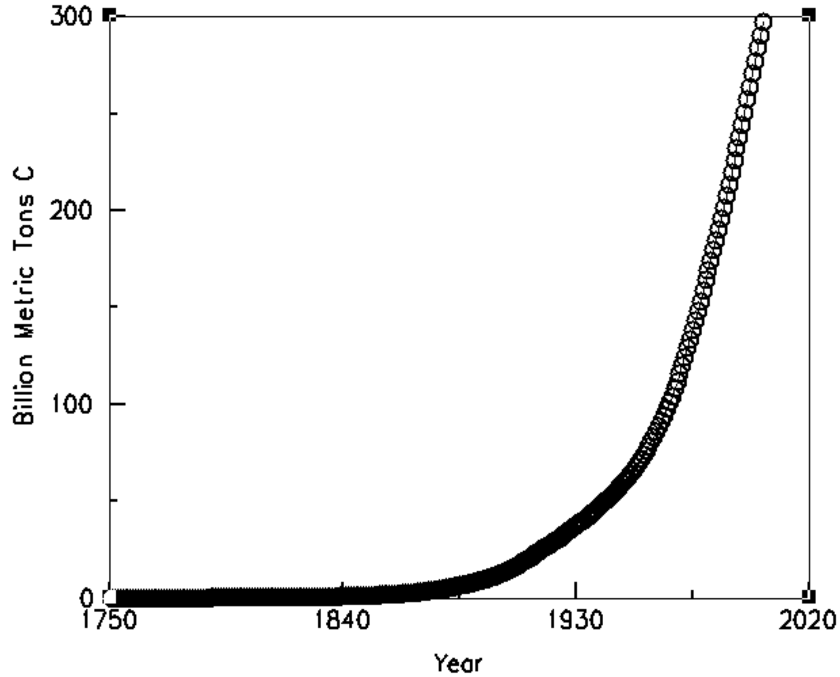
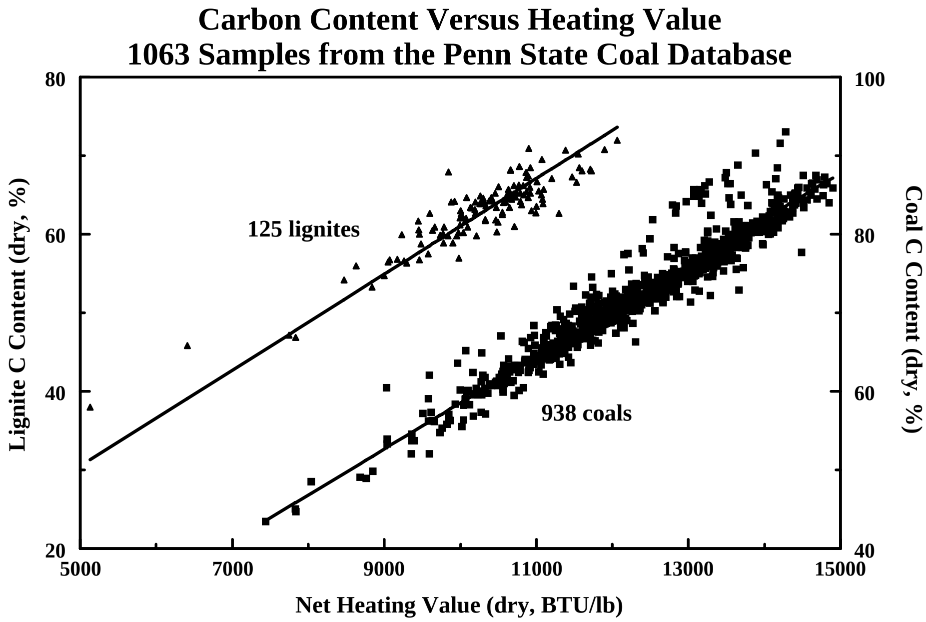


Figure 1. Cumulative global emissions of CO_2 from fossil-fuel combustion and cement manufacture from 1751 to 2002.



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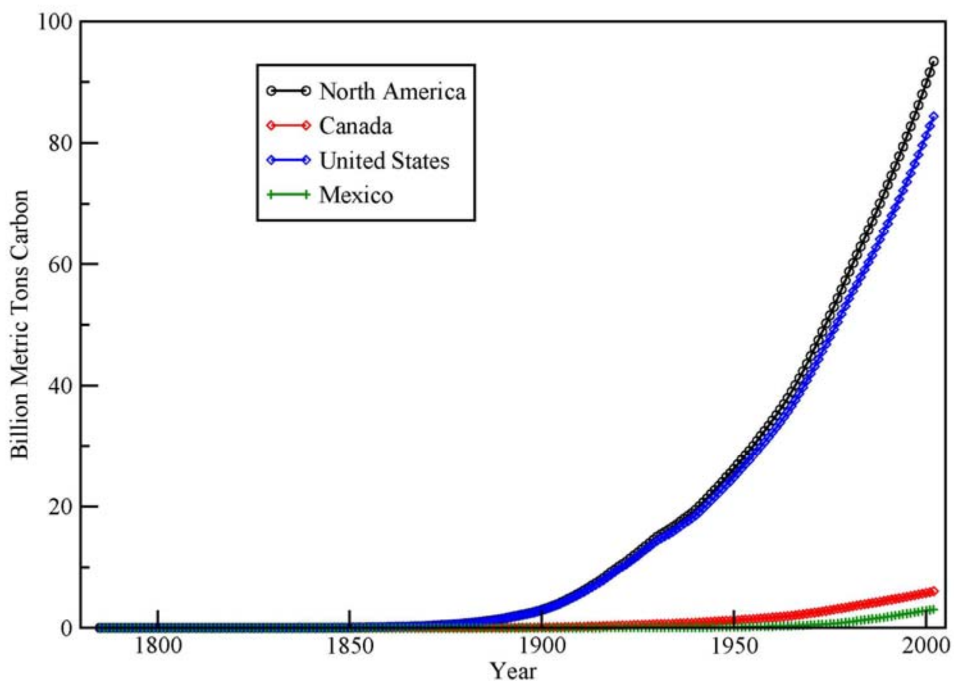
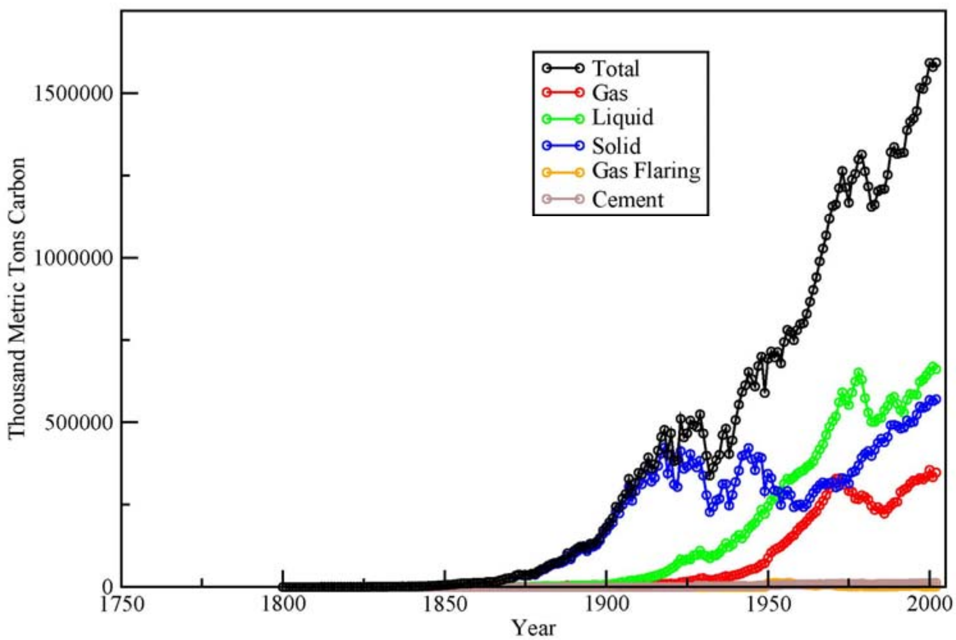


Figure 3. The cumulative total of CO_2 emissions from fossil-fuel consumption and cement manufacturing as a function of time, for the three countries of North America and for the sum of the three.

(a)



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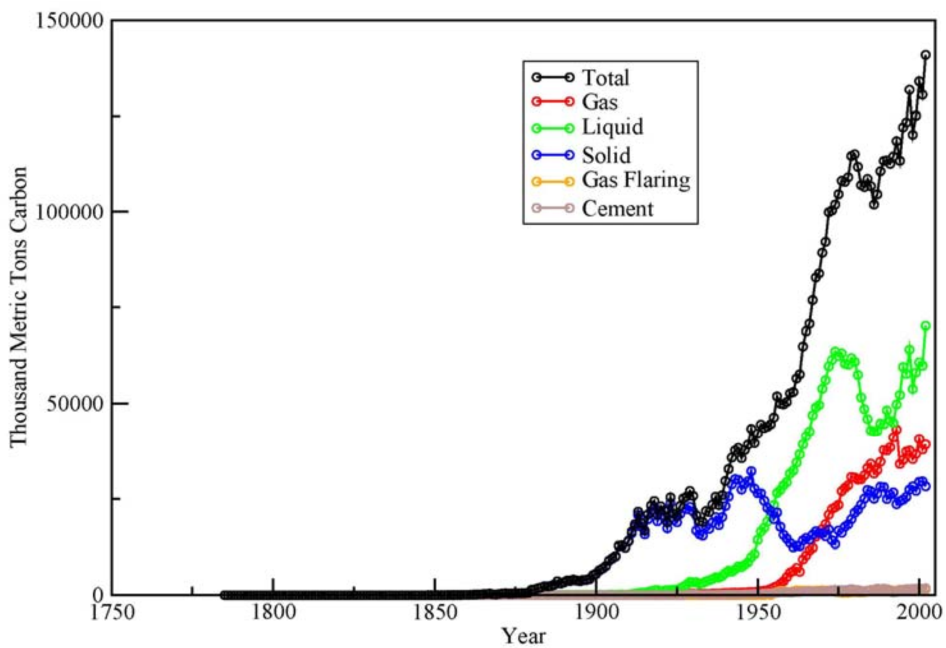
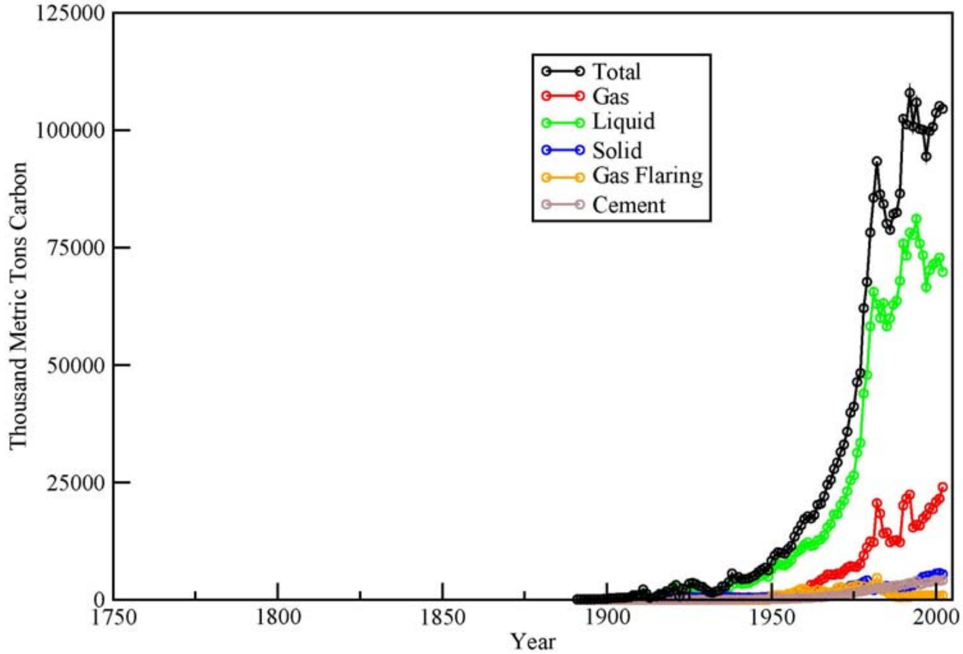


Figure 4a and 4b. Annual emissions of CO_2 from fossil-fuel use by fuel type. Figure 4a is for the United States, Figure 4b is for Canada, Figure 4c is for Mexico, and Figure 4d is for the sum of the three. Note that in order to illustrate the contributions of the different fuels, the four plots are not to the same vertical scale (from Marland et al. 2005).

(c)



(d)

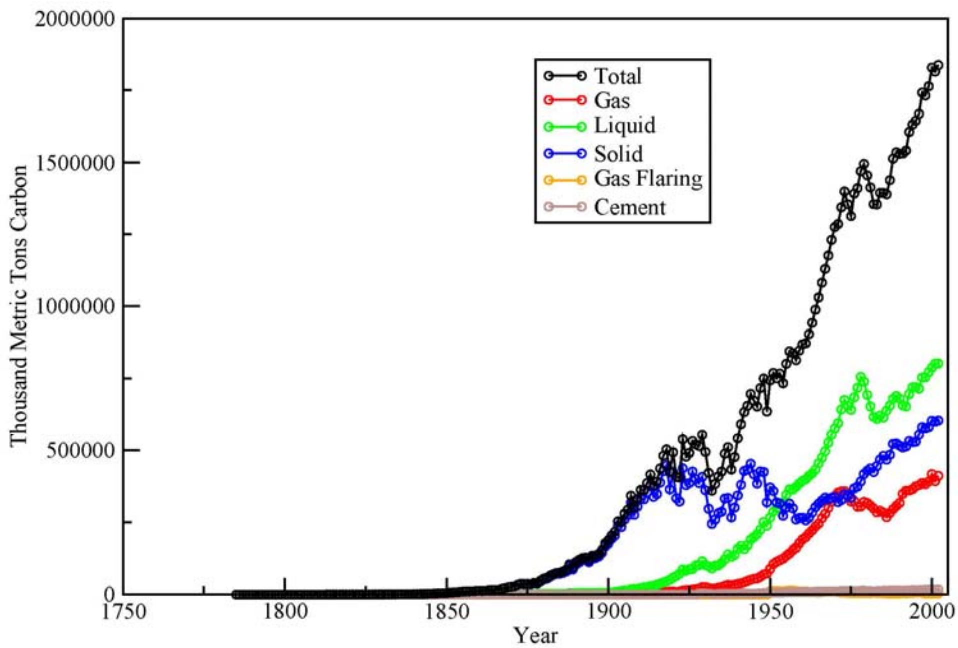


Figure 4c and 4d. Annual emissions of CO_2 from fossil-fuel use by fuel type. Figure 4a is for the United States, Figure 4b is for Canada, Figure 4c is for Mexico, and Figure 4d is for the sum of the three. Note that in order to illustrate the contributions of the different fuels, the four plots are not to the same vertical scale (from Marland et al. 2005).

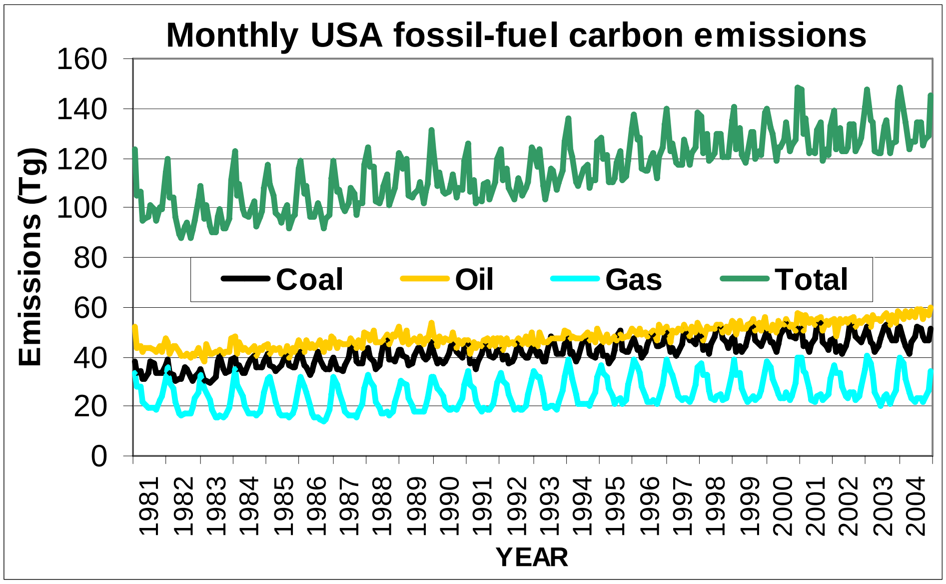
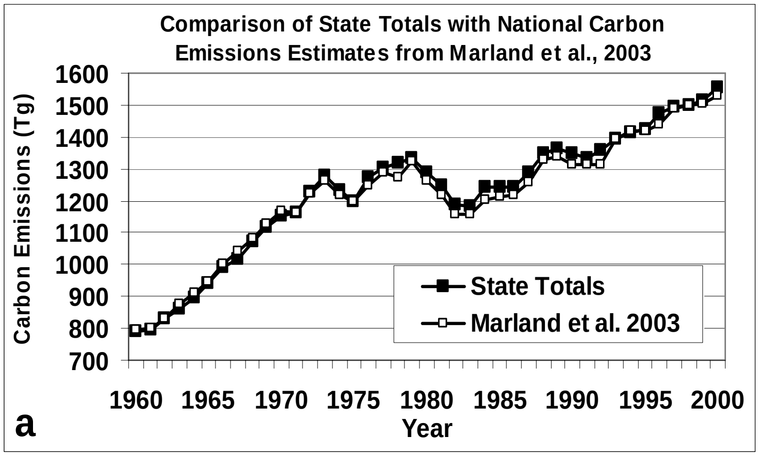
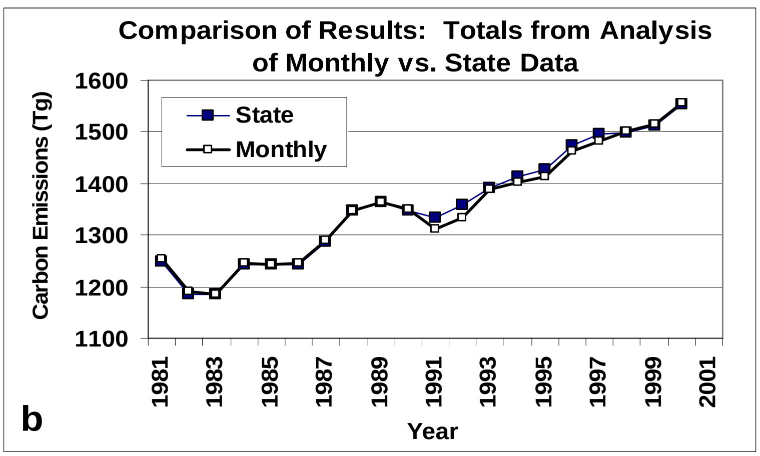


Figure 5. Emissions of CO_2 from fossil-fuel consumption in the United States, by month. Emissions from cement manufacturing are not included (from Blasing et al. 2005a).



Estimates from DOE data on fuel consumption by state (black squares) vs estimates based on the UN Statistics Office data on apparent fuel consumption for the full United States (open squares).



Estimates based on DOE data on fuel consumption in the 50 U.S. states (black squares) vs estimates based on national fuel consumption for each of the 12 months (open squares). The state and monthly data include estimates of oxidation of non-fuel hydrocarbon products; the UN-based estimates do not (from Blasing et al. 2005b).

Figure 6. A comparison of three different estimates of national annual emissions of CO_2 from fossil-fuel consumption in the United States.

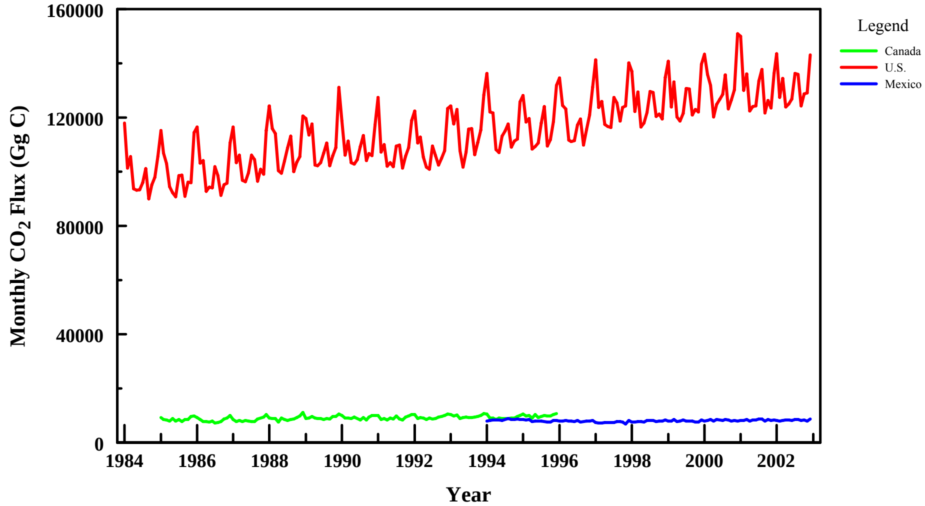


Figure 7. CO_2 emissions from fossil-fuel consumption in North America, by month. Monthly values are shown where estimates are justified by the availability of monthly data on fuel consumption or sales (from Andres et al. 2005).

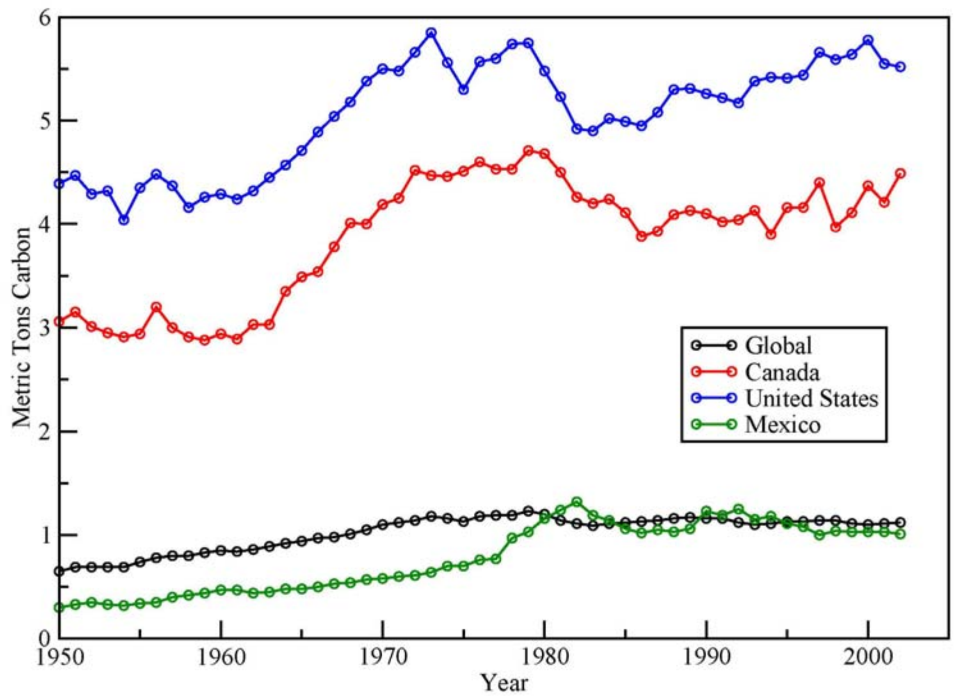


Figure 8. Per capita emissions of CO_2 from fossil-fuel consumption (and cement manufacturing) in the United States, Canada, and Mexico and for the global total of emissions (from Marland et al. 2005).

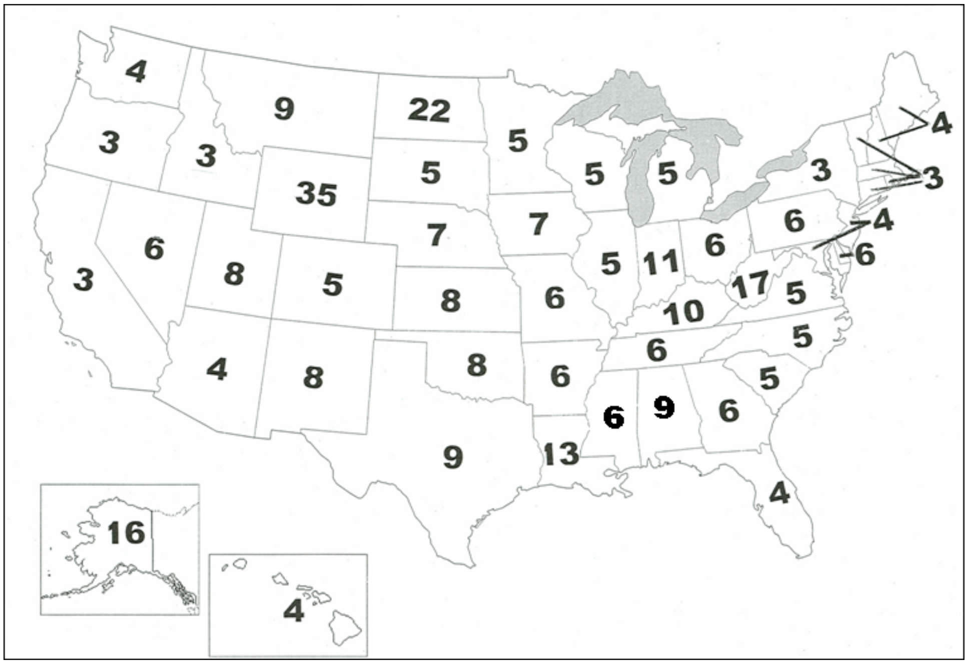


Figure 9. Per capita emissions of CO_2 from fossil-fuel consumption for the 50 US states in 2000. To demonstrate the range of values, values have been rounded to whole numbers of metric tons per capita. A large portion of the range for extreme values is related to the occurrence of coal resources and inter-state transfers of electricity (from Blasing et al. 2005b).