# Chapter 8. Industry and Waste Management

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## KEY FINDINGS

- In 2002, North America's industry (not including fossil fuel mining and processing or electricity generation) contributed 826 Mt $CO_2$, 16% of the world's $CO_2$ emissions to the atmosphere from industry. Waste treatment plants and landfill sites in North America accounts for 13.4 Mt of $CH_4$ (282 Mt $CO_2$e), roughly 20% of global totals.
- Industrial $CO_2$ emissions from North America decreased nearly 11% between 1990 and 2002, while energy consumption in the United States and Canada increased 8% to 10% during that period. In both countries, a shift in production activity toward less energy-intensive industries and dissemination of more energy efficient equipment kept the rate of energy demand growth lower than industrial GDP growth.
- Changes in industrial $CO_2$ emissions are a consequence of changes in industrial energy demand and changes in the mix of fossil fuels used by industry to supply that demand. Changes in industrial energy demand are themselves a consequence of changes in total industrial output, shifts in the relative shares of industrial sectors, and increases in energy efficiency. Shifts from coal and refined petroleum products to natural gas and electricity contributed to a decline in total industrial $CO_2$ emissions since 1997 in both Canada and the United States.
- An increase in $CO_2$ emissions from North American industry is likely to accompany the forecasted increase in industrial activity (2.3% $yr^{-1}$ until 2025 for the United States). Emissions per unit of industrial activity will likely decline as non-energy intensive industries grow faster than energy intensive industries and with increased penetration of energy efficient equipment. However, continuation of the trend toward less carbon-intensive fuels is uncertain given the rise in natural gas prices relative to coal in recent years.
- Options and measures for reducing $CO_2$ emissions from North American industry can be broadly classified as methods to: (1) reduce process/fugitive emissions or converting currently released emissions; (2) increase energy efficiency, including combined heat and power; (3) change industrial processes (materials efficiency, recycling, substitution between materials or between materials and energy); (4) substitute less carbon intense fuels; and (5) capture and store carbon dioxide.

- Further work on materials substitution holds promise for industrial emissions reduction, such as the replacement of petrochemical feedstocks by biomass feedstocks, of steel by aluminium in the transport sector, and of concrete by wood in the buildings sector. The prospects for greater energy efficiency technologies, including efficient Hall-Heroult cell retrofits in aluminium production, black liquor gasification in kraft pulp production, and shape casting in iron and steel industries are equally substantial.

## INTRODUCTION

This chapter presents two components of the carbon cycle. The first section assesses carbon flows through industry (manufacturing, construction, and industry process emissions, but excluding fossil fuel mining, and processing).[1] The second section assesses municipal waste disposal (primarily landfills) for its impact on the fate of carbon and the release of methane and other carbon-based gases.

In 2002, industry was responsible for 5220.6 Mt of $CO_2$, 21% of anthropogenic $CO_2$ emissions to the atmosphere worldwide (this includes 4322.9 Mt from fuel combustion and 897.7 Mt from the industrial processes described later in this chapter). North America's industry contributed 758.7 Mt of combustion-sourced emissions and 66.8 Mt of process emission for a total of 826 Mt, 16% of global totals. The manufacturing industry and its process emissions contributed only 12% of total North American GHG emissions, lower than in many other parts of the world, because of the high $CO_2$ intensity of the continent's transportation sector and the significance of heating and cooling energy demands. But with North America's population at 6.8% of the world total, the continent's industry contributed a proportionally larger share of total industrial emissions than the rest of the world (see comparative tables and graphs, Fig. 8-1a).[2]

**Figure 8-1a. $CO_2$ emissions by sector in 2002.**

Industrial $CO_2$ emissions decreased nearly 11% between 1990 and 2002, while energy consumption in the United States and Canada increased 8% to 10% during that period (EIA, 2005; CIEEDAC, 2005). In both countries, a shift in production activity toward less energy-intensive industries and dissemination of more energy efficient equipment kept the rate of energy demand growth lower than industrial GDP

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[1] This includes direct flows only. Indirect carbon flows, such as the carbon released due to electricity generation, are not associated with the industry that consumed the electricity but with power generation (see Chapter 6).

[2] North America, including Mexico, was responsible for about 27% of global $CO_2$ emissions in 2002.

growth (IEA, 2004).[3] This slower demand growth in concert with a shift toward less carbon-intensive fuels explains the decrease in industrial $CO_2$ emissions.

The municipal waste stream excludes agricultural and forestry wastes but includes wastewater. $CO_2$ is generated from aerobic metabolism in waste removal and storage processes. Because this $CO_2$ arises from biological material, it is considered neutral in terms of GHG emissions. Methane ($CH_4$), released from anaerobic activity at waste treatment plants and landfill sites, forms a substantial portion of carbon emissions to the atmosphere. Given its much higher rating as a GHG gas in terms of global warming potential, methane plays an important role in the evaluation of possible climate change impacts (see Fig. 8-1b).[4] Globally, $CH_4$ emissions from waste amount to 66 Mt, or 1386 Mt $CO_2$ equivalent. North American activity accounts for 13.4 Mt of $CH_4$ (282 Mt $CO_2$ equivalent), roughly 20% of global totals.

**Figure 8-1b. GHG emissions by sector in 2000, $CO_2$, $CH_4$, $N_2O$, PFCs, HFCs, and $SF_6$.**

Landfills are not “efficient” aerobic or anaerobic digesters; substantial sequestration of carbon occurs.[5] Data on carbon buried in landfills are poor. The Environmental Protection Agency (EPA) used data from Barlaz (1990, 1994) estimated that 30% of carbon in food waste and up to 80% of carbon in newsprint, leaves, and branches remain in the landfill. Plastics show no deterioration and are assumed to remain in the landfill site as sequestered carbon. In all, more than 80% of the carbon entering a landfill site may be sequestered, depending on moisture, aeration, and other conditions of the site. In another paper, Bogner and Spokas (1993) estimate that “in general, more than 75% of the carbon deposited in landfills remains in sedimentary storage.”

## INDUSTRY CARBON CYCLE

Carbon may enter industry as a fuel, providing energy for the completion of industrial processes, or as a feedstock where the carbon becomes entrained in the final product generated by that industry. Thus, carbon exits industrial sites either as a constituent of a product or as a waste. Carbon in the waste stream can be distinguished as atmospheric and non-atmospheric, the former being comprised of process and combustion-related emissions. Process emissions refer to $CO_2$ emitted as a result of the transformation of the material inputs to the production process (i.e., a non-combustive source). For example, cement

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[3] Decomposition analyses assess the changes in the overall energy consumption or emissions release in terms of the major factors affecting such a change. Changes in energy consumption, for example, can result from increase industry activity, changes in relative productivity to or from more intense industry subsectors, or changes in material or energy efficiency in industrial processes.

[4] While not carbon-based, $N_2O$ from sewage treatment is shown in Fig. 2 to show its relative importance as a GHG.

[5] IPCC guidelines currently do not provide a methodology for addressing landfill sequestration. Such guidelines are to be included in the 2006 guidelines.

production involves the calcination of lime, a process that chemically alters limestone to form calcium oxide and releases $CO_2$. Combustion-related emissions such as $CO_2$ occur when carbon-based fuels provide thermal energy to industrial processes.

## Overview of Carbon Inputs and Outputs

Relatively speaking, industry as it is here defined generates about one-third as much emitted carbon as the production of electricity and other fuel supply in North America, and only about 55% as much as is generated by the transportation sector.

### Carbon In

Carbon-based raw materials typically enter industrial sites in the form of biomass (primarily wood), limestone, soda ash, oil products, coal/coke, natural gas, and natural gas liquids. These inputs are converted to dimension lumber and other wood products, various types of paper and paperboard, cement and lime, glass, and a host of chemical products, plastics, and fertilizers based on oil, coal, natural gas, and natural gas liquids.

While the bulk of the input raw material leaves the industrial site as a product, some of the carbon leaves the process as $CO_2$ (e.g., from limestone in cement production), and some is converted to fuel combusted in the plant. Waste wood (or hog fuel) and black liquor, a product generated in the production of chemical pulps, are burned to provide process heat or steam for digesting wood chips in the production of chemical pulp and for drying paper or wood products. In some cases, electricity is cogenerated from this biomass energy. Chemical processes utilizing natural gas or natural gas liquids often generate off-gases that can be mixed with conventional fuels to provide process heat. Finally, some of the carbon that enters as a feedstock leaves as solid or liquid waste.

In some industries, carbon is used to remove oxygen from other input materials in a process known as “reduction.” In most of the literature, such carbon is considered an input to the process even though it acts as a fuel (i.e., it unites with oxygen to form $CO_2$ and releases heat, just as it would in combustion processes). For example, in metal smelting and refining processes, a carbon-based reductant is used to separate oxygen from the metal atoms. Coke, a product of the destructive distillation of high-quality coal, enters a blast furnace with iron ore to strip off the oxygen associated with the iron, leaving pig iron at the bottom of the blast furnace with $CO_2$ exiting at the top. Carbon anodes in electric arc furnaces in steel mills and in the specialized electrolytic “Hall-Heroult” cells oxidize to $CO_2$ as they melt recycled steel or reduce alumina to aluminum.

### Carbon Out

Carbon leaves industry as part of the intended commodity or product (wood, paper, chemical products), as a waste product (waste wood, pulp mill sludge), or as a gas, usually $CO_2$. The carbon in the commodities generated may, in turn, be utilized by other industries to be released as another commodity or as a waste product or emission.

Process emissions are $CO_2$ emissions that occur as a result of the process itself—the calcining of limestone releases about 0.5 Mt $CO_2$ per metric ton of clinker (unground cement) or about 0.8 Mt per metric ton of lime,[6] depending on the degree to which limestone or dolomite is used as a feedstock.[7] The oxidation of carbon anodes generates about 1.5 Mt $CO_2$ in the production of a metric ton of aluminium.[8] Striping hydrogen from methane to make ammonia releases about 1.6 Mt $CO_2$ per metric ton of ammonia.

Combustion of carbon-based fuels results in the release of $CO_2$ to the atmosphere. In many cases, the combustion process is not complete, and other carbon-based compounds may also be released, such as carbon monoxide, methane, or mixtures of more complex carbon products known as volatile organic compounds (VOCs). These often decompose into $CO_2$, but their life spans in the atmosphere vary.

### Carbon Flow

Figure 8-2 illustrates the flows of carbon in and out of industrial sites as per the industry categories in Sect. 2.2. Numbers for the full North American budget are defined in the figure. Comparable diagrams for the individual countries are presented in Appendix 8A. On the left side of Fig. 8-2, all carbon-based material is accounted for by industry sector, whether in fuel or in feedstock. On the right, the exiting arrows portray how much of the carbon leaves as part of the final products from that industry. The carbon in the fossil fuel input to industry, as well as some of the feedstock materials, leave in the waste stream as emissions from fuel combustion, process emissions, or as other products and waste. The potential for carbon capture and storage is assessed in the industry subsections below.

**Figure 8-2. Carbon flows for Canada, the United States, and Mexico combined.**

## Sectoral Trends in the Industrial Carbon Cycle

Energy-intensive industries differ significantly in their carbon cycle dynamics. Figure 8-2 shows the current contribution to the carbon cycle of different industries.

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[6] In these industries, more $CO_2$ is generated from the process of limestone transformation than from the fossils fuels combusted to drive the transformation.

[7] The calcination of limestone also takes place in the iron and steel, pulp and paper, glass and sugar industries.

[8] Ceramic anodes may soon be available to aluminum producers and significantly reduce $CO_2$ release in the production of aluminum.

## Pulp and Paper

While pulp and paper products are quite energy-intensive, much of the energy used in their production is obtained from biomass. By using biomass waste, such as hog fuel and black liquor, some types of pulp mills (and associated paper plants) are energy self-sufficient. These plants could be considered carbon neutral because the capture of carbon as forests grow is assumed to offset the $CO_2$ released from such activities.[9] However, fuel handling difficulties and air quality concerns (especially from particulates) can arise from the use of biomass as a fuel depending on the location.

## Cement, Lime, and Other Nonmetallic Minerals

Cement and lime production requires the calcination of limestone, which releases $CO_2$. This process emission is releases about 0.78 Mt $CO_2$ per metric ton of lime calcined.

$$\underset{\text{calcium carbonate}}{CaCO_3} \rightarrow \underset{\text{calcium oxide}}{CaO} + \underset{\text{carbon dioxide}}{CO_2}$$

Outside of the combustion of fossil fuels, lime calcining is the single largest anthropogenic source of $CO_2$ emissions. Annual growth in cement production is forecast at 2.4% in the United States for at least the next decade. This industry could potentially utilize sequestration technologies to capture and store $CO_2$ generated during the calcining process.

The production of soda ash (sodium carbonate) from sodium bicarbonate in the Solvay Process releases $CO_2$ in its manufacture and, in some cases such as glass production, in its utilization. Soda ash is used in the production of pulp and paper to manufacture detergents and soften water.

$$\underset{\text{sodium bicarbonate}}{2NaHCO_3} \rightarrow \underset{\text{sodium carbonate}}{Na_2CO_3} + \underset{\text{carbon dioxide}}{CO_2} + \underset{\text{water}}{H_2O}$$

## Nonferrous Metal Smelting and Iron and Steel Smelting

Often metal smelting requires the reduction of metal oxides to obtain the pure metal. In such operations, a reductant, a substance that can carry away the oxygen from the metal, is required. Typically, the reductant is carbon, usually in the form of coke. The coke is added to the hot metal oxide, as in the case of iron, zinc, or magnesium, to generate the reduced metal and $CO_2$. Such reduction processes

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[9] Based on guidelines from the United Nations Framework Convention on Climate Change, biomass-based industries such as pulp and paper are deemed, in effect, to be carbon neutral in so far as biomass is concerned (UNFCCC, IPCC guidelines).

generate relatively pure streams of $CO_2$ (with some CO), which improves the potential for capture and storage.

In electric arc furnaces, carbon anodes decompose to $CO_2$ as they melt the scrap iron and steel feed in steel mini-mills. In a Hall-Heroult cell in the aluminium industry, a carbon anode oxidizes when an electric current forces oxygen from aluminium oxide (alumina) in the production of aluminium, with $CO_2$ as a by-product.

### Metal and Nonmetal Mining

Mining involves the extraction of ore and its transformation into a more concentrated form. This involves milling (grinding) the ore after it has been transported from the mine site and removing mineral-bearing material from the ground rock. Much of the process involves grinding and separating, most of which is done through the action of devices driven by electric motors. Thus, a large proportion of the activity in mining operations requires electricity rather than fossil fuels directly—although fossil fuels may have produced the electricity. Some processes, like the sintering or agglomeration of iron ore and the liquid extraction of potash, use a considerable amount of fossil fuels directly. And, of course, much of the movement of the ores from mine to mill is accomplished by diesel-driven motorized vehicles.

### Chemical Products

This diverse group of industries includes energy-intensive electrolytic processes as well as the consumption of large quantities of natural gas and natural gas liquids (hydrocarbon liquids found with natural gas) as a feedstock to produce commodities like ammonia, methanol, and hydrogen from natural gas and monomers such as ethylene and propylene from natural gas liquids. These products provide the feedstock for many synthetic resins and plastics. Some chemical processes, such as the production of ammonia, generate fairly pure streams of $CO_2$ suitable for capture and sequestration.

### Forest Products

This industry uses biomass waste to dry commercial products such as lumber, plywood and other laminated wood types, milled work, and shingles. The industry also includes silviculture, the practice of replanting and managing forests.

### Other Manufacturing

Most of the remaining industries, while economically important, each play a relatively minor role in the carbon cycle because they are not energy intensive and use little biomass—the exceptions being the food industry, the beverage industry, and some textile industries. Industries in this group include the automotive industry, electronic products, leather and allied products, fabricated metals, furniture and related products, and plastics and rubber products. In aggregate, however, these various industries contribute significantly to total industrial $CO_2$ emissions.

## Changing Role of Industry in the Carbon Cycle

Energy consumption per unit GDP has declined in Canada and the United States by more than 30% since the mid-1970s. In manufacturing, the decline was even greater—more than 50% in the United States since 1974.

The National Energy Modelling System operated by the United States Energy Information Administration applies growth forecasts from the Global Insight macroeconomic model. While the United States economy is forecast to grow at an average rate of 3.1% per year to 2025, industrial growth is forecast at 2.3% per year—an amalgam of manufacturing growth of 2.6% per year and non-manufacturing of 1.5% per year. Manufacturing industries are further disaggregated into energy-intensive industries, growing at 1.5% per year, and non-energy intensive industries, growing at 2.9% per year. The slower growth in the energy-intensive industries is reflected by an expected decline of 1.6% per year in the energy intensity of United States industrial output over the forecast (EIA forecast 2005).

The International Energy Agency reviewed energy consumption and emissions during the last 30 years to identify and project underlying trends in carbon intensity.[10] The review's decomposition analysis (Fig. 8-3) attributes changes in industrial energy demand to changes in total industrial output (activity), shifts in the relative shares of industrial sectors (structure), and increases in energy efficiency (intensity).

**Figure 8-3. Decomposition of energy use, manufacturing section, 1990–1998.**

Changes in carbon emissions result from these three factors, but also from changes in fuel shares—substitution away from or toward more carbon-intensive fossil fuels. The shift from coal and refined petroleum products to natural gas and electricity[11] contributed to a decline in total industrial $CO_2$ emissions since 1997 in both Canada and the United States. The continuation of this trend is uncertain given the rise in natural gas prices relative to coal in recent years.

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[10] Most of the information in this section is obtained from this report (IEA, 2004a).

[11] Emissions associated with electricity are considered "indirect" to industry and are allocated to the electricity supply sector. Thus, a shift to electricity is like a shift from coal to natural gas, moving from a more $CO_2$ intense energy supply to a less intense one (in this case, to 0 $CO_2$/unit). However, one shifts the allocation of associated $CO_2$ to another sector as well; there is no net reduction in $CO_2$ emitted, unless the supply sector chooses to generate electricity from a less $CO_2$ intense source.

## Actions and Policies for Carbon Management in Industry

Industry managers can reduce carbon flows through industry by altering the material or energy intensity and character of production (IPCC, 2001). Greater materials efficiency typically reduces energy demands in processing because of reduced materials handling. For example, recycling materials reduces energy consumption per unit of output by 26 to 95% (see Table 8-1). Further work on materials substitution also holds promise for reduced energy consumption and emissions reduction, such as the replacement of petrochemical feedstocks by biomass feedstocks, of steel by aluminium in the transport sector, and of concrete by wood in the buildings sector.

**Table 8-1. Energy reductions in recycling**

The prospects for greater energy efficiency are equally substantial. Martin *et al.* (2001) characterized more than 50 key emerging energy efficient technologies, both generic and industry-specific. These include efficient Hall-Heroult cell retrofits in aluminium production, black liquor gasification in kraft pulp production, and shape casting in iron and steel industries. Worrel *et al.* (2004) covers many of the same technologies and notes that significant potential exists in utilizing efficient motor systems and advanced cogeneration technologies.

At the same time, energy is a valuable production input that along with capital can substitute for labor as a means of increasing productivity. Thus, overall productivity gains in industry can be both energy-saving and energy-augmenting, and the net impact depends on the nature of technological innovation and the expected long-run cost of energy relative to other inputs. This suggests that, if policies to manage carbon emissions from industry are to be effective, they would need to provide a significant signal to technology innovators and adopters to reflect the negative value that society places on carbon emissions. This suggests the application of regulations or financial instruments, examples being energy efficiency regulations, carbon management regulations, and fees on carbon emissions.

## WASTE MANAGEMENT CARBON CYCLE

The carbon cycle associated with human wastes includes industrial, commercial, construction, demolition, and residential waste. Municipal solid waste contains significant amounts of carbon. Paper, plastics, yard trimmings, food scraps, wood, rubber, and textiles made up more than 80% of the 236 Mt of municipal solid waste generated in the United States in 2003 (EPA, 2005), as shown in Table 8-2. Of the 25 Mt generated in Canada, the contribution from each of these sources is about the same (Statistics Canada, 2004). In Mexico, as much as 20% of wastes are not systematically collected, and no disaggregated data are available (EPA, 2005).

**Table 8-2. Waste materials flows by region in North America, 2003**

A portion of municipal solid waste is recycled: 31% in the United States, 27% in Canada. Up to 14% of the remaining waste is incinerated in the United States, a slightly lower percentage in Canada. Incineration can reduce the waste stream in a given location by up to 80%, but this ensures that more of the carbon reaches the atmosphere as opposed to being buried in solid form (or subsequently released as methane) in a landfill. Incineration, however, can be used to cogenerate electricity and useful heat, which may reduce carbon emissions from stand-alone facilities for electricity generation and heat production.

Once in a landfill, carbon in wastes may be acted upon biologically, releasing roughly equal amounts of $CO_2$ and methane ($CH_4$) by volume[12] depending on the conditions of the landfill site, as well as a trace amount of carbon monoxide (which soon becomes $CO_2$ in the atmosphere) and volatile organic compounds. While no direct data on the quantity of $CO_2$ released from landfills exists, one can estimate the $CO_2$ released by using this ratio; the estimated amount of $CO_2$ released from landfills in Canada and the United States (no data from Mexico) would be approximately 38 Mt,[13] a relatively small amount compared to total other (sub)sectors in this chapter. One should consider this derived estimate highly uncertain and not of the same calibre as other emissions data provided here. Also recall that, in the context of IPCC assessment guidelines, $CO_2$ emissions from biological sources are considered GHG-neutral and that these emissions are from biomass.

Depending on the degree to which aerobic or anaerobic metabolism takes place, a considerable amount of carbon remains unaltered and more or less permanently stored in the landfill (75%–80%; see Barlaz, 1990, 1994; and Bogner and Spokas, 1993). Because data on the proportions of carboniferous material entering landfills can be estimated, approximate carbon contents of these materials can be determined and the degree to which these materials can decompose, it would be possible to estimate the amount of carbon sequestered in a landfill site (see EPIC, 2001; Mohareb *et al.*, 2003; EPA, 2003; EPA, 2005). However, the complexity of this assessment and the data required to support it from the multiple sources prevented any further assessment from taking place for this report.

Fugitive methane gases are the result of anaerobic digestion and can be captured and, like incineration, used to generate power and steam. Many of the 1,800 municipal solid waste sites in 2003 in the United States captured and combusted landfill-generated methane; about half of all the methane produced was combusted or oxidized in some way (EPA, 2005). In Canada, about 23% of the methane emissions were captured and utilized to make energy in 2002 (Mohareb *et al.*, 2003). The resultant $CO_2$

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[12] When based on gas volumes, this would mean that roughly equivalent amounts of carbon are released to the atmosphere in $CO_2$ as in $CH_4$.

[13] 14 Mt of $CH_4$ (see Table 8-3) are equivalent, volume wise at standard temperature and pressure, to 38 Mt of $CO_2$.

released from such combustion is considered biological in origin (i.e., the methane used arose from biological material). Thus, only methane emissions, at 21 times the $CO_2$ global warming potential, are included as part of GHG inventories.[14] Their combustion greatly alleviates the net contribution to GHG emissions and provides power or steam that might prevent the combustion of fossil fuels elsewhere for these purposes.

## COSTS RELATED TO CONTROLLING ANTHROPOGENIC IMPACTS ON THE CARBON CYCLE

The subject of defining costs associated with reducing anthropogenic impacts on the carbon cycle is one of the most contentious of issues in any carbon-focussed analysis. Different modelling approaches to cost assessments (top-down, bottom-up, applicable discount rates, social costing, cost effectiveness, no regrets, etc.), different understandings of what costs actually include (risk, option values, welfare, intangibles, etc.), different values associated with energy demand in different countries (accessibility, availability, infrastructure, resource type and size), the number of possible actions and technologies included in the analysis, and the perspective on technology development all have an impact on how one evaluates costs. Should analysts consider only historical responses to energy prices, production and demand elasticities, income changes and the like? Does one consider only technology options and their strict financial costs? Should one review producers' or consumers' welfare issues associated with new technologies? Are there local, national, international issues to be broached?

How might one reduce emissions in industrial and waste sectors? Methods of reduction can be classified as:

- reducing process/fugitive emissions or converting currently released emissions (e.g., reduce process emissions from cement, lime production, capture or prevent fugitive emissions leaks from pipelines or combustion of emissions such as methane from landfills, cogeneration using landfill offgases);
- energy efficiency, including combined heat and power;
- process change (materials efficiency, recycling, substitution between materials or between materials and energy);
- fuel substitution; and
- carbon capture and storage.

Variation within industries is significant, but some simple allocation of a broad range of costs can be attributed to potential reductions over a set time period. We suggest the cost categories ("A" through "D")

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[14] Theoretically, one should assume a factor of 20 because, were the methane released as $CO_2$, it would be considered to have no net GHG effect.

shown in Table 8-3. The table contains estimates of the percentage reduction at the grouped cost levels. The costs represented here are not drawn from a single source but, rather, are the authors' estimates based on a long history of interaction with cost reported in various documents.

**Table 8-3. Approximate costs and reductions potential**

When looking at cost numbers like this, one should remember that, for each \$10 cost increment per Mt $CO_2$ (or \$2.73 per Mt C), gasoline prices would increase about 2.4¢/L (9¢/U.S. gal). Diesel fuel cost would be slightly higher, at nearly 2.7¢/L (10¢/U.S. gal). At this rate, costs per GJ (slightly smaller than one million BTU) vary by fuel: coal would rise about 90¢/GJ, depending on type, HFO by 73¢, and natural gas by 50¢. Were one to use these fuels to generate electricity at a 35% efficiency rate, the cost increase in coal-fired electricity generation would be about 0.8¢/kWh, about 0.65¢/kWh for HFO fired electricity, and about 0.45¢/kWh if natural gas was used.

Of course, as the cost of carbon increases one can always obtain greater reductions, but the return on these expenditures becomes marginal or insignificant and so are not included in the cells of Table 8-3. If two cost categories are shown in a cell (e.g., A/B) and the quantity reduced ($\%Q_{red}$) as 15/20 in the neighbouring cell, the value associated with the second portrays the marginal addition that may be made at that increased expenditure level. In this example, spending up to \$25/t $CO_2$ may reduce emissions by 15% and with a further expenditure of up to \$50/t $CO_2$ would add a further 20% for a total of 35% were all expenditures to reduce emissions made (see "Metal Smelt" in Table 8-3).

Because not all actions are applicable to all industries, as one aggregates to an "all industry" level (top line in the table), the total overall emissions reduction level may be less than any of the individual industries sited. We provide an approximation of each industry, but if potentials for a certain option are not available in that industry (e.g., process change), this lowers the average for the aggregate category.

## Some Explanatory Notes

The five categories are not independent, and thus, reductions are not additive across categories. We have tried to isolate somewhat what reductions might be like were one to focus only on that particular category. Data come from a variety of sources and often focus on more than one of the following aspects (Hertzog, 1999; Martin *et al.*, 2001; Jaccard *et al.*, 2002; Jaccard *et al.*, 2003; Jaccard, Nyboer, *et al.*, 2003; Worrel *et al.*, 2004; DOE, 2006).

**Process and Fugitives:** Process and fugitive reductions are only available in certain industries. For example, cement and lime calcination, ammonia production, and others (see above) have process emissions that one may be able to control or manipulate. Because wood products industries burn a lot of wood waste, fugitives (methane and VOCs) are higher than in other industries and reduction potentials exist. In this particular example, fugitive emission and reduction potential are small compared to those possible in petroleum refining and upstream gas and oil.

In the waste sector, the reductions potentials are very large; we have simply estimated possible reductions if we were to trap and burn all landfill methane. The costs for this are quite low. In an EPA study (EPA, 2003a), estimates of between 40% and 60% of methane available for capture may generate net economic benefits.

**Energy Efficiency**: While efficiency is important for more than just $CO_2$ reduction, depending on how one views the advent and penetration of new technologies, potentials for reduction are limited if one does not consider changing processes or switching fuels; that is, the potential for emissions reductions from efficiency improvements is strongly linked with these other two avenues. For example, using DRI processes in iron smelting, moving to Cermet anodes in electric arc furnaces in iron and steel and aluminium smelting industries or shifting to hydrometallurgic processes from pyrometallurgic ones in nonferrous metal smelting can significantly improve efficiencies and lower both combustion and process GHG emissions; we include them here as an efficiency improvement even though they may be considered a process change and fall under the next column in Table 8-3.

Because so much emphasis is placed on this particular avenue to reductions, we define it here as a separate category even though it is difficult to disaggregate from fuel switching and process change. Modeling from a more technical, strict end-use approach using technology possibility curves or similar factors for efficiency improvement over time tends to show higher potentials than when one uses hybrid approaches that try to assess the impacts of costs on technology choice (and thus energy demand); we have portrayed the outcome of the latter and provide what some may consider conservative estimates of reduction potential (see particularly Martin *et al.*, 2001; Jaccard *et al.*, 2002; Jaccard *et al.*, 2003; Jaccard, Nyboer, *et al.*, 2003; Worrel *et al.*, 2004).

**Process Change**: Process change in its broader sense is difficult to estimate; it requires not only an understanding of the industry and its potential for change but also an understanding of the market demand for industry products that may be different than before the change was made. In pulp production, for example, one could move away from kraft pulp and increase production ratios (the kraft process only converts one-half the tree into pulp), but will market acceptability for the end product be unaffected? Reducing the actual clinker content of ground cement can radically alter emissions levels. Numerous substitution possibilities exist in the rather diverse Other Manufacturing section (carpet recycling, alternative uses for plastics, etc.).

**Fuel Substitution**: As mentioned, it is difficult to isolate fuel substitution and efficiency improvement because fuel types do contain inherent qualities that affect efficiency. While fuel substitution is an important method of reducing carbon, this is beneficial only if options to move to less carbon-intense fuels exist. In pulp and paper, one can move to biomass, but the industry already depends on at least one-half of its energy from biomass. Some operating pulp and paper plants are totally self-sufficient. Even so, further potential exists especially in combination with energy efficiency improvement such as cogeneration. Most of the cement and lime, in Canada at least, is produced using coal or coke, allowing for reductions were they to move to biomass, waste fuels, natural gas, or even oil. In some industries, like mining, the bulk of the energy used is electricity, and direct reduction opportunities are small.

**Carbon Capture and Storage (CC&S)**: In one sense, all industries and landfills could invoke CC&S but the methods to accomplish this are not well understood and/or the costs are very high. For example, one could introduce an oxygen stream into all combustion devices such that the exhaust steam is $CO_2$ rich, suitable for capture and storage. Some industries, like cement production (nonmetal minerals), are reasonable candidates for capture, but transport of the $CO_2$ for storage may prohibit implementation (see particularly Hertzog, 1999; DOE, 2006).

## REFERENCES

Barlaz, Morton A., and Robert K. Ham. 1990 "The Use of Mass Balances for Calculation of the Methane Potential of Fresh and Anaerobically Decomposed Refuse," in *Proceedings from the GRCDA 13th Annual International Landfill Gas Symposium, March 27–29, 1990* (Silver Spring, MD: GRCDA—The Association of Solid Waste Management Professionals) 1990, p. 235.

Barlaz, M. 1994 *Measurement of the Methane Potential of the Paper, Yard Waste, and Food Waste Components of Municipal Solid Waste*. Unpublished paper, Department of Civil Engineering, North Carolina State University, 1994.

Bogner, J., and K. Spokas. 1993. *Landfill $CH_4$: Rates, Fates, and Role in the Global Carbon Cycle.* Chemosphere, Vol. 26, Nos. 1–4, pp. 369–386.

California Environmental Protection Agency. 2003. *Environmental Technologies and Service Opportunities in the Baja California Peninsula*. International Affairs Unit.

Canadian Industrial Energy End-Use Data and Analysis Centre. 2005. *Development of Energy Intensity Indicators for Canadian Industry: 1990–2004*, Simon Fraser University, Vancouver.

Energy Information Administration. 2005. International Energy Outlook, 2005.

EPIC (Environment and Plastics Industry Council). 2002. Opportunities for Reducing Greenhouse Gas Emissions through Residential Waste Management. Prepared by Environment and Plastics Industry Council.

Environmental Protection Agency. 2003a. *International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21.*

Environmental Protection Agency. 2003b. *Municipal Solid Waste in the United States: 2003 Facts and Figures.*

Environmental Protection Agency. 2005. Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990–2003.

Hershkowitz, Allen. 1997. *Too Good to Throw Away: Recycling's Proven Record.* National Resources Defense Council. February 1997.

Herzog, H. 1999. "The Economics of $CO_2$ Capture," P Reimer, B Eliasson, A Wokaum, eds., *Greenhouse Gas Control Technologies*, Oxford: Elsevier Science Ltd., pp. 101–106 (1999).

International Energy Agency. 2004. *30 Years of Energy Use in IEA Countries.*

IPCC (Intergovernmental Panel on Climate Change). 2001. *Third Assessment Report, Volume 3 Mitigation*, Chapter 3.

Jaccard, M., J. Nyboer, and B. Sadownik. 2002. *The Cost of Climate Policy*. Vancouver, UBC Press.

Jaccard, M., J. Nyboer, C. Bataille, and B. Sadownik. 2003. *Modeling the Cost of Climate Policy: Distinguishing Between Alternative Cost Definitions and Long-Run Cost Dynamics.* The Energy Journal 24(1): 49–73.

Jaccard, M., R. Loulou, A. Kanudia, J. Nyboer, A. Bailie, and M. Labriet. 2003. *Methodological contrasts in costing GHG abatement policies: Optimization and simulation modeling of micro-economic effects in Canada.* European Journal of Operations Research 145 (1): 148–164.

Martin, N., E. Worrell, M. Ruth, L. Price, R. N. Elliott, A. M. Shipley, and J. Thorne. 2001. *Emerging Energy-Efficient Industrial Technologies: New York State Edition.* LBNL Report Number 46990, published by American Council for an Energy-Efficient Economy (ACEEE).

Mohareb, A. K., M. Warith, and R. M. Narbaitz. 2003. Strategies for the municipal solid waste sector to assist Canada in meeting its Kyoto Protocol commitments. Environmental Review 12: 71–95.

Statistics Canada. 2004. *Human Activity and the Environment*. Statistics Canada, Cat no.16-201-XIE.

DOE. 2006. www.fossil.energy.gov/programs/sequestration/overview.html Accessed on March 27, 2006. U.S. Department of Energy.

Worrell, Ernst, Lynn K. Price, and Christina Galitsky. 2004. *Emerging energy-efficient technologies in industry: Case studies of selected technologies.* Environmental Technologies Division, Lawrence Berkeley Laboratory, University of California at Berkeley.

**Table 8-1. Energy reductions in recycling**

| Recycled material | Energy saved | Recycled material | Energy saved |
|---|---|---|---|
| Aluminum | 95% | Glass | 31% |
| Tissue paper | 54% | Newsprint | 45% |
| Printing/writing paper | 35% | Corrugated cardboard | 26% |
| Plastics | 57%–75% | Steel | 61% |

*Source*: Hershkowitz, 1997.

**Table 8-2. Waste materials flows by region in North America, 2003**

| | United States | Canada | Mexico |
|---|---|---|---|
| Total waste (Mt $\text{yr}^{-1}$) | 236.0 | 24.8 | 29.2 |
| Recycled | 72.0 | 6.6 | – |
| Carbon-based waste | 197.1 | 19.6 | – |
| Carbon recycled | 47.3 | 4.3 | – |
| Methane (kt $\text{yr}^{-1}$) | | | |
| Generated | 12,486 | 1,452 | – |
| Captured, oxidized | 6,239 | 336 | – |
| Emitted | 6,247 | 1,117 | – |
| Emitted ($CO_2$ equivalents) | 131,187 | 23,453 | – |

*Source*: EPA, 2003b, 2005; Statistics Canada, 2004; Mohareb, 2003 for Canada methane data; California Environmental Protection Agency, 2003 for Mexico data point.

**Table 8-3. Approximate costs and reductions potential**

| Sector | Reduction of fugitives | | Energy efficiency | | Process change | | Fuel substitution | | Carbon Capture and Storage | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Cost category | %$Q_{red}$ | Cost category* | %$Q_{red}$* | Cost category | %$Q_{red}$ | Cost category | %$Q_{red}$ | Cost category | %$Q_{red}$ |
| **All industry** | B | 3 | A/B | 12/8 | B | 20 | A | 10 | C | 30 |
| P&P | B | 5 | A/B | 10/5 | B | 40 | A | 40 | D | ? |
| Nonmetal min | | | A | 10 | A | 40 | A | 40 | C | 80 |
| Metal smelt | | | A/B | 15/20 | B | 10 | A | 15 | C | 40 |
| Mining | | | A | 5 | | | | | | |
| Chemicals | B | 10 | A/B | 10/5 | B | 25 | A | 5 | C/D | 40/20 |
| Forest products | B | 5 | A | 5 | | | | | | |
| Other man | | | A | 15 | A | 20 | A | 5 | D | ? |
| Waste | A | 90 | | | | | | | D | 30 |

*If two letters appear, two percent quantities reduced are shown. Each shows the quantity reduced at that cost. That is, if all lesser and higher costs were made, emissions reduction would be the sum of the two values.

Note: The reductions across categories are NOT additive. For example, if "Carbon Capture and Storage" is employed, then fuel switching would have little bearing on the emissions reduction possible. Also, it is difficult to isolate process switching and efficiency improvements.

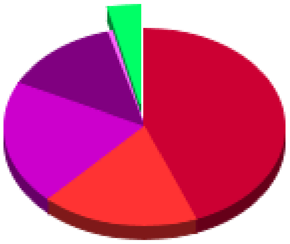
**The "Cost Categories" are as follows:**

**$CO_2$-Based:** **A:** \$0–\$25/t $CO_2$; **B:** \$25–\$50/t $CO_2$; **C:** \$50–\$100/t $CO_2$; **D:** >\$100/t $CO_2$

**Carbon-Based:** **A:** \$0–\$92/t C; **B:** \$92–\$180/t C; **C:** \$180–\$367/t C; **D:** >\$367/t C

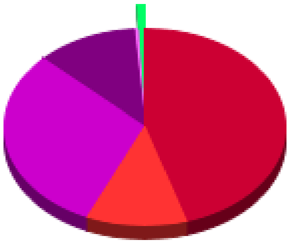
**World**

| Sector | MtCO$_2$ | % |
|---|---|---|
| Energy | 23,432.1 | 96.3 |
| 🟥 Electricity & Heat | 10,731.8 | 44.1 |
| 🟥 Manufacturing & Construction | 4,322.9 | 17.8 |
| 🟪 Transportation | 4,964.5 | 20.4 |
| 🟪 Other Fuel Combustion | 3,265.3 | 13.4 |
| 🟪 Fugitive Emissions | 147.6 | 0.6 |
| 🟩 Industrial Processes | 897.7 | 3.7 |
| **Total** | **24,329.8** | |



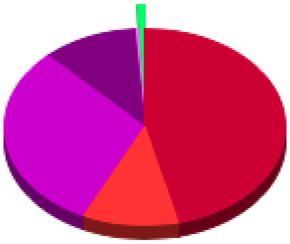
**North America (w/ Mexico)**

| Sector | MtCO$_2$ | % |
|---|---|---|
| Energy | 6,576.5 | 98.9 |
| 🟥 Electricity & Heat | 3,017.0 | 45.3 |
| 🟥 Manufacturing & Construction | 758.7 | 11.3 |
| 🟪 Transportation | 2,016.6 | 30.5 |
| 🟪 Other Fuel Combustion | 757.1 | 11.6 |
| 🟪 Fugitive Emissions | 27.2 | 0.4 |
| 🟩 Industrial Processes | 66.8 | 1.0 |
| **Total** | **6,643.3** | |



**United States of America**

| Sector | MtCO$_2$ | % |
|---|---|---|
| Energy | 5,675.4 | 99.2 |
| 🟥 Electricity & Heat | 2,645.0 | 46.2 |
| 🟥 Manufacturing & Construction | 621.4 | 10.9 |
| 🟪 Transportation | 1,761.4 | 30.8 |
| 🟪 Other Fuel Combustion | 624.5 | 10.9 |
| 🟪 Fugitive Emissions | 23.1 | 0.4 |
| 🟩 Industrial Processes | 44.7 | 0.8 |
| **Total** | **5,720.1** | |



**Canada**

| Sector | MtCO$_2$ | % |
|---|---|---|
| Energy | 535.9 | 98.8 |
| 🟥 Electricity & Heat | 191.7 | 35.3 |
| 🟥 Manufacturing & Construction | 89.2 | 16.4 |
| 🟪 Transportation | 150.5 | 27.7 |
| 🟪 Other Fuel Combustion | 100.5 | 18.5 |
| 🟪 Fugitive Emissions | 4.1 | 0.7 |
| 🟩 Industrial Processes | 6.6 | 1.2 |
| **Total** | **542.5** | |

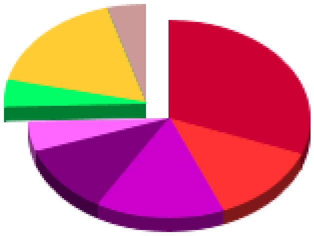
**Mexico**

| Sector | MtCO$_2$ | % |
|---|---|---|
| Energy | 365.2 | 95.9 |
| 🟥 Electricity & Heat | 180.3 | 47.4 |
| 🟥 Manufacturing & Construction | 48.1 | 12.6 |
| 🟪 Transportation | 104.7 | 27.5 |
| 🟪 Other Fuel Combustion | 32.1 | 8.4 |
| 🟪 Fugitive Emissions | -- | -- |
| 🟩 Industrial Processes | 15.5 | 4.1 |
| **Total** | **380.6** | |

**Fig. 8-1a. CO$_2$ emissions by sector in 2002.** *Source*: Climate Analysis Indicators Tool (CAIT) Version 3.0 (Washington, D.C.: World Resources Institute, 2005).

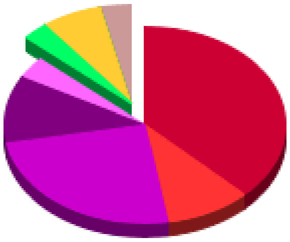
### World

| | Sector | | $MtCO_2$ | | % |
|---|---|---|---|---|---|
| | Energy | | 24,789.9 | | 74.5 |
| 🟥 | Electricity & Heat | 10,269.4 | | 30.9 | |
| 🟥 | Manufacturing & Construction | 4,327.9 | | 13.0 | |
| 🟪 | Transportation | 4,809.7 | | 14.5 | |
| 🟪 | Other Fuel Combustion | 3,742.4 | | 11.2 | |
| 🟪 | Fugitive Emissions | 1,640.5 | | 4.9 | |
| 🟩 | Industrial Processes | | 1,366.8 | | 4.1 |
| 🟨 | Agriculture | | 5,631.5 | | 16.9 |
| 🟫 | Waste | | 1,483.6 | | 4.5 |
| | **Total** | | **33,271.8** | | |



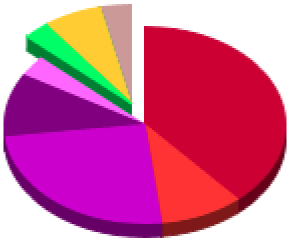
### North America (w/ Mexico)

| | Sector | | $MtCO_2$ | | % |
|---|---|---|---|---|---|
| | Energy | | 7,004.8 | | 86.2 |
| 🟥 | Electricity & Heat | 3,027.6 | | 37.3 | |
| 🟥 | Manufacturing & Construction | 809.6 | | 10.0 | |
| 🟪 | Transportation | 1,971.1 | | 24.3 | |
| 🟪 | Other Fuel Combustion | 877.2 | | 10.8 | |
| 🟪 | Fugitive Emissions | 319.2 | | 3.9 | |
| 🟩 | Industrial Processes | | 239.0 | | 2.9 |
| 🟨 | Agriculture | | 580.9 | | 7.1 |
| 🟫 | Waste | | 300.0 | | 3.7 |
| | **Total** | | **7,610.9** | | |



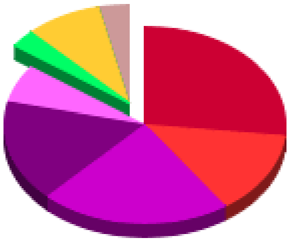
### United States of America

| | Sector | | $MtCO_2$ | | % |
|---|---|---|---|---|---|
| | Energy | | 6,005.5 | | 86.8 |
| 🟥 | Electricity & Heat | 2,670.6 | | 38.6 | |
| 🟥 | Manufacturing & Construction | 657.9 | | 9.5 | |
| 🟪 | Transportation | 1,719.9 | | 24.9 | |
| 🟪 | Other Fuel Combustion | 723.6 | | 10.5 | |
| 🟪 | Fugitive Emissions | 233.5 | | 3.4 | |
| 🟩 | Industrial Processes | | 198.4 | | 2.9 |
| 🟨 | Agriculture | | 469.9 | | 6.8 |
| 🟫 | Waste | | 243.3 | | 3.5 |
| | **Total** | | **6,917.1** | | |



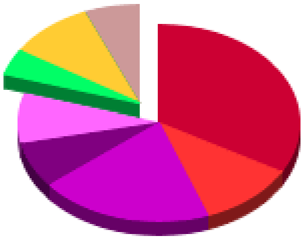
### Canada

| | Sector | | $MtCO_2$ | | % |
|---|---|---|---|---|---|
| | Energy | | 589.5 | | 85.0 |
| 🟥 | Electricity & Heat | 185.9 | | 26.8 | |
| 🟥 | Manufacturing & Construction | 94.6 | | 13.6 | |
| 🟪 | Transportation | 150.0 | | 21.6 | |
| 🟪 | Other Fuel Combustion | 115.3 | | 16.6 | |
| 🟪 | Fugitive Emissions [1] | 43.6 | | 6.3 | |
| 🟩 | Industrial Processes [2] | | 19.3 | | 2.8 |
| 🟨 | Agriculture | | 60.8 | | 8.8 |
| 🟫 | Waste | | 24.2 | | 3.5 |
| | **Total** | | **693.8** | | |



### Mexico

| | Sector | | $MtCO_2$ | | % |
|---|---|---|---|---|---|
| | Energy | | 409.8 | | 79.8 |
| 🟥 | Electricity & Heat | 171.1 | | 33.3 | |
| 🟥 | Manufacturing & Construction | 57.1 | | 11.1 | |
| 🟪 | Transportation | 101.2 | | 19.7 | |
| 🟪 | Other Fuel Combustion | 38.3 | | 7.5 | |
| 🟪 | Fugitive Emissions [1] | 42.1 | | 8.2 | |
| 🟩 | Industrial Processes [2] | | 21.3 | | 4.2 |
| 🟨 | Agriculture | | 50.2 | | 9.8 |
| 🟫 | Waste | | 32.5 | | 6.3 |
| | **Total** | | **513.8** | | |



[1] $N_2O$ data not available. [2] $CH_4$ data not available.

**Fig. 8-1b. GHG emissions by sector in 2000, $CO_2$, $CH_4$, $N_2O$, PFCs, HFCs, and $SF_6$.** *Source*: Climate Analysis Indicators Tool (CAIT) Version 3.0 (Washington, D.C.: World Resources Institute, 2005).

North America Carbon Flows (All Values in Kilotonnes of C)

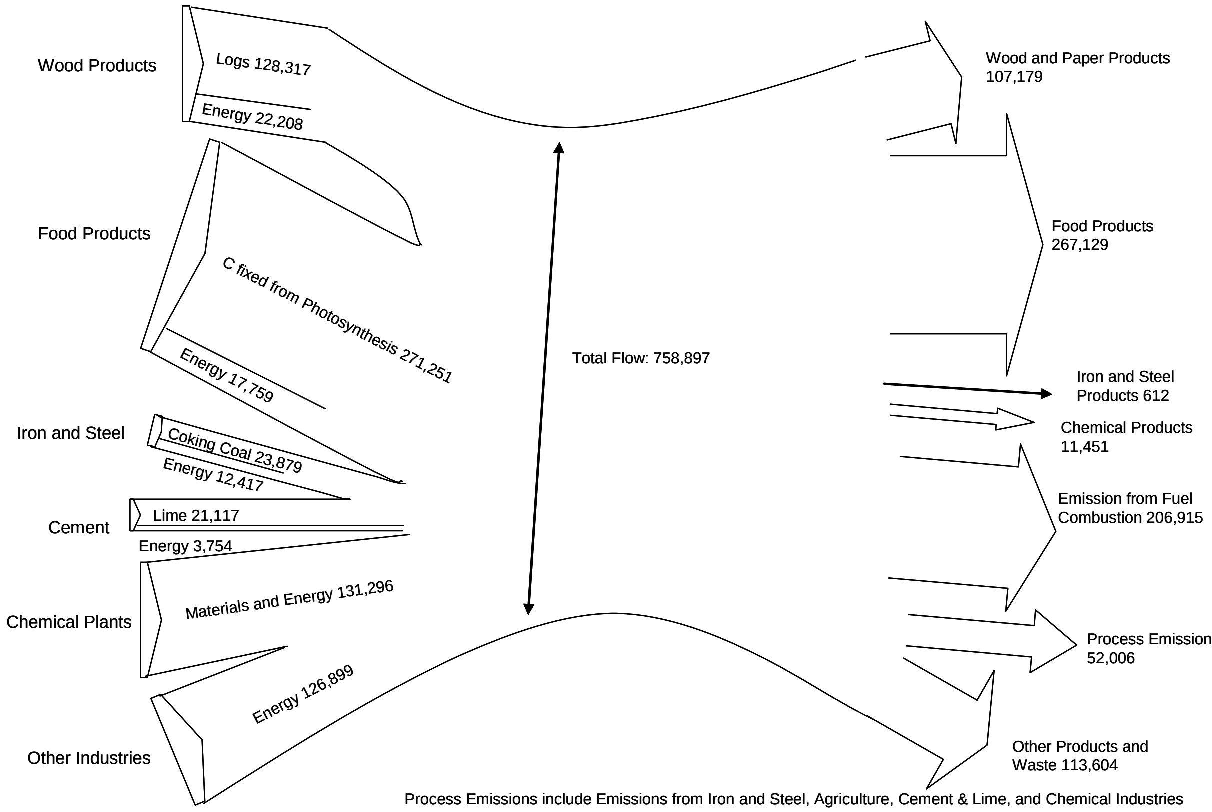


**Fig. 8-2. Carbon flows for Canada, the United States and Mexico combined.** Values in kilotons carbon can be converted to kilotons $CO_2$ equivalents by multiplying by 44/12, the ratio of carbon dioxide mass to carbon mass. Comparable diagrams for the individual countries are in Appendix 8A**.** *Source*: Energy data from Statistics Canada Industrial Consumption of Energy survey, Conversion coefficients, IEA Oil Information 2004, IEA Coal Information 2005, IEA Natural Gas Information 2004. Process emissions from Environment Canada, *Canada GHG Inventory, 2002,* EPA, U.S. Emissions Inventory. Production data from Statistics Canada, CANSIM Table 002-0010, Tables 303-0010, -0014 to -0021, -0024, -0060, Pub. Cat. Nos.: 21-020, 26-002, 45-002, Canadian Pulp and Paper Association on forestry products. Production of forestry products: USDA Database; FO-2471000, -2472010, -2482000, -2483040, -6342000, -6342040, U.S. Timber Production, Trade, Consumption, and Price Statistics 1965–2005. Production of organic products (e.g., food): USDA PS&D Official Statistical Results. Steel: International Iron and Steel institute, World steel in figures 2003. Minerals production: USGS mineral publications.

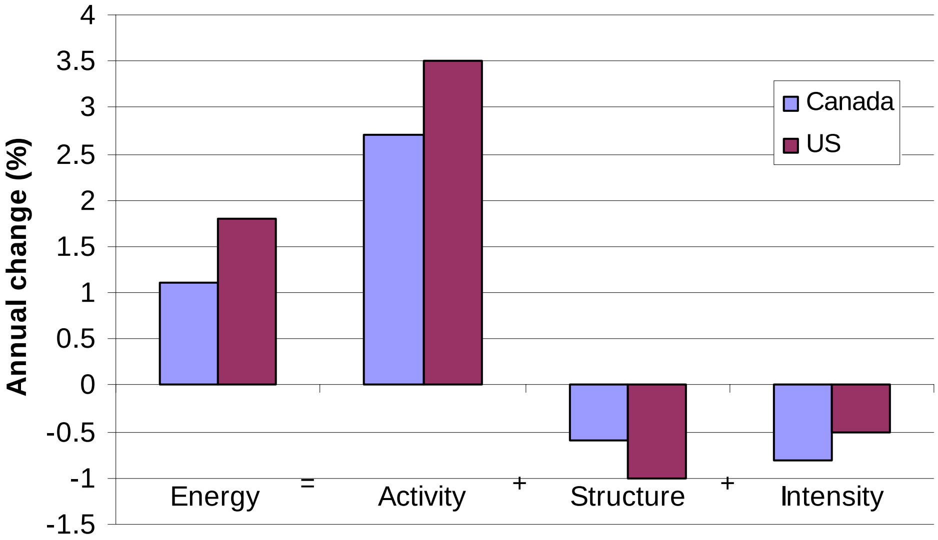
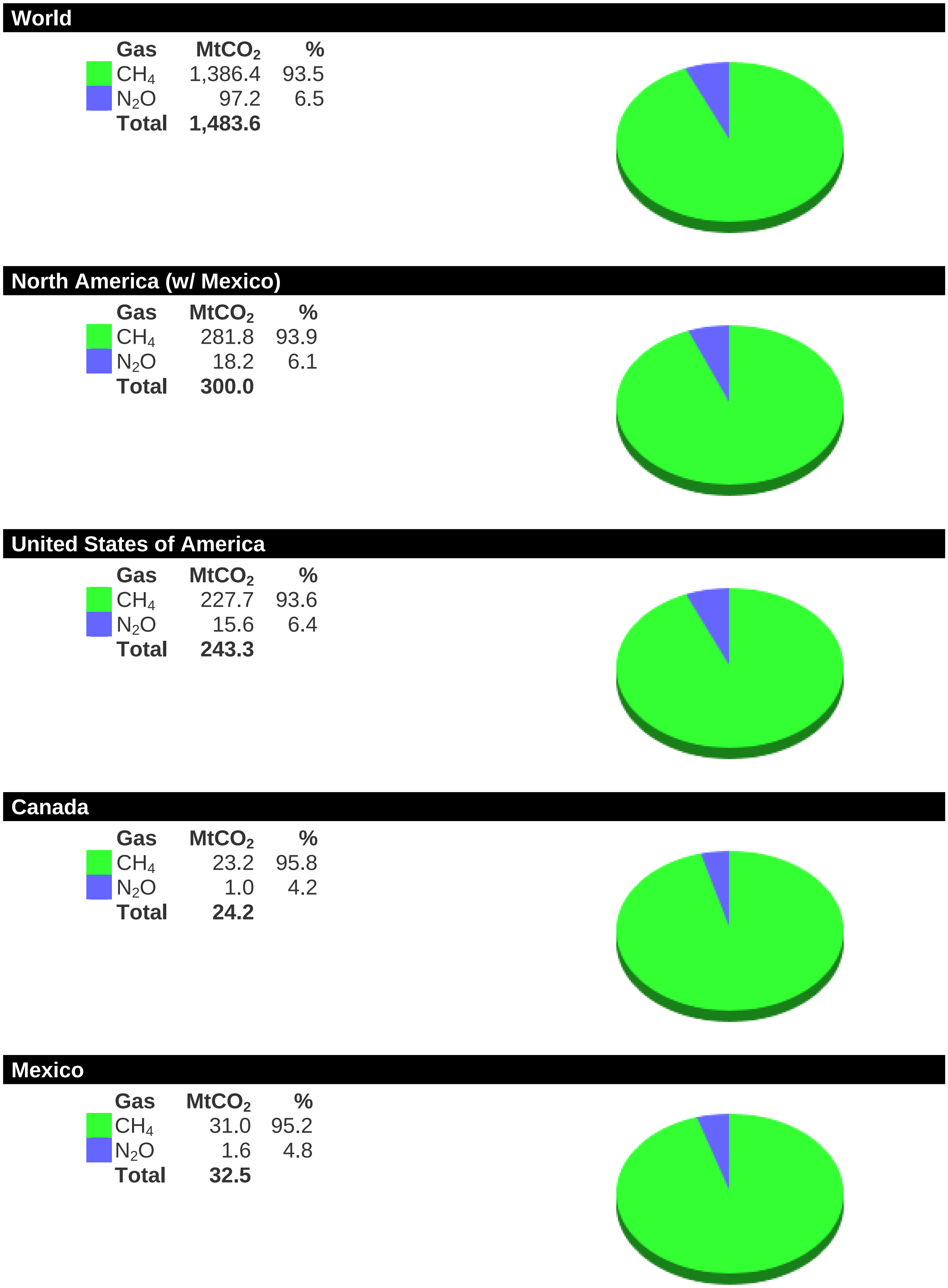


**Fig. 8-3. Decomposition of energy use, manufacturing sector, 1990–1998.** *Source*: IEA, 2004.



**World**

| | Gas | $MtCO_2$ | % |
|---|---|---|---|
| 🟩 | $CH_4$ | 1,386.4 | 93.5 |
| 🟦 | $N_2O$ | 97.2 | 6.5 |
| | **Total** | **1,483.6** | |

**North America (w/ Mexico)**

| | Gas | $MtCO_2$ | % |
|---|---|---|---|
| 🟩 | $CH_4$ | 281.8 | 93.9 |
| 🟦 | $N_2O$ | 18.2 | 6.1 |
| | **Total** | **300.0** | |

**United States of America**

| | Gas | $MtCO_2$ | % |
|---|---|---|---|
| 🟩 | $CH_4$ | 227.7 | 93.6 |
| 🟦 | $N_2O$ | 15.6 | 6.4 |
| | **Total** | **243.3** | |

**Canada**

| | Gas | $MtCO_2$ | % |
|---|---|---|---|
| 🟩 | $CH_4$ | 23.2 | 95.8 |
| 🟦 | $N_2O$ | 1.0 | 4.2 |
| | **Total** | **24.2** | |

**Mexico**

| | Gas | $MtCO_2$ | % |
|---|---|---|---|
| 🟩 | $CH_4$ | 31.0 | 95.2 |
| 🟦 | $N_2O$ | 1.6 | 4.8 |
| | **Total** | **32.5** | |

**Fig. 8-4. GHG emissions by gas from waste in 2000.** *Source*: Climate Analysis Indicators Tool (CAIT) Version 3.0 (Washington, D.C.: World Resources Institute, 2005).

# Appendix 8A

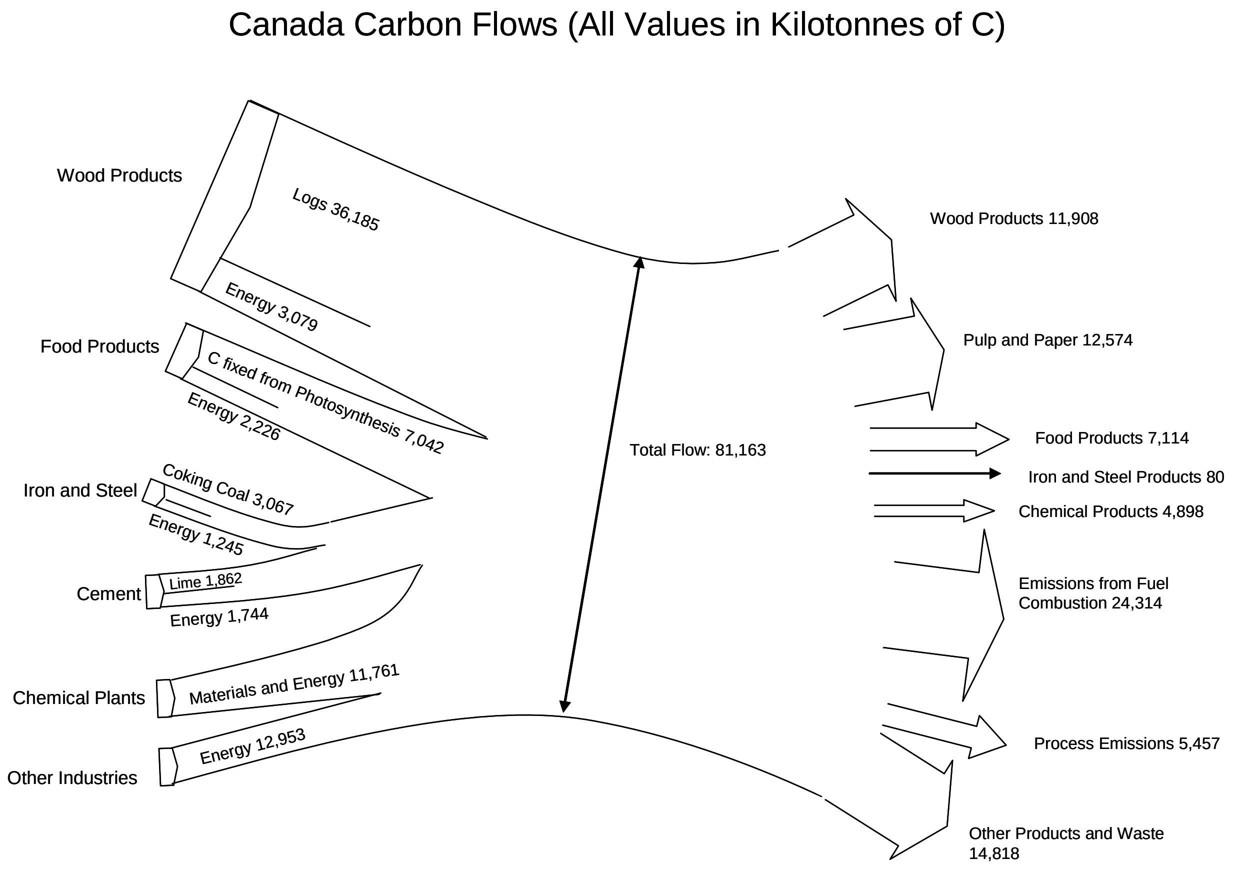
## Industry and Waste Management – Supplemental Material

This appendix presents diagrams of the carbon flows in Canada, the United States, and Mexico, respectively (Figs. 8A-1 through 8A-3). The numerical data in these figures are shown in thousands of metric tons of carbon, which can be converted into thousands of metric tons of $CO_2$ equivalents by multiplying the carbon values by 44/12 (i.e., the ratio of carbon dioxide mass to carbon mass). The combined carbon flows for all three nations are presented in Fig. 8-2 in Chapter 8 of this report.

**Figure 8A-1. Carbon flows, Canada.**

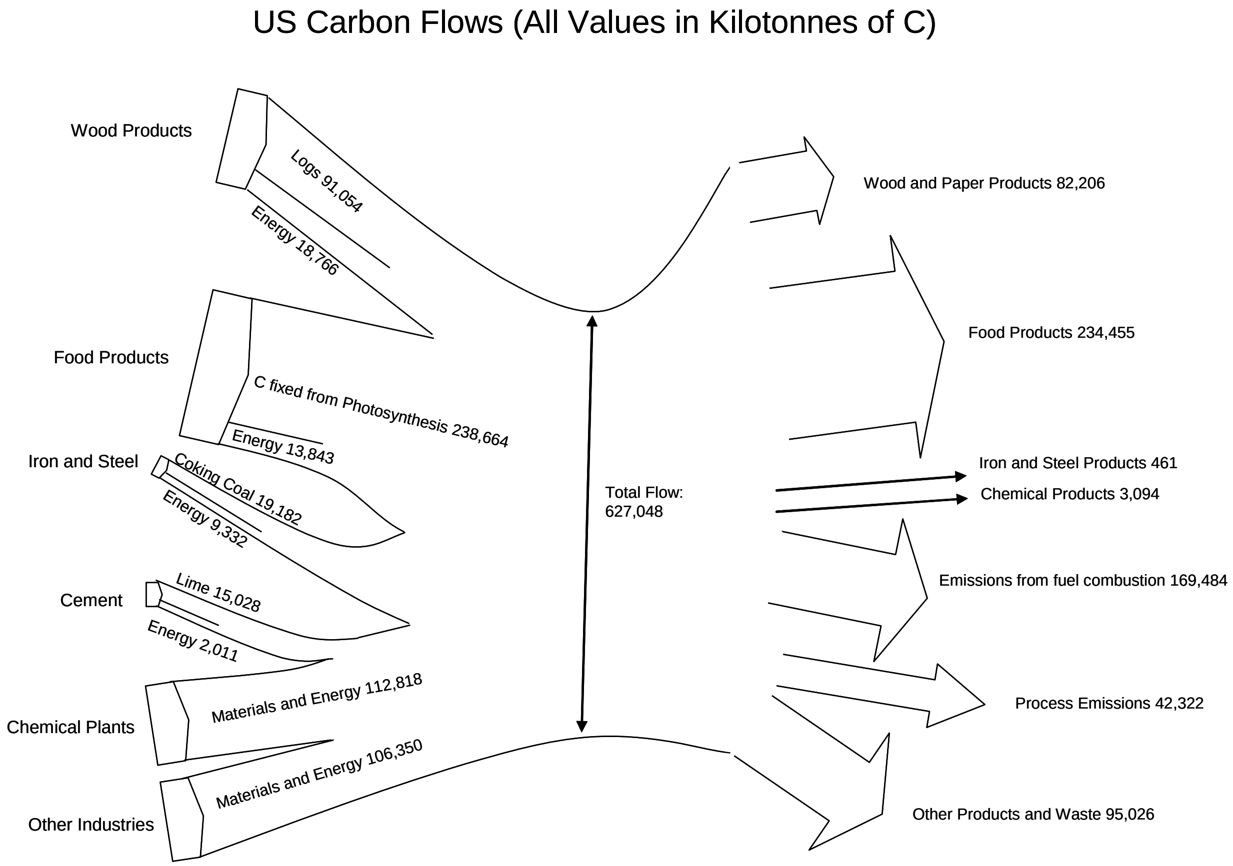
**Figure 8A-2. Carbon flows, United States.**

**Figure 8A-3. Carbon flows, Mexico.**



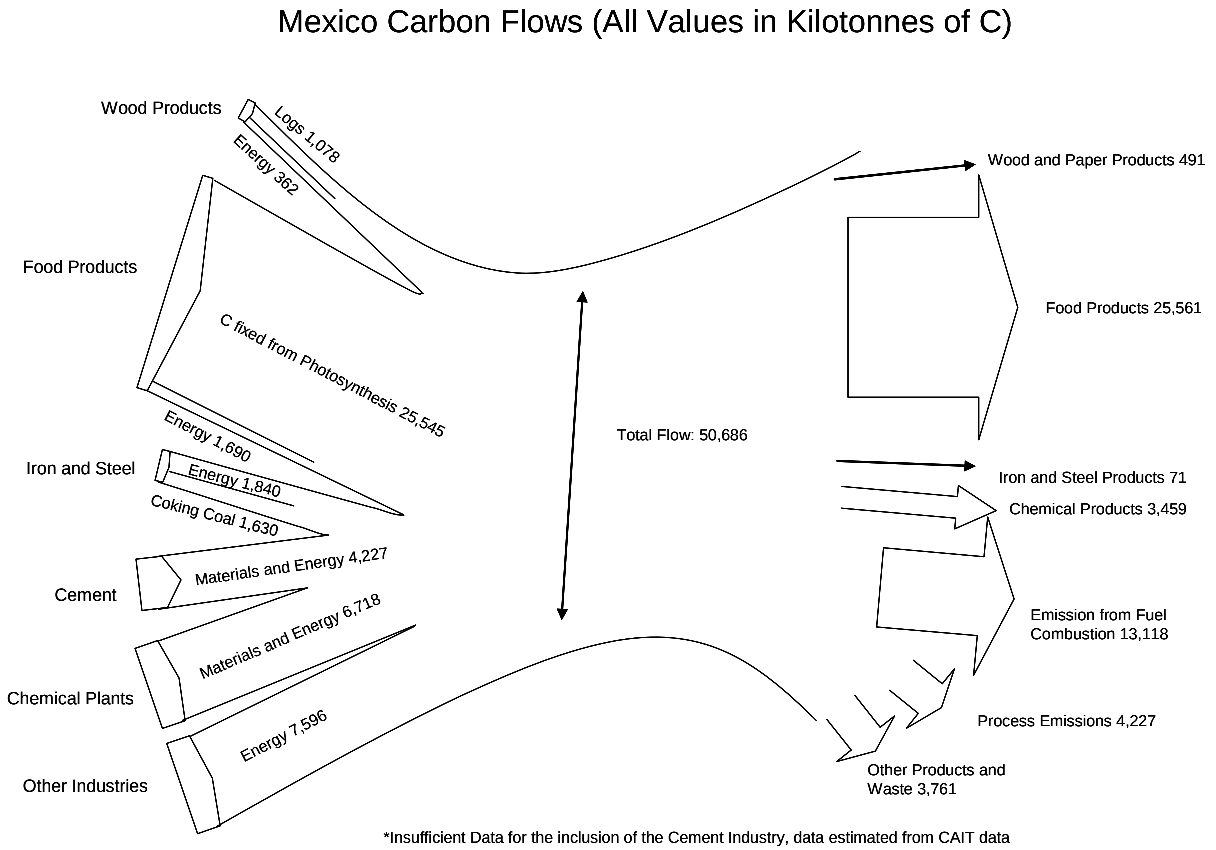
Process Emissions include Emissions from Iron and Steel, Agriculture, Cement & Lime, and Chemical Industries

**Fig. 8A-1. Carbon flows, Canada.** *Source*: Energy data from Statistics Canada Industrial Consumption of Energy survey, conversion coefficients and process emissions from Environment Canada, *Canada GHG Inventory, 2002*. Production data from Statistics Canada, CANSIM Table 002-0010, Tables 303-0010, -0014 to -0021, -0024, -0060, Pub. Cat. Nos.: 21-020, 26-002, 45-002, Canadian Pulp and Paper Association on forestry products.



Process Emissions include Emissions from Iron and Steel, Agriculture, Cement & Lime, and Chemical Industries

**Fig. 8A-2. Carbon flows, United States.** *Source*: Energy data from IEA Oil Information 2004, IEA Coal Information 2005, IEA Natural Gas Information 2004. Process emissions: EPA, U.S. Emissions Inventory. Production of forestry products: USDA Database; FO-2471000 and -2472010, U.S. Timber Production, Trade, Consumption, and Price Statistics 1965–2005, Production of organic products (e.g., food): USDA PS&D Official Statistical Results, Steel: International Iron and Steel institute, World steel in figures 2003, Minerals production: USGS mineral publications.



Mexico Carbon Flows (All Values in Kilotonnes of C)

*Insufficient Data for the inclusion of the Cement Industry, data estimated from CAIT data

**Fig. 8A-3. Carbon flows, Mexico.** *Source*: Energy data from IEA Oil Information 2004, IEA Coal Information 2005, IEA Natural Gas Information 2004. Process emissions: EPA, U.S. Emissions Inventory. Production of forestry products: USDA Database; FO-2471000, -2472010, -2482000, -2483040, -6342000, -6342040. Production of organic products (e.g., food): USDA PS&D Official Statistical Results. Steel: International Iron and Steel institute, World steel in figures 2003.