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Trends in Global Emissions: Carbon, Sulfur, and Nitrogen

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Global anthropogenic emissions of carbon, sulfur and nitrogen are reviewed by major category. Both present and historical emissions are reviewed including respective uncertainty ranges. The article concludes with a brief discussion of how to relate trends in emissions to the evolution of their underlying driving forces using energy-related carbon emissions as an example.

Main conclusions for the three gases are summarized below:

Anthropogenic emissions of carbon are small compared to the sizes of natural carbon reservoirs and the annual flow rates between them. Yet they constitute important perturbations of the natural carbon cycle, well quantified for industrial carbon emissions (mostly the burning of fossil fuels), but remaining uncertain for carbon emissions arising from biomass burning and land-use changes. Since the onset of the Industrial Revolution, some 530 billion tons of carbon (Pg C) gross emissions have been released by human activities to the atmosphere, part of which was balanced by (highly uncertain) terrestrial biospheric carbon sinks. Net carbon emissions over the period 1800–2000 are estimated at 280 Pg C. After accounting for oceanic uptake, these emissions have increased the atmospheric carbon loading by 200 Pg C, or by one-third natural levels. In the absence of stringent climate policies, between 770 and 2540 Pg C could be released to the atmosphere over the next 100 years. A significant amplification of humankind's "discernible influence on the climate system" is thus likely.

Anthropogenic emissions of sulfur have surpassed natural flows ever since the first quarter of the 20th century. Since about 1975 global emissions (mostly from burning of sulfur-rich fossil fuels such as coal and oil) have stayed roughly constant. A continued rise in sulfur emissions in developing countries has been compensated by drastic declines in emissions in Organization for Economic Cooperation and Development (OECD) countries as a result of environmental policies. Similar policies will be required also in developing countries to counter local and regional environmental impacts of high sulfur emissions. A slowdown and ultimately a trend reversal of sulfur emission growth trends also in developing countries could thus be likely over the next few decades.

Emissions of nitrogen take a variety of forms and originate from a wide array of different sources including: nitrogen oxides, principally formed in high temperature combustion (burning of fossil fuels); ammonia, principally arising from animal manure; and nitrous oxide (N_2O), a powerful greenhouse gas, principally arising from soil microbiological process as well as agricultural activities and animal manure. Because of the multitude of gases and sources, emission estimates are poorly understood and uncertain. There is also a paucity of both past and present inventory data and future emission scenarios. More research is therefore needed before considering policy interventions to control these gases beyond well established source categories (e.g., nitrogen oxide emissions from automobiles, or nitrous oxide emissions from adipic acid production).

CARBON

Anthropogenic emissions of carbon arise predominantly from the combustion of fossil fuels, the burning of biomass, as well as oxidation of soil carbon following land-use changes (e.g., deforestation). These anthropogenic emissions are embedded in large fluxes between the (yet larger) carbon reservoirs (atmosphere, oceans, vegetation and soils, as well as deposits of fossil fuels) that characterize the carbon cycle (Houghton and Skole, 1990; Schimmel *et al.*, 1995, *see* **Carbon Cycle**, Volume 2). Due to the magnitude of the reservoirs and the annual exchange rates between them, that are known only approximately, human alterations to the carbon cycle are comparatively

small, are difficult to quantify and are hence subject to considerable uncertainties, especially for land-use change carbon emissions.

The Intergovernmental Panel on Climate Change (IPCC) summarizes current knowledge on the size of the respective carbon reservoirs and fluxes for the 1980s as follows (Schimmel *et al.*, 1995; Nakicenovic *et al.*, 1996): the largest carbon reservoirs are the oceans (close to 40 000 Pg C [Pg C = Petagrams (10^{15} g) elemental carbon, 1 Pg = 1 Gt (gigatons, or one billion metric tons), 1 Pg = 1000 Tg (teragrams, or 10^{12} g)]), deposits of fossil fuels (coal, conventional and unconventional oil and gas (such as *inter alia* oil shales, tar sands, gas in tight formations, in aquifers, and coal seams), including methane hydrates: 25 000 Pg C), vegetation and soils (2200 Pg C), and finally the atmosphere (750 Pg C). Only the latter carbon reservoir size is directly measurable, and the increasing atmospheric carbon dioxide concentrations are proof that human activities and resulting emissions are indeed altering the carbon cycle, the composition of the atmosphere, and hence the radiative (heat) balance of the planet (global warming). The global carbon cycle involves the annual exchange of some 90 Pg C between the atmosphere and the oceans, and some 60 Pg C between the biosphere (vegetation and soils) and the atmosphere. The inter-annual variations of measured atmospheric carbon dioxide concentrations (5.4 parts per million by volume (ppmv) in 1998 at Mauna Loa, Hawaii (Keeling and Whorf, 1999)) clearly indicate the importance of seasonal vegetation cycles in biospheric carbon fluxes. The inter-annual variation of 5.4 ppmv corresponds to some 11 Pg C. Compared to the size of annual fluxes that characterize the carbon cycle and its inter-annual variations, anthropogenic alterations to the carbon cycle are comparatively small and hence impossible to measure directly. Emission estimates need therefore to be based on inventory data linking socio-economic activity data such as fossil fuel use or land use changes, with specific emission factors in the case of fossil fuel emissions, or micro- and meso-scale models of how soil and vegetation carbon reservoirs, and the exchange rates between them, are affected by human activities.

Currently (AD 2000), human-induced alterations to carbon flows include emissions of some 6.6($\pm$0.6) Pg C year^{-1} from industrial activities (mostly the burning of fossil fuels) that constitute a net addition to natural carbon fluxes, albeit not necessarily in the same year. In addition, estimates indicate a net additional flux of about one (uncertainty range: 0–2.8) Pg C year^{-1} from the burning of biomass and changes in soil carbon in conjunction with land use changes. This estimated net biospheric flux is the difference between estimates of a variety of carbon sources and sinks (see discussion below) and is affected by high uncertainty margins. This is illustrated in the following simplified representation of the global annual carbon balance in Pg C for the 1980s (Schimmel *et al.*, 1995; Houghton, 1999).

$$\begin{aligned}\text{atmospheric increase} &= \text{industrial emissions} \\ &\quad + \text{net land-use emissions} - \text{ocean uptake} \\ &\quad - \text{residual (missing sink)} \\ 3.3(\pm 0.2) &= 5.5(\pm 0.5) + 1.1(0 - 2.8) - 2.0(\pm 0.8) \\ &\quad - 1.3(0 - 3.3)\end{aligned}$$

Table 1 summarizes the main, contemporary anthropogenic industrial and biotic carbon emission sources as well as associated uncertainty ranges. The numbers exclude carbon dioxide fluxes arising from the metabolism of human and animal populations for which inventory data are lacking.

Industrial sources of carbon emissions are comparatively well understood and quantified. The dominant source is fossil energy production, conversion, and use, i.e., burning of fossil fuels (6 Pg C). Secondary sources are the manufacture of cement (0.2 Pg C) and the flaring of natural gas (0.06 Pg C) which occurs when gas is produced together with crude oil, but due to the absence of local markets or infrastructures cannot be used as a fuel and is flared (burned) instead. Re-injection into the oil reservoir for repressuring avoids the need for flaring and is practiced in many oil fields (CEDIGAZ, 1998). Yet even the modest costs involved seem not to justify the preservation of natural gas resources for future uses in many locations. Hence flaring continues (albeit declining). Globally some 120 billion m^3 of natural gas are flared, about equal to the global trade in LNG (liquefied natural gas) or the natural gas consumption of Germany, Austria, Switzerland, and Belgium combined (CEDIGAZ, 1998). Minor carbon emission sources include the manufacture of lime and ammonia (Harvey, 1999), the release of carbon dioxide from carbon dioxide rich fossil fuel reservoirs, and the production of carbon dioxide from natural reservoirs for tertiary oil recovery and for the food (beverage) industry. Even if small when compared to natural carbon fluxes, carbon emissions are the largest material flow of the industrial metabolism. The 6 Pg C of industrial carbon emissions compares, for instance, to an annual production volume of 2.5 Pg for the seven most important industrial commodities (in decreasing order of tonnage: cement, steel, paper, fertilizers, glass, aluminum, copper, cf. Grübler, 1998a).

Emission estimates for industrial sources are quite accurate ($\pm$10%). As energy is a preferred target for taxation, production, trade, and stock statistics are fairly accurate, at least for commercially traded energy forms such as fossil fuels. (Uncertainties for non-commercial energy use such as the traditional biomass fuels used in developing countries are however substantial (*see* **Biomass Burning in Rural Homes in Tropical Areas**, Volume 3).) The net balance between production, trade flows and stock changes allows one to determine annual apparent fossil

Table 1 Global carbon emissions as estimated for 1990 per major source category and uncertainty ranges (in Tg C year^{-1})[a]

		Net	Gross	Uncertainty range
	Coal	2424		
	Oil (fuels)	2285		
	Oil (feedstocks)		324	
	Gas	1135		
	Cement	157		
	Gas flaring	60		
Industrial		6061	6385	5800–7000
	Fuelwood[b]		530	
	Traditional biofuels[b]		630	
Biofuels[b]			1160	??–1600
	Savannah fires[c]		1660	
Other biomass				??–1700
	Tropical forests[d]		1100	
	Temperate forests[d]		0	
Land-use change[b]			1100	0–2800[e]
Total		6061	8645	5800–>13 100

[a] Emission categories that are not balanced by (uncertain) biospheric carbon sinks or that are not released to the atmosphere in the same year are listed as gross emissions, all others as net emissions (see text). For land-use change related emissions, the net biospheric flux as estimated by IPCC (1995) for the 1980s (the latest period for which global estimates are available) and the uncertainty range as estimated by Houghton (1999) for the same period are given. (Data source: see text.)
[b] Emissions of biofuels and land-use change not necessarily entirely additive.
[c] Andreae (1991). Not included in total gross emissions.
[d] Estimated net biospheric flows (IPCC, 1995).
[e] Upper range for net biospheric flux due to land-use change (Houghton, 1999), no estimates of gross emissions available.

fuel consumption, and that combined with carbon emission factors makes quantification of corresponding carbon emissions rather straightforward. Emission estimates are made regularly from the energy statistics of the United Nations (Marland *et al.*, 1999), the International Energy Agency (IEA, 1998), or the statistics published by British Petroleum (BP, 1999, see Table 1) drawing on similar methodologies (for the IPCC/IEA guidelines, see Houghton *et al.*, 1996). Aggregate results yield comparable global numbers, albeit differences (i.e., uncertainties) remain in the partition between various fuel types and between regions as a result of statistical differences and uncertainties in the heat content of different fuels, especially for coal. As an approximation, carbon emission factors are practically constant per unit energy content for different qualities of fuelwood, coal, oil, and gas, respectively, reflecting their molecular composition (ratio of hydrogen to carbon atoms). Characteristic emission factors (based on lower heating values) are 29.9 kg C GJ^{-1} for fuelwood (and other biomass fuels), 25.8 kg C GJ^{-1} for coal, 20 kg C GJ^{-1} for oil, and 15.3 kg C GJ^{-1} for gas (Nakicenovic *et al.*, 1996). Hence, uncertainties in heat values of different fuel qualities translate into proportional uncertainties of carbon emissions. Emission estimates for non-energy uses of fossil fuels (feedstocks) are affected by larger uncertainties, as the carbon contained in feedstock fuel (mostly oil) ends up in a wide variety of products (plastics, asphalt, bitumen, lubricants) which are in many instances long lived. Several decades may therefore pass before the carbon contained in these products is ultimately oxidized (e.g., when these products are burned) and released to the atmosphere. Hence, for any given year, it is necessary to distinguish between gross and net emissions. *Gross emissions* result from the transfer of carbon between various reservoirs due to human activity such as converting crude oil extracted from an oilfield where it has remained for geological ages to combustible fuel (e.g., gasoline) or long-lived materials (e.g., plastics, asphalt). *Net emissions* of any given year are those that result from human activities in that year, e.g., burning of gasoline in an internal combustion engine car. For fossil fuel, the differences between gross and net emissions are comparatively minor: some 0.3 Pg C, or 5%. Yet the difference is of similar importance as the secondary industrial sources i.e., cement manufacture and gas flaring.

Another source of uncertainty relates to biomass fuels. When produced at sustainable rates, sources and sinks will balance, albeit not necessarily in a given year. Whenever, biomass regrowth falls short of the rate of biomass burning, sources exceed sinks, giving rise to net emissions. Historically, this was the case for industrialized countries. Recently, biotic sinks have exceeded biotic emissions in the Northern Hemisphere, justifying the classification of biofuels as *carbon neutral*. The current situation in many developing countries is far removed from this carbon

benign state of affairs, resembling that in the industrialized countries some decades to a few centuries ago, characterized by deforestation and unsustainable biomass fuel use. The historian of pre-industrial Europe Carlo Cipolla (1981) characterizes medieval European forestry use as "eminently parasitic and extremely wasteful". Biomass fuels are therefore included in the biotic carbon sources given in Table 1 as they usually are accounted for in detailed land-use change carbon inventories (Houghton, 1999). Note however, that the values given for gross emissions of biomass burning (e.g., fuelwood) and those from land-use changes are not necessarily additive because fuelwood gathering in connection with deforestation is usually also accounted for in the respective land-use change related carbon fluxes. Thus, part (perhaps up to 0.5 Pg C) of the 1.2 Pg C gross emissions due to biofuel burning may already be included in the 1.1 Pg C gross emissions due to land-use changes reported in Table 1. This uncertainty and the risk of possible double counting has led to the doubtful practice of generally ignoring biofuel related carbon emissions in energy studies and emission inventories.

Differences between gross and net emissions as well as uncertainties are especially pronounced in the case of biotic carbon emissions. In that case, gross emissions, e.g., from biomass burning, need to be balanced with corresponding sinks, i.e., the uptake of carbon dioxide by vegetation in order to determine net emissions. In addition, both sources and sinks operate frequently on different time scales (burning a wood log takes an hour, growth of a tree many decades). To complicate things further, changes in vegetation cover also involve changes in soil carbon. The response rates of top and deep soil layers to a change in vegetation cover (e.g., conversion of forests to agricultural fields) are poorly understood and involve time scales of many decades (Houghton and Skole, 1990; Houghton, 1999).

Consider the burning of agricultural residues either in the field or as energy for rural households: emissions from biomass grown on an annual rotational cycle are balanced by corresponding vegetation regrowth (carbon uptake) in the following or preceding growing season. A similar case is that of savannah fires (natural or induced by human activities). Combined, these two categories involve the annual burning of some 5.7 billion tons dry matter per year and an estimated release of 1.6 Pg C (Andrae, 1991, see Table 1). As sources and sinks are assumed to balance over a time scale of approximately a year, these emission categories are generally excluded from carbon inventories (and are also not shown in the Figures below, not the least because historical estimates are unavailable. An exception is biomass fuel outside fuelwood, for which a conservative estimate is included in the data presented here (based on interpolated values given in UN, 1952; Putnam, 1954; Nakicenovic *et al.*, 1998. As simplification, the carbon emission factor for these other traditional biofuels like agricultural residues, dried animal dung, etc., is assumed to be the same as fuelwood).

For a complicated case consider the case of forest clearing: Felling of trees may entail short-term carbon emissions when wood is used as fuel, and a significantly delayed response when used as construction material (when a wood structure eventually burns down). In most cases, the dominant source of carbon emission is the decay of woody material after forest clearing (Houghton *et al.*, 2000). Carbon releases from soils depend critically on the ensuing land uses: secondary forest regrowth, or conversion to intensive agriculture. Soil carbon release rates depend therefore on (changing) land uses that follow deforestation and involve a time scale of many decades. Estimating corresponding carbon fluxes is thus a formidable challenge.

Large uncertainties thus prevail for biospheric carbon sources and sinks. Assuming high biospheric (gross) emissions implies assuming a large biospheric sink (frequently assumed to be located in northern latitudes, cf. Schimmel *et al.*, 1995) in order to balance the global carbon cycle. Low biospheric emission fluxes, especially when combined with upper range estimates of oceanic uptake rates, reduce the size of the residual (missing) sink required to balance the global carbon cycle. The average value of 1.1 Pg C $year^{-1}$ net biospheric carbon emissions for the 1980s suggested in the IPCC review (Schimmel *et al.*, 1995) is derived from adopting a mean value of 1.6($\pm$1) Pg C from tropical latitudes balanced against an estimated uptake rate of 0.5($\pm$0.5) Pg C $year^{-1}$ for northern latitudes. The estimated net biospheric flow of 1.1 Pg C represents a top down estimate, based on balancing the global carbon cycle as well as on carbon cycle model calculations. These models are frequently initialized with a 1980s global biospheric flux of 1.1 Pg C when reproducing the historical record of carbon dioxide concentration changes or when calculating future scenarios (for an overview see Houghton *et al.*, 1997; for a representative model see e.g., Wigley *et al.*, 1994).

Conversely, bottom-up assessments based on detailed inventory models, that yield changes in vegetation and soil carbon in response to land-use changes, typically yield higher estimates of net biospheric carbon flows: 2($\pm$0.8) Pg C $year^{-1}$ for the 1980s, including 1.9($\pm$0.6) Pg C in the tropics and 0.1($\pm$0.5) Pg C in temperate latitudes (Houghton, 1999). Available (uncertain) forest inventory data indicate an average rate of tropical forest clearing of some 13.3 million ha $year^{-1}$ for the 1980s, and an average 12.6 million ha $year^{-1}$ for the period 1990–1995, compared to an average afforestation rate of 1.3 million ha $year^{-1}$ in non-tropical regions for the period 1990–1995 (FAO, 1997; WRI, 1998). Translating these land-use change numbers into estimates of gross biospheric emissions and balancing those against sinks to determine estimates of net emissions

is highly problematic because of uncertainties in secondary forest regrowth, soil carbon, as well as the magnitude of the (undisturbed) forest carbon sink. Recent estimates for the Brazilian Amazon, characterized by high rates of forest clearing and regrowth (*see* **Deforestation and Habitat Fragmentation in the Amazon Basin**, Volume 3), conversion to agricultural uses followed by later abandonment, and wood logging, indicate nonetheless a roughly balanced carbon budget between emissions due to land-use changes and carbon uptake by vegetation regrowth and by natural ecosystems in the region (Houghton *et al.*, 2000). However, considerable variations exist between individual years: the Brazilian Amazon is estimated to have been either a (net) source or sink of about 0.2 Pg C for different individual years over the period 1989–1998.

Whereas bottom-up assessments thus continue to be the best way for estimating current and historical gross biotic carbon emissions, it is not possible yet to accurately determine net biospheric carbon emissions. This is why no estimates of respective current net emissions are given in Table 1. Also in the figures of historical emissions given below, respective biospheric carbon emissions are reported as gross values only.

From a combination of direct atmospheric measurements and analyses of air samples trapped in glacier ice, there is compelling evidence that atmospheric carbon dioxide concentrations have increased from some 280 ppmv (Neftel *et al.*, 1985; Schimmel *et al.*, 1995) in pre-industrial times to some 370 ppmv (estimate for AD 2000): i.e., an increase in the atmospheric carbon reservoir of close to 200 Pg C over the last 200 years. How can this increase in atmospheric concentration be allocated to different carbon emission categories?

Historical emission inventories for fossil fuel use and other industrial sources have a long scientific history starting from the pioneering contributions of Putnam (1954) and Keeling (1973). For land-use related emissions, the main historical data sources are the estimates of Houghton and Skole (1990) and Houghton (1999). A combined historical inventory of industrial and biotic carbon emissions was developed by Grübler and Nakicenovic (1994), an update of which is summarized in Figures 1 and 2. The original inventory spanned the period 1800–1988. Updates for fossil fuels, cement and gas flaring to 1998 are based on BP (1999) (and earlier vols.), CEDIGAZ (1998); and Marland *et al.* (1999). Values for the year 2000 are estimates based on extrapolation of short-term (1995–1998) trends. For biotic emissions, a comparable value as estimated by the IPCC (Schimmel *et al.*, 1995) for the 1980s, i.e., average annual net biotic emissions of 1 Pg C, was assumed for the 1990s, based on FAO (1998) forest inventory data that indicate similar average deforestation rates in the two time periods.

Figure 1 presents an overview of historical carbon emissions by source since 1800. Figure 2 adds these emissions categories, presenting them as cumulative totals. Only emissions from burning of fossil fuels and from the manufacture of cement can be classified clearly as net contributions to the atmosphere. As discussed above, the fraction of gross emissions that is not absorbed by sinks, or that may be released over long time periods (feedstocks) is highly uncertain. Hence these emission categories are shown as

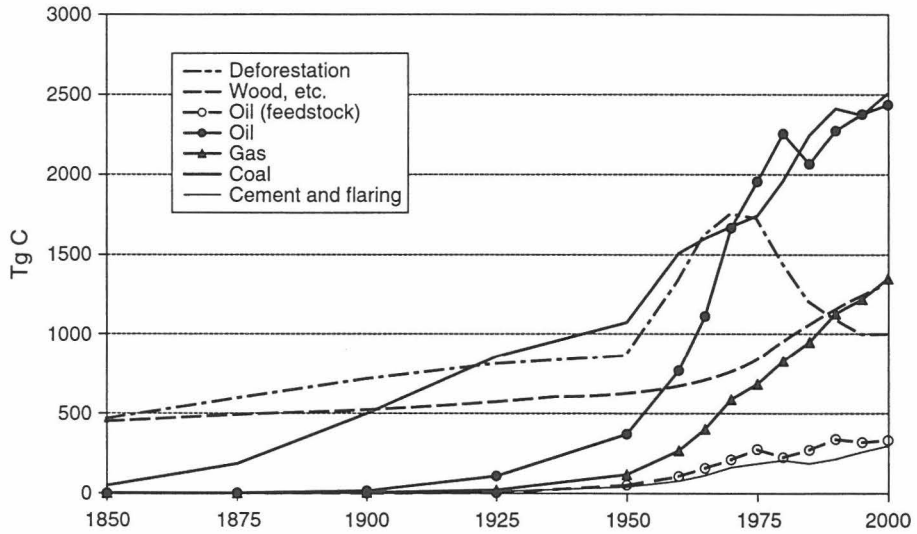

Figure 1 Annual carbon emissions per major source category 1850–2000 (in Tg C year^{-1}). Emission categories that are not balanced by (uncertain) biospheric carbon sinks or that are not released to the atmosphere in the same year are shown as gross emissions (dashed lines), all others as net emissions (solid lines). Values for the year 2000 are preliminary estimates. (Reproduced from Grübler and Nakicenovic, 1994 and Grübler, 1998a [Updated (see text)])

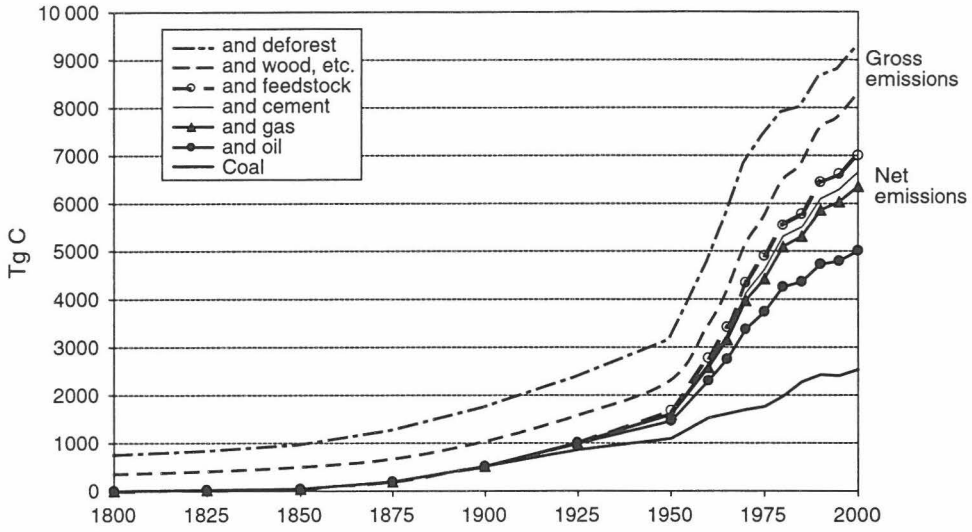

Figure 2 Annual carbon emissions per major source category 1800–2000, cumulative totals (in Tg C year^{-1}). (Reproduced from Figure 1)

gross emissions only in Figure 2. Cumulatively over the period 1800–2000, net carbon emissions total (a minimum) of some 280 Pg C, whereas gross carbon emissions total (a maximum) of 530 Pg C. In explaining the growth of atmospheric carbon, net emissions need to be balanced against the magnitude of the oceanic carbon sink, whereas gross emissions need to be balanced against the size of both the oceanic and the terrestrial carbon sinks.

In order of decreasing importance in terms of cumulative emissions since 1800 (derived from Figures 1 and 2), burning of coal and emissions due to land use changes are the two most important emission categories (148 Pg C net for coal and 155 Pg C gross for land-use changes). Houghton (1999) estimates for the period 1850–1990 that land-use changes (including fuelwood burning and logging) released a total of 373 Pg C to be balanced against an estimated terrestrial sink uptake of 249 Pg C (211 Pg C carbon uptake by vegetation regrowth and 38 Pg C soil carbon recovery). This yields an estimated net biospheric carbon flux of 124 Pg C, a comparable magnitude to the 155 Pg C gross carbon emissions due to land-use changes (excluding fuelwood burning) estimated here for the period 1800–2000. Oil ranks third (91 Pg C net emissions or 103 Pg C when non-energy feedstock uses (12 Pg C), classified here as gross emissions, are added). Burning of fuelwood and other (traditional) biomass fuels for energy purposes is estimated to have released some 77 Pg C (gross) emissions, albeit this quantity is not necessarily entirely additive to the emissions estimated from land-use changes. Burning natural gas as fuel is estimated to have released some 38 Pg C (net) since 1800 (most of it since 1950), whereas the manufacture of cement and the flaring (waste) of natural gas yields a comparatively small number of 5 Pg C (net) emissions since 1800.

Thus, the historic atmospheric increase of some 200 Pg C balances against a range of between 280 and 530 Pg C (net/gross) carbon emissions from all sources and an inferred cumulative uptake by all carbon sinks (oceanic and terrestrial) of between 80 and 330 Pg C over the period 1800–2000.

Most of the historical human-induced perturbations of the global carbon cycle originate from emissions in the industrialized countries. From the estimated cumulative net carbon emissions since 1800 (some 280 Pg C), about three-quarters originate from the industrialized countries, and one quarter from developing countries. For gross emissions, the difference is less pronounced: about 55% originate from the industrialized countries versus 45% from developing countries. Yet, such comparisons of historical emissions ignore important regional disparities in emission drivers such as population, levels of affluence, and levels and efficiency of technologies employed. When making these comparisons, it must be remembered that since 1800 70% of the world's people have lived in the developing countries (Grübler and Nakicenovic, 1994). Therefore when measured on a *per capita* basis the share of developing countries in historical or current emissions is much smaller than the simple numbers above would suggest (for detailed calculations see Fujii, 1990; Grübler and Fujii, 1991).

The division of annual gross and net emissions since 1800 for three macroregions is illustrated in Figure 3. The definition of these three macroregions follows that of the original UN Framework Convention on Climate Change (UNFCCC, 1992). It comprises: the countries of the OECD as of 1990 (Annex II in United Nations Framework Convention on Climate Change (UNFCC)); the countries of Central and Eastern Europe as well as of the

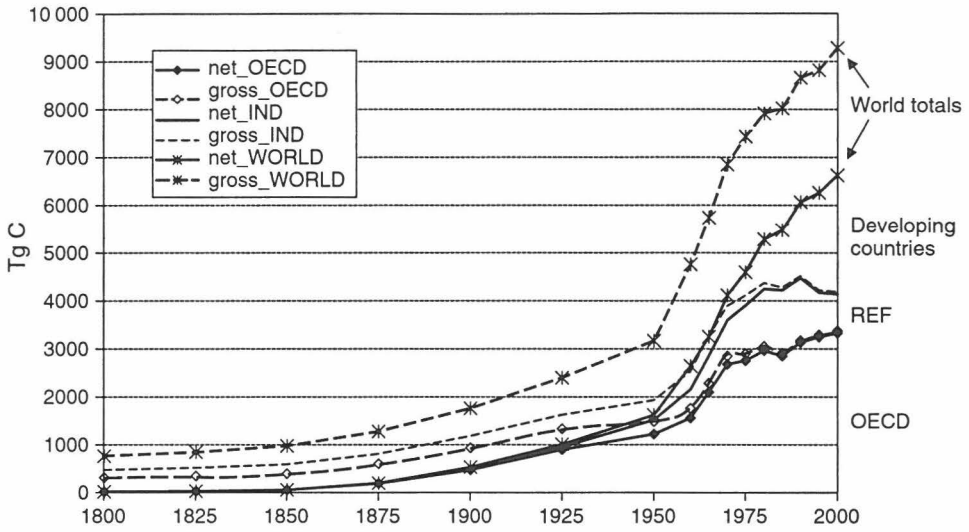

Figure 3 Annual carbon emissions per major emitting regions and given as cumulative totals (in Tg C year^{-1}). The regions are as defined in the 1990 UNFCC (*see* **United Nations Framework Convention on Climate Change and Kyoto Protocol**, Volume 4): OECD countries as of 1990 (OECD, UNFCCC Annex II countries), countries undergoing economic reform (REF, UNFCCC Annex I countries outside Annex II), and developing countries (DEV, UNFCCC non-Annex I countries). OECD and REF combined represent the industrialized countries referred to in the UNFCC as Annex I countries (IND in Table 3). Respective totals for gross and net carbon emissions (all sources) are shown as dashed and solid lines respectively (see text). (Reproduced from Grübler and Nakicenovic, 1994 [updated (see text)])

former Soviet Union undergoing economic reform (Annex I outside Annex II in UNFCC); as well as developing countries (non-Annex I countries in UNFCCC). Combined OECD and economic reform countries constitute the industrialized countries (IND in Figure 3) as defined by Annex I of the 1992 UNFCCC (*see* **United Nations Framework Convention on Climate Change and Kyoto Protocol**, Volume 4).

It is important to note that differences between gross and net emissions for different regions change over time. For instance, whereas this difference is substantial for the industrialized countries throughout the 19th century and also up to approximately 1950, the difference gets smaller, gradually disappearing after the 1970s. In other words, biotic carbon emissions such as land-use changes and fuelwood use (the main source for the difference between gross and net emissions shown in Figure 3), while being important in the early history of industrialization, are no longer important in the industrialized countries. There, the dominant emission source at present is the burning of fossil fuels. Currently, biotic carbon emissions in industrialized countries are close to zero. Historically, they account for about one quarter of cumulative carbon emissions of the industrialized countries since 1800. For developing countries, the situation resembles that of the industrialized countries more than a century ago (when the industrial countries had similar (low) levels of *per capita* incomes as the developing countries have today): an important share of emissions comes from biotic sources, with fossil fuel shares increasing in importance over time. Industrial emission sources account for around 40% of cumulative emissions of developing countries since 1800; by the year 2000 they already account for two thirds of carbon emissions from developing countries.

A brief discussion of how to relate the historical trends in emissions discussed above to main driving forces is given at the end of this contribution using energy-related carbon dioxide as example (*see* **Carbon Dioxide Concentration and Climate Over Geological Times**, Volume 1; **Carbon Dioxide, Recent Atmospheric Trends**, Volume 1; **Carbon Cycle**, Volume 2; **Boreal Forest Carbon Flux and it's Role in the Implementation of the Kyoto Protocol Under a Warming Climate**, Volume 4).

Concerning future emission trends, the (vast) literature on this subject cannot be reviewed in detail here. A comprehensive, quantitative overview of the scenario literature is given by Nakicenovic *et al.* (2000), who also present the latest long-term emissions scenarios developed under the auspices of the IPCC. In this scenario set, representative of current understanding of the underlying uncertainties in demographic, economic and technological developments, global carbon emissions could range anywhere between 8 and 27 Pg C by 2050 and between 3 and 37 Pg C by the end of this century. It is also instructive to look at projected levels of cumulative emissions, which are a (rough) first approximation of the possible magnitude of climate change. By 2100 cumulative carbon emissions could range between 770 and 2540 Pg C, or between equal, to more than three

times the amount currently contained in the atmosphere. In the absence of vigorous climate change policy initiatives (the new IPCC scenarios were developed under the mandate of explicitly excluding additional climate policies) even the lowest scenarios suggest that more carbon will be released to the atmosphere over the next 100 years (>770 Pg C) than has cumulatively been released since the onset of the Industrial Revolution (range of 230–530 Pg C net/gross emissions since 1800, respectively). A significant amplification of humankind's "discernible influence on the climate system" (IPCC, 1995) is thus likely.

SULFUR

Studies of the global sulfur cycle (good reviews are provided by Husar and Husar, 1990; and Smil, 1997) indicate that anthropogenic emissions of sulfur have surpassed natural flows ever since the first quarter of the 20th century. Dominant natural sources include the weathering of rocks and soil, volatile biogenic sulfur emissions from land and the oceans as well as volcanoes. Combined, natural sources are estimated to release between 40 and 60 Tg S (1 Tg S = one million (metric) tons elemental sulfur (MtS). To convert to SO_2, the customary unit of most sulfur studies, multiply by 2 (IPCC, 1995; Husar and Husar, 1990). This compares to total anthropogenic sulfur emissions of between 65 and 90 Tg S in the early 1990s (Benkovitz *et al.*, 1996; Olivier *et al.*, 1996; WMO, 1997). The dominant form of anthropogenic sulfur emissions is airborne emissions of SO_2 with some smaller quantities of SO_3 (hence sulfur emissions are frequently referred to as SO_x).

The ecological impacts of large anthropogenic sulfur emissions arise at three spatial and temporal scales. First, at the local level, high ambient concentrations of SO_2 have well documented (WHO and UNEP, 1993; WMO, 1997) impacts on human health, vegetation, and materials (corrosion, "stone cancer" of historical sandstone buildings). Second, sulfur emissions are one of the main contributors to acidic deposition (acid rain) that affects ecosystems up to a continental scale (changes in pH of streams and lakes and resulting decline in fish populations, reductions in the vitality of the forest ecosystem. Forest dieback, or "Waldsterben" however is increasingly recognized as a multiple stress phenomenon that cannot be related simply to a single source of environmental stress such as acidic precipitation) (*see* **Waldsterben**, Volume 5). Typically, impacts accrue in a highly non-linear fashion (dependent on acidic deposition levels and the buffering capacity of soils) which have led to the formulation of *critical loads* of acidic deposition (see e.g., Amann *et al.*, 1995; Posch *et al.*, 1996) (*see* **Critical Load**, Volume 3). Thirdly, sulfur emissions also assume global ecological significance; evidence is increasing that sulfate aerosols exert a pronounced cooling effect (counterbalancing greenhouse gas (GHG)-induced warming) in the Northern Hemisphere (IPCC, 1995).

A detailed review of available sulfur emission inventories is given in Grübler (1998b), where available global sulfur emission inventories are also compared for the year 1990. The best-guess value suggested in that review is 76 Tg S global anthropogenic sulfur emissions for 1990.

The dominant anthropogenic sources of sulfur emissions are (as for carbon emissions) the burning of fossil fuels. In the case of sulfur, emissions are dominated by burning of coal (some 53 Tg S in 1990, Lefohn *et al.*, 1999) and to a smaller degree by oil products (12 Tg S). Natural gas is (with a few exceptions that do not assume any global significance) almost sulfur free (small traces of sulfur compounds (H_2S) are added deliberately as a safety measure; a smelly tracer helps to detect gas leakages) and hence not a significant source. The third largest emissions category is metallurgical processes (reduction of sulfide ores during the smelting of copper, lead, and zinc), estimated at some 6 Tg S in 1990 (Lefohn *et al.*, 1999). Smaller additional emissions sources are biomass burning (some 2 Tg S, cf. Pepper *et al.*, 1992), as well as marine bunker fuels (usually high sulfur-containing heavy fuel oil which is generally not allowed to be burned on land) with some 3 Tg S in 1990 (4 Tg S in 1994, cf. Corbett *et al.*, 1999). Finally, sulfur emissions from pulp and paper mills, although globally marginal, may have important local ecological effects (apart from their offensive smells). For the sake of completeness, it also should be mentioned that the elemental sulfur mined (some 25 Tg S, Smil, 1997) as feedstock for the chemical industry (mostly used in the production of sulfuric acid) generally does not result in airborne emissions. This market however, is declining with the increasing availability of elemental sulfur recovered in oil refineries as a byproduct of fuel desulfurization to meet environmental standards (likewise gypsum mining faces increasing competition from gypsum produced from flue gas desulfurization units of coal-fired power stations).

Sulfur emission inventories are developed on a regular basis in a number of regions, including within the EMEP and CORINAIR programs in Europe and the National Acid Precipitation Assessment Program (NAPAP) in North America. Recently more detailed emission inventories have become available for Asia, where emission growth rates are particularly high (Streets *et al.*, 2000), including work in conjunction with the World Bank sulfur project (Foell *et al.*, 1995), and the detailed bottom up estimates of Akimoto and Narita (1994) and Kato (1996). Sulfur emissions in all regions not mentioned above (i.e., Pacific OECD countries like Australia and New Zealand, and all developing countries outside Asia) are much less well studied. Even if presently small when compared to those of Europe, North America and Asia, the sulfur emissions in these regions are likely to grow significantly in the longer-term.

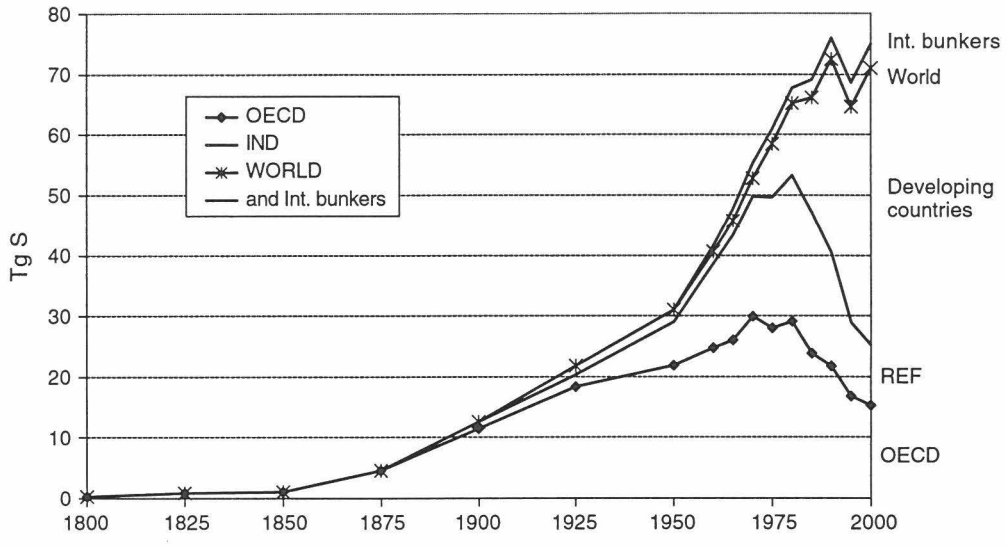

Figure 4 Annual sulfur emissions per major emitting region as defined in Figure 3, 1800–2000, shown as cumulative totals (in Tg S year^{-1}). Emissions from international marine bunker fuels that are usually not accounted for in national/regional emission inventories are shown separately. (Data sources: see text)

At the global level, a number of spatially detailed sulfur emission inventories have been developed. Global, gridded (1 × 1 degrees) sulfur emissions inventory data are needed for a variety of purposes, most notably for climate modeling purposes. As a rule, the required cycle times for the development of such detailed inventories are rather long, implying that data can be quite outdated. With the exception of the EDGAR data base (Olivier *et al.*, 1996) referring to 1990, global gridded data sets available are quite outdated in view of rapidly changing regional sulfur emission trends. For instance, the Spiro *et al.* (1992) inventory refers to the year 1980; the Global Emissions Inventory Activity (GEIA) (Benkovitz *et al.*, 1996) gridded sulfur emission data are an update of the Spiro *et al.*, data set for 1985 for a number of regions, most of them OECD countries, but retain 1980 values for many countries and regions.

Contrary to carbon emissions, global and regional sulfur emission trends are much more dynamic, particularly since the early 1970s. As a result of sulfur abatement efforts, emissions in the OECD countries, particularly in Europe and Japan have declined drastically. Emissions in Central and Eastern Europe as well as the successor states of the former Soviet Union have also declined, especially in the wake of their economic restructuring. Conversely, with accelerated economic development, the growth of sulfur emissions in many part of Asia has been fast, albeit growth rates have declined recently (Streets *et al.*, 2000). Thus sulfur emission trends must be analyzed regularly and with as recent data as possible.

Historical sulfur emission inventories were first developed for Europe (cf. the formidable historical work of Mylona, 1993, 1996) as well as for the US (Gschwandner *et al.*, 1985; EPA, 1995). Global estimates have been developed by Dignon and Hameed (1989); Stern and Kaufmann (1996) and Lefohn *et al.* (1999). A synthesis of these long-term sulfur emission trends is given in Figure 4.

The long-term pattern of global sulfur emissions is characterized by three phases: First until about the 1920s, sulfur emissions rose very rapidly (at an estimated average annual growth rate of some 4% year^{-1}) with the expanding use of coal, the fossil fuel richest in sulfur. In the period 1925 to ca. 1975, growth in global emissions continued, albeit at slower rates (some 2% year^{-1} on average), as coal increasingly was replaced by oil, generally lower in sulfur content. Since around 1975, global emissions have stayed roughly constant. The continued rise of sulfur emissions in developing countries has been compensated by the drastic declines in emissions in the OECD countries (first Japan, then Europe and North America) as a result of environmental policies leading to fuel substitution, fuel desulfurization as well as stack gas cleaning (scrubbing). Emissions in Central and Eastern Europe, as well as in the successor states of the former Soviet Union, have also declined drastically as a result of replacement of coal by other fuels, as well as the drastic economic recession since the early 1990s (the effects of environmental control measures like flue gas desulfurization have been more limited to date). The industrialized countries accounted with some 50 Tg S for well over 80% of global sulfur emissions in 1975. By 2000, their sulfur emissions were down to some 25 Tg S (33% of global emissions), whereas those of the developing countries (mostly in Asia) have risen to some 50 Tg S (around 67% of global emissions).

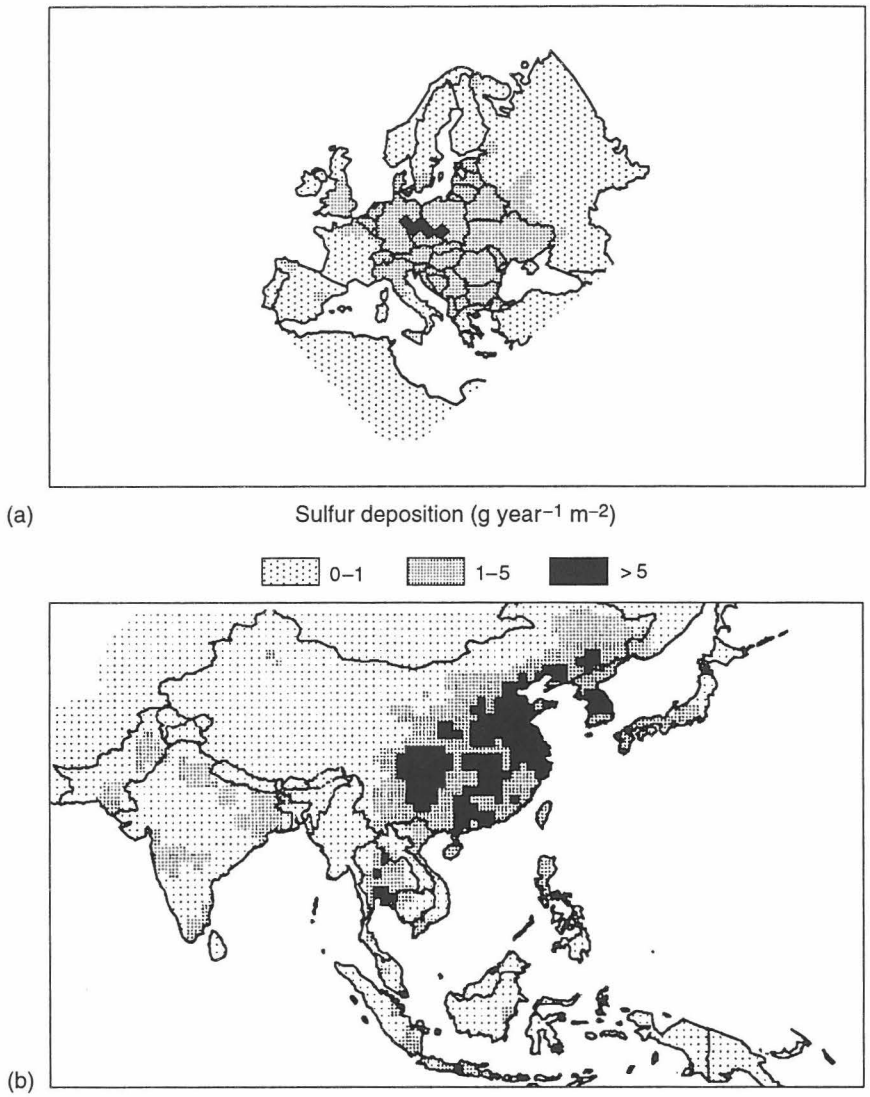

Figure 5 Extent of likely peak sulfur deposition levels: 1990 sulfur deposition in Europe (a) and projection for an (unabated) high-growth scenario for Asia in 2020 (b), in grams sulfur (S) m^{-2}. (Reproduced from Grübler, 1998a based on Amann *et al.*, 1995)

Recent estimates for Asia (Streets *et al.*, 2000) indicate however, that also there, emission growth rates are declining as a result of the introduction of sulfur control legislation (Grübler, 1998b; IEA, 1999; Nakicenovic *et al.*, 2000; Streets *et al.*, 2000). An acceleration of these trends seems highly desirable in view of the projected large-scale impacts on human health, food production, as well as ecosystems of unabated growth in sulfur emissions in the densely populated, coal intensive economies in Asia. A representative result of such projected scenarios (based on Amann *et al.*, 1995) is shown in Figure 5, which contrasts 1990 European sulfur deposition levels with those of Asia by 2050 in a high (unabated) sulfur emission scenario. Typically, in such scenarios, sulfur emissions in Asia alone could surpass current global levels as early as 2020 (Amann *et al.*, 1995; Posch *et al.*, 1996). Sulfur deposition above 5 g m^{-2} $year^{-1}$ occurred in Europe in 1990 in the area of the borders of the Czech Republic, Poland, and Germany (the former GDR); often referred to as the "black triangle". In view of its ecological impacts, it was officially designated by the United Nations Environment Programme (UNEP) as an "ecological disaster zone". In the scenario of high sulfur emission growth in Asia illustrated in Figure 5, similar high sulfur deposition would occur by around 2020 over more than half of Eastern China, large parts of southern Korea, and some smaller parts of Thailand and southern Japan.

In order to avoid excessive damages, sulfur controls similar to those used previously in the OECD countries

are required, and indeed are already beginning to be implemented in a number of Asian countries. Doubtless, similar challenges will have to be faced by other developing countries outside Asia over the next two to three decades. The recent long-term scenario literature (reviewed in more detail in Grübler, 1998b; and Nakicenovic *et al.*, 2000) indeed reflects such developments. Characteristic projected future global sulfur emission levels range between 20 and 80 Tg S by 2050 and between 15 and 60 Tg S by 2100. The comparatively low levels of projected future sulfur emissions reflects the assumed phase in of sulfur controls also outside the industrialized countries.

Sulfur reduction policies aiming to protect local and regional populations and ecosystems have one interesting side effect: they lower the cooling effect caused by sulfate aerosols in the atmosphere, thus increasing the warming arising from future greenhouse gas emissions (Rogner and Nakicenovic, 1996; Subak *et al.*, 1997) (*see* **Aerosols, Effects on the Climate**, Volume 1).

NITROGEN

Emissions of nitrogen compounds take many forms and originate from a wide array of different sources, natural and anthropogenic. Because of this diversity, individual source categories are studied in much less detail and therefore large uncertainties prevail.

Nitrogen emissions occur in three principal molecular forms: as nitrogen oxides (NO and NO_2 that are subsumed generally as NO_x), principally formed in high temperature combustion (burning of fossil fuels, or natural lightning); as ammonia (NH_3), principally arising from animal manure; and as nitrous oxide (N_2O), a powerful greenhouse gas, principally arising from soil microbiological process as well as agricultural activities and animal manure. Both NO_x and NH_3 are characterized by short atmospheric residence times and thus by only regional to continental dispersion from their respective emission sources. Their ecological significance arises principally in connection with acidification impacts (although NO_x has also a significant influence on atmospheric chemistry, including ozone (O_3) destruction, and therefore is indirectly affecting GHG concentrations in the atmosphere). Nitrous oxide is a powerful, long-lived (120 years) greenhouse gas whose atmospheric concentrations are estimated to have been 275 parts per billion by volume (ppbv) in pre-industrial times and have been measured at above 310 pbbv in the mid 1990s (IPCC, 1995). For ease of comparability, all emissions are expressed here in elemental weight of nitrogen per year (Tg N year^{-1}).

NO_x has long been of concern in the context of acidic deposition. In the last decade, however, the question of nitrogen over-fertilization of the biosphere has also been raised. See, for example, Munn *et al.* (1999, 468). Possible long-term consequences include the creation of mineral deficiencies in forest soils due to leaching, and a general decrease in biodiversity, particularly in grasslands. Indeed, some ecologists are concerned that nitrogen overfertilization constitutes a long-term threat to the whole boreal forest system.

Until now, most research has focussed on emissions of nitrogen oxides (NO_x, for a review see Smil, 1990), especially for energy-related emissions source categories since motorized traffic is one of the main sources of NO_x emissions and a major contributor to urban smog. Conversely other source categories, including natural processes have been much less studied and large uncertainties prevail. The first nitrogen inventory covering all three gases and all source categories at a regionally highly desegregated level has been developed by Olivier *et al.* (1998), based on earlier studies of Olivier *et al.* (1996), Lee *et al.* (1997); and Bouwman *et al.* (1997), and the discussion here draws heavily on this study. A summary of main emission categories is given in Table 2.

Nitrogen emissions are dominated by anthropogenic sources: 77(37–113) Tg N compared to 42(16–80) Tg N natural sources. In terms of their contributions to total nitrogen emissions, NO_x and NH_3 dominate with 50(22–81) and 54(23–88) Tg N each, compared to 15(8–24) Tg N in the case of nitrous oxide. For anthropogenic emissions, ammonia (43(20–61) Tg N) surpasses NO_x (31(16–46) Tg N), whereas nitrogen-wise, nitrous oxide is a comparatively small source of nitrogen (3(1–6)) (IPCC, 1995 indicates a slightly higher uncertainty range of 4–8 Tg N for nitrous oxide), cf. Olivier *et al.* (1998).

For emissions of nitrogen oxides (NO_x), the dominant anthropogenic source category is the burning of fossil fuels, most notably of automobile fuel and in the generation of electricity. NO_x emission levels depend both on nitrogen content in fuels as well as on very diverse and variable operating and firing characteristics: NO_x emissions tend to increase with increasing burning temperature. In this case, tradeoffs in improving environmental performance become apparent: improving efficiency of energy conversion and lowering of carbon emissions, e.g., in an electric power plant, requires an increase in firing temperatures (the second law of thermodynamics), which tends to increase NO_x emissions. Reducing the latter requires catalytic reduction, which in turn involves an efficiency penalty, slightly increasing fuel use and hence carbon emissions. For cars de-NO_x catalytic equipment also depends critically on operating temperature: at cold engine startup catalytic converters do not function. Therefore related emission estimates of this category of emissions are highly uncertain. Because of the dominance of industrialized countries in global car ownership and electricity consumption, they account for over 75% of global NO_x emissions from road transport and for 70%

Table 2 Global nitrogen emissions as estimates for 1990 per major source category and flux (NO_x, NH_3, and N_2O) and uncertainty ranges (in Tg N year^{-1})

	NO_x (1990)	+/–	NH_3 (1990)	+/–	N_2O (1990)	+/–
Anthropogenic						
Fossil fuel burning	21.9	13–31	0.1	0–0.2	0.2	0.1–0.5
Industrial processes	1.5		0.2	0.1–0.3	0.3	0.1–0.5
Agriculture:						
Animals			21.6	10–30	1	0–2
Fertilizers			9	4.5–13.5	1	0.3–2.3
Crops and waste			4.1	1.4–5	0.1	
Biomass burning	7.7	3–15	5.4	3–7.7	0.6	0.4–1
Sewage			2.6	1.3–3.9		
Total	31.1	16–46	43	20–61	3.2	0.9–6.3
Natural						
Soils	5.5	4–12	2.4	0–10	5.2	2.6–7.8
Grasslands, wild animals, etc.			0.1	0–1	2.3	1.1–3.5
Oceans			8.2	3–16	3.6	2.8–5.7
Lightning	12.2	2–20				
Atmospheric processes	1.6	0.4–2.6			0.6	0.3–1.2
Total	19.3		10.7	3–27	11.7	6.8–18.2
Grand total	50.4	22–81	53.7	23–88	14.9	7.7–24.5

Source: Olivier *et al.* (1998).

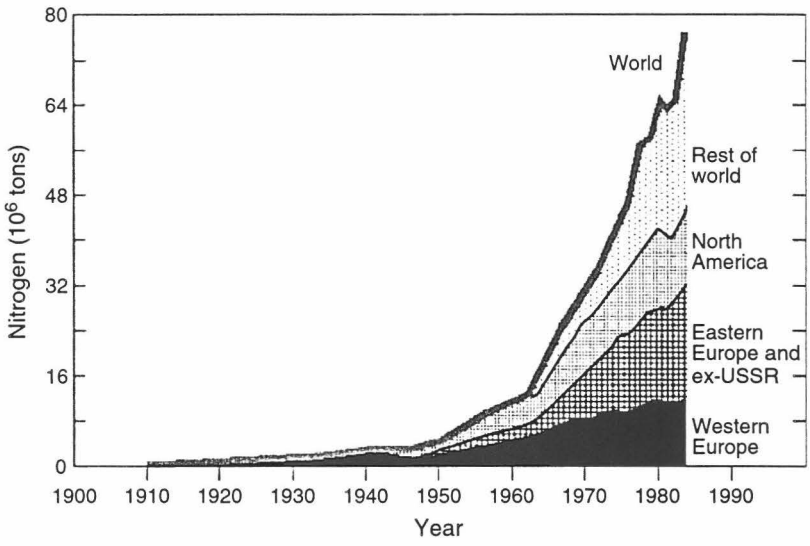

Figure 6 World nitrogen fertilizer use by region (cumulative totals, in Tg N year^{-1}). (Reproduced from Grübler, 1998a)

of all NO_x emissions from fossil fuel burning (Olivier *et al.*, 1998). Anthropogenic NO_x emissions are also the only ones where estimates of long-term historical time series are available. For instance, the estimates of Dignon and Hameed (1989) indicate that global NO_x emissions have increased by almost a factor five over the period 1930–1980.

For ammonia (NH_3), the dominant source of anthropogenic emissions is the agricultural sector, including emissions from animal manure (22(10–30) Tg N) and application of fertilizer (9(4–14) Tg N), that combined account for over 70% of NH_3 emissions globally. The dominance of agricultural sources also explains that contrary to the case of NO_x ammonia emissions predominantly originate in developing countries (a detailed discussion of NO_x, NH_3 and N_2O emissions in India is given by Parashar *et al.*, 1998), which accounted for approximately 70% of agricultural and total ammonia emissions in 1990. Rising animal populations, as well as rising fertilizer use and resulting ammonia (and nitrous oxide, see discussion below) emissions are the other side of the coin of vastly increased agricultural production for ever rising populations (Figure 6). The increase to over 80 Tg N year^{-1} would have been impossible without

the major technological breakthrough of the Haber-Bosch method of ammonia synthesis introduced in 1912.

For emissions of nitrous oxides, the dominant anthropogenic sources are again fertilizer applications and animal husbandry (manure) in the agricultural sector (2(0.3–4.3) Tg N $year^{-1}$ in 1990). The third largest source are industrial processes (production of adipic and nitric acid) with 0.3(0.1–0.5) Tg N estimated for 1990 (Olivier *et al.*, 1998), albeit these emissions are declining rapidly due to implementation of voluntary industry measures due to climate change concerns (Nakicenovic *et al.*, 2000). Yet, even with drastic emission reductions, a long-term legacy of nitrous oxide emissions remains due to its long residence time in the atmosphere. As in the case of ammonia emissions, developing countries, with their high population and food requirements, dominate global emissions, producing about 60% of agricultural and of total nitrous oxide emissions (Olivier *et al.*, 1998). Even though emissions from natural processes, particularly microbiological processes in soils, greatly exceed anthropogenic emissions (3–8 Tg N versus 1–6 Tg N respectively), emissions of nitrous oxide are a good illustration of the impacts of a growing world population and of changing diets (towards higher meat consumption) on NO_x emissions. These in turn require increased food output and changes in agricultural practices and technologies that result in increased emissions, even if the long-term history of ammonia and nitrous oxide emissions remains to be researched.

The literature on long-term nitrogen emissions scenarios is sparse. Due to the multitude of gas species and source categories, no scenarios exist that treat nitrogen emissions comprehensively. The most detailed projections available currently are those developed under the auspices of the IPCC Special Report on Emissions Scenarios (Nakicenovic *et al.*, 2000), but even there, projections for ammonia emissions are lacking as the study focussed on (direct and indirect) greenhouse gases. Nonetheless, the study reflects current best knowledge on uncertainties in future nitrogen emission levels. By 2050, global nitrogen emissions could span a range of 45–110 MtN (N_2O and NO_x) and by 2100 a range of 20–170 MtN (compared to 37.6 MtN excluding NH_3) in 1990 as estimated in Nakicenovic *et al.* (2000). Thus, over the long-term, nitrogen emissions could range between half of current to about four times current levels indicating the large uncertainties in underlying driving forces such as population and economic growth, future developments in the agricultural, energy, and transport sectors as well as in technology.

Because of the multitude of gases and sources, nitrogen emission estimates are poorly understood and uncertain with the paucity in both past and present inventory data and future emission scenarios. More research is therefore needed before considering policy interventions to control these gases beyond well established source categories (e.g., nitrogen oxide emissions from automobiles, or nitrous oxide emissions from adipic acid production). *See* **Nitrogen Cycle**, Volume 2; **Nitrogen Deposition on Forests**, Volume 2.

LINKING EMISSIONS TO DRIVING FORCES: THE CASE OF ENERGY-RELATED CARBON DIOXIDE

Emissions are the result of a large set of interrelated driving variables in the domains of demographics, economics, resources and technology as well as (environmental) policies. Economic, social and technical systems and their interactions are highly complex and this short discussion cannot provide a comprehensive overview.

Instead, the links from demography and the economy to resource use and emissions will be discussed in a simplified format using proxy variables for various categories of driving forces. A frequently used analytical approach to describe these linkages is through the so called IPAT identity (Equation 1):

$$\text{Impact} = \text{population} \times \text{affluence} \times \text{technology} \quad (1)$$

where environmental impacts (emissions) are the product of the level of population times the affluence (income per capita) times the level of technology deployed (emissions per unit of income) (*see* **DPSIR (Driving Forces–Pressures–State–Impacts–Responses)**, Volume 4). The IPAT identity has been widely used in the analysis of energy related carbon dioxide emissions (for a review see Alcamo *et al.*, 1995; Gaffin, 1998; and Nakicenovic *et al.*, 2000) where it is generally referred to as the KAYA identity (Kaya, 1990) (Equation 2):

$$\begin{aligned}\text{Carbon dioxide emissions} &= \text{population} \\ &\times (\text{GDP/population}) \times (\text{energy/GDP}) \\ &\times (\text{carbon dioxide/energy}) \quad (2)\end{aligned}$$

In this extended IPAT identity, emissions are represented as the product of population times their level of affluence (gross domestic product (GDP)/capita), multiplied with two proxy variables for the level of technology, i.e., the efficiency of energy use per unit of GDP (Energy/GDP) as well as the carbon intensity of energy used (carbon dioxide/Energy). We classify these latter two variables as proxy variables for technology as they represent highly aggregated indicators that in addition also depend on many other factors, all related to income levels. These include the structure of the economy (e.g., industry versus service orientation), consumption patterns and the extent and nature of environmental policies. Energy price differences also matter, but are generally not related to differences in income levels. Frequently, the poor while unable to afford (high

priced) commercial energy forms such as electricity, rely on traditional fuels gathered largely outside the formal economy. Their costs however can be very high when considering the amount of time spent gathering fuelwood and environmental externalities such as high levels of indoor air pollution associated with burning of traditional fuels in open fire places (Smith, 1993). In turn, with rising incomes, consumer preferences shift to higher priced commercial energy forms (electricity, gas). Cleanliness and convenience of use afford a quality premium (willingness to pay higher prices), including higher energy efficiency and lower emissions (particulates, sulfur, carbon dioxide) per unit of energy. Thus, at the point of final energy use the energy and carbon intensity of the KAYA identity are related to income levels (affluence). This may not necessarily be visible in aggregated data, as the provision of clean energy forms at the point of consumption can entail efficiency losses and proportionately higher emissions at the point of energy production, e.g., when electricity is generated in traditional coal fired power stations.

This multiplicative identity has the advantage that percentage growth rates of its components are additive, thus giving a first approximation of the scale of influence on emissions growth of different driving variables. However, despite the appeal of a simple representation, there are important caveats to bear in mind when using the above identity in interpreting past emissions trends (or future emission scenarios). The first is the issue of spatial heterogeneity. The second one is that it is not possible to treat the growth of individual components independently.

For example, on face value, the KAYA and IPAT identities would suggest that carbon dioxide emissions scale linearly with population; that is, doubling the population means doubling the emissions. However, there are reasons to doubt such a simplified view. There is great heterogeneity among populations with respect to greenhouse gas emissions, so where the population increase takes place is not necessarily the same as where emissions increase. The ratio of *per capita* emissions of the world's richest countries to that of its poorest countries approaches ratios of several hundred (Gaffin, 1998). This problem requires one to consider spatially desegregated population growth. Of course, some level of aggregation is necessary for a global analysis. The biggest correction on emissions takes place when switching from a global to a breakdown of industrialized (IND) versus developing (DEV) countries (Lutz, 1993) (Table 3).

The second caveat relates to the fact that it is not population *per se* that emits carbon dioxide, but the technologies that people employ and the goods and services they consume with their available income. This raises the issue about the relationship between demographics and economic growth (between population and affluence in the IPAT identity) as well as between technology and affluence, which in turn would preclude consideration of a simple linear interpretation of the role of population growth in emissions.

Demographic development interacts in many ways with social and economic development. Fertility and mortality trends depend, amongst other things, on education, income,

Table 3 Major components (population, per capita income, energy and carbon intensities) for the increase of energy-related (gross) carbon emissions (Kaya Identity) and their average annual growth rates, 1800–2000, global (WOR) and regional totals[a]

		1800	*%/yr*	1900	*%/yr*	1950	*%/yr*	1975	*%/yr*	2000	**1800–2000** **%/yr**
POP	IND	246	*0.82*	555	*0.81*	833	*1.10*	1096	*0.77*	1327	**0.85**
million	DEV	737	*0.39*	1083	*0.88*	1681	*2.21*	2901	*2.00*	4764	**0.94**
	WOR	983	*0.51*	1639	*0.86*	2514	*1.87*	3996	*1.70*	6091	**0.92**
GDP/POP	IND	675	*1.26*	2352	*1.39*	4686	*3.35*	10 674	*1.68*	16 188	**1.60**
$/capita	DEV	500	*0.21*	619	*0.69*	874	*2.73*	1715	*2.28*	3013	**0.90**
	WOR	544	*0.80*	1206	*1.15*	2137	*2.71*	4171	*1.39*	5883	**1.20**
ENE/GDP	IND	0.743	*−0.40*	0.497	*−0.20*	0.448	*−0.33*	0.413	*−1.49*	0.284	**−0.48**
kgoe/$	DEV	0.450	*−0.17*	0.379	*−0.01*	0.377	*−0.54*	0.329	*−0.48*	0.292	**−0.22**
	WOR	0.541	*−0.17*	0.457	*−0.13*	0.429	*−0.40*	0.388	*−1.20*	0.287	**−0.32**
C/ENE	IND	1.238	*−0.12*	1.103	*−0.33*	0.937	*−0.64*	0.798	*−0.66*	0.676	**−0.30**
kg C/kgoe	DEV	1.252	*0.00*	1.249	*−0.23*	1.112	*−0.36*	1.017	*−0.40*	0.921	**−0.15**
	WOR	1.246	*−0.09*	1.144	*−0.31*	0.979	*−0.55*	0.853	*−0.38*	0.776	**−0.24**
Carbon	IND	152	*1.56*	715	*1.67*	1638	*3.48*	3851	*0.27*	4123	**1.66**
Tg C	DEV	208	*0.43*	318	*1.33*	616	*4.05*	1664	*3.42*	3858	**1.47**
	WOR	360	*1.06*	1033	*1.57*	2254	*3.64*	5516	*1.49*	7980	**1.56**

[a] The two regions are defined in the UNFCCC, including Annex-I countries (IND, for industrialized countries) and non-Annex-I countries (DEV, for developing countries). For units, see table. Estimates of energy use, energy intensities, and (gross) carbon emissions include non-commercial, traditional biofuels which are particularly uncertain.
Source: Updated (see text) from Grübler and Nakicenovic (1994) and Nakicenovic and Grübler (2000).

social norms and health provisions. In turn, they determine the size and age composition of the population. All factors combined are recognized as important in explaining long-run productivity and economic growth and technological change as well (Barro, 1997). In turn, long-run per capita economic growth is closely linked with advances in knowledge and technological change. In fact, analysis of long-run macrocconomic growth accounts (e.g., Solow, 1956; Denison, 1962, 1985; Maddison, 1995; Barro and Sala-I-Martin, 1995) confirm that advances in knowledge and technology form the single largest source for long-run economic growth, more important than growth in other factors of production like capital and labor. Abramovitz (1993) demonstrates that capital and labor productivity cannot be treated as independent from technological change. In terms of the IPAT identity, it is thus not possible to treat the affluence and technology variables as independent from each other either. In addition, pollution abatement efforts appear to increase with income, a relationship often referred to as the environmental Kuznets curve that seems well established for traditional pollutants such as particulates and sulfur (e.g., World Bank, 1992) but which has not been demonstrated for aggregate greenhouse gas emissions.

Technological, economic and social innovations have long been means by which a greater number of people could live from the same environmental resources. The best known historical examples of major periods of innovation include the Neolithic revolution (beginnings of organized agriculture from around 10 000 years ago); and the Industrial Revolution beginning two centuries ago (Rosenberg and Birsdzell, 1996). In each case, changes in patterns of primary production (food, energy, materials), the efficiency of resources use, as well as changes in environmental impacts have been linked to changes in social organization, institutions, economy and technology (Mumford, 1934; Landes, 1969; Mokyr, 1990). No one of these changes can be considered to be the primary driver, nor as independent from the others: each played a role in an interconnected system.

Before the Neolithic revolution, the world population amounted to perhaps 5–10 million. Over the following millennia complex societies developed based around cities, with highly differentiated social roles and complex political, economic and legal systems. By the birth of the current major religions 1500–2500 years ago, world population had increased to around 300 million. Following a period of cultural, economic and technical stagnation to about 1000 AD with notable exceptions in China and the Islamic world (Mokyr, 1990), further population growth began with the productivity increases resulting from cultural, economic and technological developments associated with the European Renaissance. By the time of Thomas Malthus in the late 18th century, the global population had reached about one billion. The six-fold increase in global population over the following 200 years has been enabled by a continuing revolution in medical, agricultural and industrial technology. However, the most remarkable change in recent decades has been the so-called *demographic transition*, as people increasingly manage their own rate of reproduction, leading to a decline in population growth rates (see Table 3) or to a stabilization of population size in many parts of the world (*see* **Population Sizes, Changes**, Volume 2; **Demographic Change: the Aging Population**, Volume 3; **Global Population Trends**, Volume 3; **Urban Population Change**, Volume 3; **Demographic transition**, Volume 5).

This transition has typically been linked to improved education, female empowerment, access to information, improved medical services (and related reductions in infant mortality) and social and economic development facilitated by the international diffusion of new technologies. Therefore, it is not possible to treat changes in demographics, income, and technology as independent from each other.

With the above caveats in mind, let us consider the quantitative evidence since the onset of the Industrial Revolution (ca. 1800), cast in terms of the KAYA identity.

Table 3 summarizes the growth of population, *per capita* income, energy use per unit economic activity and energy related (gross) carbon emissions per unit energy used since 1800. The estimated indicators represent a revised updated data set based on Grübler (1998a); Grübler and Nakicenovic (1994) and Nakicenovic and Grübler (2000). Data with a finer temporal and spatial resolution are available from the author upon request. Because the energy use data include the historically important non-commercial uses of traditional biofuels, the resulting energy use and energy intensities (energy use per unit of GDP) estimates are subject to a high degree of uncertainty; the values given here represent a conservative lower bound estimate and are subject to further research and revision. Total energy use in the 19th century industrialized countries and in developing countries prior to 1975 (see the discussion in Nakicenovic *et al.*, 1998) are thus likely to be underestimated. Resulting historical improvements in energy intensities (including all energy forms) may consequently also be significantly underestimated. For instance the aggregate improvements in energy intensity of 0.5% year^{-1} since 1800 for the industrialized countries (including Eastern Europe and Russia) given in Table 3, need to be contrasted with estimates for individual countries with good historical records that indicate long-term improvement rates of about 1% year^{-1} since the 19th century (Nakicenovic, 1984; Martin, 1988; Grübler, 1991) and much higher rates since the early 1970s (reflected in Table 3). Non-commercial energy use and resulting energy intensity improvement rates for developing countries prior to 1975 are particularly

uncertain, possibly underestimated by up to a factor of three.

In order to simplify, only two macro-regions (industrialized versus developing countries) and trends between five major dates are shown. Interspersed between the main historical dates, the respective annual growth rates of these indicators calculated over their respective time periods are shown in italics. Total period (1800–2000) growth rates are presented in bold (most far right column in Table 3). As mentioned above, the relative magnitude of the growth rates and how they sum up to explain the growth rates in energy related carbon dioxide emissions are indicative only as they do not capture the interdependence among variables; notably between technology and economic growth on the one hand and demographics on the other.

A first observation on Table 3 is that there is no uniform, unambiguous answer about what (proxy) driving force dominates in explaining historical emissions growth. Component growth rates are highly variable across regions and over time. On the positive (i.e., emission increasing) side of the KAYA identity are population growth and increases in *per capita* incomes, on the negative (emission decreasing) side of the identity are improvements in energy intensity (energy use per unit of GDP) as well as decreases in the ratio of (gross) carbon emissions per unit energy used, a trend termed frequently as *decarbonization* (Grübler, 1991; Nakicenovic, 1993).

Demographic and economic development tend to increase emissions, a trend partly compensated by improvements in the two proxy variables representing technology. Globally, an average increase of 1.6% $year^{-1}$ in (gross) energy related carbon emissions since 1800 can be decomposed into roughly equal contributions from population and *per capita* income growth (average 2.1% $year^{-1}$) to be contrasted against an about equal contribution from improvements in technology (energy intensity improvements and decarbonization) of jointly −0.5% $year^{-1}$. However, these numbers vary enormously depending on which time period is being considered, as well as across regions.

As discussed above, the component variables of the KAYA identity are not independent from each other. For instance, the influence of technological change goes far beyond the numbers captured in the percentage rates of change of the energy intensity and decarbonization variables presented in Table 3; this is because technological change is also the main source for productivity growth and hence increases in *per capita* incomes. This illustrates the paradox of technological development (Gray, 1989), where technology is both the source as well as the (partial) remedy of the historical increases in environmental burdens. Prometheus unbound (Landes, 1969) has released the powers of technology that helped humans to expand in numbers at ever higher levels of affluence, thus increasingly burdening the global commons. But technological change has also helped to reduce (part of) these environmental burdens by improved efficiency in the use of energy and the carbon atom. More research is needed to answer the question, if and how fast the paradox of technological development may be resolved in the future, tilting the balance of the equation towards stabilizing emissions, even their long-term decline. The challenge becomes compounded by the inevitable demographic momentum (the mothers of the future are already born today) that makes in increase of global population to some 8 billion almost a certainty (Lutz *et al.*, 1997). There is also a need for continued social and economic development for the larger part of the global population still excluded from the benefits of the use of modern technology.

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