Chapter 1: Current Status and Past Trends of the Global Carbon Cycle

Christopher L. Sabine[1], Martin Heiman[2], Paulo Artaxo[3], Dorothee Bakker[4], Chen-Tung Arthur Chen[5], Christopher B. Field[6], Nicolas Gruber[7], Corinne LeQuéré[2], Ronald G. Prinn[8], Jefferey E. Richey[9], Patricia Romero Lankao[10], Jayant Sathaye[11], Riccardo Valentini[12]

Abstract

Processes relevant to the carbon cycle span the range of scales from molecular to global. They also include a wide range of biological, chemical and physical phenomena, as well as interactions between humans and the environment. To better comprehend and predict potential global carbon cycle changes in the future, we must first appreciate how the system is operating today. Our understanding of the current carbon cycle is improving very rapidly thanks to aggressive research in this field. This chapter examines our current understanding of the global carbon cycle and the processes relevant to controlling atmospheric CO_2 concentrations.

The third assessment report of the IPCC recently compiled a basic global carbon budget [Prentice et al., 2001]. While that budget reflected the state-of-the-art at that time, this chapter presents a revised budget based on new information from model studies and oceanographic observations. Although the basic global budget provides some indication of the overall carbon balance between the major active reservoirs of land, atmosphere, and ocean, it does not adequately reflect the multitude of exchange fluxes or processes responsible for this global budget. A somewhat more comprehensive representation of the connections between the reservoirs together with our current understanding of the biogeochemical processes and human driving forces controlling these exchanges is presented in this chapter.

[1] NOAA/PMEL, Seattle WA, USA
[2] Max-Planck-Institut für Biogeochemie, Jena, Germany
[3] Universidade de Sao Paulo, Sao Paulo, Brazil
[4] University of East Anglia, Norwich, UK
[5] National Sun Yat-sen University, Kaohsiung, Taiwan
[6] Carnegie Institution of Washington, Stanford CA, USA
[7] University of California-Los Angeles, Los Angeles CA, USA
[8] Massachusetts Institute of Technology, Cambridge MA, USA
[9] University of Washington, Seattle WA, USA
[10] Universidad Autonoma Metropolitana, Mexico City, Mexico
[11] Lawrence Berkeley National Laboratory, Berkeley CA, USA
[12] Disafri- University of Tuscia, Viterbo, Italy

Introduction

In a global, long-term perspective, variations of the atmospheric CO_2 content document the magnitude and speed of climate driven variations, such as the glacial – interglacial cycles (~100 ppm over 420,000 years), but these observations also document a remarkable stability with variations in atmospheric CO_2 of <20 ppm during at least the last 11,000 years prior to the anthropogenic perturbation [Joos and Prentice, this volume]. In this longer-term context, the anthropogenic increase of ~100 ppm during the last 200 years is a dramatic alteration of the global carbon cycle. This atmospheric increase is also a graphic documentation of profound changes in human activity. The atmospheric record documents the earth system's response to fossil fuel releases that increased by more than 1200% between 1900 and 1999 [Nakicenovic, this volume].

Processes relevant to the carbon cycle span the range of scales from molecular to global. They also include a wide range of biological, chemical and physical phenomena, as well as interactions between humans and the environment. Studies of the carbon cycle must adequately address the full range of these issues. In order to understand and predict future changes in the global carbon cycle, we must first understand how the system is operating today. In many cases, the current fluxes of carbon are a direct result of past processes affecting these fluxes [Nabuurs, 2003]. Thus, it is important to understand the current carbon cycle in the context of how the system has evolved over time. This chapter presents a brief overview of the current carbon cycle, highlighting the principle connections between the land, ocean, atmosphere and humans. The key processes relevant to controlling atmospheric concentrations of CO_2 and relevant non-CO_2 gases (e.g. CH_4, N_2O) that may be susceptible to changes in the future, either through deliberate management or as direct and indirect consequences of global change, are also introduced here.

The Global Carbon Budget

On time scales of up to a few thousand years, atmospheric CO_2 is controlled by exchanges with the carbon reservoirs of the oceans and the terrestrial biosphere. The global budget of atmospheric carbon dioxide quantifies the relative importance of these two reservoirs and the budget uncertainty reflects our understanding of the exchanges between these reservoirs. Table 1.1, section 1 shows the global budget recently compiled by the IPCC Third Assessment Report [Prentice et al., 2001]. This assessment primarily uses the partitioning of the uptake into

net terrestrial and oceanic components as determined by observations of the concurrent global trends of atmospheric CO_2 and oxygen. Since the compilation of the IPCC report, new evidence from model studies and oceanographic observations indicates that this budget has to be slightly revised because of a previously ignored oceanic oxygen out-gassing flux. This flux is the result of enhanced oceanic stratification as inferred from observed increases in oceanic heat content [LeQuéré et al., 2003]. The revised values are presented in section 2 of Table 1.1.

The breakdown of the net land-atmosphere flux through the 1990s into emissions from changes in land use and a residual terrestrial sink, based on the updated land use change emissions of Houghton [2003], is given in section 3 of Table 1.1. This breakdown has recently been challenged based on new estimates of land use change determined from remote sensing data (Table 1.1, sections 4 & 5). These new estimates lie at the lower end of the stated uncertainty range of the estimates based on data reported by individual countries [Houghton, 2003]. If correct, they imply a residual terrestrial sink in the 1990s that is about 40% smaller than previous estimates.

The basic budget, of course, does not attempt to represent the richness of the global carbon cycle. The land-atmosphere-ocean system is connected by a multitude of exchange fluxes. The dynamical behavior of this system is determined by the relative sizes of the different reservoirs and fluxes, together with the biogeochemical processes and human driving forces controlling these exchanges. Figure 1.1 shows the globally aggregated layout of the carbon cycle together with the pools and exchange fluxes that are relevant on time scales of up to a few millennia. Panel "a" in figure 1.1 presents a basic picture of the global carbon cycle including the preindustrial (black) and anthropogenic (red) ocean-atmosphere and land-atmosphere exchange fluxes. The anthropogenic fluxes represent average values for the 1980s and 1990s. Panel "a" also shows components of the long-term geological cycle and the composite estimates of CO_2 emissions from geological reservoirs (i.e. fossil fuels and the production of lime for cement). Panels "b" and "c" provide more detailed pictures of the ocean and terrestrial fluxes, respectively. Individual component pools and fluxes, including key climatic and anthropogenic drivers, are discussed in the sections below and in subsequent chapters.

Although figure 1.1 primarily focuses on fluxes directly related to CO_2, a number of non-CO_2 trace gases also play significant roles in the global carbon cycle (e.g. CO, CH_4, non-methane hydrocarbons) and/or climate forcing (e.g. CH_4, N_2O, chlorofluorocarbons). The global

cycles of these trace gases, which share many of the processes driving the CO_2 cycle, are briefly discussed below.

Reservoir Connections

The background chapters in this volume discuss the various carbon reservoirs and the processes relevant to controlling atmospheric CO_2 and related trace gas concentrations. To appreciate the Earth's carbon cycle and its evolution, it is necessary to examine the connections between the various carbon pools. This must be done within a framework that provides an integrated perspective across both disciplinary and geographic boundaries, with particular emphasis on the carbon cycle as an integral part of the human-environment system.

Fossil Fuel-Atmosphere Connections

The world energy system delivered approximately 380 EJ (10^{18} J) of primary energy in 2002 [BP Statistical review of World Energy 2002]. Of this, 81% was derived from fossil fuels, with the remainder from nuclear, hydroelectric, biomass, wind, solar, and geothermal energy sources (Figure 1.2). The fossil fuel component released 5.2 PgC in 1980 and 6.3 PgC in 2002 [CDIAC, 2003]. Cement production is the other major industrial release, which increased to 0.22 PgC in 1999. The combined release of 5.9 PgC shown in figure 1.1a represents an average emission for the 1980s and 90s. Underground coal fires, which are poorly known and only partly industrial, may be an additional as yet unaccounted for source of carbon to the atmosphere as large as cement manufacturing [Whitehouse, 2003]. In terms of energy released, the current mix of fossil fuels is approximately 44% oil, 28% coal, and 27% natural gas (figure 1.2). At current rates of consumption, conventional reserves of coal, oil, and gas (those that can be economically produced with current technology; see figure 1.1c) are sufficient to last 216, 40, and 62 years, respectively [BP Statistical review of World Energy 2002]. If estimates of undiscovered oil and gas fields are included with the conventional reserves oil and gas lifetimes increase to 101 and 142 years, respectively [Ahlbrandt et al., 2000].

Conventional reserves represent only a fraction of the total fossil carbon in the earth's crust. For example, vast quantities of methane, exceeding all known fossil fuel reserves, exist in the form of methane hydrates under continental shelf sediments around the world, in the Arctic permafrost, and in various marginal seas. With current technology, however, these reserves do

not appear viable as a future energy source. The best estimates for total fossil resources that might ultimately be recovered are in the range of 6000 Pg [Nakicenovic, this volume; figure 1.1] or about 2.5 times the conventional reserve estimates.

Although not included in Table 1.1 or figure 1.1, combustion of fossil fuels also releases a number of non-CO_2 carbon gases. In particular, carbon monoxide (CO) can be used as an effective tracer of fossil fuel combustion in atmospheric gas measurements. The relative impact of these gases is discussed in a later section.

Land-Atmosphere Connections

The exchange of carbon between the terrestrial biosphere and the atmosphere is a key driver of the current carbon cycle. Global net primary production (NPP) by land plants is about 57 PgC yr^{-1} (figure 1.1). Of this, about 4 PgC yr^{-1} is in crops. Humans co-opt a much larger fraction of terrestrial NPP, probably about 40%, where co-opting is defined as consuming, removing some products from, or altering natural states of the terrestrial biosphere through ecosystem changes [Vitousek et al., 1986]. Total NPP is approximately 40% of gross primary production (GPP), with the remainder returned to the atmosphere through plant respiration. For many purposes, NPP is the most useful summary of terrestrial plant activity. NPP can be assessed with inventories and harvest techniques, and it represents the organic matter passed to other trophic levels [Lindemann, 1941]. For other purposes, including isotope studies and scaling from eddy flux, GPP is a more useful index.

Most of the annual flux in NPP is returned to the atmosphere through the respiration of heterotrophs, including micro-organisms, saprophytes, and animals. A smaller fraction, 5-10%, is released to the atmosphere through combustion (Figure 1.1). Approximately 5% of NPP leaves land ecosystems in organic form, as CH_4 or volatile organic carbon [Prinn, this volume]. In recent decades, the land was close to carbon neutral (in the 1980s) or a modest net sink (in the 1990s) for atmospheric CO_2 (Table 1.1). This net flux represents a balance between substantial emissions from biomass clearing or fires and enhanced uptake as a physiological response to rising CO_2 or the re-growth of previously cleared areas.

Land plants contain slightly less carbon than the atmosphere. Soils contain substantially more (Figure 1.1). The estimates for soil carbon in figure 1.1 are higher than shown in previous budgets for two reasons. First, previous budgets estimated soil carbon to a depth of 1 m.

Jobaggy and Jackson [2000] extended these to 3 m, adding about 55% to the known stock. Second, previous budgets have ignored carbon in wetland and permanently frozen soils. The exact magnitudes of these stocks are very uncertain. However, the potential for substantial carbon losses from these stocks in coming decades is a strong incentive for careful quantification and further analysis.

Tropical forests contain the largest carbon pool of terrestrial biota, and also the largest NPP (see table 1.2) [Saugier et al., 2001]. Averaged over several years, tropical forests traditionally have been believed to be close to carbon neutral, with uptake from NPP balanced by releases from decomposition and fire. The difference between NPP and the sum of all of the processes that release carbon from the land is net ecosystem production (NEP). Recent studies based on in situ flux measurements and forest inventory techniques indicate net carbon uptake or positive NEP of 100 to 700 gC m^{-2} yr^{-1}, corresponding to ~1 PgC yr^{-1} across the tropical evergreen forest biome. The duration and spatial scale of these studies is not yet extensive enough for solid extrapolation. Still, the estimated uptake is in the proper range to compensate for emissions from tropical land use [DeFries et al., 2002; Achard et al., 2002]. The tropical NEP estimates, however, are also in the range of recent estimates of CO_2 releases from tropical rivers, caused mainly by the decomposition of material transported from the land [Richey, this volume]. A full carbon accounting has yet to be accomplished, but these individual flux estimates need to be reconciled with top-down estimates from atmospheric inverse modeling studies, which indicate that the overall net carbon balance of the tropical land areas (30°S-30°N) must be close to zero, albeit with large uncertainty ranges [Gurney et al., 2002, Heimann et al., this volume].

Temperate forests cover about 60% of the area of tropical forests and contain the second largest pool of plant carbon. Together, tropical and boreal forests account for approximately 75% of the world's plant carbon and for, 31% of the non-wetland, non-frozen soil carbon (Table 1.2).

Carbon emissions from land use and land management have increased dramatically over the last two centuries resulting from the expansion of crop land and pasture, infrastructure extension and other effects driven by market growth, pro-deforestation policies, and demographic pressures [Geist et. al., 2001]. Prior to about 1950, carbon emissions from land use change were mainly from temperate regions. In recent decades, however, carbon releases from land use change have been concentrated in the topics [Achard et al., 2002; DeFries et al., 2002; Houghton, 2003]. Cumulative emissions from land use, estimated at approximately 185

PgC, entail substantial fluxes from every continent except Antarctica [DeFries et al., 1999]. Prior to about 1910, cumulative emissions from land use and land management were larger than cumulative emissions from fossil fuel combustion.

As with fossil fuel combustion, carbon is lost from terrestrial vegetation in a variety of non-CO_2 gases including biogenic VOCs (volatile organic compounds). Globally VOC emissions are 0.2 to 1.4 PgC yr^{-1} [Prinn, this volume]. For grassland and cultivated land, large emissions of other greenhouse gases such as N_2O, CH_4 and other gases can also occur. These emissions are strongly affected by land management and land use change [Smith, this volume; Robertson, this volume].

Ocean-Atmosphere Connections

The oceans contain about 50 times more CO_2 than the atmosphere and 6 times more than the latest estimates of the plant and soil carbon stores (figure 1.1). CO_2 moves between the atmosphere and the ocean by molecular diffusion when there is a difference between the CO_2 gas pressure (pCO_2) in the oceans and the atmosphere. For example, when the atmospheric pCO_2 is higher than the surface ocean pCO_2, CO_2 diffuses across the air-sea boundary into the seawater. Based on about 940,000 measurements of surface water pCO_2 obtained since the 1960's, the climatological, monthly distribution of pCO_2 in the global surface waters has been calculated with a spatial resolution of 4^o x 5^o [Takahashi et al., 2002]. These estimates indicate a net global air-sea flux of 2.2 (-19% to +22%) PgC into the ocean for the reference year 1995 (Figure 1.3). The asymmetrical error estimates reflect the paucity of data relative to the spatial and temporal variability in sea surface pCO_2 concentrations and limitations in the non-linear wind speed parameterizations for the gas exchange coefficient. Ocean models and observations suggest that the interannual variability in the global ocean CO_2 flux is around ±0.5 PgC yr^{-1} [Greenblatt and Sarmiento, this volume].

Isotopic evidence suggests that the gross exchanges of CO_2 across the air-sea interface, as shown in figure 1.1, are much larger than the net flux. The global budget presented in this figure shows the preindustrial oceans as a net source of ~0.6 PgC yr^{-1} to the atmosphere to partially offset the addition of carbon from rivers. The total net modern flux of Takahashi et al. [2002] is somewhat larger than the modern balance implied by figure 1.1 (21.9-20 +70-70.6 = 1.4 PgC yr^{-1}). However, the coastal zone fluxes are not adequately represented in the Takahashi et al.

estimate. The coastal zone fluxes represent a large unknown in the net CO_2 uptake of the oceans. If the coastal zone is a net source of CO_2 to the atmosphere of a magnitude necessary to offset the input of carbon from the rivers (i.e. ~0.6 PgC yr^{-1}), then the Takahashi et al. estimate is very consistent with other, independent approaches [e.g. Le Quéré and Metzl, this volume; table 1.1]. If the coastal zones are net sinks for CO_2, as indicated by Chen [this volume] and discussed in sections below, then one must reevaluate whether the standard approaches for estimating ocean uptake adequately represent the coastal zone fluxes. This topic is still an active area of research.

Significant advances have been made in separating the anthropogenic component from the large background of ocean dissolved inorganic carbon (DIC) during the past decade. Data-based approaches estimate a global inventory of anthropogenic CO_2 in the oceans to be ~111±13 PgC for a nominal year of 1994 (Figure 1.4). High inventories are generally observed in the mid-latitudes, with the lowest inventories in the high latitude Southern Ocean and near the Equator.

The high inventory regions are associated with convergence zones, where waters with relatively high anthropogenic concentrations are moving into the ocean's interior. Because of the formation of North Atlantic Deep Water in the North Atlantic, anthropogenic CO_2 can be found throughout the water column accounting for the exceptionally large inventories in this region. Roughly 25% of the total inventory of anthropogenic carbon is found in the North Atlantic. The low inventory waters are associated with general regions of upwelling, where waters with low anthropogenic concentrations are brought near the surface. The high latitude Southern Ocean generally has very low anthropogenic CO_2 inventories and very shallow penetration. The southern hemisphere mode and intermediate waters at around 40-50°S, on the other hand, contain some of the largest inventories of anthropogenic CO_2. Over 56% of the total anthropogenic CO_2 inventory is stored in the Southern Hemisphere.

Over the long term (millennial time-scales), the ocean has the potential to take up approximately 85% of the anthropogenic CO_2 that is released to the atmosphere. The reason for the long time constant is the relatively slow ventilation of the deep ocean. Most of the deep and intermediate waters have yet to be exposed to anthropogenic CO_2. As long as atmospheric CO_2 concentrations continue to rise, the oceans will continue to take up CO_2. However, this reaction is reversible. If atmospheric CO_2 were to decrease in the future, the recently ventilated waters will start releasing the accumulated anthropogenic CO_2 back out into the atmosphere as they

return to the surface and the thermodynamic drive to store anthropogenic CO_2 in the deep waters will decrease.

Land-River-Ocean Connections

One of the most visible lateral transfers between carbon cycle reservoirs is that from land to the oceans via rivers. The transfer of organic matter from the land to the oceans via fluvial systems is a key link in the global carbon cycle. Rivers also provide a key link in the geological-scale carbon cycle by moving weathering products to the ocean (figure 1.1). The conventional perspective is that rivers are simply a conduit for transporting carbon to the ocean. Re-evaluation of this model suggests that the overall transfer of terrestrial organic matter through fluvial systems may be more complex than originally thought [Richey, this volume]. A robust evaluation of the role of rivers, however, is complicated by both the complex dynamics and multiple time constants involved, and the fact that data are scarce, particularly in many of the most impacted systems.

Humans have had a significant impact on the concentrations of carbon and nutrients in river systems. Intensifying agriculture has led to extensive erosion, mobilizing perhaps 10-100 times more sediment, and its associated organic carbon, than undisturbed systems. Sewage, fertilizers, and organic waste from domestic animals also contribute to the carbon and nutrient loads of rivers. Not all of these materials make it to the ocean. Much of it may be deposited near and along river channels. The retention of particulate material in aquatic systems has increased since preindustrial times because of the proliferation of dams (primarily in the 30-50°N regions), which has increased the average residence time of waters in rivers. If the carbon mobilized via erosion were subsequently replaced by newly-fixed carbon in agriculture, then a sink on the order of 0.5-1.0 PgC yr^{-1} would be created. But organic carbon doesn't move passively through river systems; even very old and presumed recalcitrant soil carbon may be remineralized partly or fully in aquatic systems. Remineralization of organic carbon during transport leads to elevated levels of dissolved CO_2 in rivers, lakes and estuaries worldwide. These high concentrations subsequently lead to out-gassing back to the atmosphere on the order of ~1 PgC yr^{-1}, with the majority in the humid tropics [Richey, this volume].

Despite the increased particulate retention in rivers, a significant amount of carbon escapes to the ocean. Values used in figure 1.1 for the export of DIC, PIC, DOC, and POC from

rivers to the coastal ocean are 0.4, 0.2, 0.3, and 0.2 PgC yr^{-1}, respectively [Chen, this volume]. This includes a pronounced, but difficult to quantify, anthropogenic component. These values are poorly constrained by direct measurements and may represent minimum estimates of inputs to the coastal ocean [Richey, this volume]. Groundwater discharges, comprising about 10% of the surface flow to the ocean, also contribute poorly known concentrations of carbon and nutrients to the coastal oceans.

The final step in the land-to-ocean pathway is the marine fate of that fluvial carbon. Previous estimates have suggested that the marginal seas are net heterotrophic. Chen [this volume], has suggested that continental shelves are in fact net autotrophic, mostly because of production from coastal upwelling of nutrient rich waters. If this is correct, biological production in the coastal zone may decrease the thermodynamic drive to out-gas the terrestrial carbon delivered by rivers, resulting in greater preservation in the marine environment.

Trade/Commerce Connections

The lateral fluxes of carbon are poorly constrained by measurements and are frequently excluded from models. The river fluxes outlined in the previous section are only beginning to be quantified. The lateral transport of carbon through trade has not been constrained or quantified in global carbon budgets based on inventories of terrestrial carbon stocks and fluxes. Approximately one-third of the 4 PgC fixed annually through agriculture represents harvested products that are directed toward some form of human or domestic animal consumption [Tschirley and Servin, this volume]. In 2001, $547 million in agriculture and forest-related products entered into international trade, amounting to 9% of total trade (excluding services). Imports and exports of cereals, wood and paper products accounted for about 0.72 PgC of "embodied" carbon traded in 2000.

As we move from the basic carbon budget presented in Table 1.1 to a more detailed review of the fluxes shown in figure 1.1 and on to regional assessments of carbon budgets, it becomes increasingly important to recognize and quantify the lateral transports of carbon. The transport of carbon through trade/commerce represents a flux that is nearly as large as the net terrestrial and oceanic sinks. This carbon is assumed to be respired back to the atmosphere, but if the CO_2 is taken out of the atmosphere on one continent, then transported to another continent before being respired, it can have a significant impact on regional budget assessments.

Embodied carbon represents the carbon that resides directly within the product itself (for cereals, wood and paper, about half of the final weight is carbon). In addition to embodied carbon, at least two other components are usually excluded from estimates of carbon content in international trade. One is the "production" carbon, which comprises the inputs required to produce a final product, primarily energy-related consumption to provide inputs (e.g. pesticides, fertilizers) and processing (e.g. machinery for harvesting, milling, sawing etc.). A second element is the "transport" carbon, which represents the energy costs of transporting the processed products to a final destination. Countries that use intensive production systems and engage in significant exports (primarily in the developed countries) would have higher ratios of carbon content to product mass exported, possibly up to 20%, and would therefore have higher carbon emissions to the atmosphere than currently stated, under a system of full carbon accounting. Other countries would have lower carbon release to the atmosphere under full carbon accounting. Trade/commerce carbon accounting has a political background and differs from budget studies by atmospheric inversion and inventory checks. For example, CO_2 emissions during production and transport of products across regional boundaries would fully and partly, respectively, be accounted for by the country of origin using inventory studies. Inverse models based on atmospheric measurements, however, would reflect the emissions as they were actually distributed over the regions. As we begin to move from the global carbon budget presented here to regional carbon budgets, fluxes like the trade and commerce transports will need to be better quantified.

Non-CO_2 Trace Gas Connections

Rising concentrations of a large number of potent anthropogenic greenhouse gases other than carbon dioxide have collectively contributed an amount of radiative forcing comparable to that of CO_2 since pre-industrial times. Many of these non-CO_2 gases (e.g. CH_4, N_2O, CF_2Cl_2, SF_6) are emitted at the earth's surface and contribute directly to this forcing [Prinn, this volume]. They are characterized by atmospheric lifetimes of decades to millennia (lifetime as used here is the amount of the gas in the global atmosphere divided by its global rate of removal). Other non-CO_2 gases (e.g. isoprene, terpenes, nitric oxide (NO), carbon monoxide (CO), sulphur dioxide (SO_2), dimethyl sulphide ($(CH_3)_2S$), most of which are also emitted at the earth's surface, contribute indirectly to this forcing either through production of tropospheric ozone (which is a

powerful greenhouse gas), or tropospheric aerosols (which directly reflect sunlight back to space, absorb it, or indirectly change the reflection properties of clouds). This second group of climatically important non-CO_2 gases is characterized by much shorter lifetimes (hours to months).

The role of non-CO_2 carbon gases is not typically included in global carbon budgets, like the one shown in figure 1.1, because the sources and sinks for these gases are not well understood. Figure 1.5 summarizes, albeit with great simplification, the basic cycles and fluxes of the major non-CO_2 trace gases relevant to climate. Note that the emissions of the carbon-containing gases alone contribute about 2.3 PgC yr^{-1} to the carbon cycle [Prinn, this volume]. To aid the handling of the non-CO_2 gases in the policy processes under the United Nations Framework Convention on Climate Change (UNFCCC), scientists have calculated so-called global warming potentials (GWPs). These dimensionless GWPs, which range from 20 to 20,000 for the major non-CO_2 gases, are intended to relate the time-integrated radiative forcing of climate by an emitted unit mass of a non-CO_2 trace gas to the forcing caused by emission of a unit mass of CO_2. The GWP concept has difficulties, because the removal mechanisms for many gases (including CO_2 itself) involve complex chemical and/or biological processes, and because the time period (e.g. decade, century) over which one integrates the instantaneous radiative forcing of a gas to compute its GWP is somewhat arbitrary [Manne and Richels, this volume]. Nevertheless, by multiplying the emissions of each major non-CO_2 greenhouse gas by its GWP, we obtain equivalent amounts of CO_2 emissions, which are comparable to the total actual emissions of CO_2 (e.g. current total emissions of CH_4 and N_2O are equivalent to 3.8 and 2.1 PgC yr^{-1} respectively). For this reason, a "CO_2 emissions only" approach for global warming policy may lead to significant biases in the estimation of global warming abatement costs [Manne and Richels, this volume]. Thus, a multi-gas approach for studying the carbon cycle and how it relates to climate change needs to be implemented.

Carbon Cycle Processes

To fully understand the significance of the connections described above, as well as the potential that these fluxes might change in the future, one must consider the processes responsible for controlling the fluxes within and between reservoirs. In some cases these processes have already been significantly impacted by human activities. In other cases, there

may not be evidence that the fluxes are currently affected, but they may be vulnerable to climate change in the future.

Terrestrial Processes

On seasonal time-scales the gains and losses from the terrestrial biosphere are reflected in the cyclic variations in atmospheric CO_2 concentrations. Although there is significant interannual variability in the seasonal balance between the gains and losses, it is the trends in this net balance between NPP and carbon losses through decomposition, fires and disturbances that can affect climate on time-scales of decades to centuries. The scientific community currently believes that the terrestrial biosphere has been acting as a net sink for atmospheric carbon for the past few decades [Foley and Ramankutty, this volume]. For example, Pacala et al. [2001] recently estimated the carbon sink of the coterminous Unites States using a combination of inventory and atmospheric concentration inversions. They determined a consistent land and atmosphere based carbon sink for the US in the range of 0.37 to 0.71 PgC yr^{-1}. Similar studies have also shown a net sink in Europe. The mechanisms underlying the sinks have been the subject of much recent research. The leading hypothesis in the 1970s and 1980s was that the sinks were mainly a result of more rapid plant growth from elevated CO_2 and climate change. This has gradually been replaced with a multi-mechanism explanation, including contributions from changes in forest management, agriculture, long-lived products (e.g. wood), aquatic systems, and nitrogen deposition, in addition to CO_2 fertilization and changes in plant growth/soil carbon pools resulting from climate change [Schimel et al., 2001].

NPP is sensitive to a broad range of factors, including climate, soil fertility, atmospheric CO_2, atmospheric pollutants, and human management. An increase in NPP can lead to a carbon sink, but only if it is not matched by a corresponding increase in carbon losses. In general, processes that promote gradual increases in NPP can lead to carbon sinks, because increases in respiration tend to follow changes in biomass and soil carbon and not NPP directly [Field, 1999]. For the last 30 years, carbon cycle researchers have hypothesized that gradual increases in NPP in response to the 30% rise in atmospheric CO_2 since preindustrial times explain much or all of the terrestrial sink inferred from atmospheric studies [Bacastow and Keeling, 1973]. Experimental studies at the ecosystem level often demonstrate accelerated plant growth in response to elevated atmospheric CO_2 [Mooney et al., 1999], but these growth rates only explain

a small fraction of the sink required to balance the global atmospheric CO_2 budget [Friedlingstein et al., 1995]. Other factors that can increase NPP, including warming, greater precipitation and humidity, nitrogen deposition, and changes in plant species composition may also contribute to terrestrial carbon sinks.

Processes that retard carbon releases can also lead to terrestrial sinks. Evidence indicates that a substantial fraction of the forest sink in temperate forests is a result of changes in land use and land management. In essence, forests, cut in the past, are regrowing, with a growth rate that is faster than the rate of harvesting [Goodale et al., 2002]. Some of this is a result of shifts in land use, especially the abandonment of agriculture over large regions of North America and parts of Europe [Foley and Ramankutty, this volume]. Fire suppression and the thickening (more trees per unit area) of marginal forests also contribute to increased forest biomass in some areas [Pacala et al., 2001].

Changes in agriculture can also promote terrestrial carbon sinks. Increases in yield, incorporation of crop residue, and areas in perennial crops, as well as a reduction in tillage can all contribute to carbon sinks [Lal et al., 1998].

Recent terrestrial carbon sinks reflect a number of mechanisms [Pacala et al., 2001]. The potential for sinks to persist varies from mechanism to mechanism. Sinks due to CO_2 fertilization are likely to persist until NPP is limited by another factor. In some settings, this might occur very soon, and in others it might be far in the future. Sinks caused by forest regrowth saturate as the forests mature. In general, sinks saturate when increases in NPP are outpaced by increases in the sum of decomposition and combustion. The persistence of terrestrial sinks in the future is by no means assured. Many lines of evidence suggest that the prospect of increasing carbon sources in the terrestrial biosphere is a real possibility [Gruber et al., this volume].

Ocean Processes

Two basic mechanisms control the distribution of carbon in the oceans: the solubility pump and the biological pump. The solubility pump is driven by two principle factors. First, more CO_2 can dissolve into cold polar waters than in the warm equatorial waters. As major ocean currents (e.g. the Gulf Stream) move waters from the tropics to the poles, they are cooled and can take up more CO_2 from the atmosphere. Second, the high latitude zones are places where

deep waters are formed. As the waters are cooled, they become denser and sink into the ocean's interior taking with them the CO_2 accumulated at the surface.

Another process that moves CO_2 away from the surface ocean is called the biological pump. Growth of phytoplankton takes CO_2 and other chemicals from seawater to make plant tissue. Although most of the CO_2 taken up by phytoplankton is recycled near the surface, a substantial fraction, perhaps 30%, sinks into the deeper waters before being converted back into CO_2 by marine bacteria [Falkowski et al., 1998]. The amount of material that sinks out of the surface ocean depends partly on the plankton types. For example, detritus from phytoplankton that form shells of calcium carbonate and silicate sink the fastest [Klaas and Archer, 2002]. However, the effect of organic carbon export on surface CO_2 is partly compensated by the release of CO_2 in the formation of the calcium carbonate shells. Overall, the sum of the two processes leads to a decrease of CO_2 in surface waters. The CO_2 that is recycled at depth is slowly carried large distances by currents to areas where the waters return to the surface (upwelling regions). When the waters regain contact with the atmosphere the CO_2 originally taken up by the phytoplankton is returned to the atmosphere. This exchange process helps to control atmospheric CO_2 concentrations over decadal and longer time scales. Only about 0.1% of the organic carbon fixed at the surface reaches the seafloor to be buried in the sediments.

The combined effects of the solubility and biological pumps, together with the slow mixing time for the deep ocean, result in deep carbon inorganic concentrations that are approximately 15% higher than surface concentrations [LeQuéré and Metzl, this volume]. The biological pump also removes inorganic nutrients such as nitrate, phosphate, silicate, and iron from surface waters and releases them at depth. Since productivity is generally limited by the availability of these nutrients, the large-scale thermohaline circulation (THC) of the oceans has a strong impact on global ocean productivity by regulating the rate at which nutrients are returned back to the surface. The long residence time for the deep oceans also means that most of the deep ocean waters have not been exposed to the rising atmospheric CO_2 concentrations observed over the last couple of centuries. Although the oceans have the potential to absorb 85% of the anthropogenic CO_2 released to the atmosphere, today's oceans are only at about 15% capacity [LeQuéré and Metzl, this volume]. Average penetration depth for anthropogenic CO_2 in the global oceans is only about 800 m [Sabine et al., 2002]. Because of its effect on ocean carbon distributions and biological productivity, changes in the THC have been used to help explain past

excursions in climate and atmospheric CO_2, including glacial-interglacial and Dansgard-Oeschger events [Joos and Prentice, this volume].

Ocean productivity can also be affected by atmospheric inputs. Iron in oceanic surface waters originates from terrestrial dust deposited over the ocean, deep ocean waters, continental shelves, and to a lesser extent from river inflow. Because of the spatial distribution of dust deposition and other iron sources, large regions of the ocean show a deficit in iron (and to a smaller extent in silicate), although other nutrients are plentiful. These are called High Nutrient Low Chlorophyll (HNLC) regions. There is a potential for enhanced biological productivity in these regions if the ocean can be "fertilized" by iron. However, the potential for CO_2 reduction in surface waters and in the atmosphere through this artificial sequestration depends on factors like the composition of plankton types and oceanic circulation, and can lead to undesirable side effects [Bakker, this volume].

Up to now, humans have had a relatively small direct impact on the global scale ocean carbon cycle. This is primarily because humans generally only transit across the oceans and because the oceans naturally contain orders of magnitude more carbon than the atmosphere and the terrestrial biosphere. Because biology is not carbon limited in the oceans, it is thought that increasing CO_2 levels have not significantly impacted ocean biology. However, some phytoplankton species, particularly those that secrete calcium carbonate shells may be negatively impacted by rising CO_2 concentrations in the atmosphere and water. For example, Riebesell et al. [2000] showed a significant reduction in the ability of two different species of coccoliths to secrete calcium carbonate shells under elevated CO_2 conditions. Similar reductions in calcification have been observed in corals. As atmospheric CO_2 concentrations continue to rise the potential for significantly altering the current balance between the solubility and biological pumps in the ocean increases.

Coastal Ocean

Although the coastal zones, consisting of the continental shelves with depths less than 200m including bays and estuaries, occupy only 10% of the total ocean area they play a crucial role in the global carbon cycle. Carbon is transported to the coastal zone by riverine inputs and transport of inorganic carbon from the open-ocean. Estuaries and proximal coastal seas are believed to be sources of CO_2, because of the decay of terrestrial organic carbon. However, since

the riverine flux of nutrients has continually been on the rise over the past few decades, these areas may now actually have enhanced biological productivity, and hence, be releasing less CO_2. At present a large fraction (~80%) of the land derived organic and inorganic materials that are transported to the ocean is trapped on the proximal continental shelves [Mackenzie and Ver, 2001]. The much wider open shelves, on the other hand, are believed to serve as sinks for atmospheric carbon. A recent overview suggests that the global coastal waters and marginal seas (extending to a water depth of 200 m) are now absorbing about 0.36 PgC yr^{-1} from the atmosphere [Chen, this volume].

Across most of the coastal seas and continental margins surface waters are transported offshore, because of fresh water inputs from land. This surface transport draws nutrient-rich subsurface waters from the open ocean up onto the shelves. Such external sources of nutrients support high primary productivity. Most of the organic material produced is respired and recycled on the shelves. The organic matter that is not recycled either accumulates in the sediments or is exported to the slopes and open oceans. The coastal zone may account for 30-50% of the total calcium carbonate accumulation and up to 80% of the organic carbon accumulation in ocean sediments [Mackenzie and Ver, 2001]. Globally the shelf seas are estimated to transport 0.6 PgC yr^{-1} of DOC, 0.5 PgC yr^{-1} of POC and 0.2 PgC yr^{-1} of PIC to the open oceans [Chen, this volume]. Although these transports have large uncertainties, because of high variability and inadequate data coverage, they represent an important and often neglected link in the global carbon cycle. Shelves and estuaries are also important sources of other greenhouse or reactive gases, such as methane and dimethyl sulfide.

Finally, while humans appear to have had only a small direct impact on the open ocean, they have had a profound and poorly understood impact on the coastal oceans. Furthermore, direct and indirect human perturbations vis-à-vis the continental margins (e.g. pollution, eutrophication, etc.) are likely to have large and dire consequences on marine ecosystems in the future. As much as 40-60% of the world population lives in coastal areas, depending on the definitions and methodologies applied. The coastal regions have the most rapidly growing population densities, because of migration from rural areas. Most mega cities in this century will develop in coastal zones, approximately half of them in Asia [IHDP/START, 2000]. Such patterns of urbanization have affected and will continue to affect coastal and marine systems, through processes such as land use change, pressure on infrastructure (water, sewage, and

transportation), coastal resource depletion and degradation, eutrophication and other carbon relevant impacts. Coastal zones support more than 60% of the global commercial fish production [World Resources Institute, 1996]. It is not clear how these fisheries will be affected by the increasing human pressures on the coastal zone. Additional studies of the coastal zone and the interaction between humans and the coastal biogeochemical systems are needed.

Human Systems

As noted in previous sections, humans have had a profound impact on carbon cycling in the atmosphere, terrestrial biosphere and to a lesser extent in the oceans. To understand how humans will continue to interact with these reservoirs in the future, one must understand the drivers responsible for how humans interact with the environment.

Energy use has historically been viewed as an essential commodity for economic growth. The paradigm of "grow or die" historically meant increasing demands for additional resources and a commensurate increase in the amount of pollutants released. Over the past thirty years, however, a complex debate has ensued about how to decouple economic growth and resource consumption. Since this debate started several scholars, policy makers, nongovernmental organizations have asked themselves how to reshape this paradigm of development? Answers have ranged from doing nothing (business as usual approach) to the slowing down and even stalling of economic growth, so as to not exceed the earth's carrying capacity. Carrying capacity here refers to the ability of natural resources and ecosystems to cope with anthropogenic pressures such as use of renewable natural resources, emission of pollutants and modification of ecosystem's structures without crossing "critical thresholds of damage beyond which [these resources] lose their ability for self-renewal and slide inexorably into deeper degradation" [Board on Sustainable Development Policy Division, 1999].

Another more tenuous response is based on the idea that one could keep economic growth as a development goal and at the same time find mechanisms aimed at reducing the amount of material input and emissions or aimed at finding replacements for non-renewable or dangerous resources (e.g. fossil fuels). This proposal has resulted in environmental policies and instruments promoting technological innovations aimed at increasing the efficiency of economic activities and at decarbonizing the economies.

Energy intensity (the ratio of total domestic energy primary consumption to gross domestic product or physical output) in the US, Japan, and other developed countries has increased far slower than economic growth. China too has made significant gains, and the growth rate of its energy consumption has been half that of its gross domestic product (GDP) growth rate since the early 1980s. While the energy use per unit of GDP has fallen or stabilized since 1970, energy use per capita has increased in most of the developed countries. This statistic may be misleading however, because there has also been a change in consumption and production patterns away from materially intensive commodities towards less intensive services and production of many of the materially intensive commodities has moved out of the developed countries. This does not necessarily mean that the developed countries are using fewer resources, but the regional distribution of this demand has changed. Countries belonging to the former Soviet Union (FSU) have also shown a decrease in energy intensity, but for very different reasons. Due to sociopolitical changes, economic activity declined substantially in these countries, resulting in a dramatic decline in energy use and associated carbon emissions.

Over the past century and a half, the use of biomass has successively given way to expanded use of coal, oil, and natural gas as the primary fuels to supply energy (Figure 1.6). Over the past two decades the use and share of nuclear and other forms of renewable energy has increased. The carbon intensity (PgC/GJ) of each successive fuel beginning with coal is lower, and this has led to the decarbonization of the global fuel mix over the past century. Critical inventions such as the steam and internal combustion engines, vacuum tubes, airplanes, etc. have accompanied and fostered the use of successive fuels and electricity.

The speed of energy consumption and land use changes have increased during the last two centuries. Three spatial and historical variations of carbon relevant social tendencies need to be considered in the understanding of where we are today.

1. Historically, industrialized countries have been the main releasers of carbon from combustion of fossil fuels. Although developing countries are expected to increase their share of emissions, the relocation strategies of corporations based in industrialized regions may actually significantly contribute to increased emissions in these developing countries. In 1925, for example, the United States, Western Europe, Japan and Australia were responsible for about 88% of the world's fossil fuel carbon dioxide emissions [Houghton and Skole, 1990]. Data from 1950-1995 indicate that 26 countries fell above

the average cumulative emissions figure. These countries include almost all developed, or Annex 1 countries and China, India, Brazil and several other larger developing countries that have seen significant growth in foreign investments [Claussen and McNeilly, 1998].

2. Until the 19th century most of the conversion from forest area to cultivated land occurred in the developed countries. During the last few decades, most of the deforestation has occurred in tropical forests, such as the Amazon.
3. Urbanization, a key driver of energy and land use, was primarily a feature of industrialized nations until the middle of the 20th century. The largest and demographically most dynamic urban agglomerations, like New York, London and Tokyo were in developed countries. As of the beginning of the 21st century, however, most urban agglomerations are situated in developing countries. These developing nation urban agglomerations have different production systems and living standards than the urban centers in developed countries. These differences impact the carbon emissions of various urban areas [Romero, this volume].

Although technology is perceived as the answer to decarbonizing economies, we need to bear in mind that other societal factors work as constrains and windows of opportunity for that purpose (e.g. institutional settings and economic dynamics, see chapter 5), and to consider that it takes decades to establish a new technological paradigm of production and consumption patterns. The main energy and production components of the *engineering* epoch for instance (1850-1940) took at least twenty years to develop. Hence, it will likely take decades to set up alternative energy sources and materials aimed at decarbonizing industrial and agricultural activities. Despite efforts aimed at decoupling economic growth from its carbon impacts, CO_2 emissions from the combustion of fossil fuels and from land-use change increased during last years. Many features of the development trends need to be studied and better understood before opportunities for modifications in life styles, technologies, institutions and other drivers of carbon emissions can be fully addressed.

Geological Processes

The discussion thus far has focused on reservoirs and processes relevant to human time-scales. With a residence time of about 300 million years, the huge reserves of carbon stored in the sedimentary rocks are not expected to play a large role in the short-term carbon budget. On

time-scales greater than 500,000 years about 80% of the CO_2 exchange between the solid earth and the atmosphere is controlled by the carbonate-silicate cycle [Kasting et al., 1988]. In this cycle, atmospheric CO_2 is used to weather calcium-silicate rock minerals on land, which are then transported to the ocean via rivers as calcium and bicarbonate ions. In the oceans, plankton and other organisms incorporate the ions into calcium carbonate shells. A portion of the calcium carbonate is deposited onto the ocean floor and eventually CO_2 is returned to the atmosphere through volcanic and diagenetic processes.

Currently there are vast quantities of carbon stored in ocean sediments as methane hydrates and as calcium carbonate. The methane hydrates are relatively stable, but could be released, if ocean temperatures increase sufficiently through global warming [Harvey and Huang, 1995]. The carbonate sediments are likely to be a significant sink for fossil fuel CO_2 on millennial time-scales [Archer et al., 1999]. As the oceans continue to take up anthropogenic CO_2, the CO_2 will penetrate deeper into the water column, lowering the pH and making the waters more corrosive to calcium carbonate. Dissolution of sedimentary carbonates binds the carbon in a dissolved form that is not easily converted back into atmospheric CO_2. Carbonate dissolution is typically thought to occur in the deep ocean, well removed from the anthropogenic CO_2 taken up in the surface waters. In portions of the North Atlantic and North Pacific Oceans, however, anthropogenic CO_2 may have already penetrated deep enough to influence the dissolution of calcium carbonate in the water column and shallow sediments [Feely et al, 2002].

Although the processes of CO_2 uptake through weathering and CO_2 release from volcanism and diagenesis appear to have been in balance on geological time-scales, short-term variability in one of these fluxes can impact the carbon cycle on time-scales relevant to humans. For example, volcanic eruptions result in the emission of CO_2, dust, ash and sulfur components. These sulfur particles may rain out and promote acid rain. Atmospheric sulfur particles block out sun light and thus cool the (regional) climate. Particles, which reach the stratosphere, may reduce global temperatures for several years. The incidental occurrence of cataclysmic volcanic eruptions or the coincidence of several large eruptions (eg. the eruptions of 1783 or the 1991 Mount Pinatubo eruption) have been known to affect the global carbon cycle, directly by their CO_2 emissions and indirectly by their impact on marine and terrestrial primary production [Hamblyn, 2001; Sarmiento and Gruber, 2002].

Understanding Today's Carbon Cycle

Although our understanding of the contemporary global carbon cycle has increased dramatically over the past few decades, there are many aspects that are still not well understood. Several specific areas where additional studies are needed have been mentioned above. However, there are two general areas of research where our understanding is exceptionally weak and focused research is necessary. One significant area that needs improvement is our understanding of regional variability. A second, somewhat related topic is how changes in the carbon-cycle may be linked to different modes of climate variability.

Regional Budgets

Although atmospheric CO_2 concentrations are changing on a global scale, the spatial scales of natural processes as well as the scales of human interventions and the associated societal mechanisms have a profound regional character. Industrialized countries for instance constitute the highest share of fossil fuel CO_2 emissions by direct release and through trade, while developing nations have become the primary CO_2 emitters through land use changes [Romero, this volume]. Insufficient observations limit our ability to do regional scale assessments globally. However, the potential benefits of such approaches in identifying the biogeochemical and human processes responsible for controlling fluxes makes these studies very important. A regional scale carbon budget assessment also provides a unique opportunity to verify and bridge independent methods and observations made over a range of spatial scales (e.g. top – down atmospheric inversion estimates versus land-based or ocean-based bottom-up observations).

In the land-based bottom-up method, carbon sinks and sources from various ecosystems (forests, croplands, grasslands and organic soil wetlands) are aggregated over all regions to provide a large-scale perspective. The land-based approach can therefore provide information as to which ecosystems and regions are accumulating, and which are losing carbon to the atmosphere. However, the diversity of land mosaics, the complexity of human activities and the lateral transports of carbon in different components make it difficult to provide a comprehensive carbon budget.

Ocean-based bottom-up methods can be used to assess the complex and often competitive controls of heat flux, mixing, and biology on air-sea gas exchange as well as develop proxies for

extrapolating limited observations to larger time and space scales. Monitoring of changes in ocean interior properties can also provide valuable information on surface processes and fluxes.

Atmosphere-based approaches, in contrast, give no information about which ecosystems or processes are contributing to a sink or source, but produce a more robust large-scale assessment of the net carbon flux to the atmosphere. No one approach holds the key to understanding regional variability in the carbon cycle. A suite of approaches much be used. In addition to providing different, but complimentary information, a combination of the bottom-up and top-down methods puts independent constraints on the integrated carbon balance of regional budgets.

The use of multiple approaches can also be used to identify key fluxes that may have been missed by the inventory approach. For example, Janssen et al. [2003] used inventories to estimate that the European continent sink was on the order of 0.11 PgC yr^{-1}, compared with a mean atmospheric inversion estimate of 0.29 PgC yr^{-1}. The discrepancy between these estimates was attributed to the intercontinental displacement of organic matter via trade, emissions of non-CO_2 gases, and a slight overestimation of fossil fuel emissions. This example illustrates the need for comprehensive assessments of the major vertical and lateral fluxes as well as illustrating the power of the multiple approaches for highlighting areas where additional studies are needed.

Variability

Observing and quantifying variability in natural processes and the impact of human interventions is of primary importance for three reasons:

(1) It provides a key diagnostic of how climatic factors and societal dynamics impact exchange fluxes and provides information that is needed for the development and validation of comprehensive process based carbon cycle models that include human dynamics.

(2) Several terrestrial and oceanic carbon cycle components effectively contain a longer-term "memory", i.e. their present state is partly a result of past natural and human perturbations. For example, enhanced fire frequencies or management strategies during a drier past period will be reflected in the age-structure of a present forest, or the carbon content in particular oceanic deep water masses will reflect climate driven variations in deep water formation in the past.

(3) Climate variability often tends to "mask" the slow, longer term signals in the carbon cycle that are of primary interest: i.e. many studies have shown that the uptake rates of the terrestrial biosphere or the ocean are highly variable. In this context, climate variability constitutes a "noise" from which the signals have to be discriminated. Indeed, a significant fraction of the uncertainty estimates given in the global budget in Table 1.1, can be traced to incomplete quantification of possible climate perturbations in the pertinent observations.

On the global scale climate driven variability can be inferred from atmospheric time series of CO_2 and associated variables, such as $^{13}C/^{12}C$ and O_2/N_2 ratios. Continental or ocean basin scale variations can be detected on time scales of up to several years by means of top-down inversions of atmospheric CO_2 concentration measurements [Heimann et al., this volume]. However, it is difficult to separate out the terrestrial signals from the ocean signals using these large-scale approaches [Greenblatt and Sarmiento, this volume]. On land and in the oceans, local-scale direct observations of variability exist from in situ flux measurements at a few time-series stations during the last few years. However, on the regional scale an observational gap exists. The present atmospheric network is not dense enough to resolve carbon sources and sinks on regional spatial scales by atmospheric inversion, while the upscaling of measured in situ oceanic and terrestrial carbon fluxes is extremely difficult. On land, the large heterogeneity of terrestrial ecosystems and complex atmospheric transport patterns resulting from topography make it difficult to scale up local measurements. In the oceans, the complex interplay between physical and biological controls on sea surface pCO_2 and the dynamics of air-sea exchange complicate the extrapolation of the in situ observations .

Interannual variability in climate leads to large changes in atmospheric temperature and rainfall patterns, as well as changes in ocean surface temperatures and circulation. All of these can have dramatic effects on biological productivity and complex effects on CO_2 exchanges with the atmosphere on land and in the oceans. For example, during El Niño events, the warming of ocean surface waters and reduction in biological productivity in the Equatorial Pacific Ocean should lead to enhanced outgasing of CO_2. However, since the upwelling of carbon rich deep waters, that release CO_2 to the atmosphere, is reduced during El Niños, the net effect is a significant reduction in the outgasing of CO_2 in this region. On the other hand, warmer temperatures and anomalous rainfall patterns during El Niños can lead to increased terrestrial biosphere respiration, forest fires and droughts. The timing of these effects and the

teleconnections between them have a direct impact on atmospheric CO_2 concentrations that are still not completely understood today.

Overall, a general consensus has emerged that the interannual variability in air-sea CO_2 fluxes is smaller than that of terrestrial CO_2 fluxes, but the exact amplitude and spatial distributions remain uncertain [Greenblatt and Sarmiento, this volume]. To better determine these signals, an expanded network of time series CO_2 measurements must be maintained for the atmosphere, oceans and land systems. These measurements together with intensive process studies, a better use of satellite data, atmospheric observations, and rigorously validated models will help us to better understand the current global carbon cycle and how it is evolving over time.

Conclusions

The current global carbon cycle is in a state of transition. Human activities over the past few centuries have had a profound impact on many aspects of the system. As we begin to assess ways to monitor and potentially manage the global carbon cycle, it is imperative that we better understand how the system, including human dynamics and the biogeochemical processes controlling CO_2 and other carbon gases in the atmosphere, has operated in the past and how it is operating today. How will the land/ocean/atmosphere processes respond to human activities, and what are the societal dynamics that will determine how humans will respond to changes in the land, ocean, and atmosphere systems? Until we can confidently explain and model the contemporary carbon cycle, our ability to predict future changes in atmospheric CO_2 concentrations will always be limited. We have made tremendous progress over the past few decades at reducing the uncertainties in table 1.1 and figure 1.1, however there are still many aspects of the system that we have yet to understand.

References

Achard, F., H. D. Eva, H.-J. Stibig, P. Mayaux, J. Gallego, T. Richards, and J.-P. Malingreau. 2002. Determination of Deforestation Rates of the World's Humid Tropical Forests. Science **297**:999-1002.

Ahlbrandt et al., 2000

Archer, D., H. Kheshgi and E. Maier-Reimer. 1999. Dynamics of fossil fuel CO_2 neutralization by marine $CaCO_3$, Global Biogeochem. Cycles, **12**: 259-276.

Bacastow, R., and C. D. Keeling. 1973. Atmospheric carbon dioxide and radiocarbon in the natural carbon cycle. II, Changes from A.D. 1700 to 2070 as deduced from a geochemical reservoir. Pages 86-135 *in* G. M. Woodwell and E. V. Pecan, editors. Carbon and the Biosphere. U.S. Dept. of Commerce, Springfield, Virginia.

Bakker, D. 2003. Storage of carbon dioxide by greening the oceans? Pages (this volume) *in* C. B. Field and M. R. Raupach, editors. Toward CO_2 Stabilization: Issues, Strategies, and Consequences. Island Press, Washington.

Board on Sustainable Development Policy Division, 1999

BP Statistical review of world energy, 2002

CDIAC. 2003. Trends Online: A Compendium of Data on Global Change Carbon Dioxide Information Center. Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee. <http://cdiac.esd.ornl.gov/trends/trends.htm>

Claussen, E., McNeilly, L. 1998. equity and global climate change. The complex elements of global fairness. Pew Center on Global Climate Change. http:/www.pewclimate.org/report2.html.

Chen, C-T. A. 2003. Exchanges of carbon in the coastal seas. Pages (this volume) *in* C. B. Field and M. R. Raupach, editors. Toward CO_2 Stabilization: Issues, Strategies, and Consequences. Island Press, Washington.

DeFries, R. S., C. B. Field, I. Fung, J. Collatz, and L. Bounoua. 1999. Combining satellite data and biogeochemical models to estimate global effects of human-induced land cover change on carbon emissions and primary productivity. Global Biogeochemical Cycles **13**:803-815.

DeFries, R. S., R. A. Houghton, M. C. Hansen, C. B. Field, D. Skole, and J. Townshend. 2002. Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 1990s. Proceedings of the National Academy of Sciences **99**:14256-14261.

Falkowski, P.G., R.T. Barber, and V. Smetacek. 1998. Biogeochemical controls and feedbacks on ocean primary production. Science **281**: 200:206.

Feely, R.A., C.L. Sabine, K. Lee, F.J. Millero, M.F. Lamb, D. Greeley, J.L. Bullister, R.M. Key, T.-H. Peng, A. Kozyr, T. Ono, and C.S. Wong. 2002. In situ calcium carbonate dissolution in the Pacific Ocean. Global Biogeochem. Cycles, **16(4)**, 1144, 10.1029/2002GB001866

Foley, J.A. and N. Ramankutty. 2003. A primer on the terrestrial carbon cycle: What we don't know, but should. Pages (this volume) *in* C. B. Field and M. R. Raupach, editors. Toward CO_2 Stabilization: Issues, Strategies, and Consequences. Island Press, Washington.

Friedlingstein, P., I. Fung, E. A. Holland, J. John, G. Brasseur, D. Erikson, and D. Schimel. 1995. On the contribution of the biospheric CO_2 fertilization to the missing sink. Global Biogeochemical Cycles **9**:541-556.

Geist et al., 2001

Goodale, C. L., M. J. Apps, R. A. Birdsey, C. B. Field, L. S. Heath, R. A. Houghton, J. C. Jenkins, G. H. Kohlmaier, W. Kurz, S. Liu, G.-J. Nabuurs, S. Nilsson, and A. Z. Shvidenko. 2002. Forest carbon sinks in the northern hemisphere. Ecological Applications **12**:891-899.

Greenblatt, J.B. and J. Sarmiento. 2003. Variability and climate feedback mechanisms in ocean uptake of CO_2. Pages (this volume) *in* C. B. Field and M. R. Raupach, editors. Toward CO_2 Stabilization: Issues, Strategies, and Consequences. Island Press, Washington.

Gruber et al. 2003. The vulnerability of the carbon cycle in the 21st century: An assessment of carbon-climate-human interactions. Pages (this volume) *in* C. B. Field and M. R. Raupach, editors. Toward CO_2 Stabilization: Issues, Strategies, and Consequences. Island Press, Washington.

Gurney, K.R. et al. 2002. Towards robust regional estimates of CO_2 sources and sinks using atmospheric transport models. Nature 415:626-630.

Hamblyn, R., 2001. The invention of clouds. How an amateur meteorologist forged the language of the skies. Picador, New York, 291 pp.

Harvey, L.D.D. and Z. Huang. 1995. Evaluation of the potential impact of methane clathrate destabilization on future global warming. J. Gephys. Res., **100**: 2905-2926.

Heimann, M., C. Rödenbeck, and M. Gloor. 2003. Spatial and temporal distribution of sources and sinks of carbon dioxide. Pages (this volume) *in* C. B. Field and M. R. Raupach, editors. Toward CO_2 Stabilization: Issues, Strategies, and Consequences. Island Press, Washington.

Houghton, 2003

Houghton and Skole, 1990

IHDP/START International Human Dimensions Workshop: "Human Dimensions in the Coastal Zones" HDP Proceeding No. 03, September 10-19, 2000, Bonn, Germany, www.ihdp.uni-bonn.de/html/publications/publications.html

Janssen et al, 2003

Jobbagy, E., and R. Jackson. 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. ECOLOGICAL APPLICATIONS **10**:423-436.

Joos, F. and I.C. Prentice. 2003. A paleo perspective on the future of atmospheric CO_2 and climate. Pages (this volume) *in* C. B. Field and M. R. Raupach, editors. Toward CO_2 Stabilization: Issues, Strategies, and Consequences. Island Press, Washington.

Kasting, J.F., O.B. Toon and J.B. Pollack. 1988. How climate evolved on the terrestrial planets. Sci. Amer. **2**:90-97.

Klaas, C. and D.E. Archer. 2002. Association of sinking organic matter with various types of mineral ballast in the deep sea: Implications for the rain ratio. Global Biogeochem. Cycles **16**(4) 1116, doi:10.1029/2001GB001765

Lal, R., J. M. Kimble, R. F. Follett, and C. V. Cole. 1998. The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect. Chelsea Press, Ann Arbor, Michigan.

Lequere, C. and N. Metzl. 2003. Natural processes regulating the oceanic uptake of CO_2. Pages (this volume) *in* C. B. Field and M. R. Raupach, editors. Toward CO_2 Stabilization: Issues, Strategies, and Consequences. Island Press, Washington.

Lequéré, C., O. Aumont, L. Bopp, P. Bousquet, P. Ciais, R. Francey, M. Heimann, C.D. Keeling, R.F. Keeling, H. Kheshgi, P. Peylin, S.C. Piper, I.C. Prentice, and P.J. Rayner. 2003. Two decades of ocean CO_2 sink and variability. Tellus (in press).

Lindemann, 1941
Mackenzie, F.T. and L.M. Ver. 2001. Land-sea global transfers. Pages 1443-1453 in J.H. Steele, K.K. Turekian, and S.A. Thorpe editors. Encyclopedia of Ocean Sciences. Academic Press. doi:10.1006/rwos.2001.0073.
Manne, A. and R.G. Richels. 2003. A multi-gas approach to climate policy. Pages (this volume) *in* C. B. Field and M. R. Raupach, editors. Toward CO_2 Stabilization: Issues, Strategies, and Consequences. Island Press, Washington.
Mooney, H. A., J. Canadell, F. S. Chapin, III, J. Ehleringer, C. Körner, R. McMurtrie, W. J. Parton, L. Pitelka, and E.-D. Schulze. 1999. Ecosystem physiology responses to global change. Pages 141-189 *in* B. H. Walker, W. L. Steffen, J. Canadell, and J. S. I. Ingram, editors. The Terrestrial Biosphere and Global Change: Implications for Natural and Managed Ecosystems. Cambridge University Press, Cambridge.
Nakicenovic, N. 2003. Socio-economic driving forces of emissions scenarios. Pages (this volume) *in* C. B. Field and M. R. Raupach, editors. Toward CO_2 Stabilization: Issues, Strategies, and Consequences. Island Press, Washington.
Nabuurs, G. J. 2003. Current consequences of past actions. Pages (this volume) *in* C. B. Field and M. R. Raupach, editors. Toward CO_2 Stabilization: Issues, Strategies, and Consequences. Island Press, Washington.
Pacala, S. W., G. C. Hurtt, R. A. Houghton, R. A. Birdsey, L. Heath, E. T. Sundquist, R. F. Stallard, D. Baker, P. Peylin, P. Ciais, P. Moorcroft, J. Caspersen, E. Shevliakova, B. Moore, G. Kohlmaier, E. Holland, M. Gloor, M. E. Harmon, S.-M. Fan, J. L. Sarmiento, C. Goodale, D. Schimel, and C. B. Field. 2001. Convergence of land- and atmosphere-based U.S. carbon sink estimates. Science **292**:2316-2320.
Prentice, C. et al. 2001. The carbon cycle and atmospheric carbon dioxide, *in* J. Houghton et al. editors. Climate Change 2001: The scientific basis, Contribution of working group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cabridge University Press, New York, NY, USA.
Prinn, R. G. 2003. Non-CO_2 greenhouse gases. Pages (this volume) *in* C. B. Field and M. R. Raupach, editors. Toward CO_2 Stabilization: Issues, Strategies, and Consequences. Island Press, Washington.
Richey, J. E. 2003. Fluvial systems. *in* C. B. Field and M. R. Raupach, editors. Toward CO_2 Stabilization: Issues, Strategies, and Consequences. Island Press, Washington.
Riebesell, U, I. Zondervan, B. Rost, P.D. Tortell, R.E. Zeebe, and F.M.M. Morel. 2000. Reduced calcification of marine plankton in response to increased atmospheric CO_2. Nature **407** (6802): 364-367
Robertson, G. P. 2003. Towards global CO_2 stabilization: Interactions with the non-CO_2 greenhouse gases. Pages (this volume) *in* C. B. Field and M. R. Raupach, editors. Toward CO2 Stabilization: Issues, Strategies, and Consequences. Island Press, Washington.
Romero Lankao, P. 2003. Pathways of regional development and the carbon cycle. Pages (this volume) *in* C. B. Field and M. R. Raupach, editors. Toward CO_2 Stabilization: Issues, Strategies, and Consequences. Island Press, Washington.
Sabine, C.L., R.A. Feely, R.M. Key, J.L. Bullister, F.J. Millero, K. Lee, T.-H. Peng, B. Tilbrook, T. Ono, and C.S. Wong. 2002. Distribution of anthropogenic CO_2 in the Pacific Ocean, Global Biogeochem. Cycles **16** (4) 1083, doi: 10.1029/2001GB001639.
Sarmiento, J.L. and N. Gruber. 2002. Sinks for anthropogenic carbon. Physics Today August:30-36.

Saugier, J., J. Roy and H.A. Mooney. 2003. Converging toward a single number? Pages (this volume) *in* C. B. Field and M. R. Raupach, editors. Toward CO_2 Stabilization: Issues, Strategies, and Consequences. Island Press, Washington.

Saugier, B., J. Roy, and H. A. Mooney. 2001. Estimations of global terrestrial productivity: Converging toward a single number? Pages 543-557 *in* J. Roy, B. Saugier, and H. A. Mooney, editors. Terrestrial Global productivity. Academic Press, San Diego.

Schimel, D. S., J. I. House, K. A. Hibbard, P. Bousquet, P. Ciais, P. Peylin, B. H. Braswell, M. J. Apps, D. Baker, A. Bondeau, J. Canadell, G. Churkina, W. Cramer, A. S. Denning, C. B. Field, P. Friedlingstein, C. Goodale, M. Heimann, R. A. Houghton, J. M. Melillo, B. M. III, D. Murdiyarso, I. Noble, S. W. Pacala, I. C. Prentice, M. R. Raupach, P. J. Rayner, R. J. Scholes, W. L. Steffen, and C. Wirth. 2001. Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems. Nature **414**:169 - 172.

Smith, P. 2003. Engineered sinks on land (biological). Pages (this volume) *in* C. B. Field and M. R. Raupach, editors. Toward CO_2 Stabilization: Issues, Strategies, and Consequences. Island Press, Washington.

Takahashi, T., S.C. Sutherland, C. Sweeney, A. Poisson, N. Metzl, B. Tilbrook, N. Bates, R. Wanninkhof, R.A. Feely, C. Sabine, J. Olafsson, and Y. Nojiri. 2002. Global sea-air CO_2 flux based on climatological surface ocean pCO_2, and seasonal biological and temperature effects, Deep-Sea Res. II **49**: 1601-1623.

Tschirley, J. and G. Servin, Carbon transport through international commerece. Pages (this volume) *in* C. B. Field and M. R. Raupach, editors. Toward CO_2 Stabilization: Issues, Strategies, and Consequences. Island Press, Washington.

Vitousek, P. M., P. R. Ehrlich, A. H. Ehrlich, and P. A. Matson. 1986. Human appropriation of the products of photosynthesis. BioScience **36**:368-373.

Whitehouse, 2003

World Resources Institute. 1996. World Resources: A Guide to the Global Environment. Oxford Univ. Press, New York, 365 pp.

Table 1.1 The global carbon budget (PgC yr^{-1}). Positive values represent atmospheric increase (or ocean/land sources), negative numbers represent atmospheric decrease (sinks).

	1980s	**1990s**
1. *Prentice et al., 2001*		
Atmospheric increase	+3.3 ± 0.1	+3.2 ± 0.1
Emissions (fossil fuel, cement)	+5.4 ± 0.3	+6.3 ± 0.4
Ocean-atmosphere flux	–1.9 ± 0.6	–1.7 ± 0.5
Net land-atmosphere flux	–0.2 ± 0.7	–1.4 ± 0.7
Land-use change	+1.7 (+0.6 to +2.5)	-
**Residual terrestrial sink*	–1.9 (–3.8 to +0.3)	-
2. *LeQuéré et al., 2003*		
Ocean corrected	–1.8 ± 0.8	–1.9 ± 0.7
Net land-atmosphere flux	–0.3 ± 0.9	–1.2 ± 0.8
3. *Houghton, 2003*		
Land use	+2.0 (+0.9 to +2.8)	+2.2 (+1.4 to +3.0)
Residual terrestrial sink	-2.3 (–4.0 to –0.3)	-3.4 (–5.0 to –1.8)
4. *De Fries et al., 2002*		
Land use	+0.6 (+0.3 to +0.8)	+0.9 (+0.5 to +1.4)
Residual terrestrial sink	-0.9 (-3.0 to 0)	-2.1 (-3.4 to -0.9)
5. *Achard et al., 2002*		
Land use		+1.0 ± 0.2
Residual terrestrial sink		-2.2 (-3.2 to -1.2)

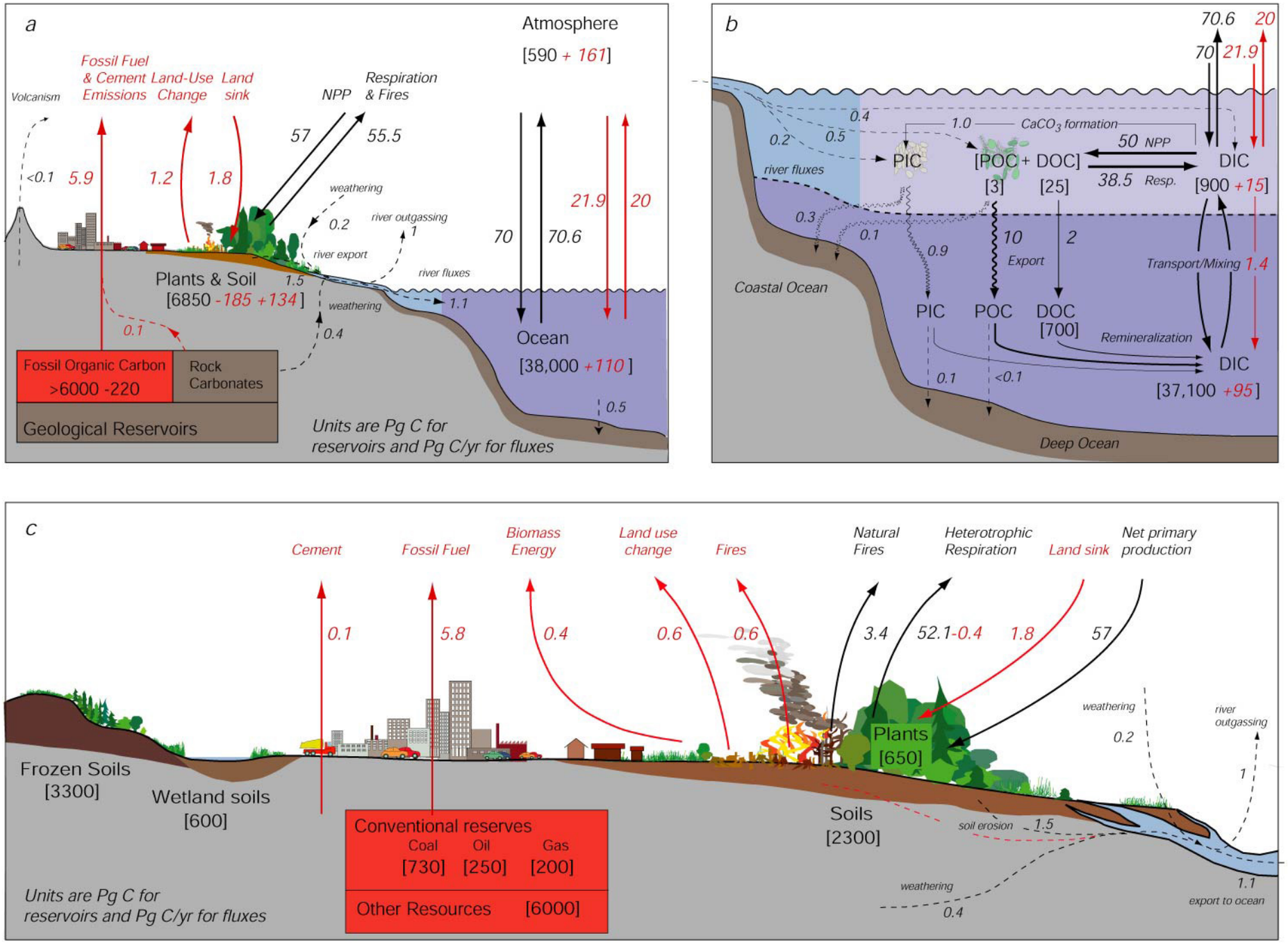
1

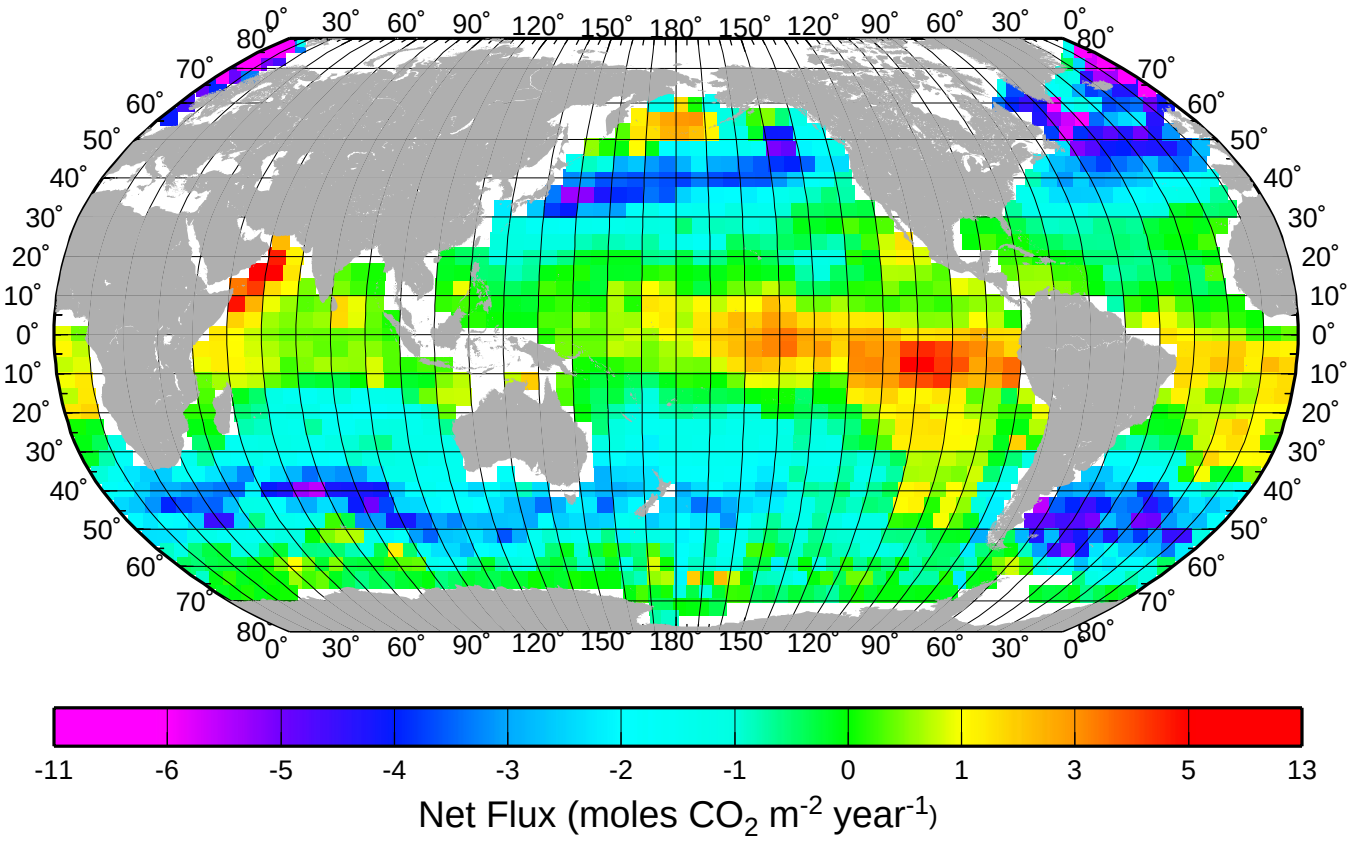
1

Table 1.2 Plant carbon, soil carbon, and net primary production in the world's major biomes. Plant carbon and NPP are from Roy et al. [Saugier et al., 2001]. Soil carbon is from Jobbagy and Jackson [2000], to a depth of 3m. Wetland soil carbon is from (ref). Carbon in frozen soils is from (ref).

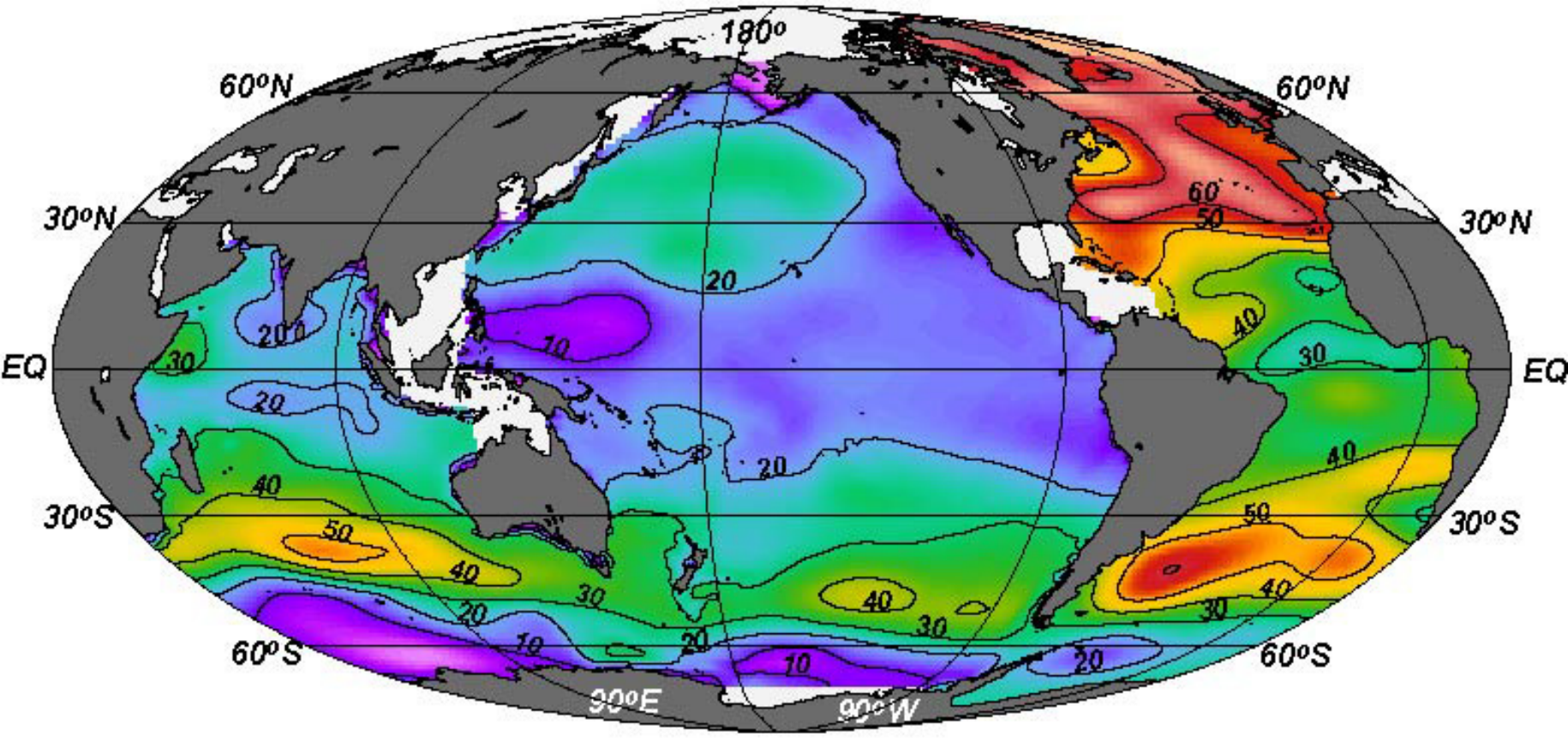
Ecosystem	Area	NPP	Plant C	Soil C
	(10^6 km^2)	Pg C yr^{-1}	Pg C	Pg C
Tropical forests	17.5	21.9	340	692
Temperate forests	10.4	8.1	139	262
Boreal forests	13.7	2.6	57	150
Arctic tundra	5.6	0.5	2	144
Mediterranean shrublands	2.8	1.4	17	124
Crops	13.5	4.1	4	248
Tropical savannas & grasslands	27.6	14.9	79	345
Temperate grasslands	15	5.6	6	172
Deserts	27.7	3.5	10	208
Subtotal	149.3	62.6	652	2344
Wetlands	?			600
Frozen soils	25.5			3300
Total	174.8?	62.6	652	6244

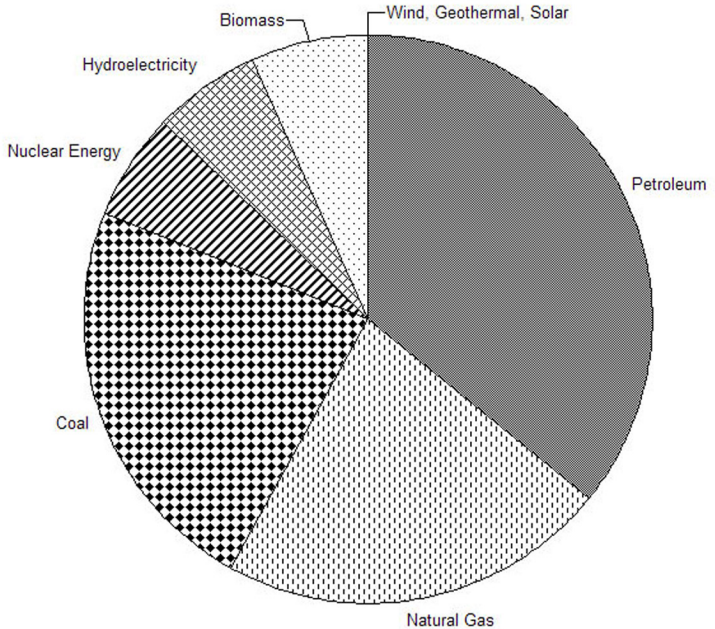
2

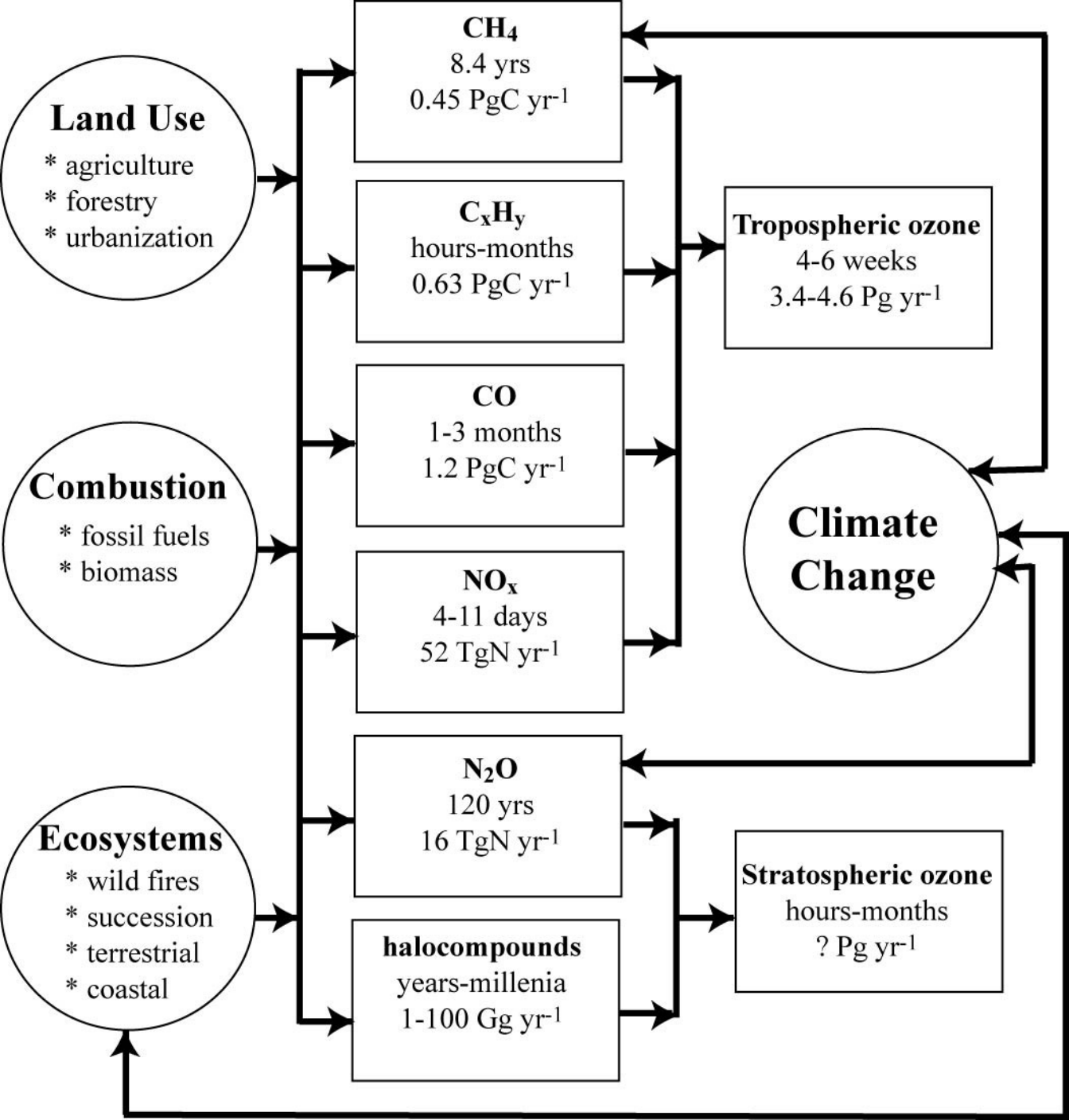

a
Atmosphere
[590 + 161]
Fossil Fuel & Cement Emissions
Land-Use Change
Land sink
Volcanism
NPP
Respiration & Fires
<0.1
5.9
1.2
1.8
57
55.5
weathering
0.2
river outgassing
1
river export
river fluxes
70
70.6
21.9
20
Plants & Soil
[6850 -185 +134]
1.5
weathering
1.1
0.1
0.4
Fossil Organic Carbon
>6000 -220
Rock Carbonates
Geological Reservoirs
Ocean
[38,000 +110]
0.5
Units are Pg C for reservoirs and Pg C/yr for fluxes
b
70.6
20
70
21.9
0.4
1.0
CaCO3 formation
50 NPP
0.2
0.5
river fluxes
PIC
[POC + DOC]
[3]
[25]
38.5 Resp.
DIC
[900 +15]
0.3
0.1
0.9
10
Export
2
Transport/Mixing
1.4
Coastal Ocean
PIC
POC
DOC
[700]
Remineralization
DIC
[37,100 +95]
0.1
<0.1
Deep Ocean
c
Cement
Fossil Fuel
Biomass Energy
Land use change
Fires
Natural Fires
Heterotrophic Respiration
Land sink
Net primary production
0.1
5.8
0.4
0.6
0.6
3.4
52.1-0.4
1.8
57
Frozen Soils
[3300]
Wetland soils
[600]
Conventional reserves
Coal
Oil
Gas
[730]
[250]
[200]
Other Resources
[6000]
Plants
[650]
Soils
[2300]
weathering
0.2
river outgassing
1
soil erosion
1.5
weathering
0.4
1.1
export to ocean
Units are Pg C for reservoirs and Pg C/yr for fluxes

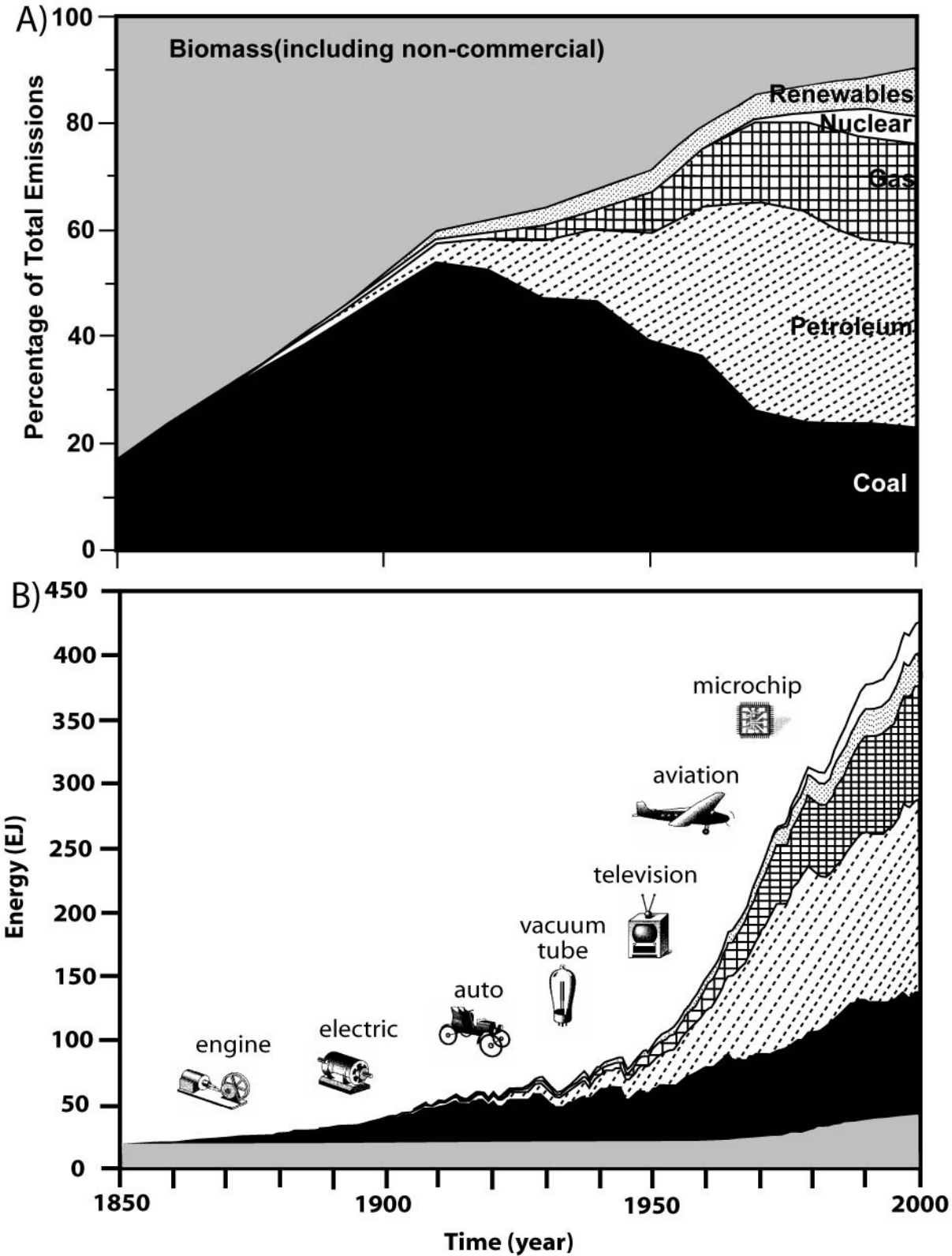

0° 30° 60° 90° 120° 150° 180° 150° 120° 90° 60° 30° 0°
80° 70° 60° 50° 40° 30° 20° 10° 0° 10° 20° 30° 40° 50° 60° 70° 80°
-11 -6 -5 -4 -3 -2 -1 0 1 3 5 13
Net Flux (moles CO2 m-2 year-1)

Anthropogenic CO_2 Column Inventory (mol m^{-2})




Biomass
Wind, Geothermal, Solar
Hydroelectricity
Nuclear Energy
Petroleum
Coal
Natural Gas


Land Use
* agriculture
* forestry
* urbanization
Combustion
* fossil fuels
* biomass
Ecosystems
* wild fires
* succession
* terrestrial
* coastal
CH4
8.4 yrs
0.45 PgC yr-1
CxHy
hours-months
0.63 PgC yr-1
CO
1-3 months
1.2 PgC yr-1
NOx
4-11 days
52 TgN yr-1
N2O
120 yrs
16 TgN yr-1
halocompounds
years-millenia
1-100 Gg yr-1
Tropospheric ozone
4-6 weeks
3.4-4.6 Pg yr-1
Stratospheric ozone
hours-months
? Pg yr-1
Climate Change


A)
Biomass(including non-commercial)
Renewables
Nuclear
Gas
Petroleum
Coal
Percentage of Total Emissions
0
20
40
60
80
100
B)
microchip
aviation
television
vacuum tube
auto
electric
engine
Energy (EJ)
0
50
100
150
200
250
300
350
400
450
1850
1900
1950
2000
Time (year)