Chapter 3
Introduction to Global Carbon Cycling: An Overview of the Global Carbon Cycle

Abstract Carbon (C) is the essential attribute of life. Therefore, its cycling gives the overall index of health of the biosphere. Global C cycling involves the exchange of C between its four main reservoirs—the atmosphere, terrestrial biosphere, oceans and sediments. Understanding the biogeochemical processes regulating the movement of C from one reservoir to another is central to control carbon dioxide (CO_2) and methane (CH_4) emissions and mitigating climate change. This introductory chapter presents an overview of the global C cycle. The atmospheric carbon burden —both CO_2 and CH_4 concentrations, has increased significantly since the beginning of the Industrial Revolution in response to anthropogenic perturbations of the global C cycle. The major sources of the increase in atmospheric C content are the utilization of fossil fuels for energy, cement production, land use conversion and deforestation. Fossil fuel and cement production released 410 ± 20 Pg C between 1750 and 2015. Similarly, land use change released 190 ± 65 Pg C over the same period. The atmospheric C burden increased by 260 ± 5 Pg between 1750 and 2015. The consequences of changes in global C cycling extend beyond the global warming associated changes in radiation balance caused by increased concentration of trace gases. It causes changes in atmospheric photochemistry, disturbances in terrestrial ecosystems as well as marine chemistry and ecosystems. In the following chapters these effects will be discussed in much more details.

Keywords Biosphere · Carbon reservoirs · Methane · Lithosphere · Carbon fluxes · Fossil fuels

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3.1 Introduction

Carbon (C) in the elemental form occurs as amorphous C, graphite and diamond. The C atoms can change their oxidation state from +4 to −6, and occurs mostly in the +4 state as carbon dioxide (CO_2) and in carbonate (CO_3^{2-}) form. The CO_2 is a trace constituent in the atmosphere, comprising $\geq 0.04\%$ of all molecules in the atmosphere. Carbonate is present in the lithosphere as calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), and siderite ($FeCO_3$). In aqueous form, carbonate exists as H_2CO_3, HCO_3^-, and CO_3^{2-}. Carbon monoxide (CO) is present in the atmosphere as oxidation state +2. The most reduced form of C (−4) is methane (CH_4).

Carbon is a fundamental element for all forms of life on Earth, and is the essential element present in all known life forms, making up $\sim 50\%$ of dry weight of living things. Therefore, estimates of global production and the decomposition of organic carbon (OC) gives the estimate of overall index of health of the biosphere—both past and present. Life requires an energy flow through the biosphere for which the dominant primary energy is solar radiation, and cycling of C through photosynthesis enables energy flow. The cycling of C approximates the flow of energy around the Earth, which include metabolism of natural ecosystems, human, and also industrial systems. Plants transform solar energy to chemical energy in organic C molecules which provide biochemical machinery underlying the evolution and use of environmental energy, the essential attribute of life. The C is one of six elements (C, H, O, N, P, and S) which form major constituents of plant tissue, and life on Earth depends on its cycling through various transformations and transfers among the atmosphere, the oceans, plants and animals, soils, rocks, and sediments at various timescales ranging from seconds (e.g., fixation of atmospheric CO_2 into carbohydrates and other plant biomass through photosynthesis) to geologic timescales (e.g., accumulation of fossil C through the diagenesis processes). C is constantly being absorbed, released, and recycled by a range of natural and human-induced physical, biological, and chemical processes in the biosphere. It also creates atmospheric greenhouse effect (as CO_2), buffers pH in sea water, and its redox buffers many reactions. The various constituents of C interact through biogeochemical cycling, a series of processes that transfers C among reservoirs and transform it among its various molecular forms during its transfers. Therefore, the global C cycling refers to exchange of C within and between array of C reservoirs linked by a network of physical, chemical, and biological processes. The overall C cycle consists of multiple nested cyclic pathways that differ with respect to some of their reservoir processes. The major reservoirs of C are: (i) the atmosphere, (ii) the oceans, (iii) terrestrial land (soil, vegetation), and (iv) lithosphere.

All C cycle pathways ultimately pass through the hydrosphere and atmosphere which is the common course that unites the entire C cycle and allow even its remote constituents to influence both the environment and the biosphere (Des Marais 2001).

Over millions of years, CO_2 is removed from the atmosphere through weathering processes—by silicate rocks and through burial of fixed C by marine plants in the marine sediments (Berner 1998). Chemical weathering, which results in CO_2 sequestration as $CaCO_3$ in sedimentary rocks at warmer Earth temperatures or release CO_2 to the atmosphere if the Earth becomes cold has enabled the Earth's climate to stay within a narrow range of temperatures through the geological timescale (Archer 2010). However, once disturbed, it will take hundreds of thousands of years for the Earth's climate to be restored through its natural C cycle balances.

The principal form of C in the atmosphere is CO_2 and CH_4. These gases have played crucial and distinct roles in the development of life forms and alteration of Earth's surface environment throughout the Earth's history. CO_2 is the principal medium of photosynthesis, metabolism and organic material decomposition. Through its transformation in weathering and CO_3^{2-} precipitation it supplies a large portion of the C cycling through the lithosphere. CO_2 is also the dominant long-lived greenhouse gas (GHG) contributing to climate forcing. Since 1750, its radiative forcing has increased by 1.94 W m^{-2} or ~65% of the increased forcing by all long-lived GHGs (NOAA 2015). Systematic atmospheric CO_2 concentration measurements began at Mauna Loa Hawaii in 1958 and established the annual mean mole fraction of 315 ppmv in 1958. The daily averaged CO_2 concentration at Mauna Loa exceeded 400 ppm for the first time in May 2013 (Fig. 3.1).

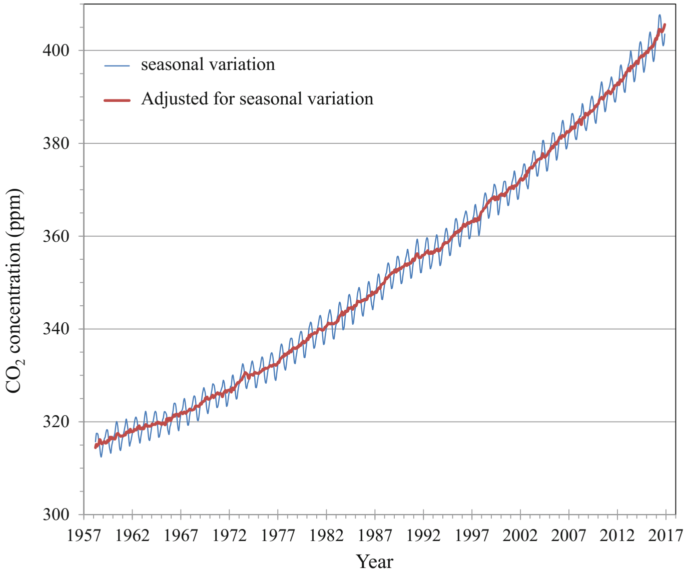

Fig. 3.1 Carbon dioxide measured at Mauna Loa, Hawaii

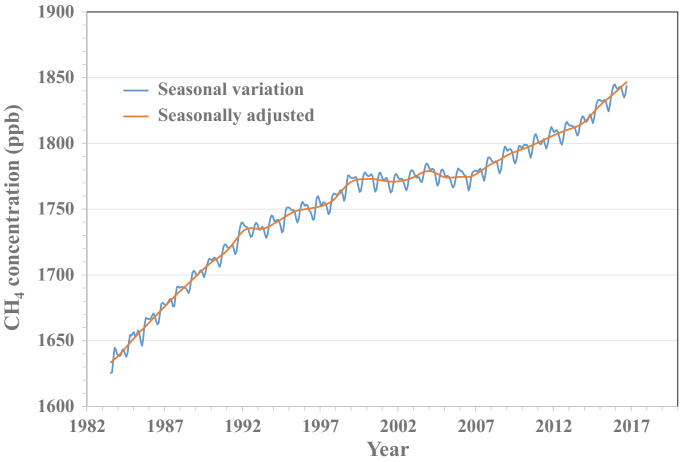

Fig. 3.2 Globally averaged dry air CH_4 mol fraction from 1983 to 2016 (data from NOAA/ESRL)

The atmospheric CH_4 has contributed ~0.5 W m^{-2} direct radiative forcing since 1750. Indirect effects from the production of tropospheric ozone (O_3) and stratospheric H_2O added another ~0.2 W m^{-2} making a total CH_4 radiative forcing of 0.7 W m^{-2} (NOAA 2015). Atmospheric CH_4 is produced by both natural (40%) and anthropogenic sources (60%). Atmospheric CH_4 has increased by about a factor of more than 2.5 since the pre-industrial era. The annual rates of increase of 10 ppb yr^{-1} in the 1980s slowed dramatically to near zero in the early 2000s' then jumped to 0.6 ppb yr^{-2} in 2007 and remaining steady since (Fig. 3.2). The CH_4 represents the anaerobic side of C cycling through microbial metabolism and release from organic matter (OM) trapped in rocks and sediments. The major transfers of C mass in the C cycle are usually associated with CO_2 through atmosphere where the atmosphere acts as a clearing station linking major C flows among its major reservoirs. However, CH_4 may have played a more important role in the past and is considered a more sensitive indicator of changes in Earth's processes. Both CO_2 and CH_4 are the primary compounds through which C cycling over all timescales has influenced the Earth's surface.

3.2 Photosynthesis and Respiration

Photosynthetic organisms take up CO_2 from the atmosphere and utilize sunlight energy to convert it to biomass as they grow, which animals and human beings use the generated biomass for food, shelter, and energy which fuels the biosphere. Therefore, photosynthesis is important fundamental process in which plants absorbs atmospheric CO_2 and also convert solar energy to chemical energy and store it in plants. When they die and decompose, the C contained in its biomass is transformed into soil organic matter (SOM), which is critical in conditioning soil quality and CO_2 production. Emissions from natural systems and anthropogenic activities return C to the atmosphere, which renews the cycle. Photosynthesis is also important for production of molecules of O_2 in the atmosphere. Thus, the C and oxygen cycles are intricately linked and the presence of O_2 in the Earth's atmosphere sets the redox potential for organic metabolism in ecosystem. The terrestrial ecosystems photosynthetic productivity changes in response to changes in temperature, precipitation, atmospheric CO_2 concentration, and plant nutrients supply. If climate changes to become more favorable for growth, productivity increases and C uptake from atmosphere is enhanced, and vice versa.

3.3 Timescales and Modes of the Carbon Cycle

The global C cycle can be viewed as a series of reservoirs of C in the Earth System which are connected by exchange fluxes of C. Two domains of C in the global cycle distinguished by the turnover rates are (i) fast turnover domain with large exchange fluxes and rapid reservoir turnovers consisting of the atmosphere, land vegetation, soils, and fresh waters, ocean, surface sediments in the ocean—with turnover ranging from few years to millennia, and (ii) slow turnover domain consisting of large pool of C in rocks and sediments with turnover in geological time—1,000,000 years or longer. The exchange of C between slow and fast domain occur only through chemical weathering, erosion and sediment formation in the ocean (Sundquist 1986). More detailed accounts on slow and fast turnover domains of C cycle are presented in Chaps. 5 and 6, respectively. The natural exchange fluxes between faster and slow domains are relatively small <0.3 Pg yr^{-1} (Pg C = Petagram C = 10^{15} g), and can be assumed to be constant over a timescales of centuries unless modified by human induced changes (Raymond and Cole 2003). Prior to Industrial Era, the fast domain was close to steady state with relatively small variations in atmosphere CO_2 and CH_4. However, fossil fuel combustion since the beginning of Industrial Era has transferred large quantities of C from slow domain to fast domain, resulting into significant and unprecedented anthropogenic perturbation of the global carbon cycle.

The biogeochemical C cycle involves abiotic and biotic processes, and transfers C within and between four major reservoirs—the lithosphere (i.e., the solid outer crust), the hydrosphere (i.e., the aqueous envelope of water bodies), the atmosphere and the biosphere linked by a complex set of natural and anthropogenic biogeochemical processes. The amount comprised in individual reservoirs illustrates their principal impact on the global cycle. The principal C emitter carrier in the C cycle is CO_2, and in the absence of anthropogenic influence, C cycle is generally in a steady state. Carbon exchange between individual reservoirs involves photosynthesis, respiration, gas exchange through the water-atmosphere interface and weathering. The C cycle has never been stable at any time in Earth's history.

Over geologic timescales, natural changes in the balance of fluxes in the global C cycle have caused past variations in atmospheric CO_2 concentrations, which has been associated with past changes in climate—such as the periods of expanded continental glaciation (i.e., ice ages) during the last several hundred thousand years which were associated with lower atmospheric CO_2 concentrations (Petit et al. 1999; Lüthi et al. 2008). Although the atmospheric CO_2 is just one of the many factors considered to have affected climate change over the course of Earth history, the existing geologic record is consistent with current understanding of the radiative contribution of CO_2 and CH_4 to the current and historic climate.

Mankind is altering these processes by transforming areas of natural vegetation to human use in agriculture, forest, and urbanization which has vastly changed Earth's land cover and redirect large quantities of global net primary productivity (NPP) to the production of food, fuel, clothing, and shelter (Haberl et al. 2007). The net result of human activities is to increase the release of CO_2 to the atmosphere.

The CO_2 moves between the atmosphere and ocean by molecular diffusion when there is a CO_2 gas pressure (pCO_2) gradient between atmosphere and the ocean. Based on large quantities of measurements of the global surface water pCO_2 since 1960's (Takahashi et al. 2002), a net decadal uptake of 2.2 ± 0.5, 2.3 ± 0.5, and 2.6 ± 0.5 Pg C yr^{-1} has been estimated for the 1990–1999, 2000–2009, 2006–2015, respectively, and an uptake of 3.0 ± 0.5 Pg C yr^{-1} is estimated for 2015 (Le Quéré et al. 2015, 2016).

The C cycle encompasses many processes, including the daily cycling of animal feeding and metabolism, the seasonal cycle of plant growth and decay, and geologic cycle of sediment burial and weathering, and all these processes are linked to the exchange of CO_2 with the atmosphere. The C cycling operates all life forms, inorganic C, organic C reservoirs, and links between them.

3.4 Introduction to Carbon Budget

The C budget is an accounting of the balances of exchanges of C among the reservoirs (i.e., how much is coming in from other reservoirs and going out at a particular time). When the inputs (i.e., the sources) to the reservoir exceed output (i.e., the sinks) the amount in reservoir increases. The cycling determines the budget observed at any particular time. The global C budget is currently out of balance, with C accumulating in the atmosphere in the form of CO_2 and methane (CH_4) since the beginning of industrial era—circa 1750.

The global mean atmospheric CO_2 concentration has increased by over 40% from approximately 278 parts per million (ppm) in 1750, the beginning of the Industrial Era at first slowly and then progressively faster (Etheridge et al. 1996; Joos and Spahni 2008) reflecting the pace of global industrial development, fossil fuel combustion, population growth, and agricultural expansion. The current atmospheric concentration is 400.0 ± 0.1 ppm by the end of 2015 (WMO 2016) the highest level measured in the past 800,000 years (Lüthi et al. 2008). These changes have been known from well-replicated measurements of the composition of air bubbles trapped in Antarctic ice. Atmospheric CO_2 concentration have been measured directly with high precision since 1957, and these measurements agree with ice core measurements and show a continuation of the increasing trend up to present. The increase was initially caused by anthropogenic release of C to the atmosphere from deforestation and other land use change and management activities. Although emission from fossil fuel combustion started before industrial era, it never became dominant source of anthropogenic emissions until around 1920s to present. The average increases in the rate of fossil fuel CO_2 emission more than tripled from $\sim 1\%\ yr^{-1}$ in the 1990's to 3.7% yr^{-1} the following decade (Raupach and Canadell 2010). Several lines of evidence have confirmed that recent and continuing increase of atmospheric CO_2 concentration is caused by anthropogenic CO_2 emissions—especially fossil fuels burning: (i) atmospheric O_2 is declining at a rate comparable with fossil fuel emissions of CO_2 since combustion consumes O_2, (ii) the characteristic isotopic signatures of fossil fuels (i.e., lack of ^{14}C and depleted content of ^{13}C) is fingerprinting and leaving their mark in the atmosphere, (iii) the increase in observed CO_2 concentration has been showing regional distribution with similar patterns of increased fossil fuel burning.

3.4.1 Changes in Atmospheric Carbon Dioxide and Methane Concentrations

Since the beginning of Industrial Era in 1750, the burden of CO_2 in the atmosphere has increased by approximately 40% from 589 Pg C in 1750 to current burden of 849 ± 5 Pg C in 2015 (Ciais et al. 2013; Le Quéré et al. 2015) at an average atmospheric increase of 0.98 Pg C yr^{-1} (Le Quéré et al. 2015, 2016). The three most important sources of the anthropogenic CO_2 in the atmosphere are (i) fossil fuels (coal, oil, and natural gas) combustion, (ii) land use change—conversion of natural forests and grasslands to agriculture land, and (iii) cement production and other industrial processes. The concentration of atmospheric CO_2 is currently significantly higher than at any time during the past several hundred thousand years and steadily heading towards a GHG burden not seen for some 20 million years.

When systematic CO_2 monitoring began at Mauna Loa, Hawaii in 1958, the annual mean mole fraction was 315 ppm. The daily CO_2 average concentrations recorded at Mauna Loa station was above 400 ppm for the first time in May, 2013 (Scripps 2014). Mauna Loa station has the longest running record of direct measurements of atmospheric CO_2 concentrations (Tans and Keeling 2014). The 27% increase is mainly due to fourfold rise in anthropogenic CO_2 emissions from fossil fuel combustion and cement production. The growth has correspondingly increased from 0.7 ppm yr^{-1} in early 1960s to 2.1 ppm yr^{-1} during the last decade (WMO 2016). The annual atmospheric increase varies considerably from year to year, ranging from 0.7 ± 0.1 to 2.8 ± 0.1 ppm yr^{-1} since 1990. The natural variations in El Nino Southern Oscillation (ENSO) are the main cause of year to year variations (Bastos et al. 2013). In 2015, globally averaged CO_2 mole fraction at the Earth's surface was 400.0 ± 0.1 ppm which was an increase of 2.3 ± 0.1 ppm over the 2014 average.

Similarly, emission of CH_4, which is released during extraction and processing of fossil fuels, leaks from natural gas extraction and distribution, and biological sources including landfills, expanding rice and livestock production, has also shown similar steady increase in concentration (Prinn 2004; Ciais et al. 2014, Fig. 3.2). Levels of CH_4 reached 1845 ± 2 parts per billion (ppbv) by the end of 2015 (WMO 2016), about 2.5 times their pre-industrial value of 722 ± 25 ppb (Etheridge et al. 1996). Atmospheric CH_4 is produced by natural (40%) and anthropogenic (60%) sources.

3.4.2 Impacts of Changing Global Carbon Cycle

Atmospheric CO_2 is increasing by slightly less than half of the rate of fossil fuels emissions however, the rest of CO_2 emitted is either dissolving in the sea water and mixing into the deep ocean or is taken up by the terrestrial ecosystems through excess primary production by photosynthesis. The atmospheric CO_2 emission that is taken up by ocean and land ecosystem can be calculated from the changes in atmospheric CO_2 and O_2 content, since terrestrial processes of CO_2 exchange involve exchange of O_2, while dissolution in the ocean does not.

The CO_2 and CH_4 are the second and third most important GHGs after water vapor ($H_2O(g)$). These GHGs have strong influence on the radiative properties of the atmosphere. As a result of this increase in atmospheric CO_2 and CH_4 concentrations, the globally averaged combined land and ocean surface temperature has increased by 0.85 ± 0.21 °C over the period 1880–2014 (IPCC 2014; Jones et al. 2013; Ruedy et al. 2015). Such large increases in atmospheric CO_2 over a short time relative to historical variations and associated increase in global temperature, together with patterns of anthropogenic activity emitting CO_2 and CH_4 to the atmosphere, which will likely continue for foreseeable future, raises serious concerns about the imbalances in the C cycle and their implications.

There is a growing concern that this increase in atmospheric CO_2 and CH_4 concentrations are causing significant warming and other changes in global climate by altering the heat and water balances of Earth's surface and atmosphere (Fig. 3.3). Ample physical evidence shows that CO_2 and CH_4 are the most important climate relevant GHGs in Earth's atmosphere, since ($H_2O(g)$) condenses and precipitate from the atmosphere at the current temperatures.

A second impact of anthropogenic CO_2 emission is ocean acidification, which refers to continuous decline in pH and reduction in ocean's carbonate (CO_3^{2-}) mineral saturation state (Caldeira and Wickett 2003; Johnson and White 2014). Over the past 200 years, the oceans has taken up ~40% of the atmospheric CO_2 emissions, which has caused pH level of world's oceans to drop by 0.1 unit,

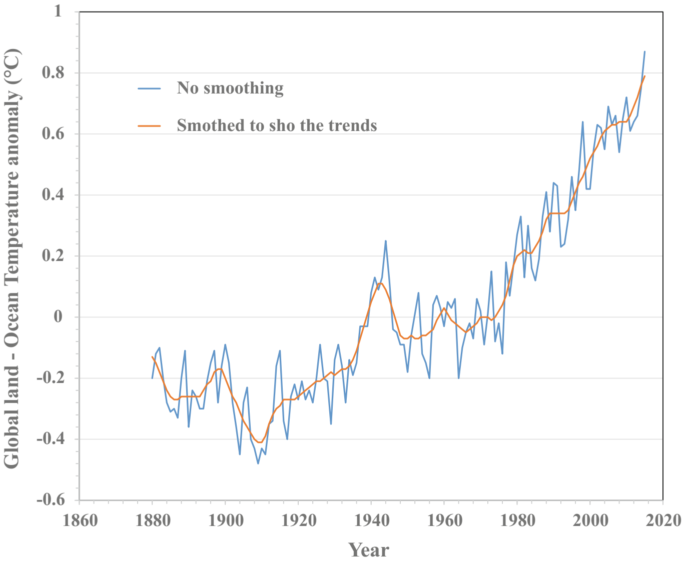

Fig. 3.3 Global land-ocean temperature anomaly. *Data source* http://data.giss.nasa.gov/gistemp

amounting to 30% increase in ocean acidity (Johnson and White 2014). Although this uptake slows the rise in atmospheric CO_2 concentration considerably, it also alters ocean chemistry with potentially negative consequences for marine life (Zeebe et al. 2008). This process has a detrimental consequences for a variety of marine organisms (Hoegh-Guldberg et al. 2007).

Other factors associated with changes in ocean chemistry include effects on speciation which could alter metal bioavailability (Millero et al. 2009), reduced NH_3/NH_4 ratios affecting ammonia oxidation rates, N cycling, and marine sources of atmospherically active trace gases (Hutchins et al. 2009; Beman et al. 2011), reduced ocean overturning (Gregory et al. 2005), sea level rise as a result of warmer temperatures and melting ice (Tyrrell 2011).

Terrestrial ecosystems are absorbing an estimated 20–30% of the annual anthropogenic CO_2 emissions, which have increased since 1990 (Le Quéré et al. 2009, 2015), probably as a response to CO_2 fertilization. Evidence suggests that the elevated atmospheric CO_2 as a result of anthropogenic CO_2 emissions is causing CO_2 fertilization effect, i.e., increase in leaf photosynthesis with rising atmospheric CO_2 concentration (Zak et al. 2011; De Kauwe et al. 2013). However, the magnitude of CO_2 fertilization and its continuity into the future are a matter of debate (Newingham et al. 2013).

Many countries have adapted a global warming temperature rise limit of 2.0 °C or below relative to pre-industrial level as a guiding principle for mitigation efforts to reduce climate change risks, impacts and damage (IPCC 2007; IPCC 2014). Despite this restriction, global emissions of CO_2 from fossil fuels combustion and cement production have continued to grow by 2.5% yr^{-1} over the past decade (Friedlingstein et al. 2014). Similarly, two thirds of the CO_2 emission quota consistent with a 2.0 °C temperature limit has already been used, and the remaining one third will likely be exhausted in the next 30 years at the emission rates of 2014 (Raupach et al. 2014; Friedlingstein et al. 2014).

Moreover, the projection of CO_2 emissions and its attendant effects of climate modification and ocean chemistry alteration have typically focused on the century time-scale, most notably until the year 2100 (IPCC 2007; IPCC 2014). However, from geological, and biogeochemical perspective, CO_2 released by anthropogenic activities have the longer term consequences which are equally, if not more important. For example, a large fraction of anthropogenic CO_2 emissions stays in the air for long time. One quarter of the anthropogenic CO_2 will remain airborne for several centuries (Archer et al. 2009; Kharecha and Hansen 2008). This implies that even if anthropogenic emission is capped at a fixed concentration, the climate change will continue for several centuries as the C cycle adjusts to new equilibrium. In contrast, if the fossil fuel combustion is fully controlled, the climate and geochemical recovery will take tens to hundreds of thousands of years well after the emissions have ceased (Archer et al. 2009), while biotic, in terms of biodiversity and ecosystem functioning may take millions of years (Alroy 2008). The complexity of the Earth system, particularly involving the contribution of physical feedbacks has made the prediction of future responses of the Earth system, and climate prediction difficult.

The accelerating CO_2 emission rate and failure of environmental sinks to keep pace with current emission rates makes stabilization of atmospheric CO_2 during this century even tougher challenge. The atmospheric CO_2 stabilization requires that net emission level off, and eventually drop to near zero, where the rate of CO_2 addition to the atmosphere equals the rate at which the natural systems can remove them (i.e., anthropogenic CO_2 emissions is balanced by the natural sink capacity). To achieve this stabilization requires transformation of energy systems worldwide, which will require many decades of development and deployment. The current GHG burden will lead to warmer future, both in our lifetime and for generations to come as energy balance of the Earth systems slowly adjusts to new equilibrium with rising GHG concentrations. Anthropogenic activities, mainly fossil fuel burning, forest clearing and agricultural activities are primarily responsible for current GHG burden. Anthropogenic CO_2 emissions are occurring on top of an active natural C cycle that circulates C between atmosphere, terrestrial biosphere and ocean reservoir on time scale ranging from days to millennia, while the circulation of geologic reservoir with other reservoirs have much longer time scales (Archer et al. 2009). There is a strong consensus that global C cycling and climate perturbations from land use change and fossil fuels CO_2 release extends hundreds of thousands of years into the future. Although the atmospheric lifetime of CO_2 is relatively short, ~100 years, modeling reveals that 20–35% of CO_2 emitted to the atmosphere now will still be in the atmosphere after 2–20 millennia. Therefore, for all practical purposes fossil fuels and land use change CO_2 emissions should be considered irreversible, and any eventual stable atmospheric CO_2 will be dictated by total accumulated emissions over the preceding centuries rather than balance of emissions and removals (Allen et al. 2009; Mackey et al. 2013).

The burning of fossil fuels which transfers large masses of fossilized C from geological reservoirs of coal, oil, and natural gas from slow domain, and releases large masses of C in the form of CO_2 into the atmosphere (i.e., a fast domain reservoir), has dominated the anthropogenic CO_2 emissions in recent years. The cumulative emissions from fossil fuel combustion from 1870 to 2013 are estimated at 390 ± 20 Pg C. An additional 3 Pg C were emitted for the earlier period 1750–1869 (Le Quéré et al. 2015). The 1800s and 1900s experienced a great rise in combustion of fossil fuels—coal, petroleum, and natural gas, releasing into atmosphere large quantities of C that was originally stored in geological formation. About 45 Pg C were emitted from land use change from 1750 to 1869, of which, 10 Pg C was emitted from 1850 to 1869. From 1870 to 2013, land use change released 145 ± 50 Pg C (Houghton et al. 2012). Emission of C from fossil fuel combustion started before the Industrial Era, however, fossil fuel combustion exceeded the CO_2 emissions from burning and decomposition of dead plant material that accompanied forest clearing for agricultural land use from around 1920 (Houghton 2014) and continued to be the dominant source until present (Chap. 6). Terrestrial systems are also an anthropogenic source of CO_2 when land use change leads to loss of C from soils and plants. Deforestation and other land use changes also release C to the atmosphere, as well as reducing the vegetation uptake of CO_2 from the atmosphere. More than 75% of Earth's ice free land shows evidence of alteration as a result of human residence and land use, with less than a quarter remaining as wild lands supporting just 11% of terrestrial net primary production (Ellis and Ramankutty 2008). Although the influence of human on the fluxes and reserves of C among the three reservoirs—atmosphere, terrestrial biosphere, and ocean represent a small changes in total pools of C, but it represent a significant perturbation of a global C cycle.

The evidence of human impact on the planet is so great that it has been suggested that the Earth has entered a new geological era dominated by human activity called 'Anthropocene' (Steffen et al. 2007; Raupach and Canadell 2010), to distinguish it from the preceding Holocene which started at about 12,000 years before present (BP; i.e., 1950). However, there is no agreed definition of Anthropocene, and also no agreeable official starting date (Doughty 2013). Because climate change may be the most important global impact of human on the planet it may also be good proxy for the onset of Anthropocene. The dates most often quoted to correspond with the start of Anthropocene is the onset of Industrial Revolution when extensive burning of coal began to greatly change the composition of the atmosphere (Steffen et al. 2007). Anthropogenic influence and trends are evident in the global C cycle and its connection with climate. Other changes in Earth system stemming from human activities include biodiversity loss and disturbance of nutrients cycles.

With the invention of steam engine, the internal combustion engine and other technological advances and economic elements of Industrial Revolution, human societies discovered the great value of fossilized C formed hundreds of millions of years ago as the energy source for economic growth. The global carbon cycling through atmospheric, terrestrial, and oceanic reservoirs have dispersed the greater part of these anthropogenic emissions, locking the CO_2 into terrestrial plant biomass and soil, and also by dissolution into oceans.

3.5 Global Warming

In 1896, Arrhenius concluded that the continued emission of CO_2 from combustion of fossil fuels could lead to a warmer climate. Although his succeeding calculations were incomplete, his fundamental conclusions of linking fossil fuels combustion, the radiation balance of the Earth system, and global climate have been confirmed by both models and studies of the past climate (Chap. 8). This early pioneering discussion of the relationships between changes in atmospheric CO_2 concentration and climate change became motivation for advancing scientific studies in many fronts. The research on global C cycle has enabled scientists to attribute the rising in atmospheric CO_2 concentrations primarily from anthropogenic activities, especially the burning of fossil fuels—coal, oil, and gas, together with the changing land use, especially deforestation. During the late 1950s, a growing number of scientists became interested in studying anthropogenic effects on the global C cycle (Keeling 1958; Revelle and Suess 1957). This interest is exemplified by Revelle and Suess (1957) who pointed out that: "*The human beings are now carrying out a large geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future. Within a few centuries we are returning to the atmosphere and oceans the concentrated organic carbon stored in sedimentary rocks over hundreds of millions of years. This experiment, if adequately documented, may yield a far reaching insight into the processes determining weather and climate. It therefore becomes of prime importance to attempt to determine the way in which carbon dioxide partitioned between the atmosphere, the oceans, the biosphere and the lithosphere*" (Revelle and Suess 1957) [pp. 19–20]. In this single phrase, Revelle and Suess (1957) described the connections between anthropogenic production of CO_2 and the array of earth and biological processes that cycles C over geologic time, and it has been a rallying desire to understand human manipulation of the atmospheric CO_2 as a profound global environmental change.

The basic understanding of the link between CO_2 emissions and climate change led to investment into formation of United Nations Framework Convention on Climate Change (UNFCCC) in 1992 signifying international recognition of vulnerability of global climate to human actions. The Intergovernmental Panel on Climate Change (IPCC) established by the United Nations as a tool for synthesizing scientific information has released 5 comprehensive assessments on scientific basis of climate change. Also, International Council for Science Unions (ICSU) has orchestrated several projects devoted to global C budget. The following 4 chapters are the synthesis of some current understanding on the global C cycling.

3.6 Conclusion

The overall objective of global C cycle research has been to account for complete mass balance of the CO_2 produced by anthropogenic activities—including its sources, processes that removes it from the atmosphere i.e., its sinks, and forms in which C from CO_2 is stored—i.e., reservoirs. Research directed towards improving projection of C cycle is increasingly intertwined with research directed towards improving understanding of climate change and improving climate change projection (Friedlingstein et al. 2006; Field et al. 2007). The challenge of controlling the increase in atmospheric concentration of CO_2 is the topic of expanding concern which has attracted national and international attention. The following chapters will describe the global carbon cycling with the emphasis on how the anthropogenic activities have altered this cycling.

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