SOM Pool of A Black Soil: Impacts of Land-use Change and Long-term Fertilization

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by

Han Xiaozeng
National Field Research Station of Agro-ecosystem in Hailun, Northeast Institute of Geography and Agro-ecology, Chinese Academy of Sciences

Li Haibo
College of Plant Sciences, Jilin Academy of Agricultural Science and Technology

Responsible Editor: Zhang Zhen

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Foreword

Human activity (fossil fuel combustion and land-use change) consumed large amounts of energy resources leading to CO_2 and other greenhouse gases emitted into atmosphere, which escalated and changed natural processes resulting in greenhouse effect and global warming, and it is estimated that atmospheric [CO_2] has increased from a pre-industrial concentration of about 280 ppm to about 380 ppm[①]. The global carbon cycle is defined as the processes of carbon flow and exchange through the biosphere, atmosphere, hydrosphere, and geosphere being one of the most complex, interesting and important global element cycles. The cycle is usually thought of as four major pools of carbon interconnected by pathways of exchange. These pools include the atmosphere, the terrestrial biosphere, the oceans and the sediments (including fossil fuels). Soil carbon pool is the largest carbon reservoir in the terrestrial biosphere, and its carbon storage is twice that of the atmosphere and three times that of the vegetation including forest, grassland and arable land. Soil carbon pool can be either sink or source depending on the carbon input and output through soil-plant-atmosphere interface. Thus, globally, not only scientists and government leaders, but common people are concerned about to what extent global soils can sequester the increasing atmospheric [CO_2].

The black soil zone in northeast China, where the soil type of Mollisol (according to US Taxonomy) is widely distributed, and it is crucial for national food production because this region occupies about 20% of the national arable land and produces more than 30% of national foods as commodity. The natural vegetation in this region was prairie and marshland grasses, and the land-use change took place about a century ago with natural landscape converted to arable land. Nowadays, intensive agricultural practices during the past three decades gave rise to serious agricultural and environmental problems, such as soil erosion, soil and water pollution, and crop yield repression. Therefore, keeping the sustainable utilization of black soil plays a key role in national food security. The studies conducted by some researchers with respect to the dynamics of soil organic carbon (SOC), the structure and composition of soil humic substances, and changes of SOC fractions have obtained lots of important achievements, of which more than 10 papers of SCI sources have been published. However, it is in need of researches to reveal the stability of carbon pool and carbon cycling of black soil. In addition, the mechanisms of carbon sequestration into and carbon losses from the black soil and the assessment on carbon budget through ecosystems and soil-atmosphere interface remain unclear. To resolve these scientific questions will help meet the national needs for

① IPCC. 2007. Climate Change 2007: the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate. United Kingdom and New York, NY, USA: Cambridge University Press, Cambridge.

the decision in dealing with global climate change, and it is also of great significance for the agriculture production and environment protection in black soil zone. On the basis of the long-term position experiments established in the National Field Research Station of Agro-ecosystem in Hailun, and Key Laboratory of Black Soil Ecology of Chinese Academy of Sciences, this research aims to examine the impact of land-use change and long-term fertilization on soil carbon stocks, the physically protected SOC, and carbon emissions from black soil as well as carbon budget through the ecosystems and soil-plant-atmosphere interface. The stability mechanism of black soil carbon pool was defined, and carbon sequestration capacity of black soil was also evaluated.

This book includes nine chapters. Chapter 1 reviewed the international and national research advances in relation to global and terrestrial ecosystem carbon cycling, the photosynthesis and the respiration including plant and soil respiration, and the assessment methodology of carbon budget through soil-plant-atmosphere system and greenhouse effects. In addition, the composition of soil carbon pool and the effects of land use and long-term fertilization on SOM pool, the advances of the physical protection mechanisms of SOM were described. Finally, the chapter introduced the research results regarding the widely used isotope techniques to fractionate SOM.

Chapter 2 gave a brief description of black soil region. Firstly, the ecological and environmental conditions in the black soil zone were introduced, i.e., the meteorological and hydrologic conditions, parent material, topography, vegetation, evolution and development of Mollisol. Secondly, the land-use change and fertilization status in black soil region, and the physical, chemical and biological characteristics of the black soil were briefly described. Finally, a brief introduction to Hailun Station was presented, in which several important long-term position experiments were introduced.

Chapter 3 introduced the related experimental methodology. The experimental sites and the long-term experiments for this research, such as different types of land use and different patterns of fertilizer and rotation management practices, were first described. Then, the SOM stocks estimation, the combined physical fractionation scheme comprised of aggregate sieving and density separation, and the chemical fractionation protocol to extract humic substances, were introduced. Finally, this chapter provided the methodology of the determination of carbon emission from the black soil and the estimation of the carbon budget through the soil ecosystems.

Chapter 4 described the variation of SOM stocks differing in land use and long-term fertilization. This part of the book estimated the changes of SOC and soil nitrogen densities due to the land-use change and long-term fertilization, and further assessed the capacity of carbon sequestration into black soil under different management practices in terms of SOC and soil nitrogen content and soil bulk density determined at different soil depths within 2 m soil matrix.

Chapter 5 introduced SOM distribution in density separated fractions affected by land-use change and long-term fertilization. This chapter characterized the distribution of organic carbon and nitrogen in separated density fractions following physical fractionation and alkali extraction procedures, and evaluated the long-term impacts of natural vegetation restoration and organic amendment on carbon sequestration into a typical Mollisol.

Chapter 6 examined aggregate stability and SOM distributed in aggregate fractions differing in land use and long-term fertilization. This part of the book determined the organic carbon storage in different sizes of water-stable aggregates and density-separated fractions of the black soil under different land use and fertilizer application management patterns. This work will provide scientific data for effective soil management to improve soil quality and mitigate greenhouse effect in the black soil region.

Chapter 7 examined aggregate stability and SOM distributed in aggregate fractions of rhizosphere soils under different continuous-rotation cropping systems and vegetation restoration. This chapter examined and assessed the effects of plant roots of continuous maize, continuous soybean and continuous wheat, and maize-soybean-wheat rotation cropping system and natural vegetation restoration on the stability of soil aggregate the SOM distributed in rhizosphere on the basis of long-term position experiments.

Chapter 8 described particulate organic matter (POM) distribution in physically protected fractions as affected by land use and long-term fertilization. In this chapter, the soil aggregate stability and organic carbon distributed in the size classes of water stable aggregates as influenced by land-use change and long-term fertilization were investigated. Additionally, organic carbon distribution in POM fractions within different sizes of water-stable aggregates was examined to assess to what extent the POMs as indicators of soil quality have impacts on aggregate stability.

Chapter 9 examined the effects of land-use change and long-term fertilization on CO_2 emission and carbon budget through soil-plant-atmosphere system. This chapter evaluated the impact of natural vegetation restoration and long-term soil management practices on the seasonal pattern of soil respiration including rhizosphere respiration and native soil respiration, and cumulative CO_2 emission from black soils of northeast China. The second part of this chapter estimated the carbon balance through grassland, bareland and agricultural ecosystems, and carbon budget through soil-atmosphere interface. These results can provide supporting evidences for the crucial decision of regional and national governments on the national food security and environmental protection.

The researches included in this book were made possible thanks to the long-term experiments conducted at the National Field Research Station of Agro-ecosystem in Hailun, Heilongjiang province, China, with the financial support of Chinese Ecological Research Network (CERN). Also, We express our gratitude to the scientists who helped to manage the experiments in the past. This work was supported in part by a grant from the National Basic Research Program of China (2005CB121101 and 2010CB134509), the National Science and Technology Sustaining Program (2006BAD05B05), the Knowledge Innovation Program of the Chinese Academy of Sciences (KZCX2-YW-407, KSCX-YW-09-09), and the Science and Technology Program of Heilongjiang province (GB06B107-2, GB05C201-01).

Han Xiaozeng
Li Haibo
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Contents

1 Carbon cycling and SOM pool

1.1 Introduction

Global climate change induced by fossil fuel combustion and land-use change leads to increasing atmospheric CO_2 concentration resulting in the occurrence of greenhouse effect and global warming, and further giving rise to the thawing of snow and ice in polar areas and elevation of sea level. The biogeochemical cycles of terrestrial ecosystem disturbed by human activities resulted in the sharp decline of SOC content and gave off greenhouse gases in the form of CO_2 and CH_4, which have direct negative effects on the survival and development of human being. Land-use changes have long-term impacts on terrestrial ecosystem, and come up with problems regarding the changes of soil carbon pool and carbon budget through soil-atmosphere systems which are becoming the hotspot of global change researches. Soil carbon pool as the largest in terrestrial ecosystem approximately amounts to the combination of atmosphere and vegetation carbon pool (Lal, 2004). Soils are globally either the source or sink of greenhouse gases depending on carbon input or output of soil ecosystem. The changes of soil carbon pool influence soil fertility, and atmospheric CO_2 concentration otherwise. The decomposition of SOM supplies energy and substrate for microbial metabolism, and mineral nutrients for plant growth and development as well. SOM plays a key role in soil aggregation as a binding agent that affects soil structure and forms different sizes of aggregates, and improves the function of aeration and water retention, and thus SOM can act as a very important factor indicating soil fertility as well as environmental quality (Tiessen *et al.*, 1994; Cai, 2004). In addition, SOM decomposes into greenhouse gases such as CO_2, CH_4 and N_2O by soil chemical or biochemical processes, and as a result the induced environmental effects detain the sustainable development of human society.

Mollisol meanly distributed in Heilongjiang, Jilin and Inner Mongolia is very fertile and productive. Corn, soybean and wheat are widely cultivated in this semi-arid agricultural zone. The black soil zone was reclaimed about a century ago, then the conversion of land use occurred from natural vegetation to crop-grass system, corn-soybean-wheat rotation system and corn-soybean rotation system. The black soil is commonly kept in the state of freezing for about half a year which has the properties of higher content of silt and clay and lower water infiltration than that inhibit microbial activity, resulting in the accumulation of SOM and biological cycling of soil mineral elements that takes place in 2 m of soil regime. The specific formation process of black soil and fertilization patterns leads to the difference of soil physical, chemical and biological as well as biochemical properties from other soil types in China. Land use and cover change drastically altered soil properties, resulting in the significant decrease of SOC and soil fertility, and redistribution of SOC and organic C fractions such as fulvic acid, humic acid and humin, and oxidized stable coefficient (*Kos*). Soil erosion frequently occurring to this region leads to the degradation of black soil ecosystem (Yu *et al.*, 2004; Meng and Zhang, 1998; Xu and Wang, 2005; Fang *et al.*, 2005; Yu and Zhang, 2004). Therefore, the study on carbon cycling and stabilization of carbon pool in black soil is crucial for improving regional and national sustainable agricultural production and providing a reference for scientific research in relation to global carbon cycling. Up to now, lots of achievements regarding SOM in black soil were obtained to examine the latitudinal distribution of SOM, the composition and function of soil humus (meanly HA, humic acid), and the impact of different soil managements on SOC contents and organic carbon distributed in fractions (Xing *et al.*, 2004, 2005; Liu *et al.*, 2003, 2005; Han *et al.*, 2006; Wang *et al.*, 2006). However, information with respect to the stabilizing mechanism of black soil carbon pool, carbon exchange and carbon budget through soil-plant-atmosphere system is still limited, and, thus, this book aims to deal with the scientific problems with respect to the distribution of physically protected SOM fractions, and assess soil carbon balance and carbon budget through soil-plant-atmosphere system and carbon sequestration capacity into black soil differing in land use and long-term fertilization under the circumstance that climate, parent material, topography and reclamation history are held constant.

1.2 Global and terrestrial ecosystem carbon cycling

1.2.1 Introduction and history

Carbon is unquestionably one of the most important elements on Earth. It is the principal building block for the organic compounds that make up life. Carbon's electron structure gives it a plus 4 charge, which means that it can readily form bonds with itself, leading to a great diversity in the chemical compounds that can be formed around carbon; hence the diversity and complexity of life. Carbon occurs in many other forms and places on Earth; it is a major constituent of limestones, occurring in the form of calcium carbonate; it is dissolved in ocean water and fresh water; and it is present in the atmosphere as carbon dioxide, the most important greenhouse gas.

The flow of carbon throughout the biosphere, atmosphere, hydrosphere, and geosphere is one of the most complex, interesting and important global element cycles (Figure 1.1). The cycle is usually thought of as four major reservoirs of carbon interconnected by pathways of exchange. The reservoirs are the atmosphere, the terrestrial biosphere (which usually includes fresh water systems and non-living organic material, such as soil carbon), the oceans (which includes dissolved inorganic carbon and living and non-living marine biota), and the sediments (which includes fossil fuels). The annual movements of carbon and the carbon exchanges between reservoirs occur because of various chemical, physical,

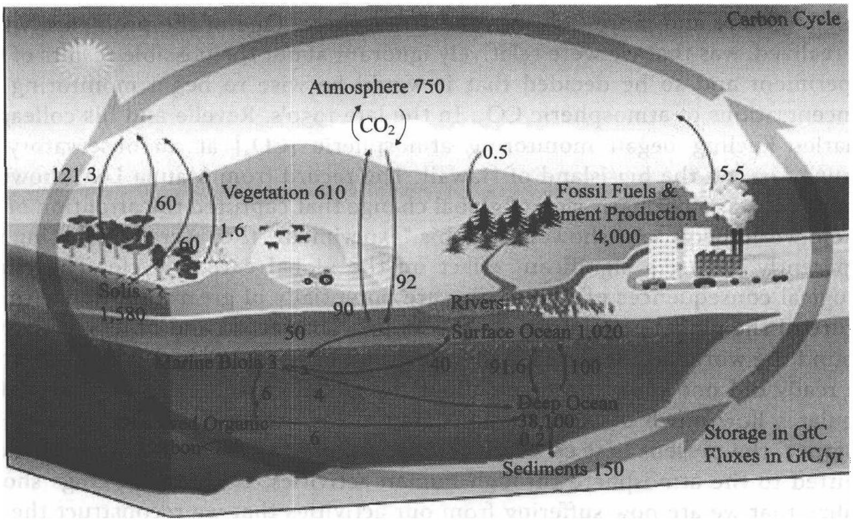

Figure 1.1 Diagram of the carbon cycle. The black numbers indicate how much carbon is stored in various reservoirs, in billions of tons ("Gt C" stands for Giga Tons of Carbon and figures are circa 2004). The purple numbers indicate how much carbon move between reservoirs each year. The sediments, as defined in this diagram, do not include the about 70 million Gt C of carbonate rock and kerogen.(Source from http//en.wikipedia.org, the free encyclopedia. Download 2009-09-20).

geological and biological processes. The ocean contains the largest active pool of carbon near the surface of the Earth, but the deep ocean part of this pool does not rapidly exchange with the atmosphere. More than any other globally biogeochemical cycling processes, the carbon cycle challenges us to draw together information from biology, chemistry, oceanography and geology in order to understand how it works and what causes it to change. The major reservoirs for carbon and the processes that carbon move from reservoir to reservoir are shown below in Figure 1.1. We will discuss these processes in detail afterwards. But first we will explore part of the history of carbon cycle studies.

The global carbon cycle is currently the topic of great interest because of its significance in the global climate system and also because human activities are altering the carbon cycle to a significant degree. The potential effects of human activities on the carbon cycle, and the implications for climate change were firstly noticed and studied by the Swedish chemist, S. Arrhenius, in 1896. He realized that CO_2 in the atmosphere was an important greenhouse gas and that it was a by-product of burning fossil fuels (coal, gas, oil). He even calculated that a doubling of CO_2 concentration in the atmosphere would lead to a temperature rise of 4-5°C which was amazingly close to the current estimates obtained with global, 3-D climate models that run on supercomputers. This early recognition of human perturbations to the carbon cycle and the climatic implications did not raise many eyebrows at the time, but the experiment was just beginning then. About 60 years later, Roger Revelle, an American oceanographer, pointed out that we were effectively conducting a giant experiment with our climate system by emitting more and more CO_2 into the atmosphere. One of the problems, which he realized, was that we were relatively ignorant about the possible results of this experiment and so he decided that it would be wise to begin monitoring the concentrations of atmospheric CO_2. In the late 1950's, Revelle and his colleague, Charles Keeling began monitoring atmospheric $[CO_2]$ at an observatory on Mauna Loa, on the big island of Hawaii. The record from Mauna Loa, shown in Figure 1.2, was a dramatic sign of global change that captured the attention of the whole world because it showed that this "experiment" they were conducting was apparently having a significant effect on the global carbon cycle. The climatological consequences of this change are potentially of great importance to the future of the global population. As the Mauna Loa record and others alike from around the world accumulated, a diverse group of scientists began to realize that we really did not know too much about the global carbon cycle that ultimately regulates how much of our emissions stay in the atmosphere. Considering, for instance, the present best estimate of what happens to all of the carbon dioxide emitted to the atmosphere through human activities, we human beings should realize that we are now suffering from our activities that we reconstruct the nature.

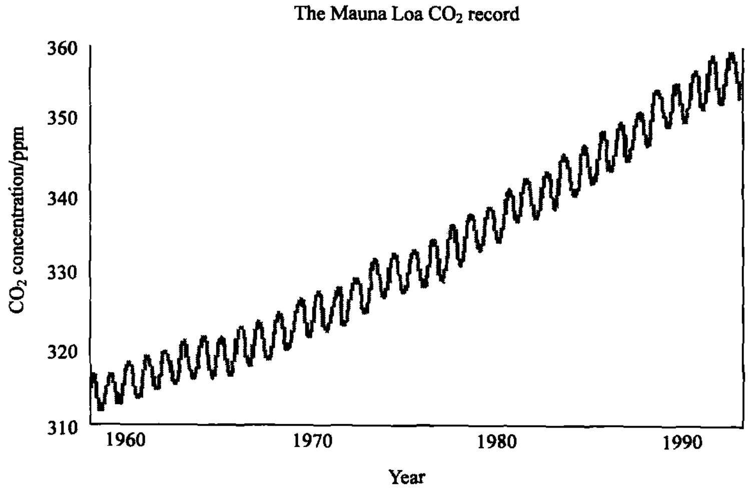

Figure 1.2 The record of CO_2 measured at Mauna Loa, Hawaii shows seasonal cycles related to the activity of plants in the northern hemisphere on top of an increasing trend to higher values. (Source from http: //www. carleton. edu/departments/geol/DavesSTELLA/carbon-intro. htm. Download 2009-9-20).

Carbon Cycle Budget for Anthropogenic Effects was estimated as follows (Figure 1.3):

Sources:

Fossil Fuel Burning & Cement Production 6.3±0.6 Gt C/yr

Net Emissions from Land-Use Change (Forest Burning & Soil Disruption) 1.6±0.8 Gt C/yr

Total Anthropogenic 7.9±1.4 Gt C/yr

Sinks:
Storage in Atmosphere 3.3±0.2 Gt C/yr
Ocean Uptake 2.3±0.8 Gt C/yr
*Boreal Forest Regrowth 0.5±0.5 Gt C/yr
Missing Sink (Unidentified Sink) 2.3±1.3 Gt C/yr
GtC = Gigatons of carbon = 10^9 tons data from IPCC, 1995

Successful carbon management strategies will require solid scientific information about the basic processes of the carbon cycle and an understanding of its long-term interactions with other components of the Earth system such as climate and the water and nitrogen cycles. Such strategies also will require an ability to account for all carbon stocks, fluxes, and changes and to distinguish the effects of human actions from those of natural system variability (Figure 1.3). Because CO_2 is an essential ingredient for plant growth, so it will be essential to address the direct effects of increasing atmospheric concentrations of CO_2 on terrestrial and marine ecosystem productivity. Breakthrough advances in techniques to observe and model the atmospheric, terrestrial and oceanic components of the carbon cycle have readied the scientific community for a concerted research effort to identify, characterize, quantify and project the major regional carbon sources and sinks with North America as a near-term priority.

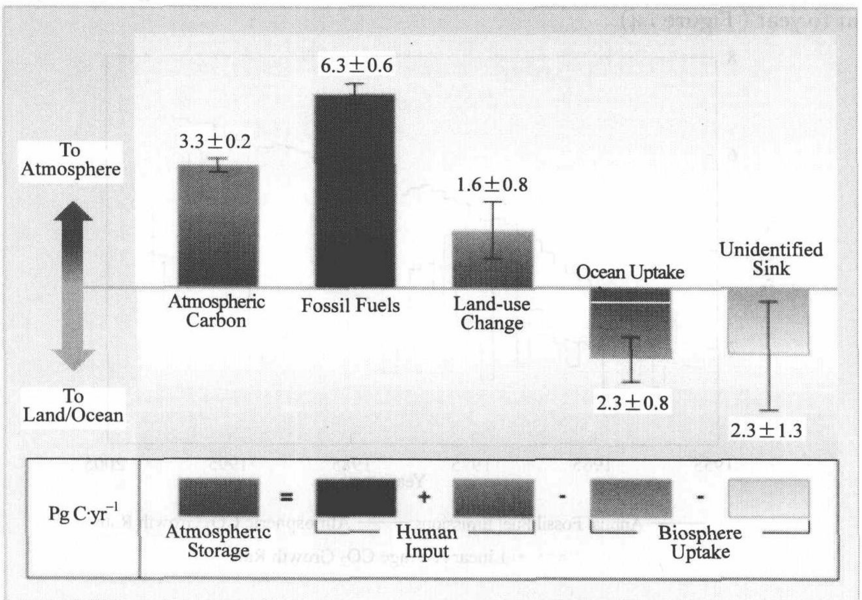

Figure 1.3 Average annual global budget of CO_2 and uncertainties for 1989 to 1998 expressed in Pg $C{\cdot}yr^{-1}$. Error bounds correspond to a 90% confidence interval. The numbers reported here are from Land Use, Land-Use Change and Forestry, a special report of the Intergovernmental Panel on Climate Change (IPCC, 2000). There is compelling evidence that a large fraction of the 'unidentified sink' may be accounted for by uptake in the temperate and/or boreal zones of the terrestrial Northern Hemisphere (Source from F Hall, Office of Global Carbon Studies, NASA Goddard Space Flight Center).

There is an apparent imbalance in the global accounting for sources and sinks, when considered with the other terms in the global carbon equation (the atmosphere, fossil fuels, and the oceans), and considerable effort has gone into explaining and finding this residual sink or missing sink of carbon (Figure 1.3). Concern about the consequences of a changing climate has led us to exploring how forests might be used to withdraw, or in other words, sequester carbon from the atmosphere. They have a significant potential for reducing the rate at which carbon builds up in the atmosphere, the major contributor to climatic change, and hence the human activity most in need of change is use of fossil fuels for energy. Advances in the technology of renewable energy sources, including wood-derived fuels, might reduce our reliance on fossil fuels and thus reduce global emissions of carbon dioxide significantly.

There is compelling evidence of a current Northern Hemisphere extra-tropical terrestrial sink of 0.6-2.3 Pg $C{\cdot}yr^{-1}$ (IPCC, 2001). Recent work suggests that this sink is a result of land-use change, including the recovery of forest cleared for agriculture in the last century, and land management practices, such as fire suppression and reduced tillage of agricultural lands. Other studies suggest that elevated atmospheric CO_2 concentration, nitrogen deposition, changes in growing season duration, and changes in regional rainfall patterns also play a critical role. Atmospheric studies indicate that the net terrestrial sink varies significantly from year to year (Figure 1.4).

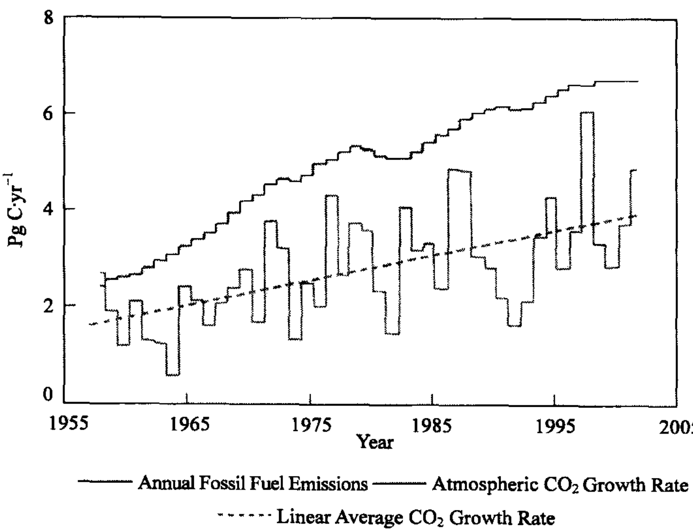

Figure 1.4 Rate of increase of atmospheric and fossil-fuel CO_2 emissions. The upper curve shows the annual global amount of carbon added to the atmosphere (in Pg $C{\cdot}yr^{-1}$) in the form of CO_2 by burning coal, oil and natural gas. The strongly varying curve shows the annual rate of increase of carbon in the atmosphere. The difference between the two curves represents the total net amount of CO_2 absorbed each year by the oceans and terrestrial ecosystems. For more information, see Annex C (For more information, see Annex C from *Climate Change Science Strategic Plan*, CCSSP, USA, 1999).

The primary problem in our understanding of the current state of the global carbon cycle is reflected by the 'missing sink' which we do not know where all of the anthropogenic CO_2 is going. We will explore this question of the missing sink in several of the modeling exercises. The importance of present-day changes in the carbon cycle, and the potential implications for climate change became much more apparent when people began to get results from studies of gas bubbles trapped in glacial ice. The bubbles are effectively samples of ancient atmospheres, and we can measure the concentration of CO_2 and other trace gases like methane (CH_4) in these bubbles, and then by counting the annual layers preserved in glacial ice, we can date these atmospheric samples, providing a record of how CO_2 changed over time in the past. Figure 1.5 shows the results of some of the ice core studies, relevant for the recent past—back to the year 900 A.D.

The striking feature of these data is that there is an exponential rise in atmospheric CO_2 (and CH_4, another greenhouse gas) that connects with the more recent Mauna Loa record to produce a rather frightening trend. Also shown in Figure 1.5 is the record of fossil fuel emissions from around the world, which show a very similar exponential trend. Notice that these two data sets shown an exponential rise that seems to begin at about the same time. What does this mean? Does it mean that there is a cause-and-effect relationship between emissions of CO_2 and atmospheric [CO_2] levels? Although we should remember that science cannot prove things to be true beyond all doubt, it is highly likely that there is a cause-and-effect relationship—it would be an extremely bizarre coincidence if the observed rise in atmospheric [CO_2] and the emissions of CO_2 were unrelated.

It is always worth considering if we can test a hypothesis. Here, the hypothesis is that anthropogenic emissions of CO_2 are the cause of the rise in atmospheric [CO_2]. Can we test this? The answer is yes; there are in fact several ways of testing this hypothesis. One involves analyzing the ratios of carbon isotopes in CO_2 molecules found in the atmosphere. A brief aside on carbon isotopes—carbon atoms don't always have the same number of neutrons in them, so they occur with different atomic weights 14, 13, and 12, with ^{12}C taking up around 98.9%, ^{13}C making up about 1.1%, and ^{14}C, the radioactive one taking up a tiny fraction. ^{12}C and ^{13}C are stable isotopes meaning they do not decay, while ^{14}C has a half-life of 5270 years and is continually being produced when ^{14}N in the atmosphere interacts with high-energy from solar radiation. The CO_2 produced by burning fossil fuels has a much lower ratio of $^{13}C/^{12}C$ than normal atmospheric [CO_2]. If we were adding new CO_2 that had the same ratio as the rest of the carbon in the atmosphere, the total amount of carbon will increase, but the $^{13}C/^{12}C$ ratio will remain the same; so by adding new with a much lower ratio of $^{13}C/^{12}C$, we are diluting the atmospheric ratio of $^{13}C/^{12}C$. Therefore, we predict that there should be a decline in the carbon isotope ratio in the atmosphere that should match the history of fossil fuel burning on the condition that our hypothesis is correct. But in order to test our hypothesis in a meaningful way, we need to have some records of the carbon isotope ratio of the atmosphere far enough back to understand the significance of recent climate changes. We can get this information from bubbles of air trapped in glacial ice, and also from tree rings, which of course