GREENHOUSE GAS EMISSIONS AND STRATEGIES FOR MITIGATION: OPPORTUNITIES IN AGRICULTURE AND ENERGY INDUSTRY

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Abstract

The impact of human activities on the atmosphere and the accompanying risks of long-term global climate change are by now familiar topics to many people. Although most of the increase in greenhouse gas (GHG) concentrations is due to carbon dioxide (CO_2) emissions from fossil fuels, globally about one-third of the total human-induced warming effect due to GHGs comes from agriculture and land-use.

This report provides a brief review of greenhouse effects and impacts on climate, human health and environment. The sources of emissions of greenhouse gases due to human activities, both current estimates and future projections, have been included. The report further discusses possible options for mitigation of greenhouse gases.

The report also discusses the role agriculture can play towards mitigation of greenhouse gases as many agricultural processes such as anaerobic digestion, manure gasification; carbon sequestration etc. can help reduce or offset greenhouse gas emissions.

Capture and sequestration of CO_2 released as a result of burning fossil fuel in power plants, energy and other industries is gaining widespread interest as a potential method of controlling greenhouse gas emissions. Various technologies such as amine (MEA)-based CO_2 absorption system for post-combustion flue gas applications have been developed, and can be integrated with existing plant operations. Removal of SO_2 by using amine-based carbon capture system offers additional benefit. Efforts are underway to develop a broader suite of carbon capture and sequestration technologies for more comprehensive assessments in the context of multi-pollutant environmental management.

Geologic formations and/ or possibly oceans can be used as sinks to store recovered CO_2. In oil and gas exploration industry CO_2 may be injected in producing or abandoned reservoirs which will not only help in maintaining the reservoir pressure (which improves overall field exploitation) but in some cases even leads to enhanced oil recovery.

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CHAPTER-1
INTRODUCTION

Climate change is one of the most important issues facing mankind and the one that has drawn significant attention of scientific community, policy makers and common man. Earth's climate has changed several times during the history of the planet due to the events ranging from ice ages to long periods of warmth. Natural factors such as volcanic eruptions, changes in earth's orbit and the amount of energy released from the Sun have affected Earth's climate in the past. However, over the past 200 years, the burning of fossil fuels and deforestation have caused the concentrations of greenhouse gases to increase in the atmosphere. The greenhouse gases (GHG) prevent heat from escaping to outside earth's atmosphere.

According to IPCC ("AR4 WG1" 2007), there has been an average warming of about 1.3 °F (0.74 ^{0}C) over the past century. According to EPA(EPA: Basic Information: Science, http://epa.gov/climatechange/basicinfo/science), the eight warmest years on record (since 1850) have all occurred since 1998 with the warmest year being 2005. This phenomenon termed as Global Warming has affected earth's climate in several observable ways such as changes in rainfall patterns, loss of arctic and glacial snow, ice covers and rise in sea levels.

According to IPCC (2007), if the concentrations of greenhouse gases continue to rise the average temperature at the Earth's surface could increase from 3.2 to 7.2 ^{0}F above 1990 levels by the end of this century with serious climactic impact which would have wide ranging effect on people and ecosystems. Some changes are already being observed including sea level rise, shrinking glacial covers, changes in the range and distribution of plants and animals, earlier blooming of trees, lengthening of growing seasons and thawing of permafrost. Some weather phenomena such as heat wave and heavy downpour are more frequent than other less frequent and intense phenomenon such as extreme cold events.

Deforestation and urbanization is already affecting agriculture landscape and this in addition to the effects of global warming could lead to severe water and food shortage in certain regions. Human settlements and mass

migration from coastal cities/ countries inward towards higher land could put pressure on land use further aggravating the problem. These are some potential extreme events that could take place due to continued global warming as a result of uncontrolled and continuous release of greenhouse gases.

Human health can be affected directly and indirectly by climate change due to extreme periods of heat and cold, storms causing an increase in climate-sensitive diseases such as malaria and smog episodes.

Human activities result in emission of four principal greenhouse gases: Carbon Dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O) and halocarbons (a group of gases containing fluorine, chlorine and bromine).

- Carbon dioxide is released from burning of fossil fuels in transportation, generation of electric energy, industrial processes, residential heating, cooking, manufacture of cement and other goods.
- Methane is released as a result of activities related to agriculture, natural gas production and distribution.
- Nitrous oxide is also emitted by human activities such as fertilizer use and fossil fuel burning. Natural processes in soils also release N_2O.
- Halocarbon gas concentrations have increased primarily due to human activities. Principal halocarbons include the chlorofluorocarbons e.g. CFC-11 and CFC-12, which were used extensively as refrigerants and in other industrial processes. However, the abundance of chlorofluorocarbons is decreasing as a result of international regulations ever since their presence in the atmosphere was found to cause ozone depletion.

There are a number of things that can be done at individual, community, national and international level that can help control and possibly reduce the greenhouse gas concentrations over a period of time. This report reviews the emission of greenhouse gases due to human activities and presents a brief overview of opportunities available and strategic options for mitigation of greenhouse gas emissions. Many agricultural and land use practices cause increased emission of greenhouse gases. However, certain agricultural processes and carbon

sequestration can help reduce or offset greenhouse gas emissions.

Similarly, there has been a growing interest in recovering and storing carbon in geologic formations and possibly oceans. The idea is to prevent carbon dioxide emissions from power plants and other industrial facilities by capturing and injecting CO_2 into ocean or geological formations for long term storage. In energy sector carbon dioxide sequestration can be used for pressure maintenance of the producing reservoirs which in some cases might even lead to enhanced oil recovery.

Humans already have increased the levels of carbon dioxide in the atmosphere since the beginning of the industrial revolution due to large-scale use of fossil fuels which is considered to be the primary reason behind the global warming being observed currently. This rate of warming has been observed to be faster than any earlier observed periods of warming.

This report looks at greenhouse gas emissions, methods of estimation of emissions and role of greenhouse gas emissions on the observed climate changes and future projected changes in temperature, rainfall, sea level etc.

CHAPTER-2
GREENHOUSE EFFECT, GLOBAL WARMING
& CLIMATE CHANGE

Earth's greenhouse effect discovered by Joseph Fourier 1824, is a natural phenomenon that helps regulate its temperature. When the Sun heats the earth, some of this heat escapes back to space. The rest of the heat, also known as infrared radiation, is trapped in the atmosphere by clouds and greenhouse gases, such as water vapor and carbon dioxide.

According to EPA (EPA: Climate Change, http//epa.gov/climatechange/fq/science.html), "If all of these greenhouse gases disappear, Earth would be 60-0F (33-0C) colder and would not be able to support life as we know it".

Greenhouse effect has been enhanced due to addition of greenhouse gases to the atmosphere causing the Earth's average temperature to rise. These additional gases come from burning of fossil fuels. Cutting down trees, generating waste and farming also produce greenhouse gases.

Global warming is an increase in average temperatures near the Earth's surface and in the lowest layer of the atmosphere. Increases in temperature in Earth's atmosphere can contribute to the changes in global climate patterns.

The global temperature record (IPCC "AR4 WG1" 2007) shows an average warming of about 1.3 ^{0}F (0.74 ^{0}C) over the past century. According to IPCC (2007), "Eleven of the last twelve years (1995-2006) rank among the 12 warmest years in the instrumental record of global surface temperature since 1850".

According to the International Panel on Climate Change (IPCC, 2007), "Warming of the Earth's climate system is now "unequivocal" (i.e. definite)". Based on observation of increases in average air and ocean temperatures, melting of snow and ice, and average sea level across the globe IPCC has concluded that there is a definite warming of Earth.
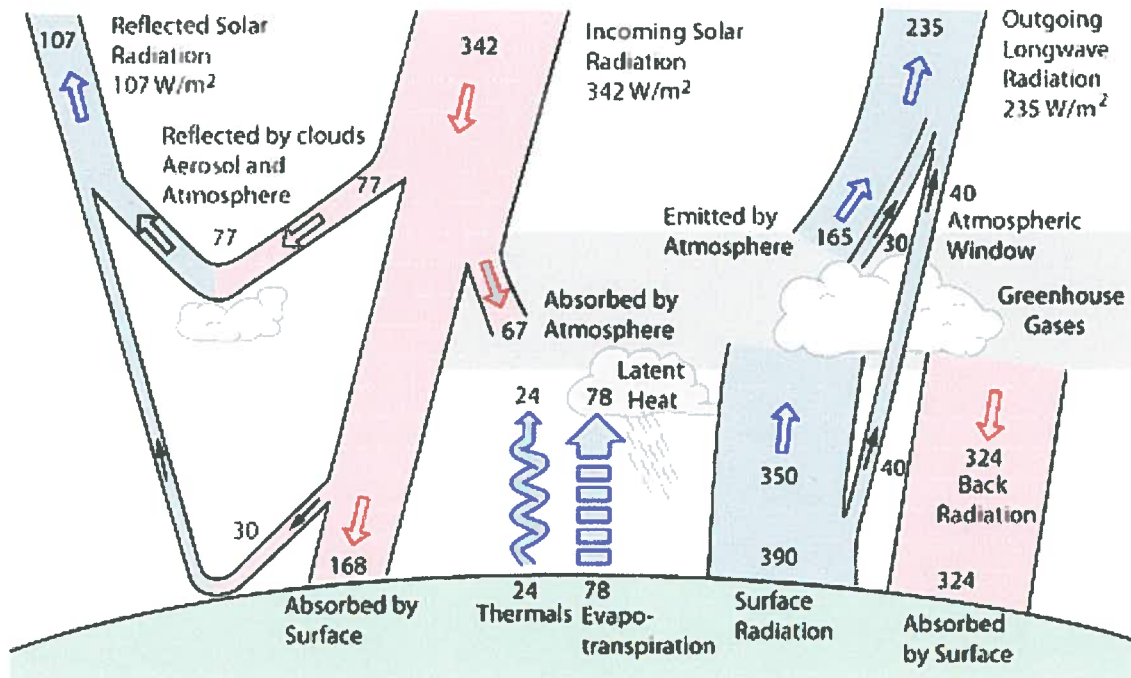
Units: Watts per m²)

Fig.2.1 Earth's climate system: Estimate of the Earth's annual and global mean energy balance. Over the long term, the amount of incoming solar radiation absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing long wavelength radiation. About half of the incoming radiation is absorbed by the Earth's surface. This energy is transferred to the atmosphere by warming of air, by evaporation and by long wavelength radiation that is absorbed by greenhouse gases and clouds. The atmosphere in turn radiates longwave energy back to Earth and to the space. Source: Kiehl and Trenberth, "Earth's Global Mean Energy Budget" (1997)
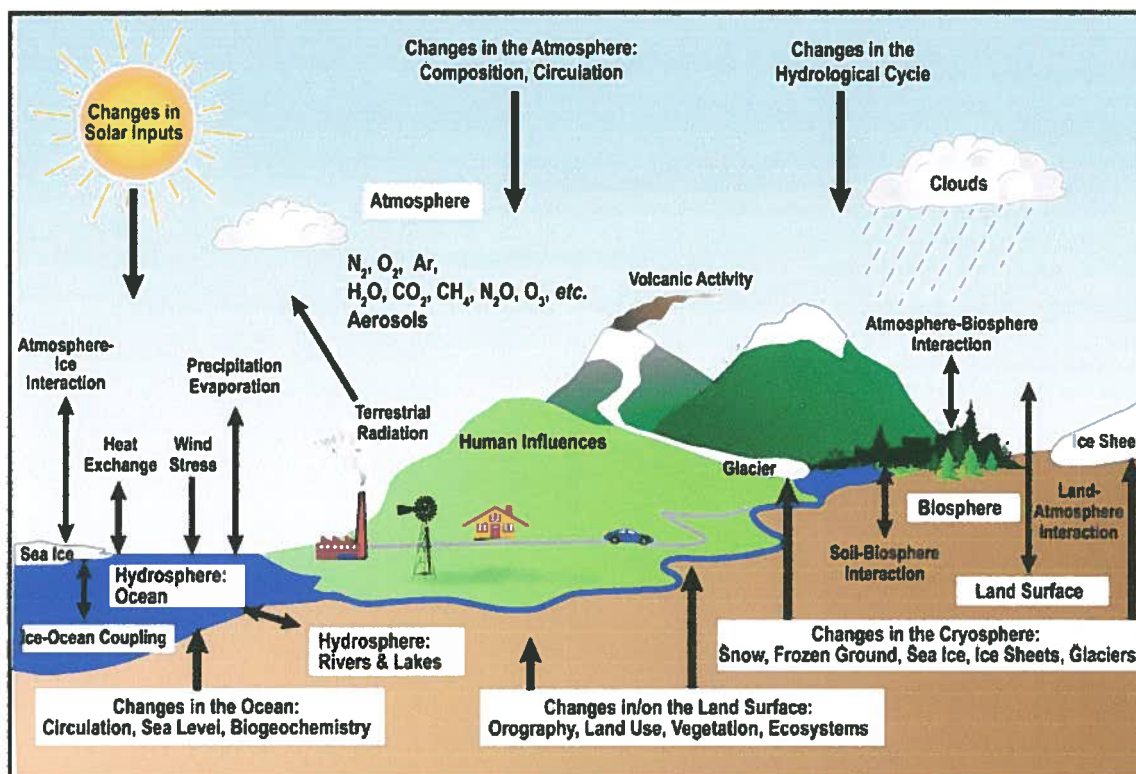
Fig. 2.2 Schematic view of the components of the Earth's climate system, their processes and interactions, Source: "A model approach to climate change", Physics World (Feb.2007), http;//physicsworld.com/cws/article/print/26946.
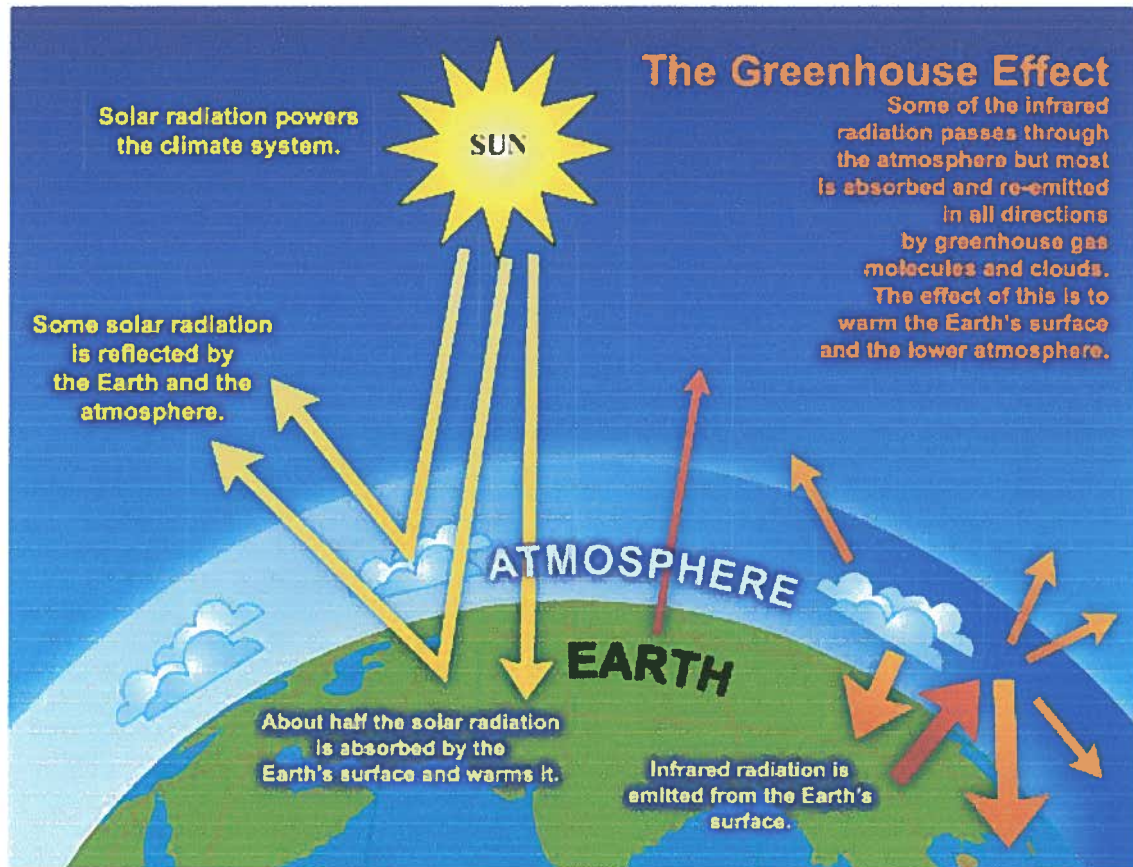
Fig.2.3 A generalized model of the natural greenhouse effect (2009)
Source: www.pathstoknowledge.wordpress.com/2009/07/13/boiling-water-contributes-to-greenhouse-effect/

The term climate change is often treated as being same as global warming. However, there are several factors which contribute to changes in climate patterns rather than just an increase in temperature due to global warming. These factors include:

a) Natural factors such as changes in the Earth's orbit around the Sun.
b) Natural processes within the climate system (e.g. changes in ocean circulation)
c) Human activities that change the atmosphere's composition (e.g. through burning fossil fuels) and the land surface (e.g. deforestation, reforestation, urbanization, desertification, etc.)

Climate change also covers other changes such as changes in precipitation and sea levels.

According to IPCC (Climate Change-2007: The Physical Science Basis), If humans continue to emit greenhouse gases at or above the current rate, it might probably result in an average temperature increase of 3 to 7 $^{\circ}$F (2 to 4 $^{\circ}$C) by 2100, and greater warming after that.

Even if the greenhouse gas emissions are reduced to year 2000 levels and kept constant, the concentration of CO_2 would still rise each year and the Earth would still warm about 1 $^{\circ}$F (0.6 $^{\circ}$C) over the next 100 years. This is due to the long lifetime of many greenhouse gases and the slow cycling of heat from the ocean to the atmosphere.

2.1 FACTORS THAT DETERMINE EARTH'S CLIMATE

According to IPCC (2007), "The climate system is a complex, interactive system consisting of the atmosphere, land surface, snow and ice, oceans and other bodies of water, and living things. Climate is usually described in terms of the mean and variability of temperature, precipitation and wind over a period of time, ranging from months to millions of years (the classical period is 30 years)".

Climate system is influenced by Earth's radiation balance which undergoes changes due to any one or more of three reasons: 1) by changing the incoming solar radiation, 2) by changing the fraction of solar radiation that is reflected, 3) by altering the longwave radiation from Earth back towards space (e.g., by changing greenhouse gas concentrations).

Climate responds directly to changes in the radiation balance as well as indirectly through a variety of feedback mechanisms. There are many feedback mechanisms in the climate system that can either amplify ('positive feedback') or diminish ('negative feedback') the effects of a change in climate forcing. As rising concentrations of greenhouse gases warm Earth's climate, snow and ice begin to melt. This melting reveals darker land and water surfaces that were beneath the snow and ice, and these darker surfaces absorb more of the Sun's heat, causing more warming which causes more melting, and so on, in a self-reinforcing cycle. This feedback loop, known as the 'ice-albedo feedback', amplifies the initial warming caused by

rising levels of greenhouse gases. Detecting, understanding and accurately quantifying climate feedbacks have been the focus of a great deal of research by scientist unraveling the complexities of Earth's climate".

2.2 CLIMATE CHANGE AND WEATHER

Climate is generally defined as average weather, and as such, climate change and weather are interrelated and interdependent. Observations show that there have been changes in weather, and it is the record of changes in weather over time that identifies a climate change. Weather and climate are closely related but there are important differences.

According to IPCC (2007), "The chaotic nature of weather makes it unpredictable beyond a few days. Projecting changes in climate (i.e., long-term average weather) due to changes in atmospheric composition or other factors is a very different and much more manageable issue.

Another common confusion of these issues is thinking that a cold winter or a cooling spot on the globe is evidence against global warming. There are always extremes of hot and cold, although their frequency and intensity change as climate changes. But when weather is averaged over space and time, the fact that the globe is warming emerges clearly from the data. A major limiting factor to the predictability of weather beyond several days is a fundamental dynamical property of the atmosphere.

Climate can be viewed as concerning the status of the entire Earth system, including the atmosphere, land, oceans, snow, ice and living things that serve as the global background conditions that determine weather patterns. An example of this would be an El Niño affecting the weather in coastal Peru. The El Niño sets limits on the probable evolution of weather patterns that random effects can produce. A La Niña would set different limits".

2.3 GREENHOUSE EFFECT

The Sun energizes Earth's climate system radiating energy at short wavelengths, predominately in the visible or near-visible (e.g., ultraviolet) part of the spectrum. Roughly one-third of the solar energy that reaches the top of Earth's atmosphere is reflected directly back to space.

The remaining two-thirds is absorbed by the surface and, to a lesser extent, by the atmosphere. To balance the absorbed incoming energy, the Earth radiates the same amount of energy back to space.

Earth is much colder than the sun so it radiates at much longer wavelengths, primarily in the infrared part of the spectrum. Much of this thermal radiation emitted by the land and the ocean is absorbed by the atmosphere, including clouds, and reradiated back to Earth. This is called the greenhouse gas effect.

The natural greenhouse effect helps Earth maintain an average temperature necessary for sustaining life on Earth. Without greenhouse effect Earth's surface would be below the freezing point of water. The two most abundant gases in the atmosphere, nitrogen (comprising 78% of the dry atmosphere) and oxygen (comprising 21%), exert almost no greenhouse effect. Instead, the greenhouse effect comes from molecules that are more complex and much less common. Water vapor is the most important greenhouse gas, and carbon dioxide is the second most important one. Methane, nitrous oxide, ozone and several other gases present in the atmosphere in small amounts also contribute to the greenhouse effect.

According to IPCC (2007), "Several components of the climate system, notably the oceans and living things, affect atmospheric concentrations of greenhouse gases. A prime example of this is plants taking carbon dioxide out of the atmosphere and converting it (and water) into carbohydrates via photosynthesis".

2.4 HUMAN ACTIVITIES AND CLIMATE CHANGE

Human activities are causing changes in Earth's atmosphere due to emissions of large amounts of greenhouse gases, aerosols (small particles), and cloudiness. Greenhouse gases and aerosols affect climate by altering incoming solar radiation and outgoing infrared (thermal) radiation that are part of Earth's energy balance. Fig. 2.4.1(A) shows changes in atmospheric concentration of greenhouse gases over last 10,000 years. Fig. 2.4.1(B)

shows changes in atmospheric concentrations of greenhouse gases over last 200-years.
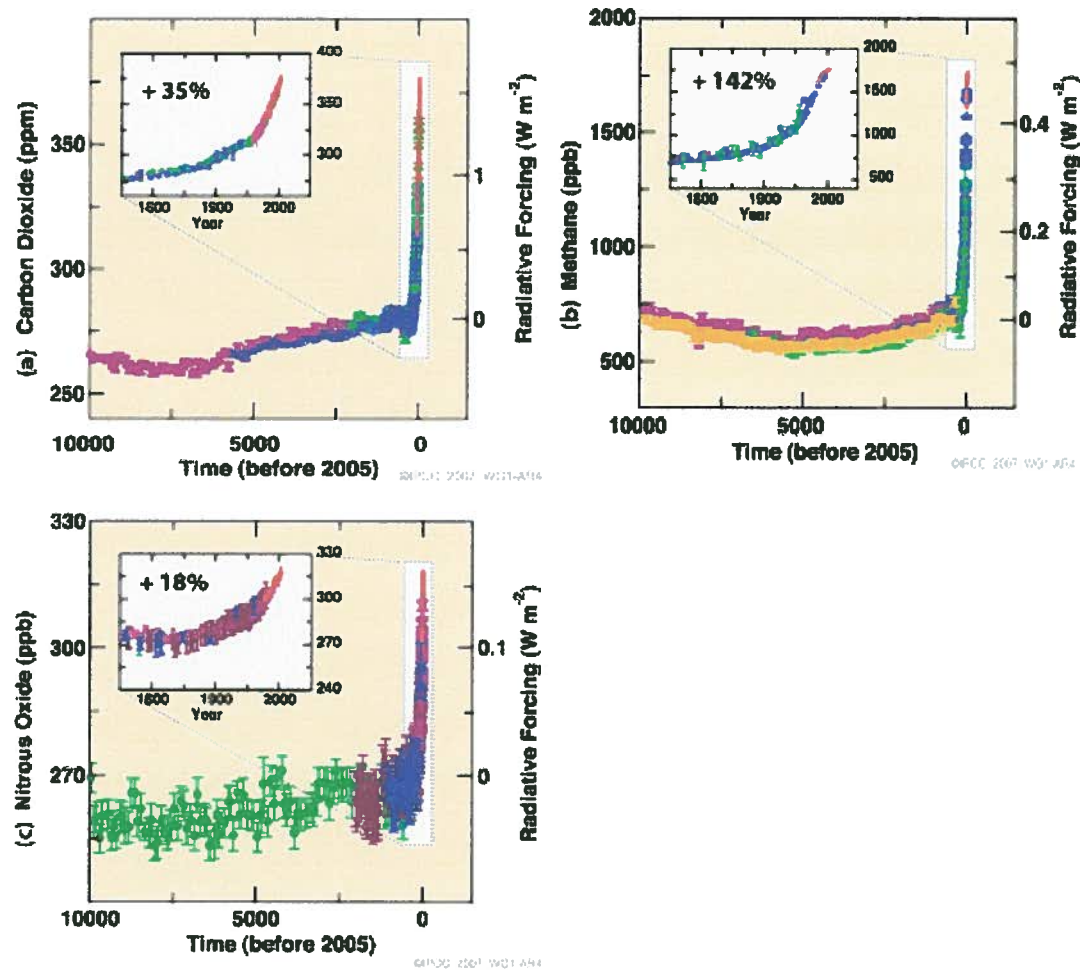
Fig. 2.4.1(A) Atmospheric concentrations of CO_2, CH_4 and N_2O over the last 10,000 years and since 1750. Measurements based on ice cores and atmospheric samples. Corresponding radiative forcings are shown on the right. Source: IPCC, The Physical Science Basis, Summary for Policy Makers (2007)

Greenhouse Gas Mixing Ratios
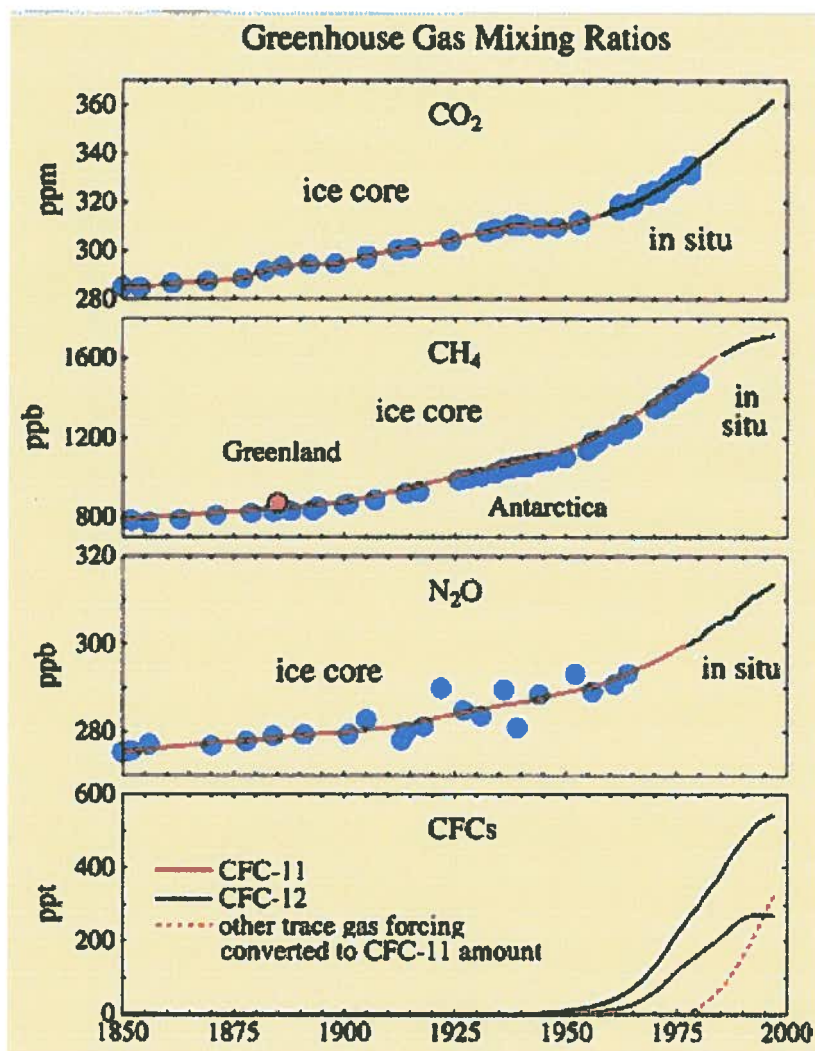
Fig. 2.4.1(B) Concentration of principal anthropogenic greenhouse gases in the industrial era (Hansen et. al 1998; Hansen and Sato, 1999)

- Blue curves denote measurements in-situ atmospheric samples collected in recent years (NOAA, 1999a, b, c; Houghton et al., 1995)
- Blue points denote concentrations determined from air bubbles trapped in polar ice sheets using ice cores obtained in Antarctica
- Red curves denote fits to these points (Etheridge et al. 1996, 1998)
- Data for CFC are from in-situ samples since 1977 (NOAA, 1999d)

Source: "Climate Change and Greenhouse Gases" Ledley, Sundquist, Schwartz et. al 1999)

[12]

2.4.1 Human and Natural Drivers of Climate Change

Global atmospheric concentrations of CO_2, CH_4 and N_2O have increased due to human activities since 1750 and far exceed pre-industrial values determined from ice cores spanning many thousands of years.

According to IPCC (2007), "Carbon dioxide is the most important anthropogenic greenhouse gas. The global atmospheric concentration of carbon dioxide has increased from a pre-industrial value of about 280-ppm to 379-ppm in 2005. The atmospheric concentration of CO_2 in 2005 exceeds by far the natural range of 180-300 ppm over the last 650,000 years as determined from ice cores. Compared to earlier periods, the annual CO_2 concentration growth rate was higher during the period 1995-2005 which averages to an increase of about 1.5 ppm per year.

The global atmospheric concentration of methane has increased from a pre-industrial value of 715 ppb to 1732 ppb in the early 1990s, and was 1774 ppb in 2005. The atmospheric concentration of methane in 2005 exceeds by far the natural range of the last 650,000 years (320 to 790 ppb) as determined from ice cores. Growth rates have declined since the early 1990s consistent with the total emissions (sum of anthropogenic and natural sources) being nearly constant during this period. It is thought that the observed increase in methane concentration is due to the anthropogenic activities, predominantly agriculture and fossil fuel use.

The global atmospheric nitrous oxide concentration increased from a pre-industrial value of about 270 to 319-ppb in 2005. The growth rate has been approximately constant since 1980. More than a third of all nitrous oxide emissions are anthropogenic and are primarily due to agriculture".

2.4.2 Direct Observation of Climate Change

According to IPCC (2007), following are some major observations:

- "Eleven out of last twelve years (1995-2006) rank among the 12 warmest years since 1850.

- Satellite measurements of lower and mid-tropospheric temperature show warming rates that are similar to those of the surface temperature record.

- The average atmospheric water vapor content has increased since at least the 1980s over land and ocean as well as in upper troposphere. The increase is consistent with the extra water vapor that warmer air can hold.

- Observations since 1961 indicate that temperature of the global ocean has increased; the ocean has been absorbing more than 80% of the heat added to the climate system. Such warming causes seawater to expand contributing to sea level rise.

- Mountain glaciers and snow cover have declined on average in both hemispheres. Widespread decrease in glaciers and ice caps has contributed to sea level rise.

- Losses from ice sheets of Greenland and Antarctica have very likely contributed to sea level rise over 1993 to 2003.

- Global average sea level rose at an average rate of 1.8-mm per year over 1961 to 2003. The rate was faster over 1993 to 2003.

- Average arctic temperatures increased at almost twice the global average rate in the past 100-years.

- Satellite data since 1978 show that annual average arctic sea ice extent has shrunk by 2.7% per decade.

- Temperatures at the top of the permafrost layer have generally increased since the 1980s in the Arctic (by up to 3°C). The maximum area covered by seasonally frozen ground has decreased by about 7% in the Northern Hemisphere since 1900, with a decrease in spring of up to 15%.

- Significantly increased precipitation has been observed in eastern parts of North and South America, northern Europe and northern and central Asia.

- The frequency of heavy precipitation events has increased over most land areas, consistent with warming and observed increases of atmospheric water vapor.

- Drying has been observed in the Sahel, the Mediterranean, southern Africa and parts of southern Asia.

- More intense and longer droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics.

- Widespread changes in extreme temperatures have been observed over the last 50-years. Cold days, cold nights and frost have become less frequent, while hot days, hot nights and heat waves have become more frequent.

- There is evidence of an increase in intense tropical cyclone activity in the North Atlantic since about 1970, correlated with increases of tropical sea surface temperatures".

Fig. 2.4.2 shows changes in temperature, sea level and northern hemisphere snow cover.

According to IPCC (2007), "Instrumented observations over the past 157 years show that temperatures at the surface have risen globally, with important regional variations. For the global average, warming in the last century has occurred in two phases, from the 1910s to the 1940s (0.35°C) and more strongly from the 1970s to the present (0.55°C). An increasing rate of warming has taken place over the last 25 years, and 11 out of 12 warmest years on

record have occurred in past 12 years. Fig. 2.4.2 shows observed global mean temperature variations recorded".
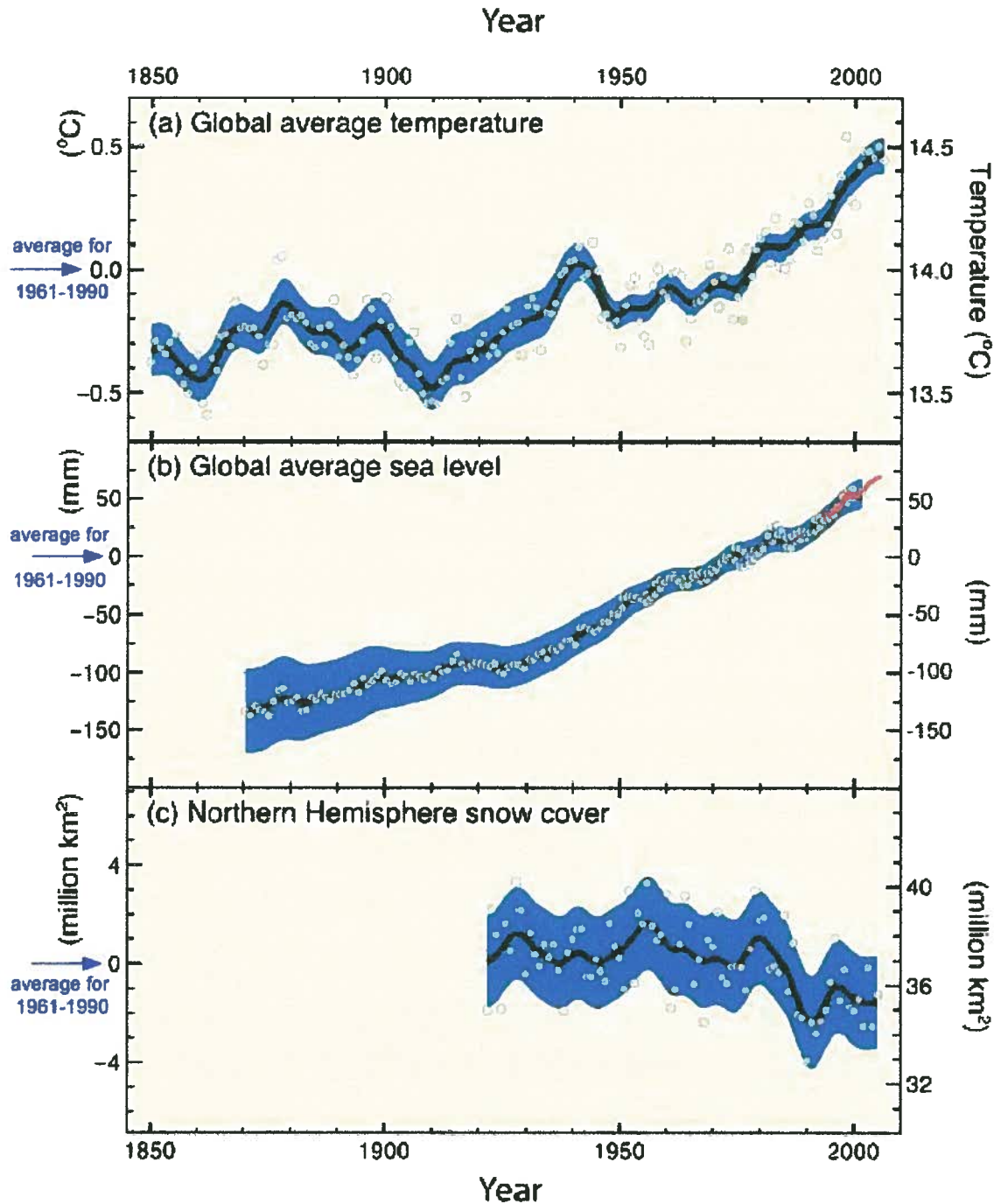
Fig.2.4.2 Observed changes in a) global average surface temperature, b) difference in average sea level relative to 1961 levels, c) Northern hemisphere snow cover (March-April), Source: IPCC Summary for Policy Makers (2007)

2.5 Future Projections

The concentrations of Greenhouse Gases (GHG) concentrations in the atmosphere are likely to increase during 21st century unless greenhouse gas emissions are reduced substantially from present levels. Increased GHG concentrations are very likely to raise the Earth's average temperature, influence precipitation and some storm patterns as well as raise sea levels (IPCC, 2007).

According to EPA (EPA: Climate Change: Science, http://epa.gov/climatechange/science/futurecc.html), "The amount and speed of future climate change will ultimately depend on:
- Whether greenhouse gases and aerosol concentrations increase, stay the same or decrease
- How strongly features of the climate (i.e. temperature, precipitation and sea level) respond to changes in GHG and aerosol concentrations
- How much the climate varies as a result of natural influences (e.g. volcanic activity and changes in the Sun's intensity) and its internal variability (referring to random changes in the circulation of the atmosphere and oceans)"

2.5.1 Atmospheric Changes

The extent and speed of future atmosphere changes will be driven by the level of greenhouse gas (and aerosol) emissions over time. Human activities are major sources of these emissions, which have increased in the past and are projected to continue increasing in the future, although the U.S. and other governments are taking steps to slow their growth.

According to EPA (EPA: Climate Change: Science, http://epa.gov/climatechange/science/futurecc.html) and the Department of Energy (DOE), following changes are very likely to occur over a short (through 2020-2030) period.

a) Global non- CO_2 greenhouse gas emissions are projected to grow 44% to 13 billion metric tons (CO_2 equivalent) by 2020 relative to 1990 levels (about 9 billion tons CO_2 equivalent) under "business as usual" conditions.

b) Global emissions of CO_2 are predicted to increase from 25 billion metric tons in 2003 to 43-44 billion metric tons in 2030, or about 74% based on changes in energy supply and demand and prices.

c) Developing countries such as China and India will be the primary source of new emissions (see Figure 2.5.1).

Total Greenhouse Gas Emissions by Region

Developing Countries

Developed Countries

Emissions (Tg CO_2 equivalent)

35
30
25
20
15
10
5
0

2000   2005   2010   2015   2020   2025   2030

Tg CO_2 = Teragrams Carbon Dioxide
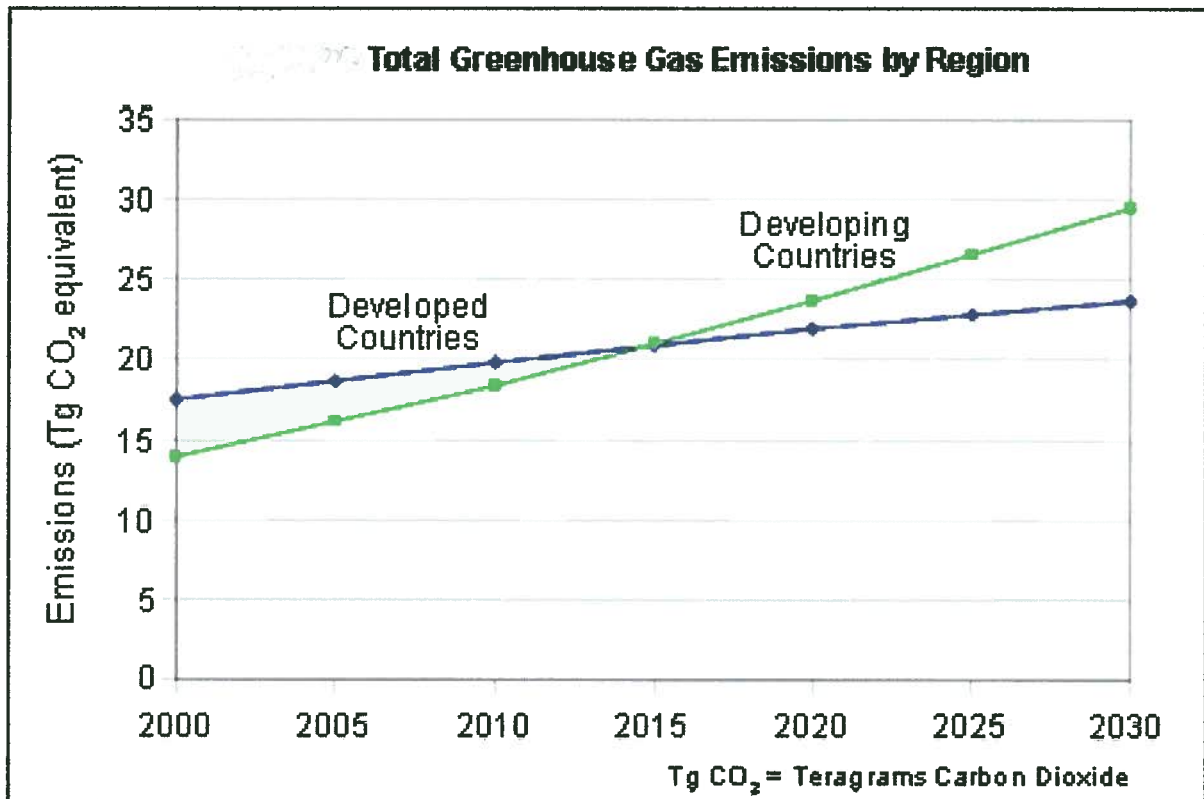
Fig. 2.5.1: Total Greenhouse Gas Emissions, *Reference*: (1) SGM Energy Modeling Forum EMF-21 Projections, Energy Journal Special Issue, in press, reference case CO2 projections. (2) Non-CO2 emissions are from EPA's Global anthropogenic Emissions of Non-CO_2 Greenhouse Gases 1990-2020; Source: EPA: Climate Change: Future Atmospheric Changes, http://epa.gov/climatechange/science/futureac.html)

According to IPCC
(2007) following are
projected changes in the
concentrations of
greenhouse gases over a
long (through 2100) time
period:

Carbon dioxide
concentrations (see
Figure 2.5.2) in the
atmosphere will increase
through the 21st century
according to all IPCC
scenarios. The IPCC
climate models predict
CO_2 concentrations
ranging from 535 to 983
parts per million (ppm)
by 2100, which is 41 to
158 percent higher than
current levels (IPCC,
2007).

Methane
concentrations (see
Figure 2.5.2) in the
atmosphere are projected
to range from 1.46 ppm
to 3.39 ppm by 2100, or
about 18 percent lower
to 91 percent higher
than the current
concentration (IPCC,
2007).

Figure 2.5.2: Long Term Scenarios for Greenhouse
Gas Concentrations, based on data provided by IPCC
WG1.Source: www.epa.gov/climatechange/science

Nitrous Oxide concentrations (see Figure 2.5.2) are
projected to be 0.36 to 0.46 ppm in 2100, values that are
11 to 45 percent higher than current concentrations (IPCC,
2007).

Fluorinated gases, such as HFCs, PFCs and SF_6 (also
known as high global warming potential gases), are expected
to increase significantly in part because some of these
gases are substitutes for chlorofluorocarbons, which are
being phased out through the Montreal Protocol.

[19]

Tropospheric ozone concentrations are projected to increase 40-60% under high emissions scenarios (IPCC, 2007). For a range of low, medium and high emissions scenarios, projections ranged from a 12% decrease to a 62% increase by 2100 (IPCC, 2007).

2.5.2 Temperature Changes

According to EPA (EPA: Climate Change: FAQ: Science, http://epa.gov/climatechange/fq/science.html), "Most climate change scenarios project that greenhouse gas concentrations will increase through 2100 with a continued increase in average global temperatures (IPCC, 2007). How much and how quickly the Earth's temperature will increase remains unknown given the uncertainty of future greenhouse gas, aerosol emissions and the Earth's response to changing conditions. In addition, natural influences, such as changes in the sun and volcanic activity, may affect future temperature, although the extent is unknown because the timing and intensity of natural influences cannot be predicted.

Future temperature changes will not depend solely on the direct effects of natural and human influences. The temperature may also change due to what are known as climate "feedbacks" – the climate system's responses to these direct effects. These feedbacks can increase or decrease the direct effect".

According to IPCC (2007), the average surface temperature of the Earth is likely to increase by 2 to 11.5°F (1.1-6.4°C) by the end of the 21st century, relative to 1980-1990, with a best estimate of 3.2 to 7.2°F (1.8-4.0°C) (see Figure 2.5.3).
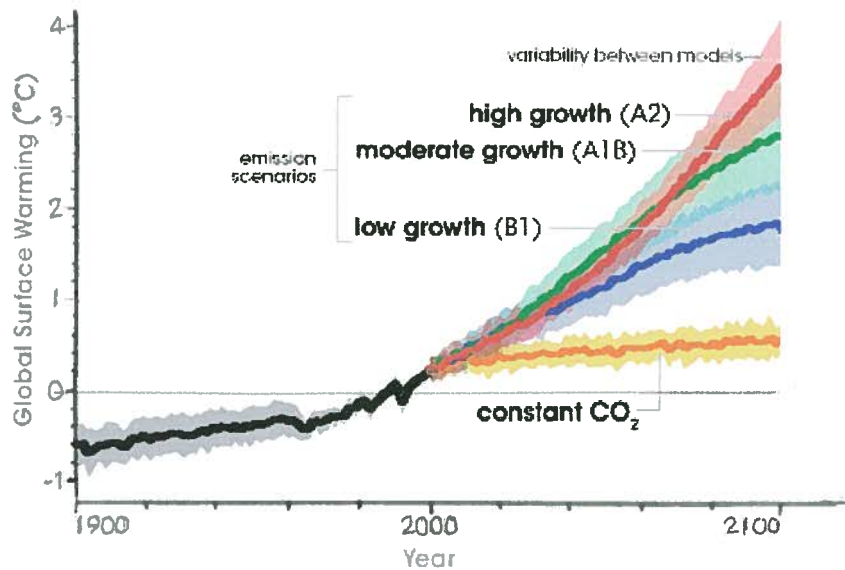
Figure 2.5.3: *Temperature projections to the year 2100, based on a range of emission scenarios and global climate models. Scenarios that assume the highest growth in greenhouse gas emissions provide the estimates in the top end of the temperature range. The orange line ("constant CO_2") projects global temperatures with greenhouse gas concentrations stabilized at year 2000 levels. Source: NASA Earth Observatory, based on IPCC Fourth Assessment Report (2007)*

According to EPA (EPA: Climate Change: Science: Future Climate Change, http://epa.gov/climatechange/science/futuretc.html), "Even if the composition of today's atmosphere was fixed (which would imply a dramatic reduction in current emissions), surface air temperatures would continue to warm (by up to 1.6°F or 0.9 °C); see the "constant CO_2" line in Figure 2.5.3(IPCC, 2007)".

2.5.3 Precipitation and Storms

An increase in the average global temperature may very likely lead to changes in precipitation and atmospheric moisture because of changes in atmospheric circulation and increases in evaporation and water vapor.

According to IPCC (2007):

- An increase is likely in global average annual precipitation during the 21st century, although changes in precipitation will vary from region to region.

[21]

- An increase is likely in the intensity of precipitation events, particularly in tropical and high-latitude regions that experience overall increases in precipitation.
- Annual average precipitation increases are likely over most of northern Europe, the Arctic, Canada, the northeastern United States, tropical and eastern Africa, the northern Pacific, and Antarctica, as well as northern Asia and the Tibetan Plateau in winter.
- Annual average precipitation decreases are likely in most of the Mediterranean, northern Africa, northern Sahara, Central America, Southwestern U.S., the southern Andes, as well as southwestern Australia during winter.
- Reduced rainfall over continental interiors during summer due to increases in evaporation.

Storm Changes

According to EPA (EPA: Climate Change: Science: Future Climate Change, http://epa.gov/climatechange/science/futurepsc.html), "Mid-latitude storm tracks are projected to shift toward the poles, with increased intensity in some areas but reduced frequency. Tropical storms and hurricanes are likely to become more intense, produce stronger peak winds, and produce increased rainfall over some areas due to warming sea surface temperatures (which can energize these storms) (IPCC, 2007). The relationship between sea surface temperatures and the *frequency* of tropical storms is not very clear".

There is currently no scientific consensus on how exactly the future climate change will affect the frequency of tropical storms in any part of the world where they occur.

2.5.4 Sea Level Changes

Higher temperatures can raise sea level due to expansion of ocean water; melting mountain glaciers and small ice caps and due to melting of portions of the coastal section of the Greenland and Antarctic ice sheets that will slide into the ocean.

[22]
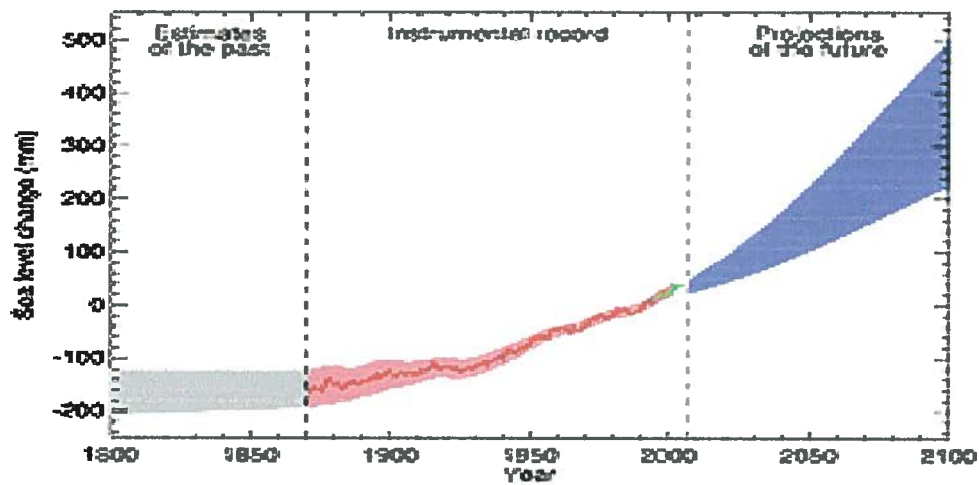
Fig. 2.5.4 Past and projected global average sea level. The gray shaded area shows the estimates of sea level change from 1800 to 1870 when measurements are not available. The red line is a reconstruction of sea level change measured by tide gauges with the surrounding shaded area depicting the uncertainty. The green line shows sea level change as measured by satellite. The purple shaded area represents the range of model projections for a medium growth emissions scenario (IPCC SRES A1B). For reference 100mm is about 4 inches. Source: IPCC (2007)

According to IPCC (2007), the global average sea level will rise by 7.2 to 23.6 inches (18-59 cm or 0.18- 0.59m) by 2100 (see Figure 2.5.4) relative to 1980-1999 under a range of scenarios.

These estimates assume that ice flow from Greenland and Antarctica will continue at the same rates as observed from 1993-2003. The IPCC cautions that these rates could increase or decrease in the future based on future emission scenarios and corresponding effects.

According to EPA (EPA: Climate Change: Science: Future Sea Level Changes, http://epa.gov/climatechange/science/futureslc.html) and IPCC (2007), "current model projections indicate substantial variability in future sea level rise between different locations. Some locations could experience sea level rise higher than the global average projection".

According to EPA (EPA: Climate Change: Science: Future Sea Level Changes, http://epa.gov/climatechange/science/futureslc.html), "Over time, more substantial changes in sea level are possible due to the vulnerability of the West Antarctic and Greenland Ice sheets. However, there are significant uncertainties about the magnitude and speed of future changes (IPCC, 2007)".

CHAPTER-3
GREENHOUSE GAS EMISSION DATA

According to EPA (EPA: Climate Change: FAQ: Emissions, http://epa.gov/climatechange/fq/emissions.html), "Atmospheric concentrations of CO_2, CH_4 and N_2O have increased markedly as a result of human activities and now far exceed pre-industrial values determined from ice cores spanning many thousands of years.

Overall, total US emissions have risen by 17 percent from 1990 to 2007. This trend is projected to continue at about 1 percent per year assuming current trends in economic growth and fuel consumption continue.

The increase is principally due to population and economic growth. Energy related human activities, power plants, transportation sector are some of the largest sources of greenhouse gas (GHG) emissions. Energy related activities account for roughly three quarters of human generated GHG emissions mostly in the form of carbon dioxide emissions from burning fossil fuels.

Electricity generation also accounted for the largest share of carbon dioxide emissions from fossil fuel combustion, approximately 42 percent in 2007. Electricity was consumed primarily by users in the residential, commercial, and industrial sectors for lighting, heating, electric motors, appliances, electronics, and air conditioning.

In the US, the transportation sector accounts for approximately 33 percent of total carbon dioxide emissions from fossil fuel combustion, the largest share of any end-use economic sector in 2007. Emissions from this sector increased by 29 percent from 1990 to 2007, representing an average annual increase of 1.7 percent. Nearly 60 percent of the emissions resulted from gasoline consumption for personal vehicle use. The remaining emissions came from other transportation activities, including the combustion of diesel fuel in heavy duty vehicles and jet fuel in aircrafts".

Table-3.0 shows atmospheric concentrations of carbon dioxide, methane and nitrous oxide.

Table-3.0: Atmospheric concentrations of CO_2, CH_4 and N_2O since pre-industrial period. Source: http://en.wikipedia.org/wiki/Greenhouse_gas, IPCC (2007), IPCC Special Report on Emission Scenarios (2007)

Gas	Preindustrial Level	Current Level	Increase since 1750	Radiative Forcing (W/m^2)
Carbon Dioxide	280 ppm	387ppm	104 ppm	1.46
Methane	700 ppb	1,745 ppb	1,045 ppb	0.48
Nitrous Oxide	270 ppb	314 ppb	44 ppb	0.15
CFC-12	0	533 ppt	533 ppt	0.17

The burning of fossil fuel upsets the natural steady state concentration by adding a surplus of carbon dioxide into the system.

The carbon in fossil fuel has been stored underground for millions of years and thus is not part of the current natural carbon cycle. When those fuels are burned, the carbon dioxide generated is over and above the amount circulating from natural sources.

3.1 GREENHOUSE GAS EMISSIONS AND INVENTORIES

Some greenhouse gases such as carbon dioxide occur naturally and are emitted to the atmosphere through natural processes and human activities. Other greenhouse gases (e.g., fluorinated gases) are created and emitted through human activities. The principal greenhouse gases that enter the atmosphere because of human activities are:

Carbon Dioxide (CO$_2$):
Carbon dioxide enters the atmosphere through the burning of fossil fuels (oil, natural gas, and coal), solid waste, trees and wood products, and also as a result of other chemical reactions (e.g., manufacture of cement). Carbon dioxide is also removed from the atmosphere (or "sequestered") when it is absorbed by plants as part of the biological carbon cycle.

Methane (CH$_4$):
Methane is emitted during the production and transport of coal, natural gas, and oil. Methane emissions also result from livestock and other agricultural practices and by the decay of organic waste in municipal solid waste landfills.

Nitrous Oxide:
Nitrous oxide is emitted during agricultural and industrial activities, as well as during combustion of fossil fuels and solid waste.

Fluorinated Gases:
Hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride are synthetic, powerful greenhouse gases that are emitted from a variety of industrial processes. Fluorinated gases are sometimes used as substitutes for ozone depleting substances (i.e. CFCs, HCFCs, and halons). These gases are typically emitted in smaller quantities, but because they are potent greenhouse gases, they are sometimes referred to as High Global Warming Potential gases ("High GWP gases"). Fig. 3.1.1 shows global greenhouse gas emissions based on EPA report "Methane to Market Partnership Factsheet" (2000).
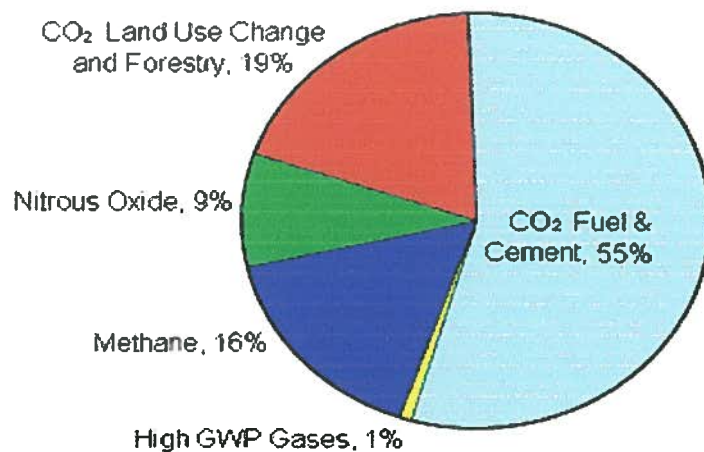
Fig.3.1.1 Global Greenhouse Gas Emissions, Source: U.S. EPA, Methane to Market Partnership Factsheet Brochure (2000)

Fig. 3.1.2 shows global fossil fuel emissions. Fig. 3.1.3 shows global CO_2 emissions from fossil fuel burning, cement production and gas flaring between years 1751-2002. Fig. 3.1.4 shows total greenhouse gas emissions by region. Fig.3.1.5 shows U.S. Greenhouse Gas Emissions between 1990 and 2006.
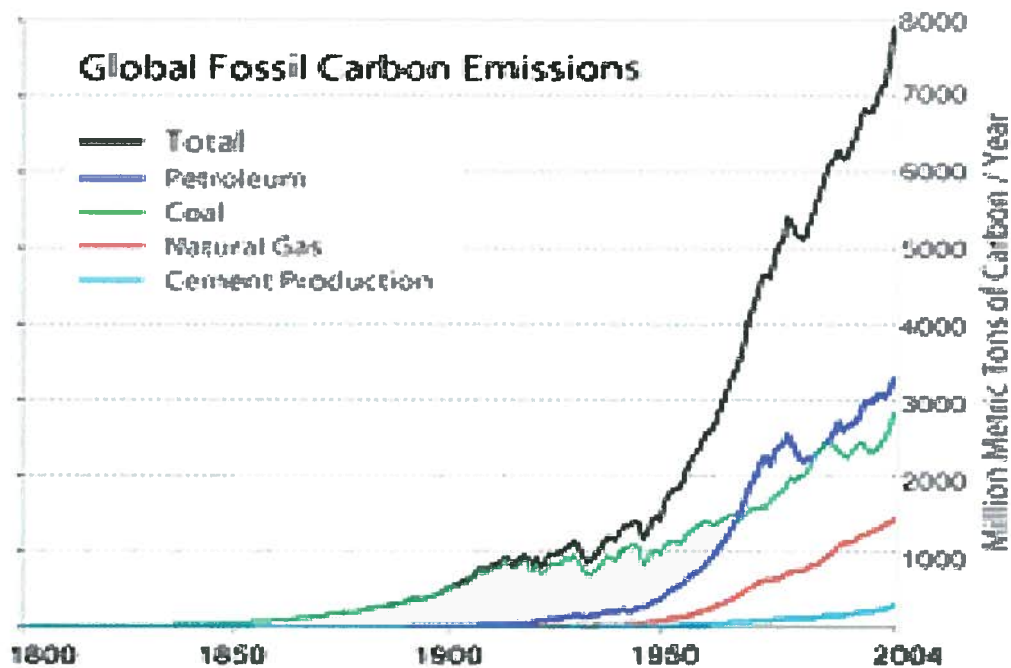
Fig.3.1.2 Global Fossil Carbon Emissions (2004)
Source: http://en.wikipedia.org/wiki/Carbon_emissions

[28]
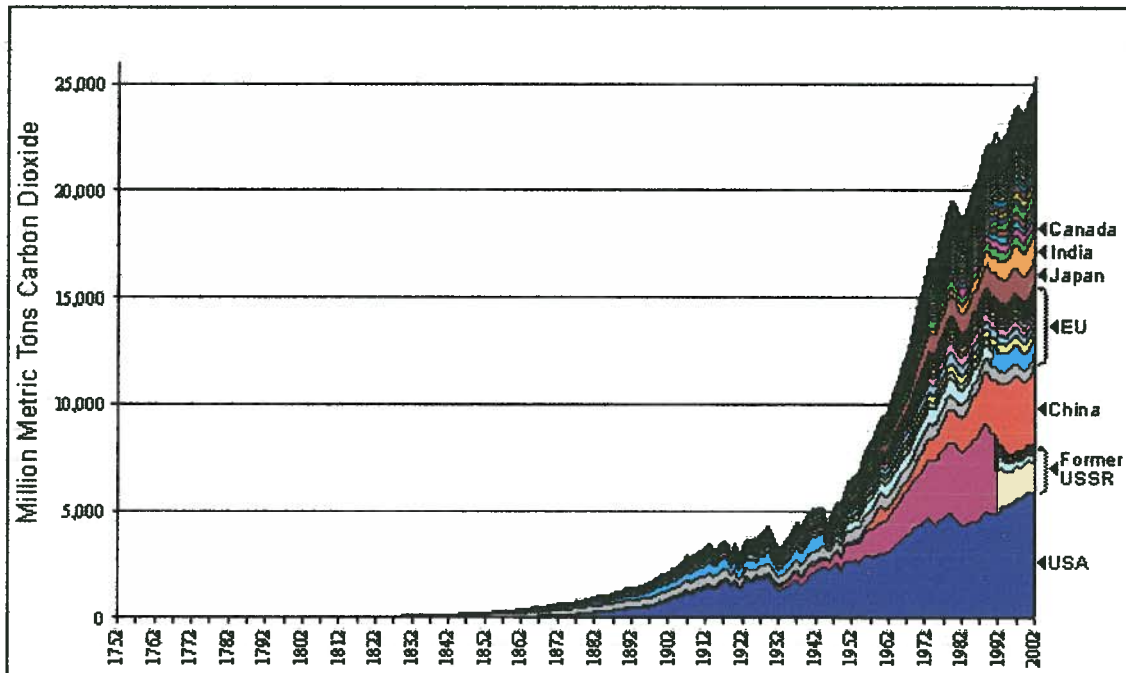
Fig.3.1.3 Global CO_2 Emissions from Fossil Fuel Burning, country wise
Source: U.S. EPA, Carbon Dioxide Information Analysis Center (2009)
(http://epa.gov/climatechange/emissions/globalghg.html)
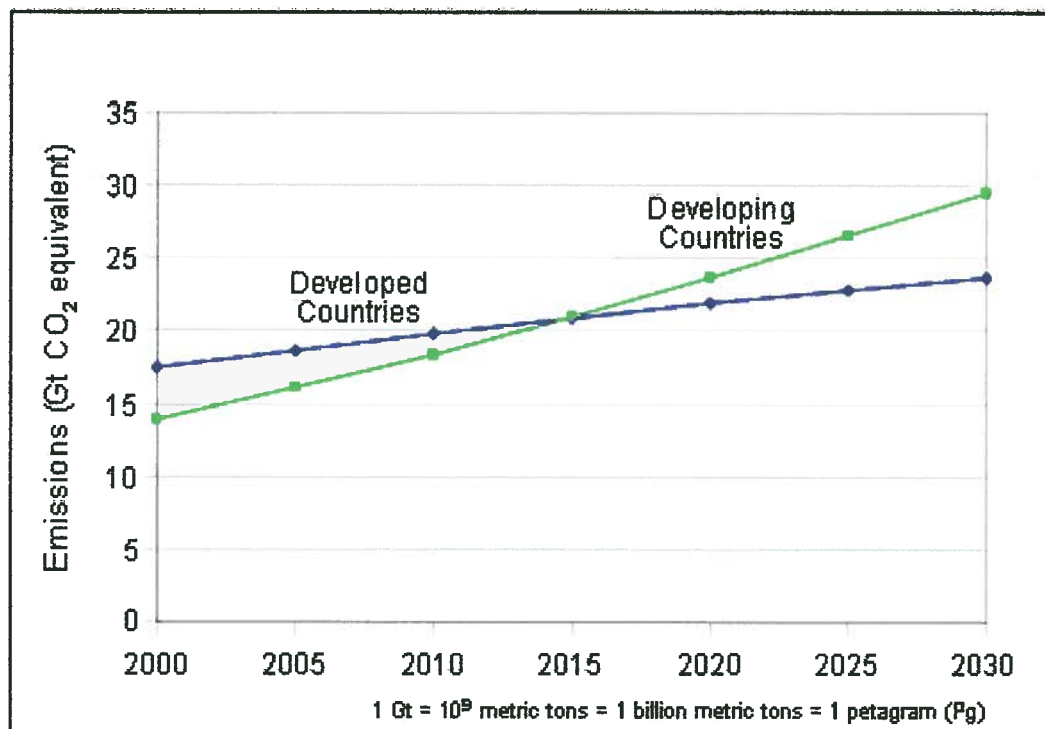
Fig.3.1.4 Total GHG Emissions by Region; Source: U.S. EPA (2009)
Source: EPA: Climate Change: Science: Future Atmospheric Changes
(http://epa.gov/climatechange/science/futureac.html)

[29]
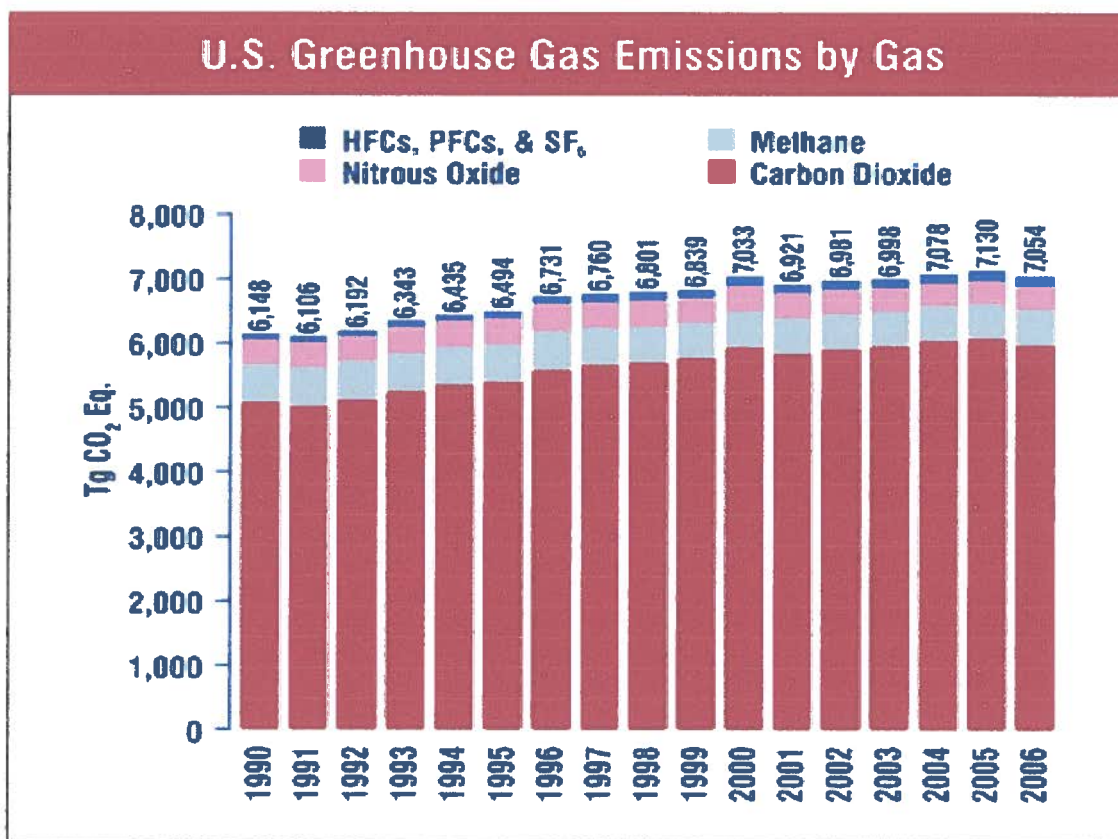
Fig.3.1.5 U.S. Greenhouse Gas Emissions by Gas
Source: U.S. EPA (2009), Inventory of U.S. Greenhouse Gas Emissions and
Sinks (1990-2007),
(http://epa.gov/climatechange/emissions/download09/inventoryusghg197.20
07)

Greenhouse Gas Inventories

A greenhouse gas inventory refers to accounting of the
amount of greenhouse gases emitted to or removed from the
atmosphere over a specific period of time (e.g., one year).
A greenhouse gas inventory also provides information on the
activities that cause emissions and removals, as well as
background on the methods used to make the calculations.
Greenhouse gas inventories are used to track emission
trends, develop strategies and policies and assess
progress.

EPA develops U.S. Greenhouse Gas Inventory each year
to track the national trend in emissions and removals since
1990. The national greenhouse gas inventory is submitted to
the United Nations in accordance with the Framework
Convention on Climate Change (UNFCC).

Similarly, many other countries are also working to develop national greenhouse gas inventories, which can be compiled into global inventories.

EPA has developed Greenhouse Gas Inventory Capacity Building templates and software tools targeting key sources, emissions factors, good practices, institutional infrastructure and use of the latest IPCC guidelines on greenhouse gas inventories. State and local governments also prepare greenhouse gas inventories, based on guidance and tools provided by EPA.

The Intergovernmental Panel on Climate Change (IPCC) has published internationally accepted inventory methodologies that serve as a basis for all greenhouse gas inventories, ensuring that they are comparable and understandable.

3.2 GHG EMISSION PROJECTIONS

According to EPA (EPA: Climate Change: Emissions: Projections, http://epa.gov/climatechange/emissions/index.html), "The Fourth U.S. Climate Action Report concluded that carbon dioxide emissions increased by 20 percent from 1990-2004, while methane and nitrous oxide emissions decreased by 10 percent and 2 percent, respectively.

The declines in methane emissions are due to a variety of technological, policy, and agricultural changes, such as increased capture of methane from landfills for energy, reduced emissions from natural gas systems, and declining cattle populations. At least some of the decline in nitrous oxide emissions is due to improved emissions control technologies in cars, trucks, and other mobile sources. (Fourth U.S. Climate Action Report, 2007)"

Fig.3.2.1 shows U.S. Greenhouse Gas Intensity in terms of MT of CO_2 equivalent per million dollars of GDP. Fig. 3.2.2 and Fig. 3.2.3 show projections for emissions of CH_4 and N_2O respectively.

U.S. GHG EMISSIONS FROM ENERGY CONSUMPTION AND OTHER ANTHROPOGENIC SOURCES ARE PROJECTED TO GROW FROM HISTORIC LEVELS, ALTHOUGH EMISSIONS PROJECTED WITH THE FULL IMPLEMENTATION OF CLIMATE PROGRAMS AND MEASURES ARE LOWER THAN UNDER THE BUSINESS AS USUAL

GREENHOUSE GASES	HISTORICAL GHG EMISSIONS Business As Usual			PROJECTED GHG EMISSIONS			
				Business As Usual		Full Implementation of Climate Programs and Measures	
	2000	2002	2004	2012	2020	2012	2020
Energy-Related CO2	5,534	5,502	5,657	6,318	6,931	6,060	6,447
Non-Energy CO2	331	314	331	361	396	361	396
Methane	567	560	557	621	667	599	621
Nitrous Oxide	416	407	387	383	399	380	397
High GWP Gases	135	133	143	434	622	312	417
Adjustments	0	0	0	-3	52	-3	52
Total Gross Emissions	6,982	6,916	7,074	8,115	9,067	7,709	8,330
Sinks	-760	-769	-780	-776	-675	-806	-709
Total Net Emissions	6,223	6,147	6,294	7,340	8,392	6,903	7,621
GROSS GHG INTENSITY							
GDP (billions of 2000 dollars)	$10,075			$13,793		$13,793	
Gross GHG Inensity	686			588		559	
2002-12 Gross GHG Intensity Reduction				-14.3%		-18.6%	

Notes:
1. Historical emissions and sinks data are from U.S. EPA/ OAP 2006c. Bunker fuels and biomass combustion are not included in inventory calculations.
2. 2012 data are interpolated when specific data are not available.
3. Energy-related CO2 projections are calculated from U.S. DOE/EIA 2006a CO2, with any CO2 from nonenergy sources removed.
4. Nonenergy CO2 includes emissions from nonenergy fuel use and other industrial emission sources.
5. Adjustments include international bunker fuels and emissions in U.S. territories.
6. Sinks projections are extrapolated from U.S. EPA/OAP 2006c, with programs and measures projections from the U.S. Department of Agriculture.

U.S. greenhouse gas intensity under *Full Implementation of Climate Programs and Measures* is projected to meet the President's target for 2012. The GHG emission reduction in 2012 is projected to be 407 Tg CO_2 Eq. (111 MMTCE), and the cumulative GHG emission reduction from 2002 through 2012 is projected to be 2,225 Tg CO_2 Eq. (607 MMTCE), relative to projected emissions under *Business As Usual* conditions. From 2002 through 2012, GHG emissions are expected to rise by 11 percent to 7,709 Tg CO_2 Eq.
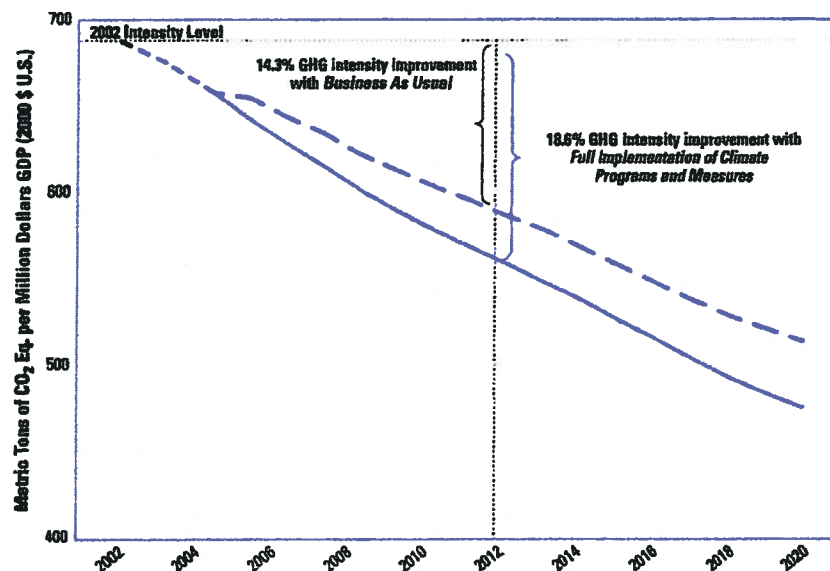
Fig.3.2.1 Historical and Projected U.S. GHG Intensity
Source: U.S. EPA Emission Inventory 2002; Inventory of U.S. GHG Emissions and Sinks (2002)

Methane Projections
with and without voluntary program reductions
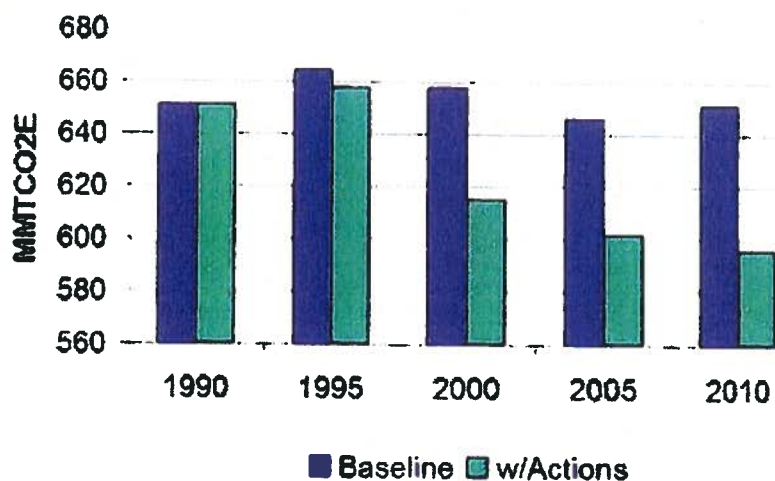
Fig.3.2.2 Projected U.S. Methane Emissions
Source: U.S. Emission Inventory 2002; Inventory of U.S. GHG Emissions and Sinks (2002)

[33]

U.S. Nitrous Oxide Projections
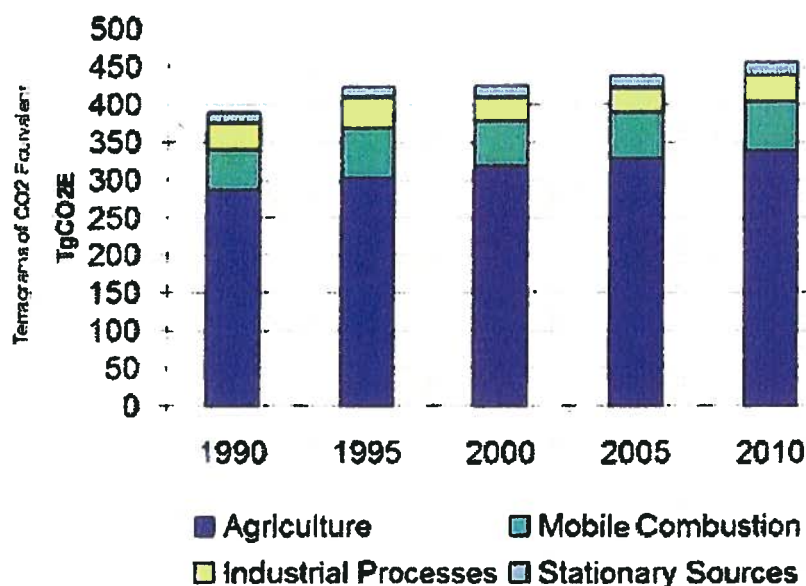
Fig.3.2.3 U.S. Nitrous Oxide Projections
Source: U.S. Emission Inventory 2002; Inventory of U.S. GHG Emissions and Sinks (2002)

3.2.1 IPCC Guidelines and General Approaches for Estimating GHG Emissions

The IPCC guidelines provide various methods for calculating a given emission. It is expected that the same general structure be used; however, the level of detail at which the calculations are carried out can vary.

The same general approach to estimating emissions is applied across various gases and human activities. Emissions are estimated by multiplying activity data by specific emission factors. The general rule can be represented as:

Emission = Activity Data x Emission Factor

Activity data refers to the quantitative amount of human activity resulting in emissions taking place during a given period of time. The annual activity data for fuel combustion sources, for example, are the total amount of

[34]

fuel burned. In the agriculture sector, annual activity data for methane emissions from enteric fermentation are the total number of animals, by species.

If heat content (higher heating value, HHV) of the fuel or carbon content is known then CO_2 emissions can be estimated by using the following equation:

Tons/ yr of CO_2 = Heat Content (MMBtu per unit quantity of fuel) x Carbon Content (kg C per MMBtu) x Oxidation Factor x (MW CO_2, 44/ MW C, 12) X (1/907,200)

Table-3.2.1.1 shows emission factors for calculating CO_2 emissions for various fuels when heating values are known.

Table-3.2.1.1: Emission factors for calculating CO_2 emissions when heat content and/ or carbon content are known. Source: Department of Air Quality, North Carolina, U.S. EPA, http://daq.state.nc.us

Fuel Type	Heat Content (Based on HHV)	Carbon Content	Fraction Oxidized
Fossil Fuel Combustion			
Coal and Coke	MMBtu/ton	Kg C/MMBtu	
Anthracite Coal	25.09	28.26	1.00
Bituminous Coal	24.93	25.49	1.00
Sub-bituminous Coal	17.25	26.48	1.00
Lignite	14.21	26.30	1.00
Unspecified (residential and	22.05	26.00	1.00
Unspecified (industrial	26.27	25.56	1.00
Unspecified (other	22.05	25.63	1.00
Unspecified (electric	19.05	25.76	1.00
Coke	24.80	31.00	1.00
Natural Gas (by HHV)	MMBtu/scf	Kg C/MMBtu	
975-1000 Btu/ scf	975-1000 x 10^{-6}	14.36	1.00
1000-1025 Btu/ scf	1000-1025 x	14.43	1.00
1025-1050 Btu/ scf	1025-1050 x	14.47	1.00
1050-1075 Btu/ scf	1050-1075 x	14.58	1.00
1075-1100 Btu/ scf	1075-1100 x	14.65	1.00
>1100 Btu/ scf	>1100 x 10^{-6}	14.92	1.00
U.S. Weighted Average	1029 x 10^{-6}	14.47	1.00
Petroleum Products	MMBtu/Barrel	Kg C/MMBtu	
Asphalt and Road Oil	6.636	20.62	1.00
Aviation Gasoline	5.048	18.87	1.00
Distillate Fuel Oil	5.825	19.95	1.00

If heat content or carbon content of the fuel is not known then emission factor can be used with following equation:

Tons/ yr of CO_2 = Fuel Quantity x Emission Factor (kg CO_2 per MMBtu or kg CO_2 per unit of fuel quantity) x C (1/907,200)

Table-3.2.1.2 shows emission factors for calculating CO_2 emissions for various fuels using emission factors.

Table-3.2.1.2: Emission factors for calculating CO_2 emissions using emission factors when fuel analysis is not available. Source: Department of Air Quality, North Carolina, U.S. EPA, http://daq.state.nc.us

Fuel Type	CO_2 Emission Factor (per Unit	CO_2 Emission Factor (Per Unit
Coal and Coke	**Kg CO_2/ MMBtu**	**Kg CO_2/ton**
Anthracite Coal	103.62	2599.83
Bituminous Coal	93.46	2330.04
Sub-bituminous Coal	97.09	1674.86
Lignite	96.43	1370.32
Unspecified (residential/commercial)	95.33	2012.29
Unspecified (industrial	93.72	2462.12
Unspecified (other	93.98	2072.19
Unspecified (electric	94.45	1884.53
Coke	113.67	2818.93
Natural Gas (by HHV)	**Kg CO_2/ MMBtu**	**Kg CO_2/scf**
975-1000 Btu/ scf	52.56	varies
1000-1025 Btu/ scf	52.91	varies
1025-1050 Btu/ scf	53.06	varies
1050-1075 Btu/ scf	53.46	varies
1075-1100 Btu/ scf	53.72	varies
>1100 Btu/ scf	54.71	varies
U.S. Weighted Average (1029	53.06	varies
Petroleum Products	**Kg CO_2/ MMBtu**	**Kg CO_2/gallon**
Asphalt and Road Oil	75.61	11.95
Aviation Gasoline	69.19	8.32
Distillate Fuel Oil	73.15	10.15

Following equation may be used for estimating CH_4 and N_2O emissions using emission factor approach:

Tons/ yr of (CH_4 or N_2O) = Fuel (MMBtu) x Emission Factor x C1

Where,
Emission Factor = gram CH_4 per MMBtu or gram N_2O per MMBtu
C1 = 1/907,200

Table-3.2.1.3 and 3.2.1.4 show emission factors for estimating CH_4 and N_2O emissions for various fuels.

Table-3.2.1.3: Emission factors (Technology Specific) for calculating CH_4 emissions-Electricity Generation Sector. Source: Department of Air Quality, North Carolina, U.S. EPA, http://daq.state.nc.us

Fuel Type	Configuration	CH_4	N_2O
Liquid Fuels			
Residual Fuel Oil/Shale Oil Boilers	Normal Firing	0.8	0.3
	Tangential Firing	0.8	0.3
Gas/Diesel Oil Boilers	Normal Firing	0.8	0.3
	Tangential Firing	0.8	0.3
Large Diesel Oil			
Solid Fuels			
Pulverized Bituminous Boilers	Dry Bottom-Wall	0.7	0.5
	Dry Bottom-	0.7	1.4
	Wet Bottom	0.9	1.4
Bituminous spreader stoker boilers	With and Without Re-injection	1.0	0.7
Bituminous Fluidized Bed Converter	Circulating Bed	1.0	61.1
Bubbling Bed		1.0	61.1
Bituminous Cyclone Furnace		0.2	1.6
Lignite Atmospheric Fluidized Bed		N/A	71.2
Natural Gas			
Boilers		0.9	0.9
Gas Fired Turbines>3.0MW		3.8	0.9
Large Dual Fuel Engines		245	N/A
Combined Cycle		0.9	2.8
Peat			
Peat Fluidized Bed Combustor		3.0	7.0
Bubbling Bed		3.0	3.0
Biomass			
Wood/Wood Waste Boiler		9.3	5.9
Wood Recovery Boilers		0.8	0.8

Table-3.2.1.4: Emission factors for calculating N_2O emissions. Source: Department of Air Quality, North Carolina, U.S. EPA, http://daq.state.nc.us

Fuel Type	Sector	CH_4	N_2O
Coal	Residential	316	1.6
	Commercial	11	1.6
	Industrial	11	1.6
	Electric Power	1	1.6
Petroleum Products	Residential	11	0.6
	Commercial	11	0.6
	Industrial	3	0.6
	Electric Power	3	0.6
Natural Gas	Residential	5	0.1
	Commercial	5	0.1
	Industrial	1	0.1
	Electric Power	1	0.1
Wood	Residential	316	4.2
	Commercial	316	4.2
	Industrial	32	4.2
	Electric Power	32	4.2
Pulping Liquors	Industrial	2.5	2.0

Source: The climate registry, General Reporting Protocol, USEPA Climate Leaders GHG Inventory Protocol-Direct Emission from Stationary Combustion Sources, Nov. 2007, Table-A1

Based on samples of measurement data, emission factors are representative rates of emission for a given activity level under a given set of operating conditions. They are estimates of average emission rate of a given pollutant for a given source, relative to units of activity.

The IPCC methods for estimating emissions are divided into "tiers," encompassing different levels of activity and technological detail. "Tier 1" methods are generally very simple, requiring less detail and expertise than the most complicated "Tier 3" methods. For example, electricity and heat generation could be measured using three different methods.

According to Canadian Environmental Sustainability Indicators: GHG Emissions Indicator: Data Sources and Methods (2005), "A Tier 1 method would entail mass balance calculation based on aggregated country-wide (or regional) statistics on consumption of basic fuels. A Tier 2 method

would involve emission calculation by source types, based on fuel use for each industry and sector of the economy. A Tier 3 method would utilize source specific data and could be used for only a small number of principal emission sources.

The intention of this tiered structure is to encourage countries to work at the most detailed level possible, while ensuring that those countries that do not have detailed data can also develop some estimates. The Tier 2 and Tier 3 methods are expected to produce more accurate emission estimates, but are more resource-intensive as they usually require extensive data collection and a more thorough understanding of technologies".

For example, emissions from fuel combustion for all energy sub-sectors can be estimated using the following equation:

Emissions = quantity of fuel combusted x Emission Factor per unit of fuel

The emission factors are based upon the physical quantity of fuel combusted and are subdivided by the type of fuel used. The equation applies to all source sectors; however, more detailed methods are often used. For example, emissions from transport sectors can be calculated using more precise GHG emission models to disaggregate fuel statistics into several categories that represent estimated fuel consumed by vehicles of similar emission characteristics determined as a function of the model year, fuel and vehicle type.

Typical national methane gas emission estimation for dairy and beef cattle can be derived using methodologies provided by IPCC using the following equation:

Methane emission estimates for Canadian dairy and beef cattle

$$CH_4 = \sum_{i=1}^{n}(P_i \times EF_i)$$

where:

CH_4	=	Enteric fermentation methane emissions for all animal categories
P_i	=	Animal population (P) for each specific livestock category or sub-category (i)
EF_i	=	Methane emissions factor for each specific livestock category (i)

Methane emission estimates for Canadian cattle are calculated using the following steps:

Step 1: Emission factors are calculated for various cattle sub-categories based on the IPCC Tier-2 methodology, along with specific information on animal sub-category, physiological status, age, gender, weight, rate of gain, level of activity, and production environment.

Step 2: Emission factors are calculated for each cattle sub-category (dairy cows, dairy heifers, beef cows, bulls, calves <1 year, heifer replacement, heifers >1 year, and steers >1 year) by province and then combined to produce a weighted national average emission factor.

Step 3: National enteric emissions are calculated by multiplying the emission factor with its cattle sub-category population, and by summing up estimates for all cattle sub-categories.

Source: Canadian Environmental Sustainability Indicators, Data source and methods, http://dsp-psd.tpsgc.gc.ca/collection/statcan

Greenhouse gases differ in their ability to absorb heat in the atmosphere based on their chemical properties and lifetime in the atmosphere.

For example, over a period of 100 years, methane is 21 times as powerful as carbon dioxide in terms of it potential to trap heat in the atmosphere, so it is considered to have a "global warming potential" of 21.

Therefore, greenhouse gases are reported in terms of "carbon dioxide equivalents" determined by multiplying the amount of emissions of a particular gas by potentials for each greenhouse gas as shown in Table-3.2.1.5 below.

Table-3.2.1.5 Global Warming Potential and Atmospheric Lifetimes, Source: Canadian Environmental Sustainability Indicators, Data source and methods, http://dsp-psd.tpsgc.gc.ca/collection/statcan

Units: Atmospheric Lifetime: Years

Greenhouse gas	Formula	100-year global warming potential	Atmospheric lifetime
Carbon dioxide	CO_2	1	variable
Methane	CH_4	21	12 ± 3
Nitrous oxide	N_2O	310	120
Sulphur hexafluoride	SF_6	23 900	3 200
Hydrofluorocarbons (HFCs)			
HFC-23	CHF_3	11 700	264
HFC-32	CH_2F_2	650	5.6
HFC-41	CH_3F	150	3.7
HFC-43-10mee	$C_5H_2F_{10}$	1 300	17.1
HFC-125	C_2HF_5	2 800	32.6
HFC-134	$C_2H_2F_4$ (CHF_2CHF_2)	1 000	10.6
HFC-134a	$C_2H_2F_4$ (CH_2FCF_3)	1 300	14.6
HFC-143	$C_2H_3F_3$ (CHF_2CH_2F)	300	1.5
HFC-143a	$C_2H_3F_3$ (CF_3CH_3)	3 800	3.8
HFC-152a	$C_2H_4F_2$ (CH_3CHF_2)	140	48.3
HFC-227ea	C_3HF_7	2 900	36.5
HFC-236fa	$C_3H_2F_6$	6 300	209
HFC-245ca	$C_3H_3F_5$	560	6.6
Perfluorocarbons (PFCs)			
Perfluoromethane	CF_4	6 500	50 000
Perfluoroethane	C_2F_6	9 200	10 000
Perfluoropropane	C_3F_8	7 000	2 600
Perfluorobutane	C_4F_{10}	7 000	2 600
Perfluorocyclobutane	$c\text{-}C_4F_8$	8 700	3 200
Perfluoropentane	C_5F_{12}	7 500	4 100
Perfluorohexane	C_6F_{14}	7 400	3 200

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3.3 ADDITIONAL METHODS TO ESTIMATE GHG EMISSIONS

3.3.1 Fugitive Emissions from Coal Mining

CH$_4$ released during the process of coal formation depends on degree of coalification. Quantity of methane relates directly to pressure and depth. CH$_4$ emissions generated from underground mining are higher than the emission from surface mining and can be calculated using the following equation (Selma Guven, 2001):

CH$_4$ Emissions (Gg) = Coal produced from underground and surface mining (tonnes) X emission factor (m^{3}xtonnes^{-1} at operating conditions) x conversion factor (Ggx10^{-6} m^{-3} at given conditions)

CH$_4$ emission factors for underground and surface mining (m^3 per tonne) are given in the Table 3.3.1 below:

Table-3.3.1: Methane emission factors for underground and surface mining, m^3/ tonne

Sources	Underground Mining	Surface Mining
Extracting of Mines	10-25	0.3-2.00
Processing of Mines	0.9-4.0	0-0.2

Source: Estimation of GHG Emissions by IPCC Methods, Selma Guven (2001)

3.3.2 Emissions from Agricultural Facilities

Emissions from agricultural facilities include those from livestock, rice cultivation, burning of agricultural resides and from agricultural land. Greenhouse gas emissions from livestock cover enteric fermentation and manure management.

3.3.2.1 Enteric Fermentation

Following table gives some examples of emission factors for enteric fermentation for different types of livestock:

Table-3.3.2.1: Emission Factors for methane emissions from enteric fermentation

Types of Livestock	EF (kg/ head/ year)
Buffalo	55
Sheep	5
Goats	5
Camels	46
Horses	18
Mules & Asses	10
Swine	1

Source: Estimation of GHG Emissions by IPCC Methods, Selma Guven (2001)

Emission from enteric fermentation can be estimated using following equation (Selma Guven, 2001):

Emission (Gg) = LPXEF CH$_4$ kgxGg.10^{-6} kg^{-1}

LP: Livestock Population
EF: Emission Factor

3.3.2.2 Methane Emission From Manure Management

Examples of emission factors for methane from manure management are given in the table below:

Table-3.3.2.2: Emission Factors (kg/head/yr) for methane emissions from manure management

Types of Livestock	Cold	Temperate	Warm
Sheep	0.10	0.16	0.21
Goats	0.11	0.17	0.22
Camels	1.3	1.9	2.6
Horses	1.1	1.6	2.2
Mules & Asses	0.6	0.9	1.2
Poultry	0.012	0.018	0.023

Source: Estimation of GHG Emissions by IPCC Methods, Selma Guven (2001)

Cold: Less than 15 °C; Temperate between 15-°C to 25-°C and greater than 25-°C. Poultry includes chicken, ducks and turkeys.

Methane emission from manure management can be estimated using the following equation (Selma Guven, 2001):

Emission (Gg) = LPXEF (CH$_4$ kgxGg.10^{-6} kg^{-1})

LP: Livestock Population
EF: Emission Factor (Gg per unit of livestock population)

3.3.2.3 Emission from Rice Cultivation

Some examples of emission factors for methane emission from rice cultivation for different average temperature of growth seasons are given in the table below:

Emission from rice cultivation can be estimated using following equation (Selma Guven, 2001):

$$Emission\ (Gg) = CRF\ (ha)\ X\ EF\ CH_4\ kg/ha/day\ xGSXGg.10^6\ kg^{-1}$$

CRF: Cultivated Rice Field (ha)
EF: Emission Factor (based on average monthly temperature)
GS: Growth Season (Growth season of rice will be specific to region)

Table-3.3.2.3: Emission Factors based on average temperature of growth season

Avg. Temp. of Growth Season, °C	EF (kg/ ha/ day)
15	2.91
16	3.07
17	3.28
18	3.48
19	3.68
20	3.91
21	4.14
22	4.39
23	4.66
24	4.94
25	5.24
26	5.56
27	5.90
28	6.25
29	6.63
30	7.03
31	7.46
32	7.91
33	8.39
34	8.90
35	9.44

Source: Estimation of GHG Emissions by IPCC Methods, Selma Guven (2001)

3.3.2.4 Emission from Burning of Agricultural Residue

Following example is based on "Methods for Estimating Greenhouse Gas Emissions from Burning of Agricultural Crop Residue" (Barbara Braatz et al, 1999).

The methodology for estimating greenhouse gas emissions from field burning of agricultural wastes is based on (Barbara Braatz et al 1999):

1. The amounts of carbon and nitrogen in the crop residue combusted
2. The emission ratio of CH_4 to carbon released in combustion (as measured in the smoke of biomass fires), and
3. The emission ratio of N_2O to nitrogen released in combustion.

To estimate emissions of CH_4 and N_2O from burning of agricultural wastes, the following steps should be performed:

1. Obtain the required data on the crop production
2. Estimate the total amount of carbon and nitrogen released
3. Estimate emissions of CH_4 and N_2O based on the amount of carbon and nitrogen released.

The method described here is from the IPCC report (1997), the methods are used in Inventory report on U.S. Greenhouse Gas Emissions and Sinks (U.S. EPA 1998). The preferred method consists of seven steps, which are outlined below:

Step-1: Obtain required data on crop

Data Required: The information needed to estimate greenhouse gas emissions from burning of agricultural wastes is the annual production of crop.

Data Source: State agricultural agencies, annual crop production data from USDA report on crop production.

Units of reporting data: Annual crop production data should be converted to pounds.

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Example:

1,000,000,000 bushels x 60 lbs/ bushel = 60 billion pounds

Step-2: Calculate the amount of dry matter burned:

For each crop calculate the dry matter burned. Use the data in Table 3.3.2.4 (A), (B), (C) with some examples.

Amount of dry matter (lbs) =Annual Crop Production (lbs)x Residue/Crop Ratio x Proportion of crop produced in fields where Residue is Burned (%) x Dry Matter Content of the Residue (%) x Burning Efficiency (%) x Combustion Efficiency(%)

Table: 3.3.2.4

A) Estimation of dry matter burned

Crop Type	A	B	C	D	E	F	G = (AXBXCXDXEX F)
	Crop Production, lbs	Residue / Crop Ratio	Proportion of Residue Burned	Proportion of dry matter	Burning Efficiency	Combustion Efficiency	Dry Matter Combusted (lbs)
Rice		1.4	0.03	0.85	0.93	0.88	
Sugarcane		0.8	0.03	0.62	0.93	0.88	
Wheat		1.3	0.03	0.85	0.93	0.88	

B) Estimation of total C and N released

Crop Type	H = G	I	J = H X I	K	L = H X K
	Dry Matter Burned, lbs	Carbon Content (lbs C/ lb.dm)	Total C Released (lbs.C)	Nitrogen Content (lbs.N/ lb.dm)	Total Nitrogen (lbs.N)
Rice		0.4144		0.0067	
Sugarcane		0.4235		0.0040	
Wheat		0.4853		0.0028	

Source: Data taken from "Methods for Estimating Greenhouse Gas Emissions from Burning of Agricultural Crop Wastes" (Oct.'99) Barbara Braatz, Randy Treed, William Driscoll of ICF Consulting for Emission Inventory Improvement Program

C) Estimation of CH₄ and N₂O Emissions

Crop Type	M = J	N = L	O	P = [M X O X (16/12)]/[2205 X (12/44) X 21]	Q	R = [N X Q X (44/28)]/[2205 X (12/44) X 310]
	Total Carbon Released (lbs. C)	Total Nitrogen (lbs.N)	CH₄-C Emission Ratios	CH₄ Emitted (metric tons carbon equivalent)	N₂O-N Emission Ratio	N₂O Emitted (metric tons carbon equivalent)
Rice			0.005		0.007	
Sugarcane			0.005		0.007	
Wheat			0.005		0.007	

Source: Data taken from "Methods for Estimating Greenhouse Gas Emissions from Burning of Agricultural Crop Wastes" (Oct.'99) Barbara Braatz, Randy Treed, William Driscoll of ICF Consulting for Emission Inventory Improvement Program

Burning Efficiency is defined as the fraction of dry biomass exposed to burning that actually burns. Combustion Efficiency is defined as the fraction of carbon in the fire that is released to the atmosphere.

Step-3 Calculate Total Carbon Released (Table 3.3.2.4(B), Columns H-J)

For each crop, take the amount of dry matter (dm) burned (estimated in step (2) – column G) and enter it in column H of Table 3.3.2.4(B). Next, multiply the amount of dry matter burned by the fraction of carbon to obtain total amount of C released.

Dry Matter Burned (lbs.) × Carbon Content of the Residue (lbs. C/lb. dm) = Total Carbon Released (lbs.)

Example:
The quantity of wheat residue burned is calculated as follows:

100 billion lbs. × 1.3 lbs. residue/lb. crop product × 0.03 portion of crop produced in fields where residue is burned × 0.85 dry matter content × 0.93 burning efficiency × 0.88 combustion efficiency = 2.71 **billion lbs. dry matter (dm)**

Step-4: Estimate emissions of CH₄
For each crop multiply the amount of C released in units of carbon by the emission ratio of CH₄ (column O) relative to total C.

Amount released (lbs. C) X 0.005 = CH₄ Emissions (lbs. CH₄-C)

In the methodology recommended by the IPCC, the "burning efficiency" is assumed to be accounted for in the factor for "fraction of residues burned." However, the number used

here to estimate the "fraction of residues burned" does not account for the fraction of exposed residue that does not burn. Therefore, a "burning efficiency factor" is added to the calculations.

Example
The total amount of carbon released from burning of U.S. wheat residue 1.0 billion dm is calculated as follows:

1.0 billion lbs. dm × 0.4853 (lbs. C/lb. dm) = 485,300,000 lbs. C

Step-5: Estimate Nitrogen Content of the Dry Matter

Dry Matter (lbs.) x Nitrogen Content (lbs. N/ lb.dm) = Total Nitrogen Released (lbs. N)

Step-6: Estimate emissions of N_2O

Amount of N Released (lbs.) x 0.007 = N_2O-Nitrogen Emissions (lbs. N_2O-N)

Step-7: Convert to Metric Tons of carbon equivalent

For each crop perform the calculations shown in columns P and R of the table to convert the emission units of metric tons of carbon equivalent. These calculations convert:

- Emissions of CH_4-C and N_2O-N to full molecular weights
- Pounds to metric tons
- Metric tons of gas to metric tons of carbon equivalent (by multiplying by the mass ratio of carbon to carbon dioxide, and by the global warming potential for each gas. The global warming potential for methane is 21 and for N_2O is 310.

For each gas, sum across all crop types to produce total emissions from burning of crop residues.

CHAPTER-4
HEALTH AND ENVIRONMENTAL EFFECTS OF GHG EMISSIONS

As per Intergovernmental Panel on Climate Change (IPCC, 2007), the climate has warmed over the past century and a further 3 to 7 °F (2 to 4 °C) is predicted over the 21st century. "In global climate terms, warming at this rate would be much larger and faster than any of the climate changes over at least the past 10,000 years."

According to EPA (EPA: Climate Change: Health and Environmental Effects, http://epa.gov/climatechange/effects/index.html), "Many elements of human society and the environment are sensitive to climate variability and change. Human health, agriculture, natural ecosystems, coastal areas, and heating and cooling requirements are examples of climate sensitive systems.

Rising average temperatures are already affecting the environment. Some observed changes include shrinking of glaciers, thawing of permafrost, later freezing and earlier break-up of ice on rivers and lakes, lengthening of growing seasons, shift in plant and animal ranges and earlier flowering of trees."

Global temperatures are expected to continue to rise as human activities continue to add carbon dioxide, methane, nitrous oxide, and other greenhouse gases to the atmosphere.

According to IPCC (2007) report, human beings are exposed to climate change through changing weather patterns and indirectly through changes in water, air, food quality and quantity, ecosystems, agriculture, and economy.

Agriculture is very sensitive to climate variability and weather extremes, such as droughts, floods and severe storms. The forces that make up our climate such as average temperature, rainfall, rising concentrations of CO_2, pollution levels are also critical to agriculture productivity.

Average temperature increases can lengthen the growing season into fall and/ or spring, adversely affecting crops in region where summer heat already limits production,

increases soil evaporation rates and increases chances of severe droughts.

Changes in rainfall can affect soil erosion rates and soil moisture, both of which are important for crop yields. As per IPCC (2007), precipitation will increase in high latitudes and decrease in most subtropical land regions.

Increasing atmospheric concentration of CO_2 levels driven by emissions from human activities can act as a fertilizer and enhance the growth of some crops such as wheat, rice and soybeans. While it is expected that CO_2 fertilization will have some positive impact on some crops, while other aspects of climate change e.g. temperature, precipitation and increasing ozone levels may offset any beneficial effect of CO_2 fertilization.

According to the IPCC report 2007, during the course of the century the resilience of many ecosystems (their ability to adapt naturally) is likely to be extended by an unprecedented combination of change in climate and in other global change drivers (especially land use change and overexploitation), if greenhouse gas emissions continue at or above the current rates.

According to EPA (EPA: Climate Change: Health and Environmental Effects, http://epa.gov/climatechange/effects/index.html), by 2100 ecosystems will be exposed to atmospheric CO_2 levels substantially higher than in the past 650,000 years, and global temperatures at least among the highest as those experienced in the past 740,000 years. This will alter the structure, reduce biodiversity and perturb functioning of ecosystems, and compromise the services they render.

Sea level is rising along most of the U.S. coast and around the world. In the last century, sea level rose 5 to 6 inches more than the global average along the Mid-Atlantic and Gulf Coasts, because coastal lands there are subsiding.

Higher temperatures are expected to further raise sea level by expanding ocean water, melting mountain glaciers and small ice caps, and causing portions of Greenland and the Antarctic ice sheets to melt." The IPCC estimates that the global average sea level will rise between 0.6 and 2 feet in the next century. Rising sea levels inundate

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wetlands and other low lying lands, erode beaches, intensify flooding, and increase the salinity of rivers, bays, and groundwater tables.

Coastal wetland ecosystems such as salt marshes and mangroves are particularly vulnerable to rising sea level because they are generally within few feet of sea level (IPCC, 2007). Wetlands provide habitat for many species, play a key role in nutrient uptake, serve as the basis for many communities economic livelihood, provide recreational opportunities, and protect local areas from flooding.

4.1 EFFECTS ON HUMAN HEALTH

The occurrence of certain diseases and other threats to human health depend largely on local climate. Extreme temperatures can lead directly to loss of life, while climate-related disturbances in ecological systems, such as changes in the range of infective parasites, can indirectly impact the incidence of serious infectious diseases. In addition, warm temperatures can increase air and water pollution, which in turn can harm human health.

The Intergovernmental Panel on Climate Change (IPCC, 2007) concluded that "Human beings are exposed to climate change through changing weather patterns (for example, more intense and frequent extreme events) and indirectly through changes in water, air, food quality and quantity, ecosystems, agriculture, and economy. At this early stage the effects are small but are projected to progressively increase in all countries and regions".

4.1.1   Direct Temperature Effects

According to EPA (EPA: Climate Change: Health and Environmental Effects, http://epa.gov/climatechange/effects/health.html), "climate change may directly affect human health through increases in average temperature. Such increases may lead to more extreme heat waves during the summer while producing less extreme cold spells during the winter. Rising average temperatures are predicted to increase the incidence of heat waves and hot extremes. In the United States, Chicago is projected to experience 25 percent more frequent heat waves and Los Angeles a four-to-eight-fold increase in heat wave days by the end of the century (IPCC, 2007). Particular segments of the population such as those with

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heart problems, asthma, the elderly, the very young and the
homeless can be especially vulnerable to extreme heat."

4.1.2   Extreme Effects

According to EPA (EPA: Climate Change: Health and
Environmental Effects,
http://epa.gov/climatechange/effects/index.html), "extreme
weather events can be detrimental to human health and well-
being. The extent to which climate change may affect the
frequency and severity of events, such as hurricanes and
extreme heat and floods, is being investigated by the U.S.
Climate Change Science Program. An increase in the
frequency of extreme events may result in more event-
related deaths, injuries, infectious diseases, and stress-
related disorders".

4.1.3   Climate Sensitive Diseases

According to EPA (EPA: Climate Change: Health and
Environmental Effects,
http://epa.gov/climatechange/effects/index.html), "climate
change may increase the risk of some infectious diseases,
particularly those diseases that appear in warm areas and
are spread by mosquitoes and other insects. These "vector-
borne" diseases include malaria, dengue fever, yellow
fever, and encephalitis. Also, algal blooms could occur
more frequently as temperatures warm — particularly in
areas with polluted waters — in which case diseases (such
as cholera) that tend to accompany algal blooms could
become more frequent.

Higher temperatures along with favorable rainfall
patterns could prolong disease transmission seasons in some
locations where certain diseases already exist. In other
locations, climate change could decrease transmission via
reductions in rainfall or temperatures that are too high
for transmission. For example, temperature and humidity
levels must be sufficient for certain disease-carrying
vectors, such as ticks that carry Lyme disease, to thrive.
Climate change could push temperature and humidity levels
either towards or away from optimum conditions for the
survival rate of ticks."

According to IPCC (2007), the global population which
is at risk from vector-borne malaria will increase by
between 220 million and 400 million in the next century.

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While most of the increase is predicted to occur in Africa, some increased risk is projected in Britain, Australia, India and Portugal.

According to EPA (EPA: Climate Change: Health and Environmental Effects, http://epa.gov/climatechange/effects/health.html), "tick-borne Lyme disease may also expand its range in Canada. However, socioeconomic factors such as public health measures will play a large role in determining the existence or extent of such infections. Water-borne diseases may increase where warmer air and water temperatures combine with heavy runoff from agricultural and urban surfaces, but may be largely contained by standard water-treatment practices."

4.1.4   Air Quality Related Health Effects

According to IPCC (2007), climate change is expected to contribute to some air quality problems. Respiratory disorders may be exacerbated by warming-induced increases in the frequency of smog (ground-level ozone) events and particulate air pollution.

According to EPA (EPA: Climate Change: Health and Environmental Effects, http://epa.gov/climatechange/effects/health.html), "ground-level ozone can damage lung tissue, and is especially harmful for those with asthma and other chronic lung diseases. Sunlight and high temperatures, combined with other pollutants such as nitrogen oxides and volatile organic compounds, can cause ground-level ozone to increase. Climate change may increase the concentration of ground-level ozone, but the magnitude of the effect is uncertain.

Another pollutant of concern is "particulate matter" also known as particle pollution or PM. Particulate matter is a complex mixture of extremely small particles and liquid droplets. When breathed in, these particles can reach the deepest regions of the lungs.

Exposure to particle pollution is linked to a variety of significant health problems. Particle pollution also is the main cause of visibility impairment (haze) in the nation's cities and national parks. Climate change may indirectly affect the concentration of PM pollution in the

air by affecting natural or "biogenic" sources of PM such
as wildfires and dust from dry soils."

4.1.5   Other Health Effects

Effects of climate change on agricultural yields and
production are likely to grow over time, with the most
negative effects expected in developing countries.
According to IPCC (2007, this is expected to increase the
number of undernourished people globally and consequently
lead to complications in child development.

Climate change may also cause social disruption,
economic decline and displacement of populations in certain
regions, due to effects on agricultural production,
already-scarce water resources, rise in sea levels, and
extreme weather events. According to IPCC (2007), These
issues are likely to be more severe in developing
countries, and may worsen human health and well-being in
affected regions.

4.2 EFFECTS ON WATER RESOURCES, AGRICULTURE AND FOOD SUPPLY

4.2.1   Effect on Water Resources

According to EPA (EPA: Climate Change: Health and
Environmental Effects,
http://epa.gov/climatechange/effects/water/index.html),
"all regions of the world show an overall net negative
impact of climate change on water resources and freshwater
ecosystems. Areas in which runoff is projected to decline
are likely to face a reduction in the value of the services
provided by water resources. The beneficial impacts of
increased annual runoff in other areas are likely to be
tempered in some areas by negative effects of increased
precipitation variability and seasonal runoff shifts on
water supply, water quality and flood risks (IPCC, 2007)

The future effects of climate change on water
resources in the U.S. and other parts of the world will
depend on trends in both climatic and non-climatic factors.
Evaluating these impacts is challenging because water
availability, quality and stream flow are sensitive to
changes in temperature and precipitation. Other important
factors include increased demand for water caused by

population growth, changes in the economy, development of new technologies, changes in watershed characteristics and water management decisions."

4.2.2   Effect on Agriculture and Food Supply

Agriculture is highly sensitive to climate variability and weather extremes, such as droughts, floods and severe storms. The forces that shape our climate are also critical to farm productivity.

According to the Intergovernmental Panel on Climate Change (IPCC, 2007) increased frequency of heat stress, droughts and floods will negatively affect crop yields and livestock beyond the impacts of mean climate change, creating the possibility for surprises, with impacts that are larger, and occurring earlier, than predicted using changes in mean variables alone.

Several factors that directly affect agricultural productivity are:
- Average temperature increase
- Change in rainfall amount and patterns
- Rising atmospheric concentrations of CO_2
- Pollution levels such as tropospheric ozone
- Change in climatic variability and extreme events

An increase in average temperature can 1) lengthen the growing season in regions with a relatively cool spring and fall; 2) adversely affect crops in regions where summer heat already limits production; 3) increase soil evaporation rates, and 4) increase the chances of severe droughts.

Changes in rainfall can affect soil erosion rates, flooding and soil moisture, which are important for crop yields. The IPCC predicts that precipitation will increase in high latitudes, and decrease in most subtropical land regions—some by as much as about 20 percent. While regional precipitation will vary the number of extreme precipitation events is predicted to increase (IPCC, 2007).

Increasing atmospheric CO_2 levels, driven by emissions from human activities, can act as a fertilizer and enhance the growth of some crops such as wheat, rice and soybeans. CO_2 can be one of a number of limiting factors that, when increased, can enhance crop growth. Other limiting factors

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include water and nutrient availability. While it is expected that CO_2 fertilization will have a positive impact on some crops, other aspects of climate change (e.g., temperature and precipitation changes) may temper any beneficial CO_2 fertilization effect (IPCC, 2007).

Higher levels of ground level ozone limit the growth of crops. Since ozone levels in the lower atmosphere are shaped by both emissions and temperature, climate change will most likely increase ozone concentrations. Such changes may offset any beneficial yield effects that result from elevated CO_2 levels.

Change in climatic variability and extreme events: Changes in the frequency and severity of heat waves, drought, floods and hurricanes, remain a key uncertainty in future climate change. Such changes are anticipated by global climate models, but regional changes and the potential effects on agriculture are more difficult to forecast.

According to EPA (EPA: Climate Change: Health and Environmental Effects, http://epa.gov/climatechange/effects/agriculture.html) and IPCC (2007), "for North America as a whole, moderate climate change will likely increase yields of North American rain fed agriculture, but with smaller increases and more spatial variability than in earlier estimates.

Most studies project likely climate-related yield increases of 5-20 percent over the first decades of the century, with the overall positive effects of climate persisting through much or all of the 21st century.

- Food production is projected to benefit from a warmer climate, but there probably will be strong regional effects, with some areas in North America suffering significant loss of comparative advantage to other regions.
- The U.S. Great Plains/Canadian Prairies are expected to be particularly vulnerable.
- Crops that are currently near climate thresholds (e.g., wine grapes in California) are likely to suffer decreases in yields, quality, or both.
- Climate change is expected to improve growing conditions for some crops that are limited by length of growing season and temperature. (e.g. fruit

production in the Great Lakes region and eastern Canada).

Agriculture in the U.S. and other industrialized countries is expected to be less vulnerable to climate change than agriculture in developing nations, especially in the tropics, where farmers may have a limited ability to adapt. In addition, the effects of climate change on U.S. and world agriculture will depend not only on changing climate conditions, but will also depend on the agricultural sector's ability to adapt through future changes in technology, changes in demand for food, and environmental conditions, such as water availability and soil quality. Management practices, the opportunity to switch management and crop selection from season to season, and technology can help the agricultural sector cope with and adapt to climatic variability and change."

4.3 EFFECTS ON FORESTS, ECOSYSTEMS AND BIODIVERSITY

The Intergovernmental Panel on Climate Change (IPCC, 2007) concluded that there may be significant regional transitions associated with shifts in forest location and composition in the U.S. due to climate change. Climate change is likely to affect the geographic distribution of North American forests, including regionally important tree species.

According to EPA (EPA: Climate Change: Health and Environmental Effects, http://epa.gov/climatechange/effects/index.html), "the effects of climate change on forests in the U.S. and other parts of the world will depend not only on climatic factors but also on stresses from pollution (e.g., acid rain); future trends in forest management practices, including fire control and demand for timber; and land-use change. It is difficult to separate the influence of climate change from these other pressures.

Climate change effects on forests are likely to include changes in forest health and productivity and changes in the geographic range of certain tree species. These effects can in turn alter timber production, outdoor recreational activities, water quality, wildlife populations and rates of carbon storage."

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The following factors are likely to play an important role in determining future forest conditions:

- Air temperature
- Precipitation amount and seasonal distribution
- Atmospheric CO_2 concentrations
- Frequency and severity of wildfire events
- Climatic variability and the frequency and severity of extreme events
- Indirect effects on pollution levels such as tropospheric ozone

4.3.1   Changes in Temperature and Precipitation

According to EPA (EPA: Climate Change: Health and Environmental Effects, http://epa.gov/climatechange/effects/index.html), "changes in temperature and precipitation are expected to change forest location, composition, and productivity. Climate change is likely to drive the migration of tree species, resulting in changes in the geographic distribution of forest types and new combinations of species within forests. In North America, many tree species may shift northward or to higher elevations. (IPCC, 2007)"

4.3.2   Tree Growth and CO_2 Sequestration

Tree growth rates may increase with increasing levels of atmospheric CO_2, but these effects are expected to saturate over time as tree communities adjust to higher CO_2 levels.

Climate change will affect tree growth and will also alter rates of carbon storage (or sequestration) in trees and soils. Increased carbon sequestration would remove more CO_2 from the atmosphere (a "This is called a negative feedback" that lessens climate change), while carbon losses through forest disturbances would result in more CO_2 entering the atmosphere (a "positive feedback" that strengthens climate change). According to IPCC (2007), "net carbon uptake by terrestrial ecosystems is likely to peak before mid-century and then weaken or even reverse, thus amplifying climate change."

4.3.3   Fire and Disease

Climate change may cause forest disturbances, such as fire or disease,which could also affect the future of U.S. forests and the market for forest products, such as timber. Increased temperatures could increase fire risk in areas that become drier due to climate change. These changes could compound existing fire risks (IPCC, 2007). Climate change could also promote the rapid increase of diseases and pests that attack tree species.

According to IPCC (2007), climate change is expected to increase the growth of forests modestly (by 10-20 percent)in North America over the next century. However, extreme and/or long-term climate change scenarios also create the potential for widespread forest decline.

Disturbances such as wildfires and insect outbreaks are increasing and likely to intensify in a warmer climate with drier soils and longer growing seasons. The frequency, extent of forest fires is likely to increase, and the areas subject to high fire danger are likely to increase significantly.

The long-term effects of fire will depend heavily on changes in forest and wildfire management systems.

4.3.4   Effects on Ecosystems and Biodiversity

According to EPA (EPA: Climate Change: Health and Environment: Ecosystem & Biodiversity, www.epa.gov/climatechange/effects/eco.html), "Climate is an integral part of ecosystems and organisms have adapted to their regional climate over time. Climate change is a factor that has the potential to alter ecosystems and the many resources and services they provide to each other and to society. Human societies depend on ecosystems for the natural, cultural, spiritual, recreational and aesthetic resources they provide.

In various regions across the world, some high-altitude and high-latitude ecosystems have already been affected by changes in climate. The Intergovernmental Panel on Climate Change reviewed relevant published studies of biological systems and concluded that 20 percent to 30

percent of species assessed may be at risk of extinction from climate change impacts within this century if global mean temperature increases exceed 2-3 °C (3.6-5.4 °F) relative to pre-industrial levels (IPCC, 2007).

These changes can cause adverse or beneficial effects on species. For example, climate change could benefit certain plant or insect species by increasing their ranges. The resulting impacts on ecosystems and humans, however, could be positive or negative depending on whether these species were invasive (e.g., weeds or mosquitoes) or if they were valuable to humans (e.g., food crops or pollinating insects). The risk of extinction could increase for many species, especially those that are already endangered or at risk due to isolation by geography or human development, low population numbers, or a narrow temperature tolerance range".

4.4 EFFECTS ON COASTAL ZONES AND SEA LEVEL RISE

Coastal zones are very vulnerable to climate change. Sea level rise, land loss, changes in maritime storms and flooding, responses to sea level rise and implications for water resources are some of the concerns.

4.4.1   Sea Level Rise

According to EPA (EPA: Climate Change: Health and Environmental Effects, http://epa.gov/climatechange/effects/index.html), "sea level is rising along most of the U.S. Coast, and around the world. In the last century, sea level rose 5 to 6 inches more than the global average along the Mid-Atlantic and Gulf Coasts, because coastal lands there are subsiding.

Higher temperatures are expected to further raise sea level by expanding ocean water, melting mountain glaciers and small ice caps, and causing portions of Greenland and the Antarctic ice sheets to melt.

Rising sea levels inundate wetlands and other low-lying lands, erode beaches, intensify flooding, and increase the salinity of rivers, bays, and groundwater tables. Some of these effects may be further compounded by other effects of a changing climate. Measures that people take to protect private property from rising sea level may have adverse effects on public uses of beaches and

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waterways. Some property and local governments are already starting to prepare for the consequences of rising sea level".

4.4.2   Land Loss

According to EPA (EPA: Climate Change: Health and Environmental Effects, http://epa.gov/climatechange/effects/index.html), "coastal wetland ecosystems, such as salt marshes and mangroves are particularly vulnerable to rising sea level because they are generally within a few feet of sea level (IPCC, 2007). Wetlands provide habitat for many species, play a key role in nutrient uptake, serve as the basis for many communities' economic livelihoods, provide recreational opportunities, and protect local areas from flooding.

As the sea rises, the outer boundary of these wetlands will erode, and new wetlands will form inland as previously dry areas are flooded by the higher water levels. The amount of newly created wetlands, however, could be much smaller than the lost area of wetlands - especially in developed areas protected with bulkheads, dikes, and other structures that keep new wetlands from forming inland. The IPCC (2007) suggests that by 2080, sea level rise could convert as much as 33 percent of the world's coastal wetlands to open water.

Tidal wetlands are generally found between sea level and the highest tide over the monthly lunar cycle. As a result, areas with small tide ranges are the most vulnerable. An EPA Report to Congress estimated that a two foot rise in sea level could eliminate 17-43 percent of U.S. wetlands, with more than half the loss taking place in Louisiana (EPA, 1989)."

4.4.3   Storm and Flooding

According to EPA (EPA: Climate Change: Health and Environmental Effects, http://epa.gov/climatechange/effects/index.html), "sea level rise increases the vulnerability of coastal areas to flooding during storms for several reasons. First, a given storm surge from a hurricane or northeaster builds on top of a higher base of water. Sea level rise also increases coastal flooding from rainstorms, because low areas drain more slowly as sea level rises.

Other impacts of climate change may further enhance or mitigate coastal flooding. Flooding from rainstorms may become worse if higher temperatures lead to increasing rainfall intensity during severe storms. An increase in the intensity of tropical storms would increase flood and wind damages."

4.4.4   Effects on Shoreline and Coastal Living

According to EPA (EPA: Climate Change: Health and Environmental Effects, http://epa.gov/climatechange/effects/index.html), "property owners and federal, state, and local governments are already starting to take measures to prepare for the consequences of rising sea level. Most coastal states are working with the U.S. Army Corps of Engineers to place sand onto their beaches to offset shore erosion. Property owners are elevating existing structures in many low-lying areas, encouraged by lower flood insurance rates.

Several states have adopted policies to ensure that beaches, dunes, or wetlands are able to migrate inland as sea level rises. Some states prohibit new houses in areas likely to be eroded in the next 30-60 years. Concerned about the need to protect property rights, Maine, Rhode Island, South Carolina and Texas have implemented some version of "rolling easements," in which people are allowed to build, but only on the condition that they will remove the structure if and when it is threatened by an advancing shoreline".

4.4.5   Coastal Water Supplies

According to EPA (EPA: Climate Change: Health and Environmental Effects, http://epa.gov/climatechange/effects/index.html), "rising sea level increases the salinity of both surface water and ground water through salt water intrusion. New York City, Philadelphia, and much of California's Central Valley obtain some of their water from portions of rivers that are slightly upstream from the point where water is salty during droughts. If sea level rise pushes salty water upstream, then the existing water intakes might draw on salty water during dry periods. Salinity increases in

estuaries also can harm aquatic plants and animals that do not tolerate high salinity.

Shallow coastal aquifers are also at risk (IPCC, 2007). The freshwater Everglades currently recharge Florida's Biscayne aquifer, the primary water supply to the Florida Keys. As rising water levels submerge low-lying portions of the Everglades, portions of the aquifer would become saline. Aquifers in New Jersey east of Philadelphia are recharged by fresh portions of the Delaware River which may become saline in the future".

4.5 EFFECTS ON ENERGY PRODUCTION AND USE

Energy production and use are affected by sensitive to changes in the climate. Effects of climate change on energy supply and demand will depend not only on climatic factors, but also on patterns of economic growth, land use, population growth and distribution, technological change and social and cultural trends.

4.5.1   Energy Use

According to EPA (EPA: Climate Change: Health and Environmental Effects, http://epa.gov/climatechange/effects/index.html), "Changes in temperature due to climate change could affect the demand for energy. For example, rising air temperatures will likely lead to substantial increases in energy demand for air conditioning in most North American cities (IPCC, 2007).On the other hand, energy needed for space-heating may decrease.

There may also be changes in energy consumed for other climate-sensitive processes, such as pumping water for irrigation in agriculture. Rising temperatures and associated increases in evaporation may increase energy needs for irrigation, particularly in dry regions across the Western U.S.

Depending on the magnitude of these possible energy consumption changes, it may be necessary to consider changes in energy supply or conservation practices to balance demand. Many other factors (e.g., population growth, economic growth, energy efficiency changes and technological change) will also affect the timing and size

of future changes in the capacity of energy systems (IPCC, 2007)."

4.5.2   Energy Production

Not much study or research work has been done on how climate change may affect energy production. According to EPA (EPA: Climate Change: Health and Environmental Effects, http://epa.gov/climatechange/effects/energy.html), some possible effects are:

- Hydropower generation is the energy source that is likely to be most directly affected by climate change because it is sensitive to the amount, timing and geographical pattern of precipitation and temperature. Furthermore, hydropower needs may increasingly conflict with other priorities, such as fishing (salmon) restoration goals in the Pacific Northwest (IPCC, 2007). The effect of climate change on hydropower will depend on the region as changes in precipitation are difficult to project.

- Infrastructure for energy production, transmission and distribution could be affected by climate change. For example, if a warmer climate is characterized by more extreme weather events such as windstorms, ice storms, floods, tornadoes and hail, the transmission systems of electric utilities may experience a higher rate of failure, with attendant costs (IPCC, 2007).

- Power plant operations can be affected by extreme heat waves. For example, intake water that is normally used to cool power plants may become warm enough during extreme heat events that it compromises power plant operations.

- Finally, some renewable sources of energy could be affected by climate change, although these changes are very difficult to predict. If climate change leads to increased cloudiness, solar energy production could be reduced. Wind energy production would be reduced if wind speeds increase above or fall below the acceptable operating range of the technology. Changes in growing conditions could affect biomass production, a transportation and power plant fuel source that is starting to receive more attention (IPCC, 2007)."

4.6 EFFECT ON PUBLIC LANDS AND RECREATION

National Parks, National Wildlife Refuges, and other protected areas house unique environments and wildlife. There are particular concerns about the vulnerability of these ecosystems to a changing climate. According to EPA (EPA: Climate Change: Health and Environmental Effects, http://epa.gov/climatechange/effects/publiclands.html), "many parks and refuges are designated to protect rare natural features or particular species of plants and animals. Changes in climate could create new stresses on natural communities, and, in the absence of adaptation, lead to the loss of valued resources."

4.6.1   National Parks and Other Protected Areas

According to EPA (EPA: Climate Change: Health and Environmental Effects, http://epa.gov/climatechange/effects/publiclands.html), "National parks and other protected areas are currently susceptible to events influenced by climatic variability, such as drought, wild fires, impaired air quality, and severe storms. Climate change may change the frequency and severity of these kinds of events. In some regions, the risk for drought and wildfire, for example, may increase with climate change (IPCC, 2007). Along coastal regions, sea level rise could erode and inundate the beaches of the National Seashores and the wetlands of various National Wildlife Refuges and National Parks, precipitating loss of beaches, loss of habitat in estuarine ecosystems, and damage to property and natural resources from storm surges (IPCC, 2007).

Observations show that changing climatic conditions are already affecting some parks. For example, Montana's Glacier National Park has only 27 glaciers today, down from an estimated 150 glaciers in 1850. The largest glaciers in the park are, on average, only 28 percent of their previous size. Retreat of mountain glaciers has already begun in other parts of North America and in other regions of the world as well (IPCC, 2007).

Bleaching of coral reefs has occurred near the Florida Keys in association with periods of climate variability, such as the 1997-98 El Niño. It is likely that warmer water

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temperatures could lead to further bleaching events in the future."

4.6.2   Outdoor Recreation and Tourism

According to EPA (EPA: Climate Change: Health and Environmental Effects, http://epa.gov/climatechange/effects.html), "Outdoor recreation and tourism are sensitive to changes in temperature, rainfall, snowfall, and storm events, and are thus sensitive to climatic variability and change.

Shifts in temperature and precipitation patterns could lead to shifts in a variety of outdoor tourism and recreation opportunities, such as skiing, fishing and hunting. The effects of climate change on tourism in any particular area depend in part on whether the tourist activity is summer or winter-oriented and, for the latter, the elevation of the area and the impact of climate on alternative activities and destinations".

4.7 REGIONAL EFFECTS

4.7.1   U.S. Regional Effects

The following list provides examples of some of the higher likelihood effects of climate change in the United States (IPCC, 2007):

In the Northeast:
- Northward shifts in the ranges of plant and animal species due to warmer temperatures
- Coastal erosion, loss of wetland habitat, due to storm surges from sea level rise
- Reduced winter recreation (skiing); increased warm season activities
- Higher heat-related morbidity and mortality, especially in urban areas; reduced winter cold stress with associated decrease in cold-related mortality
- Increase vulnerability of infrastructure (e.g. roads and utilities) from extreme events such as hurricanes and coastal flooding

In the Southeast and Gulf Coast:
- Increased coastal erosion, loss of barrier islands and wetlands

- Changing forest character as disturbances (e.g., fire and insect outbreaks) increase

In the Midwest and Great Lakes:
- Lowered lake and river levels, resulting from increased evaporation
- Warming lake and river temperatures leading to reductions in fish stocks
- Water quality deterioration leading to habitat loss
- Increased agricultural productivity in many regions resulting from increased carbon dioxide and warmer temperatures
- Higher summer heat and increase in heat-related morbidity and mortality, especially in urban areas; reduced winter cold stress with associated decrease in cold-related mortality

In the Great Plains:
- Agricultural productivity reduced due to increased potential for drought
- Intensified springtime flood and summertime drought
- Higher summer heat; reduced winter cold

In the West:
- Changes in natural ecosystems due to higher temperatures and possibly intensified winter precipitation
- Reductions in snowpack and earlier snowmelt stressing some reservoir systems
- Decreased yields of crops
- Reduction in groundwater systems
- Higher summer heat; reduced winter cold
- Increased potential of wildfire

Alaska:
- Forest disruption from warming
- General increase in biological production from warming; but reduced sea ice and warming will affect polar bears, marine mammals, and other wildlife
- Damage to infrastructure resulting from melting of permafrost

4.7.2   Polar Regions

According to EPA (EPA: Climate Change: Health and Environmental Effects, http://epa.gov/climatechange/effects/polarregions.html), "According to EPA, polar Regions include the Arctic in the Northern Hemisphere and Antarctica in the Southern Hemisphere. The Arctic encompasses a large, mostly frozen ocean surrounded by land, is home to almost four million people, and includes some or all of the territories of eight nations, including the United States. By contrast, Antarctica is an ice-covered continent surrounded by ocean and is generally uninhabited.

The Arctic is expected to experience the greatest rates of warming compared with other world regions (IPCC, 2007). In part, this is because ice has greater reflectivity (also known as albedo) than the ocean or land. Melting of highly reflective snow and ice reveals darker land and ocean surfaces, increasing absorption of the sun's heat and further warming the planet, especially in those regions.

There is evidence that climate change is already having observable impacts in the Arctic and in Antarctica. Many of these observed changes are consistent with the expected effects of climate change under a range of climate scenarios."

- **Arctic**

According to EPA (EPA: Climate Change: Health and Environmental Effects, http://epa.gov/climatechange/effects/polarregions.html) and the Arctic Climate Impact Assessment (ACIA, 2004) following are some possible effects:

"Effects on the Climate System
- Average temperatures in the Arctic have risen at faster rate than temperatures in the rest of the world over the past few decades.
- Widespread melting of glaciers and sea ice and rising permafrost temperatures present indicate strong Arctic warming.
- The above trends are expected to continue during 21st century, resulting from ongoing increases in atmospheric concentrations of greenhouse gases.

- Melting of Arctic glaciers is a contributing factor to sea-level rise around the world.
- Reduction in sea ice is very likely to have devastating consequences for polar bears, ice-dependent seals, and local people for whom these animals are a primary food source.

Effects on Biological and Human Systems
- Arctic impacts will have implications for biodiversity around the world because migratory species depend on breeding and feeding grounds in the Arctic.
- Increased areas of tree growth in the Arctic could serve to take up carbon dioxide (CO_2, the principal greenhouse gas emitted by human activities) and supply more wood products and related employment, providing local and global benefits. However, tree growth would mean absorption of additional sunlight (as the land surface would become darker and less reflective) and add to regional warming.
- Climate change is taking place within the context of many other ongoing changes in the Arctic, including observed increases in chemical contaminants entering the Arctic from other regions, overfishing, land use changes that result in habitat destruction and fragmentation, rapid growth in the human population, and cultural, governance and economic changes."

Figure 4.7.1 below shows trends in Arctic sea ice extent since the 1860s.
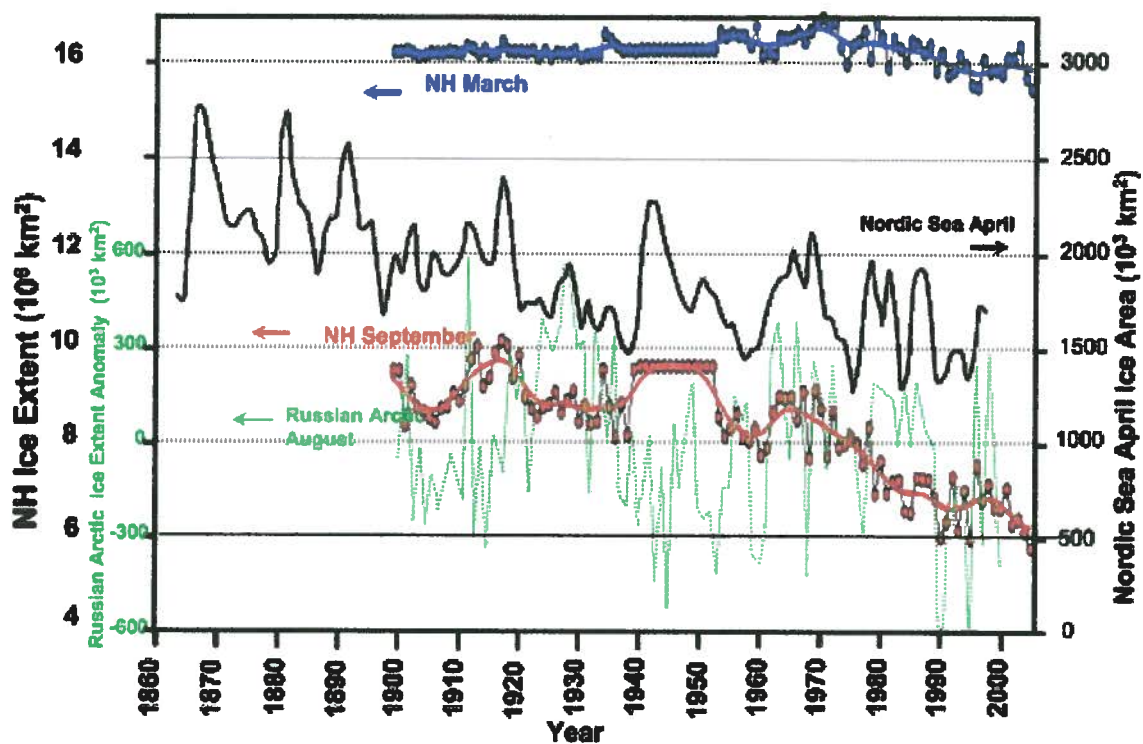
Figure 4.7.1: Long-term trends in Northern Hemisphere (NH) sea ice extent for March and September, Nordic sea ice extent for April, and Russian Arctic sea ice extent anomaly (compared with the mean for the entire period) for August. Source: IPCC, 2007a

Upward-looking sonar data from U.S. Navy submarines between 1987 and 1997 show it is very likely that average ice thickness in the Arctic has decreased by up to 1 meter (IPCC, 2007a).

The Intergovernmental Panel on Climate Change (IPCC, 2007a and 2007b) supports and extends the ACIA's conclusions with additional evidence. According to IPCC "the resilience shown historically by Arctic Indigenous Peoples is now being severely tested," with impacts on food availability and personal safety that are changing hunting and traveling practices. Community infrastructures will be harmed by the warming and thawing of permafrost.

- **Antarctica**

"Like the Arctic region in the Northern Hemisphere, Antarctica in the Southern Hemisphere has been experiencing changes in regional climate. Future changes resulting from global climate change are also expected to be significant in this region.

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Surface waters of the Southern Ocean surrounding Antarctica have warmed and become less saline, and precipitation in this region has increased (IPCC, 2007a).

Antarctica has experienced significant retreat and collapse of ice shelves, the result of regional warming (IPCC, 2007a)".

4.7.3   International Impacts

According to EPA (EPA: Climate Change: Health and Environmental Effects, http://epa.gov/climatechange/effects/international.html), "although climate change is a global issue, the impacts will not be equally across the planet. Regional changes are likely to differ from global averages in both magnitude and rates of change. Further, not all ecosystems and human settlements are equally sensitive to changes in climate. Nations (and regions within nations) vary in their relative vulnerability to changes in temperature, precipitation and extreme weather events and their ability to cope with such changes.

Many global issues are climate-related and thus may be affected by climate change. These include water resources availability and food security, especially for areas already afflicted by drought and extreme weather events. Sea-level rise is a particular concern for low-lying coasts and island nations".

4.8 EXTREME EVENTS

According to Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC, 2007) since 1950, the number of heat waves has increased and widespread increases have occurred in the numbers of warm nights. The extent of regions affected by droughts has also increased as precipitation over land has marginally decreased while evaporation has increased due to warmer conditions.

Tropical storm and hurricane frequencies vary considerably from year to year, but evidence suggests substantial increases in intensity and duration since the 1970s.In the extratropics, variations in tracks and intensity of storms reflect variations in major features of the atmospheric circulation, such as the North Atlantic Oscillation."

According to EPA (EPA: Climate Change: Health and Environmental Effects, http://epa.gov/climatechange/effects/extreme.html), "Abrupt climate changes occur when a threshold in the climate system is crossed – a trigger that causes the climate to rapidly shift from one state to a new, different one. Crossing thresholds in the climate system may lead to large and widespread consequences.

Changes in weather patterns can result from abrupt changes that might occur spontaneously due to interactions in the atmosphere-ice-ocean system, or from the crossing of a threshold from slow external forcing (as described above). In a warming climate, changes in the frequency and amplitudes of these patterns might not only evolve rapidly, but also trigger other processes that lead to abrupt climate change".

4.9 ADAPTATION

The Intergovernmental Panel on Climate Change (IPCC) defines adaptation as the "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" (IPCC, 2007).

Adaptation to environmental change is not a new concept. Human societies have shown throughout history a strong capacity for adapting to different climates and environmental changes.

All climate-sensitive systems of society and the natural environment, including agriculture, forestry, water resources, human health, coastal settlements, and natural ecosystems, will need to adapt to a changing climate or possibly face diminished productivity, functioning and health.

According to EPA (EPA: Climate Change: Health and Environmental Effects, http://epa.gov/climatechange/effects/adaptation.html), "some possible adaptation measures that can be taken in response to effects of climate change in different areas are given below:

Human Health
- Many diseases and health problems that may be exacerbated by climate change can be effectively prevented with adequate financial and human public health resources, including training, surveillance and emergency response, and prevention and control programs.
- Urban tree plantations to moderate temperature increases
- Weather advisories to alert the public about dangerous heat conditions
- Grain storage, emergency feeding stations
- Adjusting clothing and activity levels, increasing fluid intake

Coastal Areas and Sea Level Rise
- Developing county-scale maps depicting which areas will require shore protection (e.g. dikes, bulkheads, beach nourishment) and which areas will be allowed to adapt naturally
- Analyzing the environmental consequences of shore protection
- Promoting shore protection techniques that reduce destruction of beneficial habitat
- Identifying land use measures to ensure that wetlands migrate as sea level rises in some areas
- Engaging state and local governments in defining responses to sea level rise
- Improving early warning systems and flood hazard mapping for storms
- Protecting water supplies from contamination by saltwater

Agriculture and Forestry
- Altering the timing of planting dates to adapt to changing growing conditions
- Altering cropping mix and forest species to obtain plants that are better suited to the changing climatic conditions
- Breeding new plant species and crops that are more tolerant to changed climate condition
- Promoting fire suppression practices in the event of increased fire risk due to temperature increases
- Controlling insect outbreaks

Ecosystems and Wildlife
- Protecting and enhancing migration corridors to allow species to migrate as the climate changes
- Identifying management practices that will ensure the successful attainment of conservation and management goals
- Promoting management practices that confer resilience to the ecosystem

Water Resources
- Altering infrastructure or institutional arrangements
- Changing demand or reducing risk
- Improving water use efficiency, planning for alternative water sources (such as treated wastewater or desalinated seawater), and making changes to water allocation
- Conserving soil moisture through mulching and other means
- Protecting coastal freshwater resources from saltwater intrusion

Energy
- Increasing energy efficiency to offset increases in energy consumption due to warming.
- Protecting facilities against extreme weather events.
- Diversifying power supply to improve reliability in the event of power plant failures due to excess demand created by extreme heat, or by extreme weather events

CHAPTER-5
STRATEGIES FOR MITIGATION OF GREENHOUSE GASES

Mitigation efforts involve taking actions to reduce greenhouse gas emissions, reducing their concentration in the atmosphere by enhancing sinks. This is different from adaptation which involves taking actions to minimize the effects of global warming.

At the core of most proposals is the reduction of GHG emissions through use of or switching to cleaner energy sources, energy conservation methods (such as increasing fuel efficiency of equipment, machinery and vehicles, increased use of renewable energy (solar, tidal, ocean, geothermal and wind power) and increasing share of alternative energy sources such as nuclear energy. Use of carbon sinks, carbon credits and taxation are all aimed at discouraging GHG emissions.

Strategies for mitigation of GHG can be divided into following two major categories. The first category is aimed at reducing the release of GHG to the atmosphere by reducing fossil fuel consumption which can be achieved by energy conservation, improving system efficiencies where fossil fuels are used, and transitioning to more efficient alternative or renewable energy sources. The second category is based on identifying carbon sinks such as terrestrial (soils and plants), aquatic (oceans) and geologic, and ways to enhance sequestration rates. Various options aimed at mitigating greenhouse gas emissions are discussed in the following sections.

5.1 Overview of Mitigation Options:

- **Limiting Fossil Fuel Production**

Most mitigation proposals imply an eventual reduction in global production and consumption of fossil fuels by limiting by assigning direct quota for fossil fuel production.

Pacala and Socolow (Mitigation of Global Warming, 2004), (Source:http://en.wikipedia.org/wiki/Mitigation_of_global_warming)have proposed a program to reduce CO_2 emissions by 1 billion metric tonnes per year, or 25 billion tons over the

50-year period. The proposed 15 different programs, any seven of which could achieve the goal, are:

- More efficient vehicles – increase fuel economy from 30 to 60 mpg for 2 billion vehicles.
- Reduce use of vehicles – improve urban design to reduce miles driven from 10,000 to 5,000 miles per year for 2 billion vehicles.
- Efficient buildings – reduce energy consumption by 25%.
- Improve efficiency of coal plants to 60%.
- Replace 1,400 GW of coal power plants with natural gas
- Capture and store carbon emitted from 800 GW of new coal plants
- Capture and reuse hydrogen created from coal plants
- Capture and store carbon from coal to synthetic fuels conversion at 30 million barrels per day (4.8 million m^3 /day)
- Displace 700 GW of coal with nuclear
- Add 2 million 1 MW wind turbines 950 times current capacity)
- Displace 700 GW of coal with 2,000 GW (peak) solar power (700 times current capacity)
- Produce hydrogen fuel from 400 1MW wind turbines
- Use biomass to make fuel to displace oil (100 times current capacity)
- Stop deforestation and reestablish 300 million hectares of new tree plantations
- Conservation tillage – apply to all crop land (10 times current usage)

According to Romm Joseph (Cleaning Up on Carbon, 2008), if we are to have confidence in our ability to stabilize CO_2 levels below 450-ppm, emissions must average less than 5.0-billion tonnes of carbon per year over the century. This means accelerating the deployment of the wedges so they begin to take effect by 2015 and is completely operational in much less time than originally thought.

- **Energy Efficiency and Conservation**

Energy savings by improvements in efficiency provides good environmental benefits and net cost savings for user. Building insulation, fluorescent and LED lighting and

public transportation can be effective means for conserving energy and environment.

Improved efficiency lowers cost which might increase demand, it is therefore necessary to have a tax or quota system for energy use to ensure demand does not increase due to increase in efficiency. Some of the measures that can be taken to reduce energy consumption and improve efficiency are:

- Reduce energy consumption in residential, commercial, transportation and freight sectors
- Smarter urban planning with compact community development and multiple transportation choices to reduce energy needed for transportation, building and community services
- Building construction and design to reduce emissions from housing and reduce energy consumption by using solar designs, low or zero energy buildings, use of insulation and use of high energy appliances
- Increased use of bicycles, plug-in hybrid electric vehicles, hydrogen cars. A shift from air transportation and trucks to rail transportation would reduce emissions significantly

- **Alternative Energy Sources**

  - **Nuclear Power**

Currently nuclear power produces over 15% of world's electricity. Due to its low emittance of greenhouse gases (comparable to wind power) and reliability it is seen as being comparable to renewable energy and a possible alternative to fossil fuels.

The bulk of CO_2 emissions from nuclear plants can be eliminated if nuclear plants themselves generate electricity required for uranium enrichment (already being done in France and to some extent by Tennessee Valley Authority's many nuclear units in the U.S.).

Nuclear fusion is another variant of nuclear energy but it will not provide any immediate mitigation to global

warming as the time horizon for commercial deployment is expected to be after 2050.

- Renewable Energy

Most forms of renewable energy such as wind power, solar energy, hydroelectric energy and geothermal energy generate no appreciable amount of greenhouse gases except for biofuels derived from biomass.

- Eliminating Waste Methane

Methane is significantly more powerful greenhouse gas than carbon dioxide. Burning one molecule of methane generates one molecule of carbon dioxide. Hence burning methane provides a net greenhouse gas emission benefit. However, reducing amount of methane produced in the first place provides even greater benefit.

Vaccines are in works in Australia to reduce methane released by livestock via flatulence and eructation.

• Carbon Intensity of Fossil Fuels

Natural gas (predominantly methane) produces less greenhouses gases per energy unit gained than oil which in turn produces less than coal, principally because coal has a larger ratio of carbon to hydrogen. The combustion of natural gas emits almost 30 percent less carbon dioxide than oil, and just under 45 percent less carbon dioxide than coal. In addition, there are also other environmental benefits due to absence of emissions of oxides of sulfur and nitrogen.

Several studies have found that the increased use of natural gas in place of other dirtier fossil fuels can serve to lessen the emission of greenhouse gases.

• Reforestation and Adaptation

Almost 20% (8 $GtCO_2$/year) of total greenhouse gas emissions were from deforestation in 2007. If deforestation were avoided, emission savings from avoided deforestation could potentially reduce CO_2 emissions from under $5/tCO_2$, possibly as little as $1/tCO_2$. Afforestation and reforestation could save at least another $1GtCO_2$/year, at an estimated cost of $5/tCO_2$ to $15/tCO_2$ (Stern N, 2007).

Further savings could be made through cuts in agricultural emissions, fugitive emissions, waste emissions, and emissions from industrial processes.

- **Carbon Capture and Storage**

Carbon capture and storage (CCS) is a plan to mitigate climate change by capturing (CO_2) from large point sources and storing it away safely instead of releasing it into the atmosphere. Technology for capturing CO_2 is already commercially available for large CO_2 emitters. This is discussed in section 5.3 in detail.

According to IPCC (2007) Special Report on Carbon Capture and Storage, CCS applied to a modern conventional power plant could reduce CO_2 emissions to the atmosphere by approximately 80-90% compared to a plant without CCS. Capturing and compressing CO_2 requires energy and would increase the energy needs of a plant with CCS by about 10-40%. This and other system costs are estimated to increase the cost of energy from a power plant with CCS by 30-60% depending on the specific circumstances.

Storage of the CO_2 is envisaged in deep geological formations, deep oceans, or in the form of mineral carbonates. Geological formations are currently considered the most promising, and these are estimated to have a storage capacity of at least 2000 Gt CO_2. IPCC estimates that the economic potential of CCS could be between 10% and 55% of the total carbon mitigation effort until year 2100.

- **Geoengineering**

Geoengineering is defined as an option that involves manipulating the Earth's atmosphere with large scale engineering of environment to combat or counteract the effects of changes in atmosphere chemistry. Carbon sequestration is a form of mitigation, but is not mitigation as defined by climate activists. To them, the term is clearly defined as exclusively associated with reduction of greenhouse gas emissions.

- **Solar Radiation Management**

Scientists have suggested various options to change the Earth's albedo, or reflectivity, as an emergency

measure to increase global dimming and thus stave off the effects of global warming. A 0.5% albedo increase would roughly halve the effect of CO_2 doubling. These options include using aerosols and/ or sulfate dust, burning sulfur in stratosphere, marine cloud and solar shade in space.

- Greenhouse Gas Remediation

Carbon sequestration has been proposed as a method of reducing the amount of radiative forcing. Carbon sequestration is a term that describes processes that remove carbon from the atmosphere. A variety of means of artificially capturing and storing carbon, as well as of enhancing natural sequestration processes, are being explored. The main natural process is photosynthesis by plants and single celled organisms.

Although they require land, natural sinks can be enhanced by reforestation and afforestation carbon offsets, which fix carbon dioxide for as little as $0.11 per metric ton.

- Carbon Air Capture

It is notable that the availability of cheap energy and appropriate sites for geological storage of carbon may make carbon dioxide air capture viable commercially. It is, however, generally expected that carbon dioxide air capture may be uneconomic when compared to carbon capture and storage from major sources - in particular, fossil fuel powered power stations, refineries, etc. In such cases, cost of energy produced will grow significantly.

- Seeding Oceans with Iron

This idea is supported by the evidence that seeding the oceans with iron will increase phytoplankton populations, and thereby draw more carbon dioxide from the atmosphere. The effects of seeding equatorial Pacific waters with iron resulted in fixation of 700 grams of CO_2 by the resulting phytoplankton bloom per 1 gram of iron seeded (Cole et al. 1996). This approach can also boost fish production through development of the ecosystem.

- Vegetarian Lifestyle

Raising animals for food requires massive amounts of land, food, energy, and water. The byproducts of animal agriculture pollute our air and waterways.

As the world's appetite for meat increases, countries across the globe are bulldozing huge swaths of land to make more room for animals as well as crops to feed them. From tropical rain forests in Brazil to ancient pine forests in China, entire ecosystems are being destroyed to fuel humans' addiction to meat. Also chickens, pigs, cattle, and other animals raised for food are primary consumers of water in the farms.

Carbon dioxide, methane, and nitrous oxide together cause the vast majority of global warming. Producing a little more than 2 pounds of beef causes more greenhouse-gas emissions than driving a car for three hours and uses up more energy than leaving your house lights on for the same period of time.

Factory farms also produce massive amounts of dust and other contaminates that pollute the air. The Environmental Protection Agency (EPA) reports that roughly 80 percent of ammonia emissions in the U.S. come from animal waste. Each day, factory farms produce billions of pounds of manure, which ends up in lakes, rivers, and drinking water.

A vegetarian lifestyle will help environment and will go a long way in reducing emissions of greenhouse gases and other pollutants.

5.2 AGRICULTURE'S ROLE IN GREENHOUSE GAS MITIGATION

Agricultural crops, plants and trees remove CO_2 from the air through the natural process of photosynthesis. Atmospheric carbon dioxide (CO_2) is taken up through tiny openings in leaves and incorporated as carbon into the woody biomass of trees and agricultural crops. Roughly half of this biomass on a dry basis is carbon. Some of this carbon makes its way into soils when vegetation, litter and roots decay. Carbon in forests and soils can return to the atmosphere when agricultural tillage practices stir up soils or when biomass decays and burns.

Forests and agricultural soils can therefore act as either a net carbon sink or source. The movement of carbon in and out of trees and soils is part of Earth's global carbon cycle shown below in Fig.5.2.1.
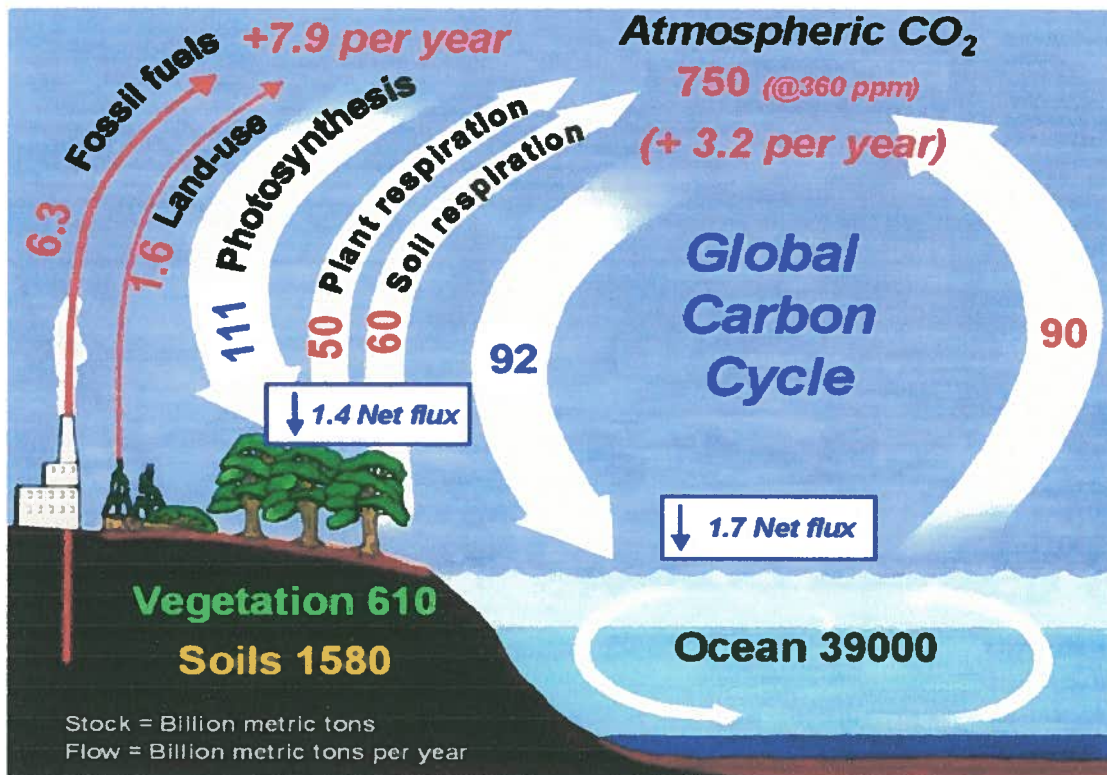
Fig.5.2.1: Global Carbon Cycle, Source: University of Michigan, Tropical Systems Intensity and Anthropogenic Alternations of the Atmosphere;
(http://sitemaker.umich.edu/section2group4/the_link_human_influences_on_storm_intensity)

Approximately 20% of the world's annual carbon dioxide (CO_2) emissions result from land-use change, primarily deforestation in the tropical regions of Central and South America, Africa, and Asia. These lands are shifting from relatively high carbon stock natural forests to generally low carbon stock crop, agroforestry, grazing, or fuel wood lands and urbanization. While this transformation of land use provides short term economic benefits and rural livelihoods, it is also a major source of greenhouse gas emissions and other social and environmental problems.

Agriculture's role in reducing GHG concentrations in the atmosphere and future climactic impact has received increasing global attention. It is seen as a low cost provider of emission reduction in the near future with additional environmental and income distribution benefits. Three of the major GHGs – carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) are emitted to and/or removed from the atmosphere in significant amounts through agricultural activity. Potential for agriculture to mitigate GHG emissions has been the subject of intensive scientific investigation over the past several years (Paustian Keith et al. 2001). The global nitrogen cycle is shown in Fig. 5.2.2.
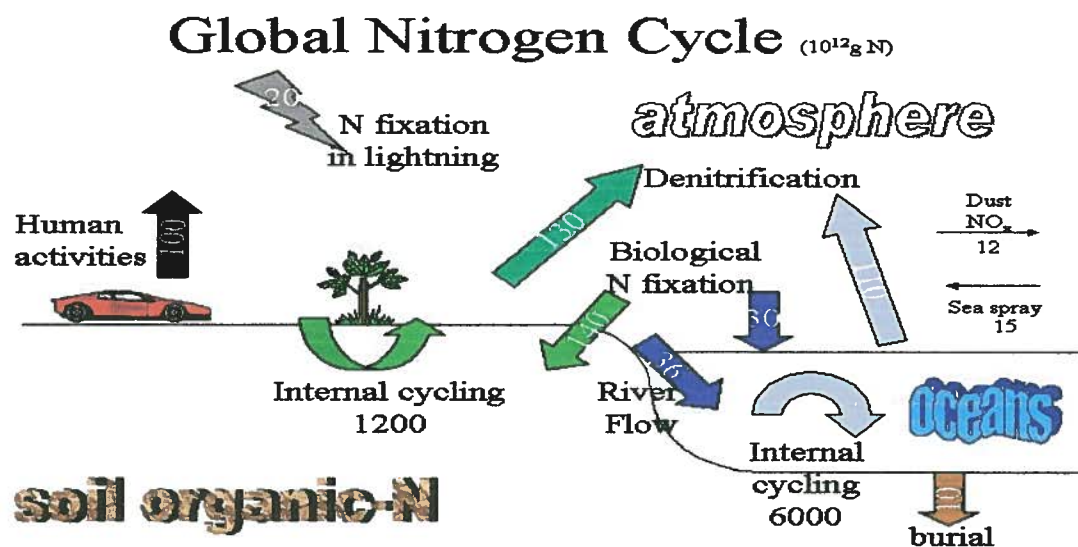
Fig.5.2.2: Nitrogen Cycle
Source: http://www.esf.edu/efb/schulz/limnology/nitrogen.html

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5.2.1 Mitigation of CO_2 Fluxes through Carbon Sequestration:

According to Paustian et al. (2001), "Carbon dioxide is exchanged continuously between soils and atmosphere, primarily through the processes of photosynthesis and incorporation of plant derived organic matter into soils (CO_2 influx), and the decomposition of that organic matter by soil organisms (CO_2 outflux).

The amount of carbon stored in soils depends primarily on balance between carbon inputs from plant (and animal) residues and carbon emissions from decomposition. Thus, increasing soil carbon stocks requires increasing carbon inputs and/or decreasing the decomposition. Both inputs and decomposition rates are affected by natural factors such as climate (temperature and rainfall) and soil physical factors (soil texture, clay mineralogy, profile development), as well as agricultural management practices.

In general, carbon sequestration will be favored under management systems that:

1. Minimize soil disturbance and erosion
2. Maximize the amount of crop residue return
3. Maximize water and nutrient use efficiency of crop production

Although it may be impossible to optimize all these systems attributes simultaneously, practices that effectively sequester carbon share one or more of these traits. Decreasing tillage intensity, especially by using no-tillage practices, has been found to promote carbon sequestration.

In long term field experiments comparing no-till to conventional tillage, i.e. intensively tilled annual crop system, adoption of no-till typically results in increase in soil carbon of 0.1 MT per hectare per year (Dick et al. 1998, Janzen et al. 1997) over periods of 10 to 30 years. Rates are generally higher in mesic climates with high level of crop residue inputs, and lower in semi-arid

regions supporting lower levels of primary production. In
semi-arid regions, no-till adoption provides increased
water storage, enabling more continuous crop rotations with
elimination or decreased frequency of bare fallowing (Black
and Tanaka 1997, Peterson et al. 1998).

Increasing the amount of residue returned to soil can be
managed through a variety of practices, including high-
residue yielding crops, hay crops in rotation, application
of manure and biosolids, and improved management of
fertilizer, water, and pests.

Most cropland soils show a clear response to increasing
amounts of carbon return such that soil organic carbon
levels, over time, are often directly proportional to the
amount of carbon added to soil under different management
treatments (Huggins et al. 1998, Paustian et al. 1998, and
Rasmussen et al. 1980). Eventually, for any given level of
input, soil carbon levels tend towards steady state
concentration, limiting the amount and duration of
additional carbon storage.

Places where production is water or nutrient limited,
increased use of fertilizer, pesticides and irrigation can
contribute to increased carbon sequestration. However,
energy costs associated with manufacture, distribution of
fertilizer, irrigation pumping, as well as potential
increased emissions of N_2O and CH_4 must be considered.
Practices that promote optimally efficient water and
nutrient use are likely to have greatest benefits in terms
of decreased GHGs.

Various management practices on grazing lands (pasture
and rangeland) can increase soil carbon. On poorly managed
grazing lands depleted of soil carbon, practices that
increase production and carbon inputs can build up soil
carbon. Such practices include improving grazing
management, using improved species, sowing legumes,
fertilizing, and irrigating.

In an analysis of more than 100 published studies, Conant
et al. (2001) reported that carbon increase rates for
different management improvements averaged between 0.1-1

metric tonnes carbon per hectare per year, the highest rates occurring with conversion of cultivated land to perennial grasses e.g. to pasture or CRP. Average rates of carbon increase were about 0.3 tonnes of carbon per hectare per year for fertilization, about 0.2 tonnes for improved grazing or irrigation and 0.1 tonnes for introduction of legumes.

Restoring degraded soils and ecosystems (Lal and Bruce 1999) reforesting and afforesting (Brown et al. 1996), retiring marginal lands through set asides such as the Conservation Reserve Program (CRP) and controlling desertification (Lal and Bruce 1999) are important options for improving biomass productivity and sequestering carbon in soil and in the ecosystem. Fig.5.2.1.4 shows increase in soil organic carbon after 2 years and 12 years of CRP in Nebraska.

As for annual crop systems, management of grazing lands and degraded lands for greenhouse gas mitigation needs to consider the net effects of practices on GWP. For example, high nitrogen fertilization rates in intensively managed pastures may cause large N_2O emissions that wipe out benefits from carbon sequestration, whereas phosphorus fertilization and/ or moderate nitrogen in phosphorus or nitrogen limited systems can yield large gains in productivity and carbon sequestration with little increase in N_2O emissions".

Figure 5.2.1.1 on next page shows potential for carbon sequestration on US agricultural and grazing lands. Figure 5.2.1.3 shows how soil organic carbon loss can be reduced to increase the SOC content by no tillage.

Table5.2.1.1 below shows tremendous potential and rates for soil organic carbon sequestration.

Table-5.2.1.1: Global Potential and Rates of Soil Organic C Sequestration,
Source: Rice, Capalbo, Hatfield (K-Stage Research & Extension)

Work Done By	Mean	SD	Activities
	Global Potential, Pg C yr-1		
IPCC (1996)	0.663	0.218	Ag. Soils, set aside, wetland, degraded land
Bruce & Lal (1999)	0.163	0.018	Bio offset, crop syst., CT, erosion, degraded land
	Global Historical Rates, Mg C ha^{-1} yr^{-1}		
West & Post (2002)	0.57	0.14	No Till
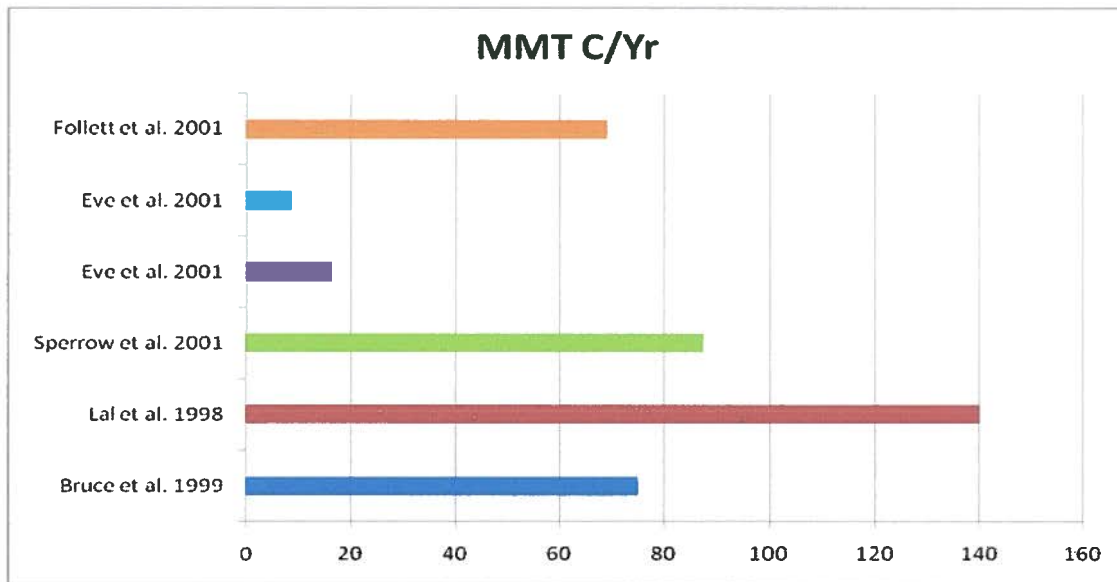
Fig.5.2.1.1: Estimates of potential carbon sequestration on US agricultural and grazing lands. All estimates are based on widespread adoption of existing management practices to sequester carbon but do not include economic factors that will limit adoption rates. Source: Agriculture's Role in Mitigation of Greenhouse Gases, Rice, Capalbo, Hatfield (http://soilcarboncenter.k-state.edu)

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Based on the work done by Lal et al. (1999, 2003),
Table 5.2.1.2 below shows potential for carbon mitigation
through U.S. Agriculture.

**Table-5.2.1.2: Potential of US Agriculture for Carbon Mitigation,
Source: Rice, Capalbo, Hatfield based on work by Lal et al. (1999,
2003)**

Scenario	MMTC/ yr
C Sequestration in cropland	132 (69-195)
C Sequestration in CRP	13
C Sequestration in rangelands	58 (30-110)
Biofuel production (C offset)	~50
Savings in fuel consumption	1-2
Reduction of C emission from eroded sediments	~15
Total	270
Total US Emissions: ~1800 MMTC/yr	

According to Paustian et al. (2001), "Some carbon
sequestering practices such as no-till will decrease fossil
carbon use (i.e. less fuel use for traction). Figure-
5.2.1.2 shows historical trend and improvement in total
soil carbon ever since the advent of reduced tillage
practices in 20th century. Other practices, for example,
adding cover crops to rotations may increase fossil carbon
use (e.g. due to more field operations). In addition to
carbon sequestration, increasing soil organic matter levels
generally carry substantial benefits to soil biological,
chemical and physical attributes, which translate into
improved fertility and soil sustainability. These
improvements include enhanced water storage capacity,
increased water filtration, reduced runoff (and erosion),
increased soil buffering capacity, and increased storage of
essential plant nutrients".

Crop management strategies for C sequestration may be
summarized in two broad categories. Firstly, those
enhancing C Inputs such as crop management, crop selection

and crop rotation. Secondly, those which reduce C losses such as tillage and fallow management.

One of the major challenges is measuring and monitoring the soil carbon sequestration. Long term experiments are essential to understand the temporal dynamics of soil C. The challenge lies in developing effective methods for detecting changes in soil C that occur in fields as a result of changes in management. It is difficult to detect changes in soil C on short time scales as the amount of change is small compared to total C.

Methods for detecting and projecting soil C changes which include direct methods (field and laboratory measurements and eddy covariance) and indirect methods including stratified accounting, remote sensing and other models.

Recent technological developments in the area of soil C measurement include, Laser Induced Breakdown Spectroscopy (LIBS), Neutron Inelastic Scattering (NIS) and Infrared.
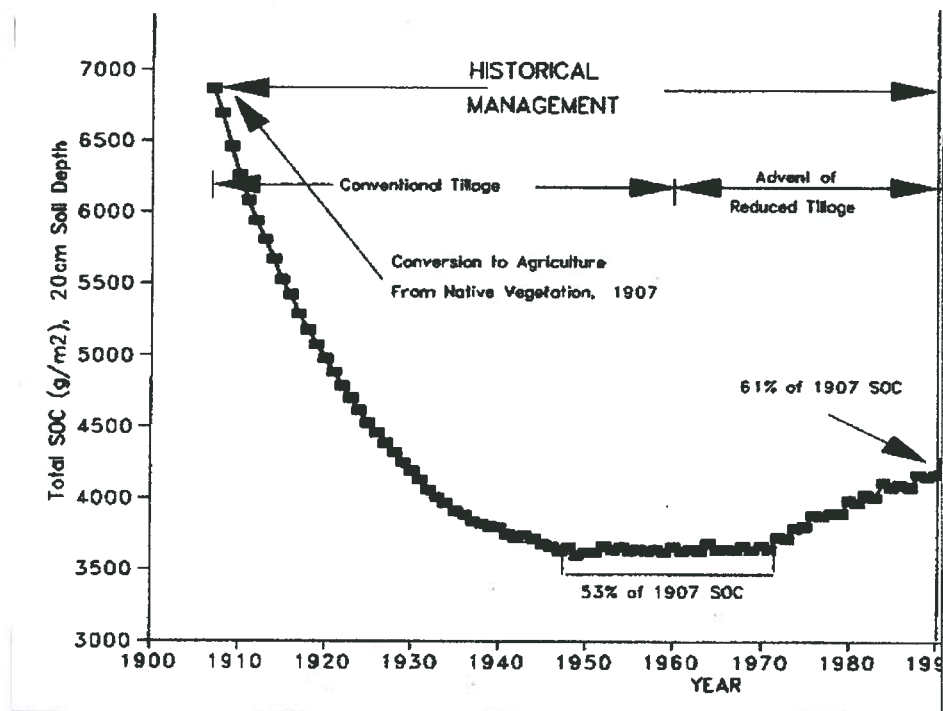
Fig.5.2.1.2: Historical Trend "SOC" Contents
Source: Rice, Capalbo, Hatfield (2005),(http://soilcarboncenter.k-state.edu)
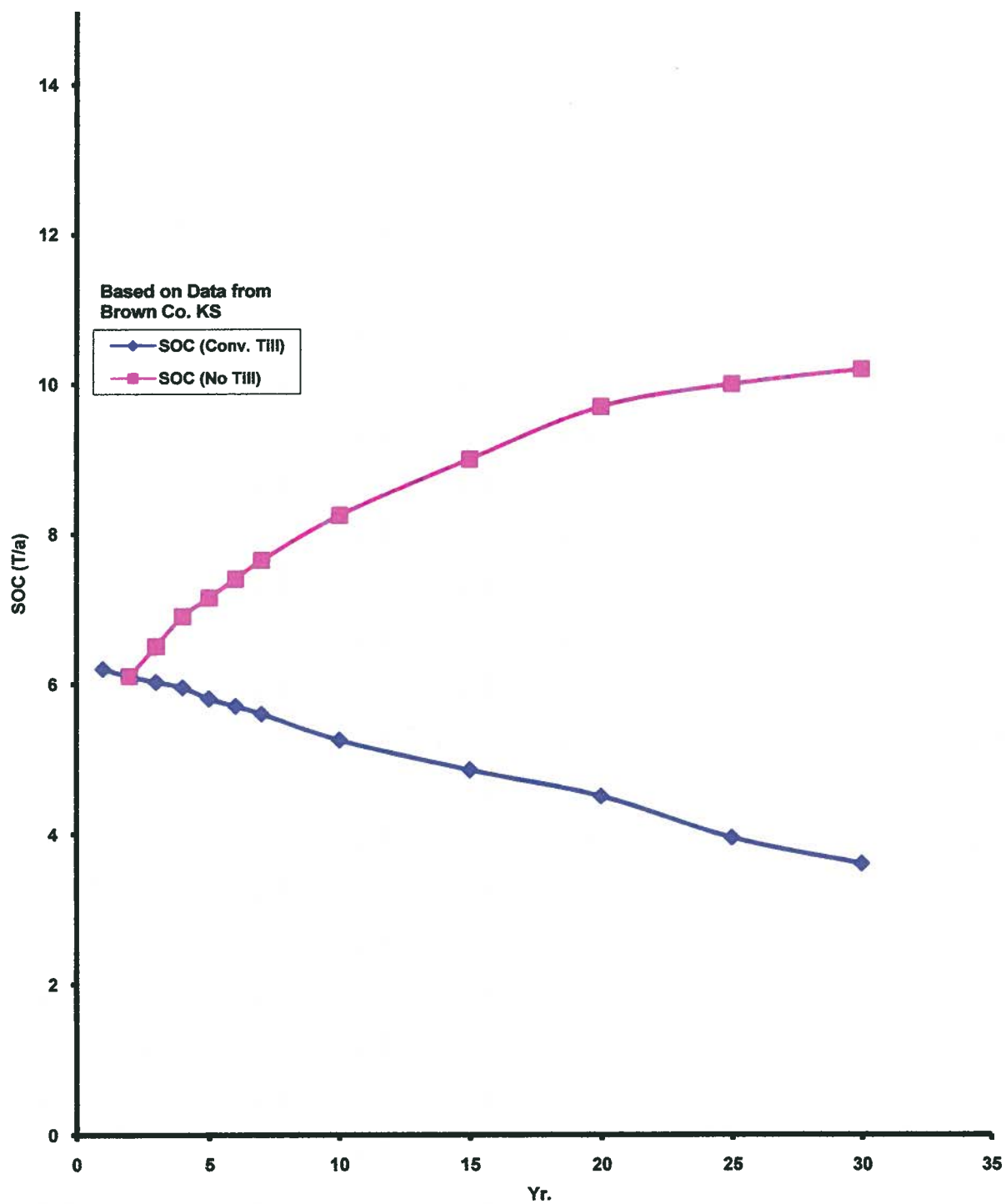
Fig.5.2.1.3: SOC Enhancement with reduced or no tillage
Source: Rice, Capalbo, Hatfield (2005),(http://soilcarboncenter.k-state.edu)

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Soil Organic Carbon After 2 and 12 yr. of CRP in Nebraska
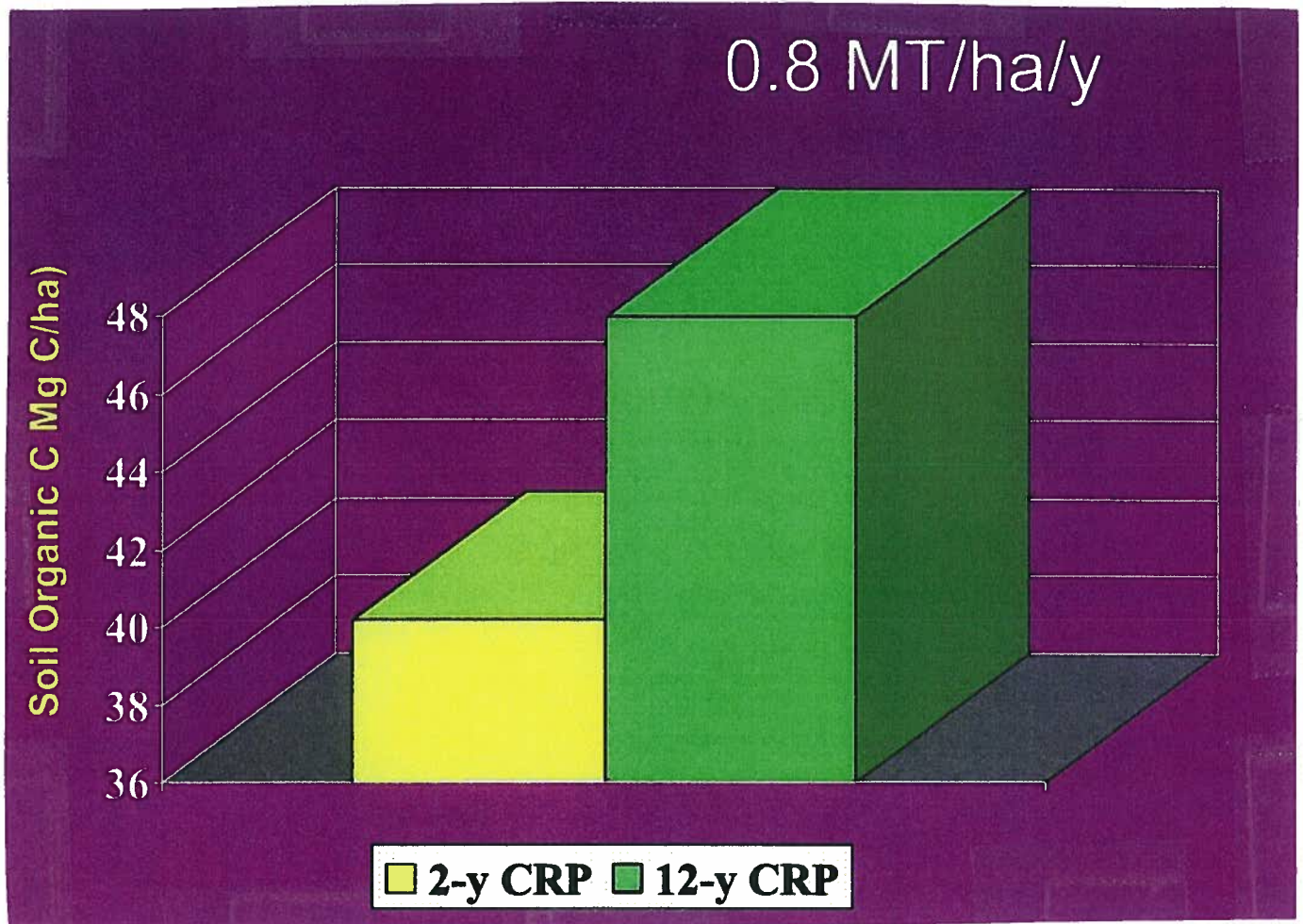
Fig.5.2.1.4: Soil Organic C increase due to CRP
Source: Rice, Capalbo, Hatfield (2005),(http://soilcarboncenter.k-state.edu)

5.2.2 Mitigation of Nitrous Oxide fluxes in Agriculture

According to Paustian et al. (2001), "Agriculture is a major contributor of nitrous oxide (N_2O) emissions to the atmosphere (Table-5.2.2.1), one of the more powerful greenhouse gases. The major sources include emissions from soils due to microbial metabolism of nitrogen, through the processes of nitrification and denitrification. The same processes act on animal wastes, resulting in emissions both in storage and in soil.

Table-5.2.2.1: US and global emissions of N_2O from agricultural sources for 1990 (Gg=gigagrams=10^9 grams=kilotonnes), based on EPA (2000) and Mosier et al. (1998a)

Emission Source	U.S., Gg N_2O	Global, Gg N_2O
Agricultural soil and management	620	3900
Manure management	40	300
Indirect emissions from agriculturally derived N on non-cropped ecosystem	270	2100

A portion of the nitrogen that cycles through soil is subject to microbial transformations, including oxidative pathways (nitrification) and reductive pathways (denitrification) involving mineral nitrogen compounds, both of which can form N_2O as a byproduct.

While rates of emissions from soil vary considerably due to a number of factors, many studies show a rough proportionality between the total nitrogen entering the soil from anthropogenic inputs (i.e. fertilizer, manure, planted legumes) and the amount lost as N_2O (Bouwman 1996). Because most cropped soils emit N_2O at a rate about 1.5% of their nitrogen input saved. The type of N input is less important than the amount i.e. synthetic fertilizers, manure, and biological N_2 fixation have equivalent effects on N_2O flux in most intensive cropping systems.

Nitrogen is used inefficiently in most cropping systems: typically, only half of N inputs are captured in crop biomass and the remainder is lost from the system through leaching and/ or through gaseous losses of N_2, N_2O, NOx, or NH_3. Because for crops in the US there is a direct relation been soil N-availability and crop yield, the agronomic challenge is to decrease N inputs without decreasing yield.

Kroeze and Mosier (2000) estimated that improved crop N-use efficiency could decrease soil derived N_2O emissions from agriculture by as much as 35% globally, with even greater savings in the input-intensive systems of North America, Europe, and former Soviet Union.

Such savings could be achieved by the application of existing technology, largely by better matching crop N-needs with soil N-availability (Table-5.2.2.2). Any practice that tightens the coupling between N-release and crop growth will lead to enhanced nutrient-use efficiency and to diminish need for external N, thereby decreasing N_2O flux. Any practice capturing N within the system before its potential loss can help conserve available N for later use by the crop.

Table-5.2.2.2: Agricultural Options for reducing N_2O fluxes. Based on Cole et al. (1996), Kroeze and Mosier (2000), Paustian Keith et al. (2001)

Mitigation Target	Practice	Comment
Soil emissions associated with N fertilization and soil N cycling	Soil N Tests	Can reduce overfertilization of crops. Only about one half of US corn acreage in the mid-1990 was tested for soil N before planting.
	Fertilizer timing	Fertilizing in synchrony with active crop growth. On only 30% of corn acreage was N applied after planting and 30% of corn acreage received fall-applied N in 1995, leading to high risk for overwinter losses and N_2O emissions.
	Fertilizer placement	Fertilizer handling can increase N use efficiency, reducing volatilization by as much as 35% and increase yield by as much as 15%. On only 40% of US corn acreage in the mid-1990s were nutrients banded.
	Nitrification and Urease Inhibitors	Nitrogen applied as ammonium or mineralized from soil must be nitrified before it is available for denitrification. Inhibitors delay the transformation of ammonium to nitrate and urea to ammonium to help match the timing of N supply with crop demand. Nitrification inhibitors were used on less than 10% of U.S. corn acreage in 1995.
	Cover crops	Winter or fallow cover crops can prevent the build-up of residual soil N, catching N that otherwise would be emitted as N_2O or leached, improving N use efficiency. Yet cover crops were used on only 4% of major field crop acres in the United States in 1995.
Emissions from animal waste	Waste storage	Storing animal waste anaerobically can minimize N_2O losses.
	Waste Disposal	Mitigating post storage emissions by same practices as for N fertilization (see above), to increase N uptake by crops and reduce losses to competing sinks such as N_2O production and leaching
Indirect soil emissions from N added to non cropland areas	Maximizing crop N use	Practices outlined above will minimize N loss for crop fields.
	Managing riparian zones	Planting filter strips and trees near riparian zones will help keep leached N from becoming N_2O at streamside or farther downstream.
	Managing ammonia	Ammonia (NH_3) gas volatilized from confined animal facilities or from anhydrous ammonia fertilizers becomes rainwater NH_4+. Animal waste can be handled to minimize NH_3 emissions by the storage of waste in lagoons or other anaerobic systems. Proper injection of anhydrous ammonia fertilizers can reduce losses.
	Treating wastewater	Much of the N in sewage wastewater derives from human food consumption. Removal of N before it is released as effluent will prevent it from becoming N_2O in downstream environment.

Nitrous oxide emissions from animal wastes can be significant (Table-5.2.2.2). Confined animals excrete as dung and urine 80 to 95% of the N in their diet, and some proportion of this N is emitted as N_2O during collection, storage, and treatment. In general, N_2O emissions increase with the N content of waste, the extent to which waste is allowed to become aerobic (allowing the initiation of nitrification-denitrification reactions) and the length of storage (Mosier et al. 1998). For waste of a given N content, anaerobic lagoons will result in the least N_2O emissions whereas solid storage and dry-lot handling will promote emissions (Table-5.2.2.2).

Nitrogen lost from agricultural fields, for example through ammonia volatilization and nitrate leaching, can be transported offsite and become available again for emission as N_2O. Nitrogen in food crops is either consumed directly by humans or used to produce meat or milk that is subsequently consumed. Most of this N then enters sewage treatment plants, where it is available for conversion to N_2O or to nitrate that enters riverine systems and subsequently may be denitrified. And N volatilized as NH_3 from fields, pastures, or animal facilities or emitted from soil as NO_2 will reenter as inadvertent nitrate and ammonium fertilizer, downwind. Both reducing the amount of off-site N loss and managing the non-cropland areas offer options for N_2O mitigation (Table-5.2.2.2).

All these mitigation strategies have other environmental benefits. First, increasing on-farm N-use efficiency will lessen groundwater nitrate loading and eutrophication of surface and coastal waters. Tighter farm N cycles will help decrease NH_3 and NO_2 emissions to the atmosphere, subsequently decreasing deposition-N inputs to nonagricultural ecosystems. Making crop N-use more efficient also will decrease the need for synthetic N-fertilizer, which produces CO_2 in its manufacture, so substituting excess manure for synthetic N will provide measurable CO_2 mitigation. Some N_2O mitigation practices also will mitigate CO_2 more directly. Riparian forests that can mitigate indirect N_2O fluxes will store C in growing vegetation for a number of decades, and both riparian

forests and cropping systems with cover crops accumulate C in soil".

One of the key aspects of nitrogen management to reduce N_2O is to reduce nitrogen availability when N_2O production potential is greatest and plant needs are the lowest. This can be achieved by proper timing (split applications, delayed applications and using nitrification inhibitors); proper placement (banded or injected) and proper rate (utilizing nitrogen from organic matter efficiently i.e. nitrogen from soil, crop residue and cover crops).

5.2.3 Mitigation of Methane Fluxes through Agriculture:

According to Paustian et al. (2001), "The most important agricultural sources of CH_4 are ruminant livestock and livestock-waste management (Paustian, 2001). Rice production and burning of agricultural crop residue are important globally but are minor sources in North America. Aerobic soils constitute an important sink for CH_4, through microbial oxidation of methane. However, intensive agriculture has been found to significantly reduce this sink compared to native forest and grassland ecosystems, which contribute indirectly to increasing methane concentrations in the atmosphere.

In the United States, CH_4 production from enteric fermentation in livestock totals approximately 5.7 Tg CH_4 (Table-5.2.3.1). Fermentation by microflora in the anaerobic environment of the rumen leads to CH_4 emissions ranging from 2 to 12% of gross feed-energy intake (Johnson et al. 1993).

Considerable CH_4 is emitted from the microbial, anaerobic decomposition of livestock waste. The relative amount of CH_4 produced is determined by the waste management system. When manure (some combination of urine and feces) is stored or treated in systems promoting anaerobic conditions, e.g. as a liquid in lagoons, ponds, tanks, or pits, organic matter decomposition generates CH_4. In anaerobic digestion the CH_4 can be recovered and used as a fuel. When manure is handled as a solid or deposited on grazing lands, it tends to

decompose aerobically and to produce little CH_4 (Safley et al. 1992).

Table-5.2.3.1: US and global emissions of CH_4 from agricultural sources (Tg = terragrams = 10^{12} = million tonnes). US numbers are from EPA (2000) and global numbers are based on Cole et al. (1996), and Paustian et al. (2001)

Emission Source	US, Tg CH_4	Global, Tg CH_4
Livestock - Enteric Fermentation	5.7	80
Livestock - Manure Management	2.9	15
Rice Production	0.4	30
Agriculture Residue Burning	<0.05	5
Total:	8	130

Methanotrophic microbes found in most aerobic soils actively oxidize atmospheric CH_4. Conversion from native grasslands and forests to managed pastures and cultivated crops generally decreases the normal aerobic soil CH_4 sink. Mosier et al. (1999) found that fertilization of native grassland decreased CH_4 uptake rates by about 35% and cultivation decreased consumption an additional 15%. In irrigated maize and wheat, N fertilization did not decrease CH_4 consumption further, but rates were 85 to 90% lower than in native grasslands.

Recovery of CH_4 oxidation after plowing in short grass steppe grassland systems likely requires several decades (Mosier et al. 1997). Robertson et al. (2000) found CH_4 oxidation rates in corn-soybean-wheat cropping systems in Michigan to be 80% lower than in adjacent native forests. Rates were equally low in perennial crops (alfalfa and poplar trees) and recovered very slowly after abandonment from agriculture.

Successful development and implementation of mitigation strategies for agricultural sources of CH_4 require comprehensive understanding of the effects of land-use change and agricultural practice on fluxes of these gases and on mechanisms of control. To ensure that

interactions and feedback are accounted for, proposed
mitigation technologies should be evaluated within the
context of farm-production systems.

Opportunities for decreasing CH_4 emissions from
intensively managed cattle are somewhat limited because
these operations currently are quite efficient. However,
the U.S. Department of Energy (DOE 1999b) recently reviewed
U.S. GHG emissions and suggested that, as a result of
expected improvements in milk production/cow, CH_4
emissions/unit milk produced will decline, with a decrease
of 30% envisioned for the dairy industry. The main options
for decreasing CH_4 emissions from the beef industry are
refinements to the marketing system and improvements in cow
calf sector performance. Achievable decreases of CH_4
emissions from beef cattle in the United States are
projected to be in the range of 20%. Specific practices to
decrease CH_4 emissions from ruminants are outlined in Table
5.2.3.2.

Most CH_4 produced in anaerobic digestion constitutes a
wasted energy source that can be recovered by adapting
manure-management and treatment practices to collect CH_4.
The by-products of anaerobic manure digestion can be
utilized as animal feeds, aquaculture supplements, or crop
fertilizers. Certain practices decreasing CH_4 emissions may
enhance N_2O emissions, their adoption must be considered in
the context of a whole-system GWP analysis (Robertson et
al.2000).

Specifically, spreading manure on crop fields will
mitigate N_2O, but only if done in a manner optimizing rate
and timing of application for maximum crop uptake.
Substituting synthetic fertilizers for compost in flooded
rice systems adds to the CO_2 cost associated with fertilizer
manufacture. And whereas draining flooded rice-fields
during the growing season may decrease CH_4 emissions, it
also may decrease soil C storage and enhance N_2O emissions.

Many of the management practices capable of mitigating
CH_4 emissions in agricultural systems also can improve crop
and animal productivity. Using feed additives to inhibit

rumen CH_4 production increases the amount of fixed C available for livestock weight gain. Using covered lagoons to capture CH_4 from livestock waste, and large-scale digesters to produce energy from the captured CH_4 will make farms less dependent on purchased energy and will decrease the CO_2 associated with energy production.

Properly spreading digested manure on crop fields will provide limited nutrients to crops, thereby decreasing reliance on synthetic fertilizer sources and saving the economic and CO_2 expense of fertilizer. Managing water and nutrients differently in flooded rice may provide both water and fertilizer savings".

Table-5.2.3.2: Agricultural Options for reducing CH₄ fluxes based on Cole et al. (1996), and Paustian et al. (2001)

Emissions from enteric fermentation	Feed ratios to decrease digestion time	Because most CH_4 is produced in the rumen by fermentation, the longer the feed remains in the rumen, the more C is converted to CH_4. Practices to speed the passage of feed through rumen include use of more digestible feed, chopping feed to increase surface area, using concentrated supplements.
	Feed additives	Edible oils and ionospheres as additives can inhibit rumen methanogens
	Specialized rumen bacteria	Researchers developing genetically modified rumen bacteria producing less CH_4.
	Livestock production efficiency	Improving the efficiency of livestock production will decrease CH_4 emission because fewer animals will be needed to produce the same amount of product.
Emissions from livestock waste	Using covered lagoons	Suitable for large scale, intensive farming operations
	Using large scale digesters	Technically advanced CH_4 digesters can be integrated with large livestock operations. Estimates of profitable emissions reduction from dairy and swine operations are 25 and 19% of 1990 emissions, respectively.
	Alternate waste storage practices	Solid rather than liquid manure handling (this practice may promote N_2O formation); applying manure to land as soon as possible, aerating manure during composting (this practice may promote N_2O formation).

Based on the work done by Robertson et al. Science 289: 1922-1925 (2000), Table-5.2.3.3 below shows the global warming

potential of different crop activities as part of a full cost accounting system which includes all activities and their effect on three major greenhouse gases.

Table-5.2.3.3: Full Cost Accounting: GWP of Field Crop Activities
Source: Rice, Capalbo, Hatfield (K-State Research & Extension) based on the
work done by Robertson et al. Science 289:1922-1925 (2000)

Activities	Soil-C	N-Fert.	Lime	Fuel	N_2O	CH_4	Net
	Gram CO_2-equivalent per m^2/ yr						
Annual Crops							
Conventional Tillage	0	27	23	16	52	-4	114
No Till	-110	27	34	12	56	-5	14
Low Input	-40	9	19	20	60	-5	63
Organic	-29	0	0	19	56	-5	41
Perennial Crops							
Alfalfa	-161	0	80	8	59	-6	-20

5.2.4 Biofuels

According to Paustian et al. (2001), "Biofuels offer a means of decreasing dependence on fossil fuels for energy and chemicals. Biofuels can include dedicated energy crops, agricultural wastes and residues, and methane from agricultural wastes. The energy supplied by such systems can be used for power, fuel, or chemical feedstock, which can supplant current fossil sources of these commodities and hence decrease the flow of associated GHGs to the atmosphere.

With respect to agriculture, the major opportunities for increased use of biofuels lie in crops and residues grown and/or collected on U.S. farms. These include corn produced for conversion to fuel ethanol, cellulosic crops such as trees, grasses, and crop residues (corn stover and bagasse). The contributions that biofuels can make to GHG mitigation depend on three factors:

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- Whether they can be produced on American farms at prices competitive with traditional agricultural products,
- Whether the energy derived from these crops will be cost competitive with fossil-energy sources; and
- Whether the ecological and economic benefits of biofuels will be factored into the pricing/evaluation equation.

The efficiency with which biofuels decrease GHGs is a function of energy expended in production, processing, and utilization of biofuel energy".

5.2.4.1 Biomass Anaerobic Digestion

According to California Energy Commission (Biomass Anaerobic Digestion: Renewable Energy Research Center: California Energy Commission, www.energy.ca.gov/research/renewable/biomass/anaerobicdigestion), "Anaerobic digestion (AD) is a biological process in which biodegradable organic matter is broken-down by bacteria into biogas, which consists of methane (CH_4), carbon dioxide (CO_2), and other trace amount of gases. The biogas can be used to generate heat and electricity. Oxygen-free is the primary requirement of AD to occur. Other important factors, such as temperature, moisture and nutrient contents, and pH are also critical for the success of AD. AD can be best at two ranges of temperatures, mesophilic (30-40°C) and thermophilic (50-60°C). In general, AD at mesophilic temperature is more common even though digestion at thermophilic temperature has the advantages of reducing reaction time, which corresponds to the reduction of digester volume. Moisture contents greater than 85% or higher are suitable for AD.

The types of anaerobic digesters include Covered Lagoon, Batch Digester, Plug-Flow Digester, Completely Stirred Tank Reactor (CSTR), Upflow Anaerobic Sludge Blanket (UASB), and Anaerobic Sequencing Batch Reactor (ASBR), and others.

The complete-mix digester is a large, vertical poured concrete or steel circular container. Today's complete-mix digester can handle organic wastes with total solid

concentration of 3% to 10%. Complete-mix digesters can be operated at either the mesophilic or thermophilic temperature range with a hydraulic retention time (HRT) as brief as 10-20 days.

The basic plug-flow digester design is a long linear trough, often built below ground level, with an air-tight expandable cover. Organic waste is collected daily and added to one end of the trough. Each day a new "plug" of organic wastes is added, slowly pushing the other manure down the trough. Plug-flow digesters are usually operated with a total solid concentration of 11%-13% at the mesophilic temperature range, with a HRT from 20-30 days.

A covered lagoon is an earthen lagoon fitted with a floating, impermeable cover that collects biogas as it is produced from the organic wastes. The cover is constructed of an industrial fabric that rests on solid floats laid on the surface of the lagoon. The cover can be placed over the entire lagoon or over the part that produces the most methane. An anaerobic lagoon is best suited for organic wastes with a total solid concentration of 0.5%-3%. Covered lagoons are not heated.

Operation and maintenance of a covered lagoon digester is simple and straightforward compared to complete-mix and plug-flow digesters. The capital cost for covered lagoon is less than those required for the complete-mix and plug-flow types of conventional digesters. However, a key issue for covered lagoon is that digestion is dependent on temperature; therefore biogas production varies seasonally if the lagoon is not externally heated. This means that methane production is greater in summer than in winter. In general, average daily biogas production in summer could be 35% higher than in winter. This may make end-use applications more problematic than plug flow and complete mix digesters. Another concern is that it can take an anaerobic lagoon as long as 1-2 years to achieve its "steady state" biogas production potential.

Production of renewable energy, improvement on environmental pollution in air and water, reduction of agricultural wastes, and utilization of byproducts as fertilizers from anaerobic digestion (AD), has increased the attractiveness of the application of AD.

AD technology is well developed worldwide. Of the estimated 5300-6300 MW worldwide anaerobic digestion capacity, Asia accounts for over 95% or 5000-6000 MW. Traditional, small, farm-based digesters have been used in China, India and elsewhere for centuries. The number of digesters of this type and scale is estimated to exceed 6 million. European (EU) companies are world leaders in development of the AD technology. Currently, EU has a total generating capacity of 307 MW from AD technology. The countries in EU with the largest development figures are Germany (150 MW), Denmark (40 MW), Italy (30 MW), Austria and Sweden (both 20 MW.

Germany led the small on-farm digesters for odor control. Italy developed a series of farm AD systems. Larger, centralized anaerobic digestion plants, which utilize animal manure and industry waste in a single facility, are a newer development and most prevalent in Denmark where there are 18 plants (worldwide there are 50 or so, all within Europe). Municipal solid waste digestion is the newest area for anaerobic digestion. The most recent is for source-separated feedstock, for which there are estimated to be over 150 commercial-scale plants. These plants have a combined capacity in excess of 6 million tons per year and the number of plants planned is increasing rapidly".

Biogas to Energy Technologies

According to California Energy Commission (Biomass Anaerobic Digestion: Renewable Energy Research Center: California Energy Commission, www.energy.ca.gov/research/renewable/biomass/anaerobicdigestion), following are "basic technologies for the utilization of digester gas:

- Medium-Btu Gas Use

Medium-Btu biogas can be used in a number of ways. Typically after condensate and particulate removal, the biogas is compressed, cooled, dehydrated and then transported by pipeline to a nearby location for use as fuel for boiler or burners. Minor modifications are required to natural-gas-fired-burners when biogas is used because of its lower heating value. Another alternative for biogas applications is to generate steam using an onsite boiler. The biogas, after condensate and particulate removal and compression, is burned in a boiler. The customer for this steam would need to be close to the site since high pressure steel insulated pipeline is expensive and heat is lost during transport.

- Generation of Electric Power using reciprocating engines, gas turbines, steam turbines, Microturbine, and Fuel Cell

Electricity generated on-site using a reciprocating engine, steam turbine, or gas turbine, is being actively used. When a reciprocating engine is used, the biogas must have condensate and particulates removed. In order to move fuel gas into a gas turbine combustion chamber, the biogas must have most of the visible moisture and any particulates removed and then compressed. Using a steam turbine requires generating the steam first. Microturbine can be used to generate electricity at a capacity as small as 30 kW. However, issues exist in the high cost for biogas clean up and limited engine running time when a Microturbine is applied. The Microturbine technology has not been commercialized. High cost associated with biogas clean up is also an important issue for potential application of the fuel cell technology.

- Injection into an existing natural gas pipeline

Biogas can be upgraded into high-Btu gas and injected into a natural gas pipeline. As compared with other power generation alternatives, the capital cost for sale of upgraded pipeline quality gas is high because of the

treatment systems that are used to remove CO_2 and impurities. Also, upgraded gas needs a significant amount of compression to conform to the pipelines pressure at the interconnect point. However, the advantage of pipeline quality gas technology is that all the biogas produced can be utilized. The CO_2 that is removed can be sequestered.

- Conversion to other chemical forms

It is possible to convert the biogas to another form such as methanol, ammonia, or urea. Of these three options, conversion to methanol is the most feasible option. However, in order to convert high methane content gas to methanol, water vapor and carbon dioxide must be removed. In addition, the gas must be compressed under high pressure, reformed, and catalytically converted. This tends to be an expensive process, which results in about 67 percent loss of available energy. The CO_2 that is removed can be sequestered".

5.2.5   Policy Options and Design for Agricultural emissions of Greenhouse Gases

Numerous papers on the economics of controlling GHG emissions have been published, but few have focused specifically on the analysis of sequestration and GHG mitigation in agricultural soils. Lal et al., 1999, 2003 presented tremendous potential in U.S. Agriculture for GHG mitigation.

Mitigation of GHG through agriculture offer relatively low cost options that provide significant benefits, when compared to other sectors.

According to Paustian et al. (2001), "There are, however, many questions that need to be answered for design and implementation of policies to encourage soil C sequestration and soil GHG emissions reductions.

There are at least three scenarios under which programs to decrease GHG emission could be established.

First, international agreements could allow terrestrial sinks, both forest and agricultural, to count toward a country's commitment to decrease GHGs. Such a scenario has the potential to create a major role for

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agricultural C sequestration, including income generation associated with altered farming and land-use practices.

Second, even in the absence of credit for agricultural sinks in the international community, the developed nations could adopt policies encouraging soil C sequestration, for soil C is an indicator of long-term soil productivity and likely is correlated with many beneficial environmental attributes. Depending on how this policy is implemented, it may have significant income-generating potential for agricultural sources.

Thirdly, voluntary arrangements whereby emitters buy offsetting credits from farmers or their representatives may arise if consumers are willing to pay extra for climate change-neutral products.

Unless international or national policies generate official credit for C sinks, however, C sequestration probably will not be a major determinant of farming practice or income.

Alternative government policies depend critically on which, if any, of these scenarios comes to pass. For example, there is little role, beyond standard market oversight, for a government program if the third scenario is adopted.

Likewise, if international credit for agricultural sinks is not approved, a GHG marketable credits program is less likely to be worth implementing in as much as trading from energy and other sectors is likely to play a key role in such a market.

Nonetheless, many issues must be addressed before any government policy concerning GHG control from agricultural sources can be implemented effectively.

Acceptance of agricultural sinks by the international community will require that a program address four key concerns (Paustian et al. 2001).

First, because damages depend on total GHG-stock, the policy will need to account fully for all changes in C uses

in a country, as well as all GHGs, e.g., N_2O and CH_4, i.e. full greenhouse land and gas accounting.

Second, it will be necessary to measure all the components of net emissions and mitigation actions with an acceptable degree of accuracy and to characterize the associated uncertainty.

Third, an understanding of how timing affects value and use of C sinks in agriculture is crucial, especially because agricultural sinks may not be permanent.

Fourth, an effective GHG-mitigation strategy in agriculture must alter farmers' behaviors relevant to the adoption of improved conservation and land-use practices.

Acceptance of agricultural sinks will require the design of policies that can convincingly induce such change.

Many alternative program designs for decreasing GHG emissions by means of agricultural sinks exist. There is much talk of "carbon trading" and of the buying and selling of C permits and various ways in which actual implementation of such trading schemes could be accomplished.

However, such specific significant government based programs are less likely to come to pass unless there is an international accord allowing agricultural sinks to count toward treaty commitments to decrease GHG emissions".

In economic terms, if the marginal cost of decreasing emissions is higher than that of storing C, total cost will be lower if storage is used, until the two marginal costs are equal.

For an effective program to be implemented, many details concerning the mechanisms for implementing agricultural-sink GHG policy must be worked out.

The important dimensions of program design are (Paustian et al. 2001):

- The definition of the commodity to be regulated or targeted;

- The organizational structure of the program;

- The enumeration of payment rules, including timeframe and reversibility issues; and

- The monitoring and verification of GHG reductions.

5.3 CARBON CAPTURE AND SEQUESTRATION

The control of greenhouse gases is one of the most challenging environmental policy issues facing the world today. An approach that is gaining widespread interest is to control CO_2 emissions by capturing and sequestering CO_2 from fossil-fuel combustion sources. This is different from conventional thinking about GHG mitigation, which requires eliminating or severely limiting the use of fossil fuels.

Due to high degree of reliance on fossil fuels (roughly 85% of commercial energy use domestically and globally), and the difficulties — technical, economic and social — of large-scale use of alternative options (like nuclear and renewables), the ability to use fossil energy while avoiding greenhouse gas emissions is a potentially attractive alternative.

Carbon capture and sequestration can be a critical tool in the efforts to restrict the rising concentration of CO_2 in the atmosphere. CO_2 recovery and sequestration technology has been available for over 40-years and has been selectively applied to enhance oil and gas recovery. Permanent sequestration of CO_2 has been used in Sleipner, Norway since 1996, Weyburn, Canada since 2000, and in Salah (Algeria) since 2004 – all without incident.

CO_2 capture can be applied to large point sources such as power plants, cement production plants, refineries, iron and steel, petrochemical and oil and gas facilities. Potential sequestration methods are geological and ocean storage.

There are different types of CO_2 capture process systems such as post combustion, pre-combustion and oxy-fuel combustion. Concentration of CO_2 in gas stream, gas pressure and fuel type (solid or gas) are important factors that influence selection of a capture process.

Post combustion capture of CO_2 in industrial plants involves separation of CO_2 from flue gases using available technologies in natural gas processing industry.

Technology required for pre-combustion capture is widely used in fertilizer industry and in hydrogen

production. Although initial fuel conversion steps of pre-combustion (converting fossil fuel to CO_2 and H_2 by steam reforming) are more elaborate and costly, the higher concentration of CO_2 and high pressure make CO_2 separation easier.

Oxyfuel combustion is in developmental phase and uses high purity oxygen which results in high concentration of CO_2 in the flue gases making the separation easier.

After separation CO_2 can be transported using pipelines to storage sites. Pipeline transportation of gases is a very common and technologically mature industrial activity. Dry CO_2 is not corrosive to pipelines even if CO_2 contains contaminants. If CO_2 contains moisture then it can be removed from CO_2 stream to prevent corrosion and to avoid the cost of constructing the pipeline with corrosion resistant materials.

This section primarily deals with the post-combustion CO_2 recovery and separation.

5.3.1   Technology Options for CO_2 Capture

A number of technology options currently exist for separation and capture of CO_2 from gas streams which can be developed and applied to large scale operations. These include different physical and chemical processes including absorption, adsorption, membranes and cryogenics.

Fig.5.3.1 shows various technological options for CO_2 separation and capture.

CO_2 Separation and Capture

Absorption	Adsorption	Cryogenics	Membranes	Microbial/Algal Systems

Chemical
- MEA
- Caustic
- Other

Physical
- Selexol
- Rectisol
- Other

Adsorber Beds
- Alumina
- Zeolite
- Activated C

Regeneration Method
- Pressure Swing
- Temperature Swing
- Washing

Gas Separation
- Polyphenyleneoxide
- Polydimethylsiloxane

Gas Absorption
- Polypropelene

Ceramic Based Systems

Fig.-5.3.1 Technology Options for CO_2 separation and capture (Rubin et al. 2002)

Some of the common CO_2 recovery processes are as follows:

- **High Pressure Absorption Processes:**

Absorption using physical solvents rely on higher pressures as CO_2 recovery is directly proportional to the partial pressure of the CO_2 in the feed gas. This limitation also applies to a lesser degree to the less reactive chemical solvents such as methyldiethanolamine (MDEA), diethanolamine (DEA), diisopropanolamine (Chapel et al. 1999).

- **Hot Potassium Carbonate:**

Hot potassium carbonate is used in many ammonia, hydrogen, ethylene oxide and natural gas plants. Activators and inhibitors are added to improve CO_2 absorption and to inhibit corrosion. These systems are known as "activated hot potassium carbonate" (AHPC) systems. The most widely used of these are the Benfield process licensed by UOP, and the Catacarb process (Chapel et al. 1999).

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Other commercial processes are the Exxon Flexsorb HP process, which uses a hindered amine activator, and Giammarco-Vetrocoke's new process, which uses an organic activator. These processes are designed for bulk CO_2 removal from high pressure streams and also produce CO_2 of high purity. The Benfield and Catacarb processes are commercially offered for applications at a minimum CO_2 partial pressure of 210 to 345 kPag.

- **Membranes:**

Membranes suffer from both the cost of compression and heat exchange to obtain a high pressure feed. This process produces relatively impure CO_2 product which is not much of concern if the produced gas is only going to be sequestered. Currently, there are no commercial applications of membranes for recovery of CO_2 from flue gases (Chapel et al. 1999).

- **Mono-Ethanol Amine (MEA)**

MEA has a long history of commercial CO_2 recovery with various feeds including flue gases. Use of uninhibited MEA is generally limited by corrosion problems to about 15-20 wt% MEA solutions.

The low MEA concentration raises the reboiler duty substantially. For example, the reboiler duty increases 20% when the MEA concentration decreases from 30 to 15 wt%. The required pump power also increases due to need for increased circulation rates. Since the reboiler heat duty is the most important key to operating costs, this is a significant handicap (Chapel et al. 1999).

Some corrosion inhibitors in conjunction with a quantitative oxygen and NOx removal system allow the MEA concentration to be raised to 25-30 weight percent.

- **Sterically Hindered Amines.**

Kansai Electric Power Company (KEPCO) and Mitsubishi Heavy Industries have been developing a proprietary hindered amine called KS-1 as an MEA replacement for flue gas applications (Chapel et al. 1999). KS-1 has a lower circulation rate (due to its higher lean to rich CO_2

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loading differential, lower regeneration temperature of about 110-°C, and 10-15% lower heat of reaction with CO_2.

It is non-corrosive to carbon steel(less than 5 mils/yr) at 130 °C in the presence of oxygen. A second sterically hindered amine, AMP (2-amino-1-methyl-1-propanol) may have similar properties to KEPCO's KS-1. The first commercial plant using KS-1 for Petronas Fertilizer Kedah Sdn Bhd's fertilizer plant in Gurun Kedah, Malaysia is now in operation (Chapel et al. 1999).

The choice of a suitable technology will also depend on the characteristics of the flue gas stream, which depends mainly on the technology used for energy generation. Flue gas characteristics are different for a coal based plant and a gas turbine based power generation or a gas compression plant due to the differences in fuel compositions, and combustion efficiencies.

Final selection of a CO_2 capture process will also depend on the overall economics taking into account the potential savings in carbon cost over the life cycle of the project.

Technology options for fossil fuel based power generation may be divided into three major categories:

a) Based on type of fuel:
   i)   Coal: This category include direct coal combustion and coal gasification based technologies
   ii) Gas: Direct combustion or gas reforming

b) Based on type of Oxidant:
   This category includes air or pure oxygen used as oxidant.

c) Based on technology:
   i)   Simple Cycle: With pulverized coal or gas turbine
   ii) Combined Cycle: Gas Turbine Combined Cycle (GTCC), Integrated Gasification combined cycle (IGCC) and other technologies

According to EPA ("Inventory of U.S. Greenhouse Gas Emission and Sinks (1990-2007), "Presently there is significant (about 300 GW) of coal-fired power generation capacity in the U.S. which provides 51% of all power

generation and accounts for 79% of carbon emissions coming from electric utilities. Even with the expected growth in natural gas for new generating capacity, coal's share of the electricity supply is still projected to be about 44% in 2020. Thus, any new policies to significantly reduce CO_2 emissions during the next two or three decades must consider not only the technology options for new power plants), but also the retrofitting of existing coal plants which will continue to operate for several decades to come. Such medium-term intervention to reduce CO_2 emissions is very important but has received relatively little attention to date".

In this context, various studies have shown that amine-based CO_2 absorption systems are the most suitable for combustion-based power plants for the following reasons (Chapel et al. 1999)

- These systems are effective for dilute CO_2 streams, such as coal combustion flue gases, which typically contain only about 10%-12% CO_2 by volume.

- Amine-based CO_2 capture systems are a proven technology that is commercially available and in use today.

- Amine-based systems are similar to other end-of-pipe environmental control systems used at power plants. These units are operated at ordinary temperature and pressure.

5.3.2   General Design Considerations for an Amine Based CO_2 Recovery Process

The practical recovery of CO_2 from flue gases is different from other gas treating applications due to low CO_2 partial pressure and high O_2 and NOx concentrations. Flue gases from coal fired boilers may also contain SOx, soot, and fly ash, which have to be dealt with.

Following are some design issues related to CO_2 recovery processes in general and amine based processes in particular.

- **Low CO_2 Partial Pressure:**

According to Chapel et al. (2001), "Flue gases and engine exhausts have very low CO_2 partial pressures because they are typically available at or near atmospheric pressure with CO_2 concentrations of typically 3 to 13 vol%. Many acid gas treatment processes operate at thousands of kPag. These high pressure processes can be used with compression to the normal operating pressure followed by recovery of a portion of the compression energy in expanders; however, the overall energy consumption invariably results in unattractive economics. The only commercial absorbents active enough for recovery of dilute CO_2 from atmospheric pressure gas are monoethanolamine (MEA) and other primary amines including the newly developed hindered amines".

- **Regeneration Energy:**

According to Chapel et al. (2002), "Absorption processes that are effective at low pressure are those with higher reaction energies that require the most regeneration energy. The design challenges are to minimize regeneration energy by selecting a solvent with relatively low reaction energy and to use low value heat sources to provide this energy".

- **Oxygen:**

According to Chapel et al. (2002), "Oxygen can cause corrosion and solvent degradation problems. Carbon steel is desirable from cost stand point, but it can rapidly corrode in the presence of oxygen, especially in hydrogen sulfide-free CO_2 recovery systems. Also, uninhibited alkalomines such as diethanolamine (DEA) and MEA can be excessively degraded in an oxygen environment. Alternate approaches include use of expensive alloys or removal of all the oxygen with a combination of a near stoichiometric burner waste heat boiler and a catalytic reactor. Another alternative continuous addition of an oxygen scavenger to the solvent system has not been commercially implemented".

- **SOx:**

According to Chapel et al. (1999), "flue gases can contain significant concentration of oxides of sulfur (SOx) unless natural gas or very low sulfur fuels are being

fired. SOx react irreversibly with MEA to produce non-reclaimable corrosive salts that are very detrimental to plant operation. For MEA based processes, it is less expensive to install a SOx scrubber than to accept the solvent losses when the flue gas contains more than 10 ppmv SO_2. Coal fired boilers produce the highest concentrations of SOx, often 300 to 5000 ppmv before flue gas desulfurization (FGD), but even oil firing can produce 100 ppmv SOx. The limestone or wet lime FGD systems in large power boilers today achieve Sox reductions in the 90-95% range. Therefore, even the flue gas from a low sulfur liquid or solid fuel or from a limestone FGD system needs further SO_2 removal. The 10 ppmv SO_2 requirement is met by using the active alkali metal neutralizing agents, caustic soda or soda ash, in relatively inexpensive spray scrubbers.

Sulfur trioxide, SO_3, presents additional problems. SO_3, like SO_2, leads to solvent losses due to the formation of non-reclaimable heat stable salts, but it also forms a corrosive H_2SO_4 aerosol in wet scrubbers. Furthermore, less than one-third of the SO_3 may be removed by the SO_2 scrubbing system unless a special mist eliminator is used. Therefore, most of the remaining SO_3 will form heat stable salts in the absorber. The fraction of SOX which forms SO_3 is a function of combustion, fuel composition, and flue gas processing factors, but SO_3 typically accounts for a few percent of the total sulfur. Minimization of SO_3 is a boiler design issue preferably handled upstream of the SO_2 scrubber".

- **Fly Ash:**

According to Chapel et al. (1999), "Fly ash in the CO_2 absorption solvent may cause foaming in the absorber and stripper, scaling and plugging of equipment, erosion, crevice corrosion, and increased solvent loss through chemical degradation and physical association with removed sludge. Furthermore, fly ash may create significant difficulties in the upstream SO_2 scrubber. It is therefore recommended to decrease the loading to very low levels".

- **Soot:**

According to Chapel et al. (1999), "Soot presents a special problem in the absorber. Soot derived from firing gas or very light fuel oil does not cause problems and

passes harmlessly through the absorber tower. However, soot derived from heavy fuel oil stabilizes an amine mist above the CO_2 absorption zone that is not captured in the water wash zone. In this instance, a special mist eliminator must be employed in the absorber to capture the micron-sized MEA mist particles".

- **NOx:**

According to Chapel et al. (1999), "Oxides of nitrogen cause corrosion of steel and amine degradation. The corrosion problems may exist until the NOx is reduced to very low levels (less than 1 ppmv) in the absorber feed. NOx is best controlled by controlling the peak flame temperature in the boilers.

The main culprit in NOx is NO_2, which reacts to form nitric acid in the amine solvents forming heat stable salts. However, typically only 10% of the NOx is NO_2 and only a fraction of the NO_2 gas is absorbed in the solvent. NOX can be a problem in the CO_2 product if it is to be used in the food and beverage industry and steps must be taken in the liquefaction unit for its removal".

- **High Flue Gas Temperature:**

Hot flue gases can cause solvent degradation and decrease absorber efficiency. The flue gas needs to be cooled prior to entering the absorber. This can be accomplished either in the SO_2 scrubber, if present, or in a water cooled heat exchanger.

5.3.3   Overview of Amine Based CO_2 Capture System

According to Rubin E.S. et al. (2002), "The idea of separating CO_2 from flue gas streams started in the 1970s, not with concern about the greenhouse effect, but as a potentially economic source of CO_2, mainly for enhanced oil recovery (EOR) operations. Several commercial CO_2 capture plants were constructed in the U.S. in the late 1970s and early 1980s. CO_2 was also produced for other industrial applications such as carbonation of brine and production of products like dry ice, urea and beverages. Some of these CO_2 capture plants are still in operation today, but all these plants are much smaller than a typical power plant".

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The first commercial CO_2 sequestration facility started in Norway in September 1996 in response to a Norwegian carbon tax. Since then, Statoil has been storing CO_2 from the Sleipner West gas field in a sandstone aquifer 1000 m beneath the North Sea. This facility is being closely monitored by the international research community (Chapel et al. 1999).

Most of the CO_2 capture processes are based on chemical absorption using a monoethanolamine (MEA) based solvent. MEA is an organic chemical belonging to the family of compounds known as amines. It was developed as a general, non-selective solvent to remove acidic gas impurities (e.g. H_2S, CO_2) from natural gas streams. The process was then adapted to treat flue gas streams for CO_2 capture.

• Process Description

A continuous scrubbing system is used to separate CO_2 from the flue gas stream. As illustrated in Figure 5.3.2, the system consists of two main elements: an absorber where CO_2 is removed, and a regenerator (or stripper), where CO_2 is released (in concentrated form) and the original solvent is recovered.

According to Chapel et al. (1999), "A key feature of amine systems is the large amount of heat required to regenerate the solvent. This heat is typically drawn from gas fired heater or an electric heater or a steam cycle in case of a power plant.

Substantial electrical energy also is needed to compress the captured CO_2 for pipeline transport to a storage site. The overall energy penalty of this process has a major impact on system performance as well as cost.

Acid gases like SO_2 and NO_2 react with MEA to form heat-stable salts that reduce the CO_2 absorption capacity of the solvent. Thus, very low concentrations of these gases (on the order of 10-ppm) are desirable to avoid excessive loss of (costly) solvent. The problem is especially acute for SO_2 because its concentration in flue gases is typically 700 to 2500-ppm at coal-fired plants. NO_x is less of a problem because most of the NO_x is nitric oxide (NO), whereas only NO_2 (typically about 5% of total NO_x) is reactive".

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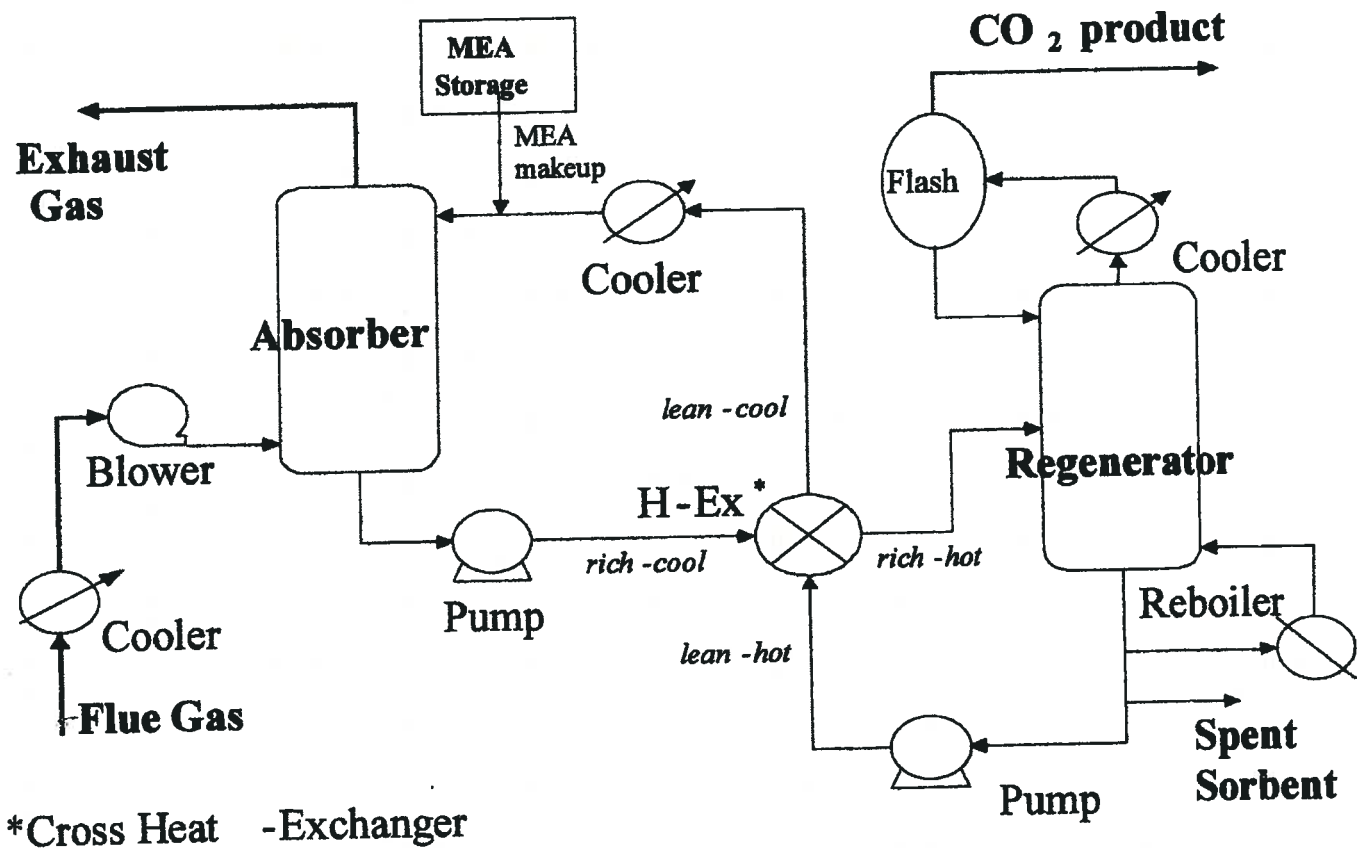
Fig.-5.3.2 Flow Diagram for CO_2 capture from flue gases using amine based system. Rubin E.S. et al. (2002)

- **KEY PERFORMANCE PARAMETERS**

According to Rubin et al. (2002), "The removal of CO_2 from flue gases using an amine scrubber depends on the gas-liquid mass transfer process. The chemical reactions that permit diffusion of CO_2 in the liquid film at the gas-liquid interface enhance the overall rate of mass transfer. Thus, the CO_2 removal efficiency in the absorber is a function of various parameters that affect the gas-liquid equilibrium (i.e. flow rates, temperature, pressure, flue gas composition, CO_2 concentration, and MEA concentration and absorber design). Similarly, the operating conditions and detailed design of the regeneration system affect the energy requirements and overall performance of the system".

The key parameters that define the performance of an amine based process system are:

a) MEA Requirement:

According to Rubin et al. (2002), "This depends mainly on the mass flow rate of CO_2 in the flue gas, the desired CO_2 capture efficiency, the MEA concentration, and CO_2 loadings in the solvent. Depending on the level of impurities in the flue gas, there is additional loss of solvent associated with removal of other acid gases such as SOx and NO_2".

b) Energy Requirements:

According to Rubin et al. (2002), "Heat requirements for solvent regeneration depend mainly on the lean sorbent loading and other system parameters. This heat is typically provided by low-pressure steam within the power plant, thus decreasing the net power generation efficiency. In addition, electrical energy is required for CO_2 product compression, solvent circulation, and other system requirements. The total amine system energy requirement is one of the most important parameters, as it dictates the net power plant output, and hence the net cost of power generation and CO_2 avoidance".

c) Environmental Emissions:

According to Rubin et al. (2002), "The CO_2 control system generates several new waste products that should be accounted for in the evaluation, principally ammonia gas (generated by degradation of MEA) and reclaimer bottoms which may contain potentially hazardous solid waste generated during recovery of spent sorbent from the process. On the other hand, the CO_2 capture system also reduces emissions of particulate matter and acid gases like SO_2 and NO_2".

5.3.4   Options for CO_2 Sequestration

Once the CO_2 is captured, it needs to be securely stored (sequestered). There are a range of options potentially available. Geologic and Ocean Sequestration options are discussed here.

a) Geologic Sequestration:

Geologic formations including deep saline reservoirs, depleted oil and gas wells below 800-m are some of the potentially attractive disposal sites. Unmineable coal bed storage may be done at shallower depths due to absorption of CO_2 on coal; however, technical feasibility of this largely depends on the permeability of the coal bed.

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As per IPCC Special Report on carbon capture and storage (2005), "it is likely that there is technical potential of at least 2000-$GtCO_2$ of storage capacity in geological formations.

CO_2 reinjection in the hydrocarbon producing reservoirs has been used for enhanced oil recovery. Some of the existing facilities include Sleipner (Norway), Weyburn (Canada) and Salah (Algeria). It is considered that about 99% or more of CO_2 can be stored for 1000-years".

At depths below 800-m supercritical CO_2 has a liquid like density that helps in efficient utilization of storage space in the pores of the sedimentary rocks (see Fig. 5.3.4.1). Supercritical CO_2 is very soluble in crude oil at reservoir conditions which helps to reduce or eliminate the forces that restrain the detachment and movement of oil which is freely swept to the producing wells.

In general, geologic formations are the most plentiful and attractive option. One important aspect in favor of carbon capture and storage is its cost competitiveness as the technologies are currently available and very mature and these are also compatible with the current energy infrastructure. Fig. 5.3.4.2 shows options for geologic storage.

b) Ocean Sequestration:

As per IPCC Special Report on carbon capture and storage (2005), "Ocean storage can be done in two ways by injecting and dissolving CO_2 into the water column (typically below 1000-m) using fixed pipeline, moving ship or onto the seafloor at depths below 3000-m using offshore facilities. CO_2 being denser than water forms a "lake" at these depths and delays any dissolution of CO_2 in the environment. Research is still continuing on ocean storage and its ecological impacts".

The dissolved and dispersed CO_2 would eventually become part of the global carbon cycle and would eventually equilibrate with CO_2 concentration in the atmosphere. Fig. 5.3.4.3 and Fig. 5.3.4.4 show options for ocean disposal and storage of CO_2.

According to the "Ocean Storage of CO_2" report by IEA Greenhouse Gas R&D Programme (2002), "World's oceans are already absorbing about 2Gt CO_2/yr from the atmosphere. Without the compensating effects of the ocean sink and

terrestrial sink atmospheric CO_2 levels would have been almost 100-ppm higher than current level.

Transfer of CO_2 at the air-sea interface is fast, especially when strong winds result in breaking waves and bubbles of air are entrained in the wind mixed layer. CO_2 is much more soluble in seawater than in fresh water because the high pH of seawater (around 8)results in the following equilibria all being pushed to right:

$CO_2 + H_2O \longleftrightarrow H_2CO_3$ (carbonic acid)
$H_2CO_3 \longleftrightarrow H^+ + HCO_3^-$ (bicarbonate ion)
$HCO_3^- \longleftrightarrow H^+ + CO_3^{2-}$ (carbonate ion)
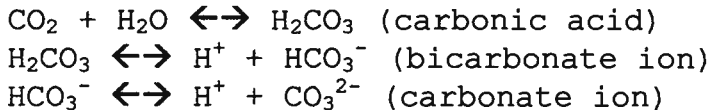
In seawater, only 1% of the CO_2 remains as molecular CO_2 and more than 90% is in the form of the bicarbonate ion. Together with carbonic acid and the carbonate ions, these are collectively referred as dissolved inorganic carbon (DIC).

The relatively warm surface waters of the sea are saturated with CO_2 but the colder deep waters of the world's oceans are unsaturated and have an enormous and underutilized capacity to dissolve CO_2.

However, the process of removing CO_2 from the atmosphere via surface water to Deep Ocean is slow. There are two mechanisms that help in transfer of CO_2 to deep oceans:

i) Solubility Pump:

CO_2 is highly soluble in the cold, dense water which, in high latitudes, sinks to the bottom of ocean. This results in a "thermohaline circulation" of seawater from cold North Antarctica deep water (rich in CO_2) is conveyed southwards nearly to Antarctica before eventually surfacing in the Indian Ocean and in the Equatorial Pacific, where CO_2 escapes to the atmosphere again. The time interval between water sinking at high latitudes and resurfacing in the tropics is estimated to be around 1000-years.

ii) Biological Pump:

Plant life in the oceans, predominantly phytoplankton is produced by photosynthesis, utilizing the CO_2 dissolved in the seawaters. The rate of phytoplankton growth and
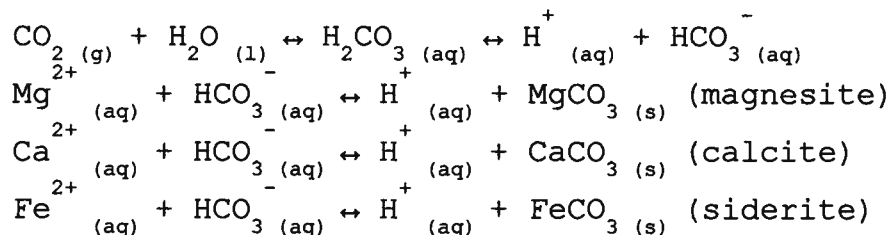
reproduction is often limited by the availability of nutrients. Phytoplanktons are only 1-5 mm in size and are rapidly grazed by zooplankton, which are in turn consumed by larger marine animals such as fish.

Over 70% of this organic matter is recycled in surface waters but the balance is exported to the deep waters, mostly by sedimentation of particulate organic matter. The biological pump therefore transfers CO_2 from the surface waters and effectively sequesters part of it in the deep ocean. This organic matter may eventually return to surface waters due to remineralization by bacterial but again this process is very slow and may take as long as 1000-years".

According to Hangx (2005), "the principle behind CO_2 sequestration by subsurface mineralization is based on a number of sequential chemical reactions:

- CO_2 dissolves in the reservoir water to form carbonic acid, and subsequently bicarbonates
- The bicarbonate reacts with cations present in the saline water to form stable carbonates.

The process can be represented as follows:

$$CO_{2(g)} + H_2O_{(l)} \leftrightarrow H_2CO_{3(aq)} \leftrightarrow H^+_{(aq)} + HCO_{3(aq)}^-$$
$$Mg^{2+}_{(aq)} + HCO_{3(aq)}^- \leftrightarrow H^+_{(aq)} + MgCO_{3(s)} \text{ (magnesite)}$$
$$Ca^{2+}_{(aq)} + HCO_{3(aq)}^- \leftrightarrow H^+_{(aq)} + CaCO_{3(s)} \text{ (calcite)}$$
$$Fe^{2+}_{(aq)} + HCO_{3(aq)}^- \leftrightarrow H^+_{(aq)} + FeCO_{3(s)} \text{ (siderite)}$$

If sufficient cations are present, these reactions can lead to the long term, safe, storage of carbon dioxide as stable carbonates".

According to the "Ocean Storage of CO_2" report by IEA Greenhouse Gas R&D Programme (2002), "There are at least two possible ways in which the ocean carbon reservoir could be used:

- By capturing CO_2 from large industrial point sources and injecting it directly into the deep ocean

CO_2 can be captured using existing technologies and transported to deep ocean using pipelines or tankers. CO_2 can be compressed and transported as a liquid or dense phase gas above its critical point 72.8 bar and 31-^{0}C. The

design of CO_2 tanker would be identical to those currently
used to transport liquid petroleum gas (LPG), refrigeration
would be used to reduce the pressure requirement with
design conditions around -55 ^0C and 6 bar pressure.

The density of liquid CO_2 exceeds that of water at depths
greater than 3000m. CO_2 can stay as a pool formed in a
hollow trench or on the sea bed. Dissolution of CO_2 into the
overlying seawater would be reduced significantly by CO_2
hydrates, forming an ice-like combination of CO_2 and water.
As a result of this and greater depths the retention time
of CO2 in Deep Ocean would be even greater.

- By fertilizing the oceans with additional nutrients to
  increase the drawdown of CO_2 from the atmosphere.

Ocean fertilization aims to increase production of
biological material in the oceans, drawing down additional
CO_2 from the atmosphere. As discussed earlier, "biological
pump" can transfer more carbon from the surface layers to
deep water.

Increasing biological productivity would also result in
an increase of fish population offering the prospect of
increased fish catches and providing a route to offsetting
some of the cost of carbon sequestration.

Three ocean fertilization strategies are being actively
looked into:

- The general addition of macro-nutrients, such as
  nitrates and phosphates which should be independent of
  the area of the ocean selected.

- The addition of iron, an essential micro nutrient to
  unproductive regions of the ocean where natural macro-
  nutrients are currently under utilized high nitrogen
  low chlorophyll areas".

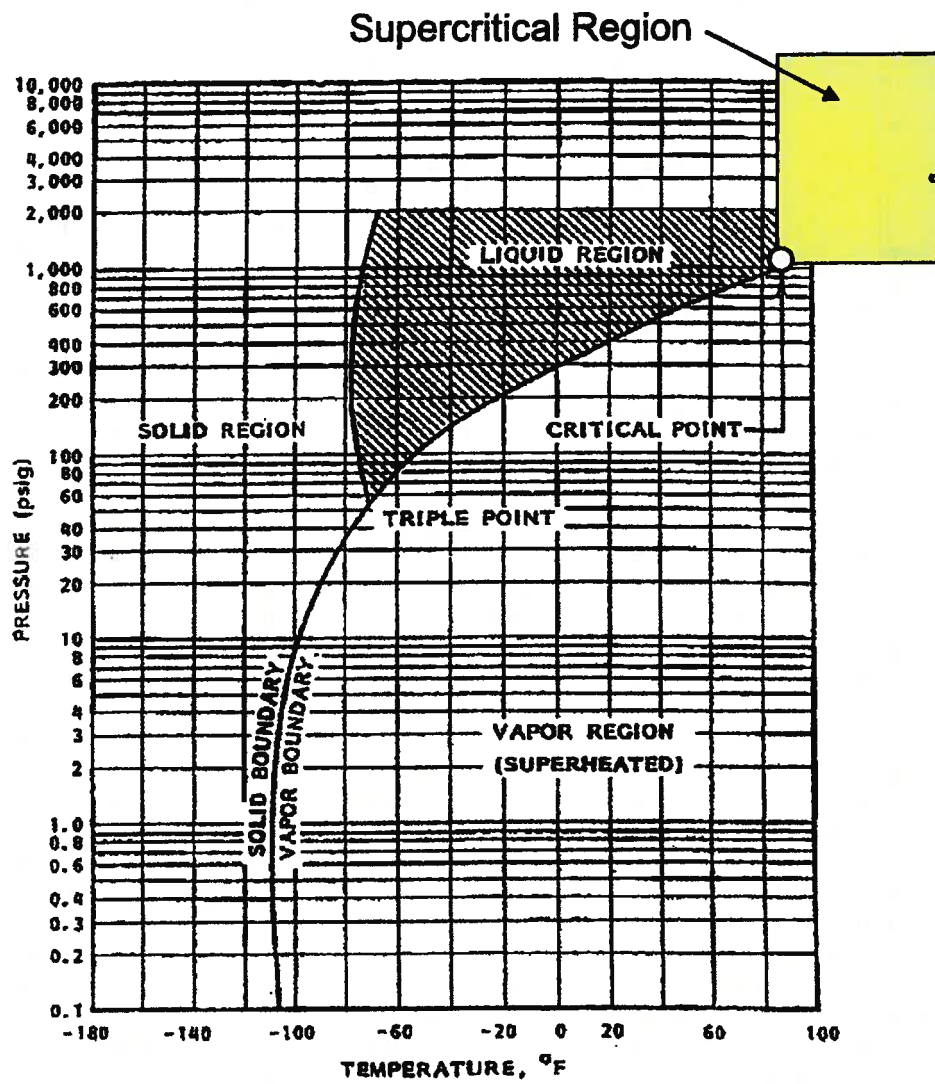Fig.:5.3.4.1 P-T Diagram for CO_2 showing supercritical region for CO_2
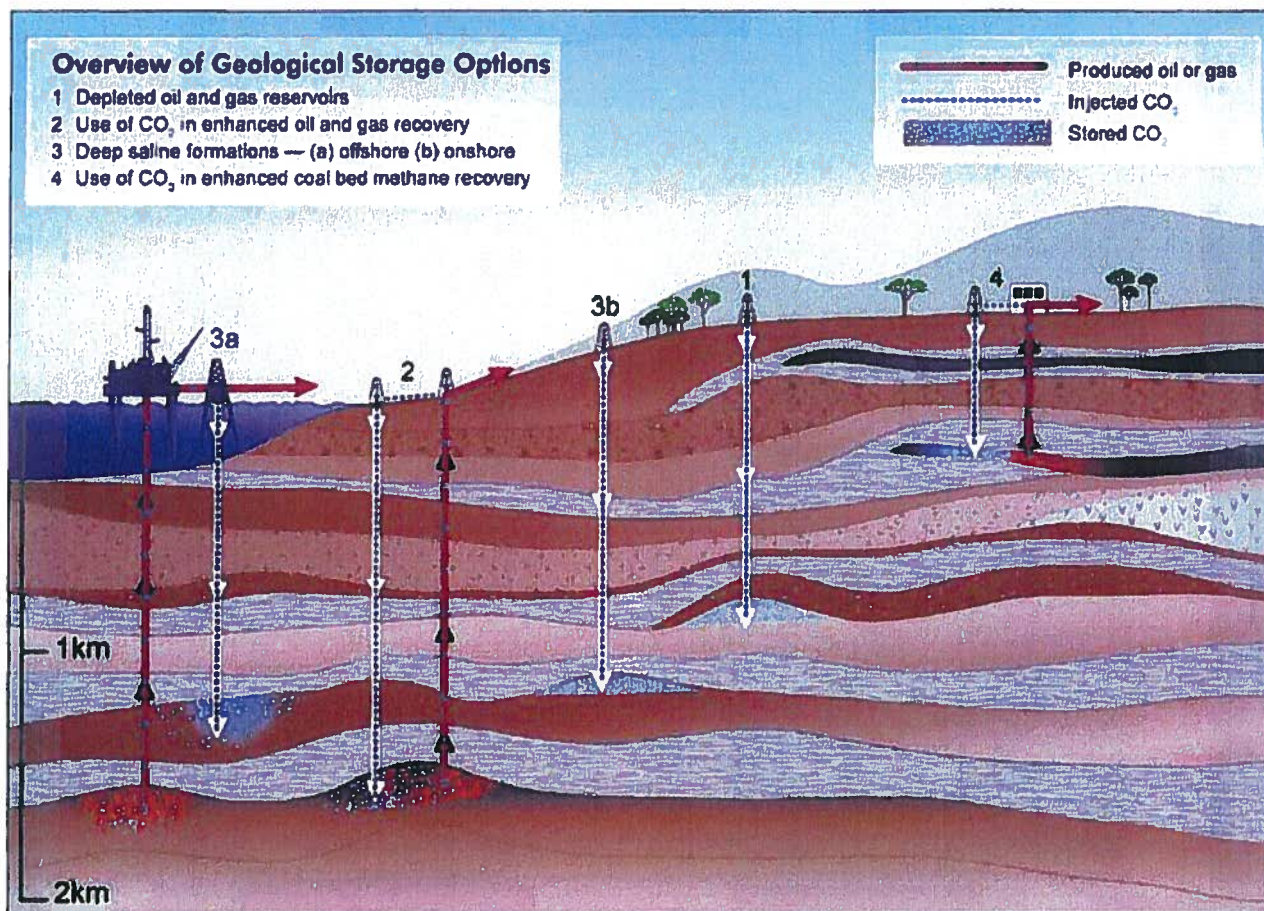
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Fig.5.3.4.2 Options for Geologic Storage of CO_2,
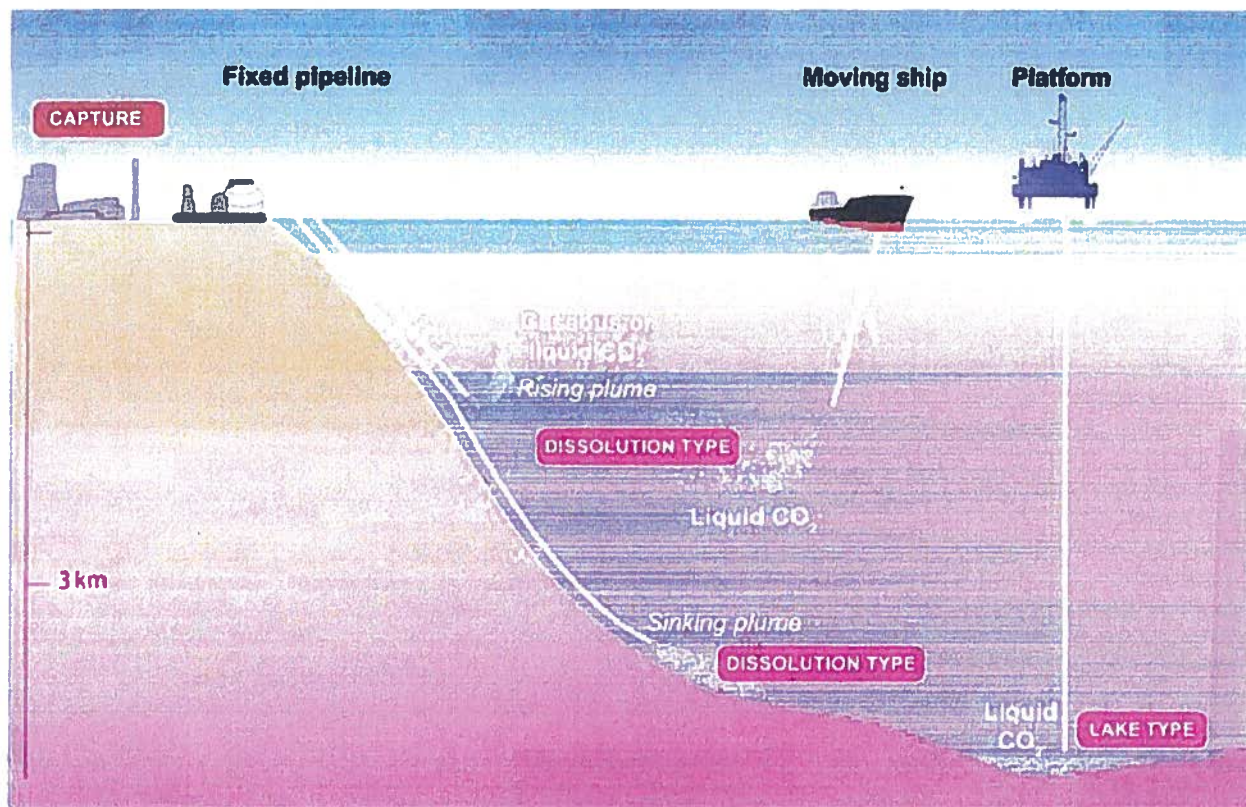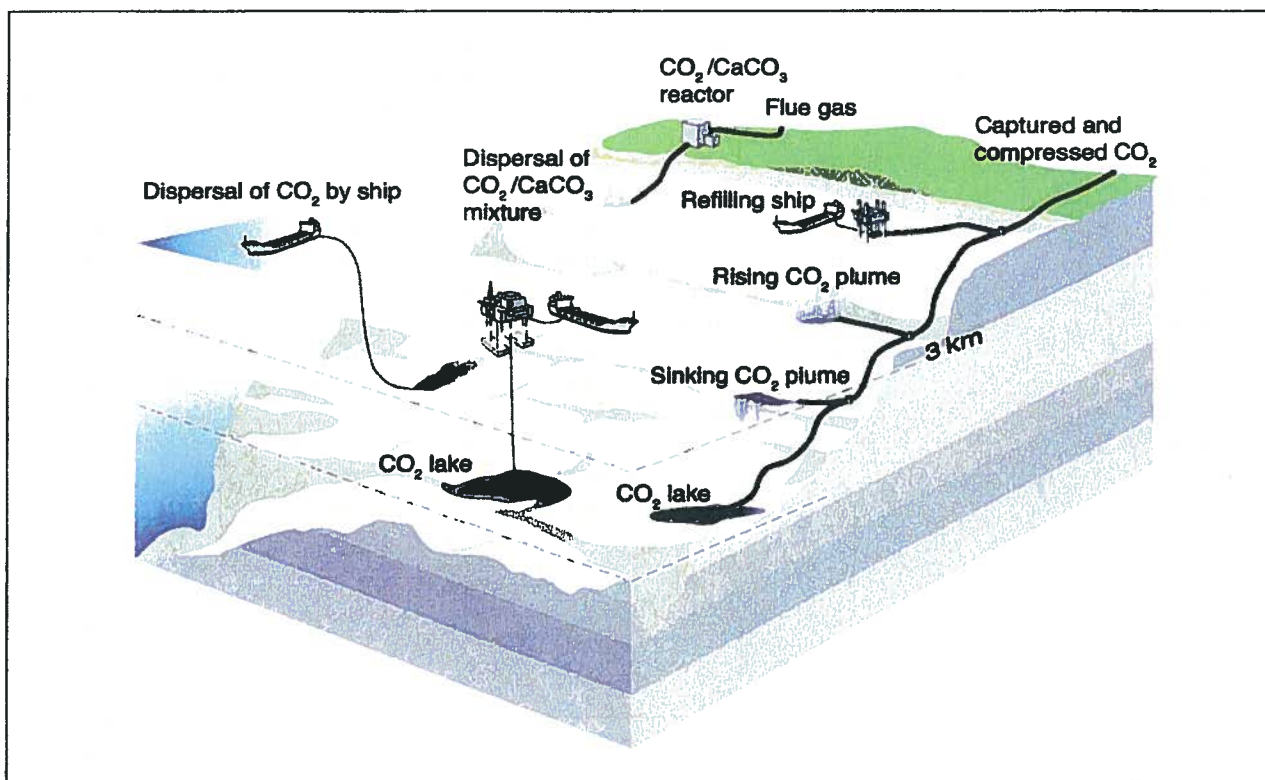Source: IPCC Special Report on Carbon Capture and Storage (2005)

Fig. 5.3.4.3 Ocean disposal of CO₂,
Source: IPCC Special Report on Carbon Capture and Storage (2005)

Fig.5.3.4.4 Options for Ocean Storage of CO_2,
Source: IPCC Special Report on Carbon Capture and Storage (2005)

5.3.5   Economic Potential of Carbon Capture and Storage

According to IPCC special report on Carbon Dioxide Capture and Storage (2005), application of CCS to electricity production is estimated to increase electricity generation costs by about 0.01-0.05 US dollars per kilowatt hour (US$/kWh), based on 2002 conditions, depending on the fuel, the specific technology, the location and the national circumstances. Inclusion of the benefits of Enhanced Oil Recovery (EOR) would reduce additional electricity production costs due to CCS by around 0.01-0.02 US$/kWh (see Table 5.3.5-1 for absolute electricity production costs and Table 5.3.5-2 for costs in US$/tCO$_2$ avoided).

Table-5.3.5.1: Costs of CCS: Production costs of electricity for different type of generation without capture and for the CCS system as a whole. Source: IPCC Special Report on Carbon Dioxide Capture and Storage (2005)

Power Plant System	Natural Gas Combined Cycle (US$/ kWh)	Pulverized Coal (US$/ kWh)	Integrated Gasification Combined Cycle (US$/ kWh)
Without capture (Reference Plant)	0.03 - 0.05	0.04 - 0.05	0.04 - 0.06
With capture and geological storage	0.04 - 0.08	0.06 - 0.10	0.05 - 0.09
With capture and EOR	0.04 - 0.07	0.05 - 0.08	0.04 - 0.07

The cost of a full CCS system for electricity generation from a newly built, large scale fossil fuel based power plant depends on a number of factors, including the characteristics of both the power plant and the capture system, the specifics of the storage site, the amount of CO$_2$ and required transport distance. The numbers assume experience with large scale plant. Gas prices are assumed to be 2.8-4.4 US$ per gigajoule (GJ), and coal prices 1-1.15 US$ per GJ. Costs refer to market prices and do not include external costs such as environmental damages and societal costs that may be associated with CCS. Base oil price used is 15-20 US$ per barrel.

Table-5.3.5.2: CO_2 avoidance costs for the complete CCS system for electricity generation, for different combinations of reference power plants without CCS (geological and EOR. Source: IPCC Special Report on Carbon Dioxide Capture and Storage (2005)

Type of power plant with CCS	Natural Gas Combined Cycle reference plant (US$/tCO$_2$ avoided)	Pulverized coal reference plant (US$/tCO$_2$ avoided)
Power Plant with capture and geologic storage		
Natural Gas Combined Cycle	40 – 90	**20 – 60**
Pulverized Coal	70 – 270	**30 – 70**
Integrated Gasification Combined Cycle	40 – 220	**20 – 70**
Power Plant with capture and EOR		
Natural Gas Combined Cycle	20 – 70	**0 – 30**
Pulverized Coal	50 – 240	**10 – 40**
Integrated Gasification Combined Cycle	20 – 190	**0 – 40**

The amount of CO_2 avoided is the difference between the emissions of the reference plant and emissions of the power plant with CCS. Gas prices are assumed to be 2.8 – 4.4 US$ per GJ; coal prices 1 – 1.5 US$ per GJ.

Table-5.3.5.3: 2002 Cost ranges for the components of a CCS system as applied to a given type of power plant or industrial source. Source: IPCC Special Report on Carbon Dioxide Capture and Storage (2005)

CCS System Components	Cost Range	Remarks
Capture from a coal or gas fired plant	15 – 75 US$/tonne CO_2 net captured	Net costs of captured CO_2, compared to the same plant without capture
Capture from hydrogen and ammonia production or gas processing	5 – 55 US$/tonne CO_2 net captured	Applies to high purity sources requiring simple drying and compression
Capture from industrial sources	25 – 115 US$/tonne CO_2 net captured	Range reflects use of a number of different technologies and fuels
Transportation	1 – 8 US$/tonne CO_2 transportation	Per 250-km pipeline or shipping for mass flow rates of 5 (high end) to 40 (low end) $MtCO_2$ per year
Geological storage	0.5 – 8 US$/tonne CO_2 net injected	Excluding potential revenues from EOR or ECBM
Geologic storage: monitoring and verification	0.1 – 0.3 US$/tonne CO_2 net injected	This covers pre-injection, injection and post injection monitoring and depends on the regulatory requirements.
Ocean storage	5 – 30 US$/tonne CO_2 net injected	Including offshore transportation of 100-500 km, excluding monitoring and verification
Mineral Carbonation	50 – 100 US$/tonne CO_2 net mineralized	Range for the best case studied. Includes additional energy use for carbonation

The costs of the separate components cannot simply be summed to calculate the costs of the whole CCS system in US$/$CO_2$ avoided. All numbers are representatives of the costs for large scale, new installations, with natural gas prices assumed to be 2.8 – 4.4 US$ per GJ; coal prices 1 – 1.5 US$ per GJ.

According to IPCC (Special Report on Carbon Capture and Storage and Storage (2005), "Increases in market prices of fuels used for power generation would generally tend to increase the cost of CCS. The quantitative impact of oil price on CCS is uncertain. However, revenue from EOR would generally be higher with higher oil prices. While applying CCS to biomass-based power production at the current small scale would add substantially to the electricity costs, co-firing of biomass in a larger coal-fired power plant with CCS would be more cost-effective.

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Costs will vary considerably in both absolute and relative terms from country to country. Since neither Natural Gas Combined Cycle, Pulverized Coal nor Integrated Gasification Combined Cycle systems have yet been built at a full scale with CCS, the costs of these systems cannot be stated with a high degree of confidence at this time.

According to IPCC Special Report on Carbon Capture and Storage (2005), "In the future, the costs of CCS could be reduced by research and technological development and economies of scale. Economies of scale could also considerably bring down the cost of biomass-based CCS systems over time. The application of CCS to biomass fuelled or co-fired conversion facilities would lead to lower or negative CO_2 emissions, which could reduce the costs for this option, depending on the market value of CO_2 emission reductions".

Results based on an economic analysis done using the Integrated Environmental Control Model developed by Carnegie Mellon University for a new 500-MW low sulfur coal based power plant complying with existing regulations for Sox and NOx emissions and particulate matter with or without carbon capture are in Table 5.3.5.4 below (Rubin et al. (2002).

Table-5.3.5.4: Results for a New 500 MW Plant, Source: A Technical, Economic and Environmental Assessment of Amine based CO_2 Capture Technology for Power Plant GHG Control, Rubin E.S. et al. (2002)

Parameter	Units	Reference Plant	w/ CO_2 Control
Net Plant Capacity	MW (Net)	462	326
CO_2 Emission Rate	Gm.CO_2/ KWh (Net)	941	133
SO_2 Emission Rate	Gm.SO_2/ KWh (Net)	2.45	0.0003
NOx Emission Rate	Gm.NOx/ KWh (Net)	0.45	0.58
CO_2 Sequestered	10^6 tonne CO_2/yr	---	2.58
Cost of electricity	$ / MWh (net)	49.2	97.0
CO_2 Mitigation Cost	$/ tonne CO_2 avoided	---	59.1
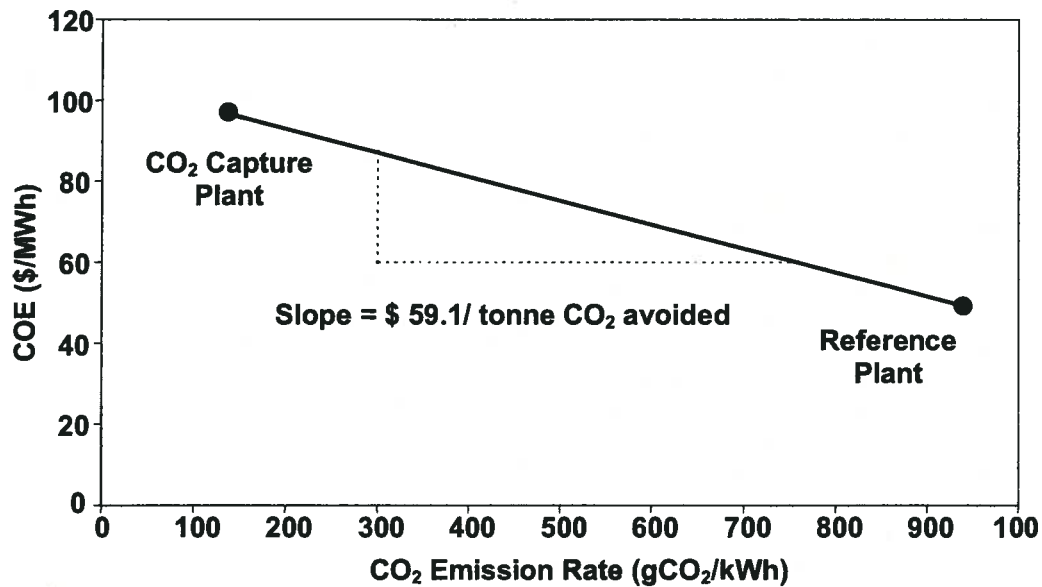
Fig.-5.3.5.1 Nominal CO_2 avoidance cost for a coal plant (500MW, Low S coal, 75% CF), addition of CO_2 capture system increases the cost from $571M to $705M. Source: A Technical, Economic and Environmental Assessment of Amine based CO_2 Capture Technology for Power Plant GHG Control, Rubin and Rao (2002)

Figure-5.3.5.1 shows graphically the relationship of electricity cost to CO_2 emissions for the two cases. The slope of the line connecting the two cost point represents the cost of CO_2 avoided which is about $59/tonne for this case. Most of this cost (about 79%) is associated with CO_2 capture process (including gas compression), CO_2 transport (8%) and storage (13%) for the remainder, Rubin et al. (2002).

According to Rubin et al. (2002), "Retrofitting the existing power plants with an MEA system could results in substantial added reductions in SO_2 emissions which is an additional environmental benefit. The interaction between SO_2 and CO_2 controls is presented in Table 5.3.5.5 above. If credits for SO_2 are taken the cost of carbon mitigation decreases slightly, however, even with SO_2 credits the cost of CO_2 mitigation for retrofit plant is likely to be higher than for a new plant. This is primarily because of limitations in efficient heat integration site specific limitations.

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Table-5.3.5.5: Effect of SO_2 controls on Carbon Mitigation Costs for low sulfur Retrofit cases, Source: Rubin and Rao (2000-2001)

Quantity	Reference Plant (no CO_2 Control)	Case-A (MEA Only)	Case-B (MEA+FGD)	Case-C (MEA+FGD upgrade)
Net Power (MW)	470	288	275	275
COE ($/MWh)	18.0	111.8	70.4	66.7
SO_2emission rate (g/kWh)	4.51	0.04	0.0004	0.0004
Total SO_2 emission (tonne/yr)	13,916	69	0.7	0.7
New SO_2 capture in FGD (tonne/yr)	0	0	13,777	7,451
New SO_2 capture in MEA (tonne/yr)	0	13,847	138	138
Total SO_2 capture (tonne/yr)	0	13,847	13,915	7,589
Mitigation cost ($/ tonne CO_2 avoided)				
No SO_2 credit	---	118.8	67.0	59.2
$150/ tonne SO_2 credit	---	117.4	65.5	58.4
No SO_2 credit, Retrofit Factor=1.25	---	123.2	70.5	62.7

Retrofitting existing plants with CO_2 capture is expected to lead to higher costs and significantly reduced overall efficiencies than for newly built power plants with capture. The cost disadvantages of retrofitting may be reduced in the case of some relatively new and highly efficient existing plants or where a plant is substantially upgraded or rebuilt. The costs of retrofitting CCS to existing installations vary".

Industrial sources of CO_2 can more easily be retrofitted with CO_2 separation, while integrated power plant systems would need more profound adjustment. In order to reduce future retrofit costs, new plant designs could take future CCS application into account. In most CCS systems, the cost of capture (including compression) is the largest cost component. Costs for the various components of a CCS system vary widely, depending on the reference plant and the wide range in CO_2 sources, transport and storage situations (See Table 5.3.5.3).

According to IPCC Special Report on Carbon Capture and Storage (2005), over the next decade, the cost of capture could be reduced by 20-30% and more should be achievable by new technologies that are still in research/ demonstration phase.

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CHAPTER-6
GLOBAL EFFORTS FOR GREENHOUSE GAS MITIGATION

The main current international agreement on combating climate change is the Kyoto Protocol, which came into force on 16th Feb. 2005. The Kyoto Protocol is an amendment to the United Nations Framework Convention on Climate Change (UNFCCC).

Countries that have ratified the Kyoto Protocol have committed to reduce their emissions of CO_2 and five other greenhouse gases (CH_4, N_2O, SF_6, HFC and PFC) or engage in emission trading if they maintain or increase emission of the gases above assigned limits.

The first phase of Kyoto Protocol expires in 2012. The United Nations Climate Change Conference in Copenhagen scheduled for Dec. 2009 will be the next in the annual series of meetings that followed the 1992 Earth Summit in Rio.

However, not all governments have ratified the Kyoto Protocol including some rapidly developing Asian nations, and several poor nations. Some poor nations have not enacted any laws and regulations and have done very little towards inventory assessment and/ or mitigation efforts due to lack of resources.

According to International Energy Agency (World Energy Outlook, 2008), "the global energy demand will increase 45% by 2030, and energy related carbon dioxide emissions will increase by the same amount. That increase to 41 gigatons of CO_2 emission per year would place the world on track for a catastrophic global temperature increase of nearly 11-°F by the end of the century.

Meeting that demand would also require 27% increase in oil production, while the demand for electricity would discourage utility companies from retiring old, inefficient plants. These projections call for renewable energy to be the fastest growing source of energy in near future, but it would still not be enough to halt the growth in GHG emissions.

If the world commits to stabilizing atmospheric concentrations of greenhouse gases at the equivalent of 450-ppm of CO_2 (the limit needed to hold the temperature

rise to 3.6-°F) it will require the concerted effort of countries throughout the world. In the absence of action from developing countries, the goal cannot be met, even if all industrialized countries cut their emissions to zero".

According to World Energy Outlook (2008), "the pathway to achieving that goal is through rapid expansion of low carbon energy sources to supply 36% of the world's energy by 2030".

Some of the mitigation efforts that are being taken by the international community are as follows:

- **Encouraging Use Changes**

    - **Carbon Emission Trading**

Carbon Trading means polluting companies buy carbon credits from companies which are engaged in carbon offsetting activities.

According to The Observer (June, 2005), "The European Union Emission Trading Scheme (EU ETS) is the largest multi-national, greenhouse gas emissions trading scheme in the world. It commenced operation on 1 January 2005, and all 25 member states of the European Union participate in the scheme which has created a new market in carbon dioxide allowances estimated at 35 billion Euros (US$43 billion) per year. The Chicago Climate Exchange was the first (voluntary) emissions market, and is soon to be followed by Asia's first market Asia Carbon Exchange). A total of 107 million metric tonnes of carbon dioxide equivalent have been exchanged through projects in 2004, a 38% increase relative to 2003 (78 Mt CO_2e)".

With the creation of a market for trading carbon dioxide emissions within the Kyoto Protocol, it is likely to become a lucrative business for financial sector, an activity that is likely to enhance environmental benefits.

    - **Carbon Tax**

This is considered as one of the tools to restrict companies from exceeding their emission limits. Currently there are no direct tax levies on emissions in most of the countries around the world.

In 1991, Sweden introduced the world's first carbon tax. The UK has had a Climate Change Levy on fossil-fuel-based electricity generation since 2001 (wikipedia.org,"Mitigation of Global Warming").

- **Non-governmental Approaches:**

  - **Legal Action**

    In some countries, those affected by climate change may be able to sue major producers, in a parallel to the lawsuits against tobacco companies. However, proving that particular weather events are due specifically to global warming may never be possible, methodologies have been developed to show the increased risk of such events caused by global warming.

    Legal action may be taken to try to force the Environmental Protection Agencies to regulate greenhouse gas emissions under the Clean Air Act and under NEPA.

  - **Personal Choice**

    While many of the proposed methods of mitigating global warming require governmental funding, legislation and regulatory action, individuals and businesses can also play a part in the mitigation effort. Environmental groups encourage individual action against global warming, often aimed at the consumer. Common recommendations include lowering home heating and cooling usage, burning less gasoline, supporting renewable energy sources, buying local products to reduce transportation, turning off unused devices, and various others. Use of communications technologies such as videoconferencing can reduce dependence on long-haul flights.

- **Business Opportunities and Risks**

  In addition to government action and the personal choices individuals can make, the threat posed by global warming provides several business opportunities for innovation, practice improvements and risk mitigation.

- **Territorial Policies Of Mitigation**

    - **United States**

    Efforts to reduce greenhouse gas emissions by the United States include their energy policies which encourage efficiency through programs like Energy Star, Commercial Building Integration, and the Industrial Technologies Program.

    Even though Kyoto Protocol has not been formally ratified by the Senate yet, the U.S. has committed itself towards achieving goals enshrined in the protocol. A cabinet level working group was established by President Bush to work on issues related to global climate change. The result of the working group was an energy policy that reflected the seriousness and practicality of the future of United States' environmental policy.

    Following the work of this Cabinet-level group, President Bush announced in February of 2002 the Clear Skies and Global Climate Change Initiatives. These initiatives collectively accomplish the following for global climate change:

    - By 2018, cuts emissions of the three worst air pollutants by seventy percent.
    - In the next ten years, commits America to cutting greenhouse gas intensity by eighteen percent.

    Major U.S. objection to Kyoto Protocol is lack of commitment from developing nations such as China and India for reducing their greenhouse gas emissions.

    - **Mitigation in Developing Countries**

    In order to reconcile economic development with mitigating carbon emissions, developing and underdeveloped countries need particular support, both financial and technological. One of the means of achieving this is the Kyoto Protocol's Clean Development Mechanism (CDM). The World Bank's Prototype Carbon Fund is a public private partnership that operates within the CDM, Prototype Carbon Fund (http://carbonfinance.org/pcf).

In July 2005 the U.S., China, India, Australia, as well as Japan and South Korea, agreed to the Asia-Pacific Partnership for Clean Development and Climate. The pact aims to encourage technological development that may mitigate global warming, without coordinated emissions targets. The highest goal of the pact is to find and promote new technology that aid both growth and a cleaner environment simultaneously. An example is the Methane to Markets initiative which reduces methane emissions into the atmosphere by capturing the gas and using it for growth enhancing clean energy generation.

However, none of these initiatives suggest a quantitative cap on the emissions from developing countries. This is considered as a particularly difficult policy proposal as the economic growth of developing countries is proportionally reflected in the growth of greenhouse emissions.

In an attempt to provide more opportunities for developing countries to adapt clean technologies, UNEP and WTO urged the international community to reduce trade barriers and to conclude the Doha trade round "which includes opening trade in environmental goods and services", U.N. News Center (2009).

- **Population Control**

Various organizations promote population control as a means for mitigating global warming. Proposed measures include improving access to family planning and reproductive health care and information, reducing nationalistic politics, public education about the consequences of continued population growth, and improving access of women to education and economic opportunities.

Population control efforts are impeded by there being somewhat of a taboo in some countries against considering any such efforts. Also, various religions resist some or all forms of birth control. Population size has a different per capita effect on global warming in different countries, since the per capita production of anthropogenic greenhouse gases varies greatly by country.

- **Education, Research & Development and Technology Application**

There is need for intensive research and educational initiatives to develop and implement measures that can provide long term benefits in efforts to reduce GHG emissions and concentration levels. Some of these are listed below:

- Continuous upgrade and validation of monitoring and evaluation models
- Standard guidelines for measurement and full cost accounting
- Institutional cooperation between government bodies and research institutions
- Demonstration projects and maintenance of long term sites
- Information outreach to educate communities, policy makers and industry on opportunities and benefits associated with key areas in agriculture targeted for GHG mitigation.
- Help assist in technology development, environmental responsiveness and community oriented financing of agricultural mitigation projects such as conservation research program.
- Encourage research activities on improving biogas yield and electricity conversion efficiency, and reducing cost of anaerobic digester.
- Encourage research activities on small-scale engine generator to fit the need of a typical size facility using anaerobic digestion technology.

- **Limiting Emissions due to Burning of Fossil Fuels**

There is also an immediate need to limit the emissions due to fossil fuel burning. This can be achieved in any of the following ways:

- Limiting quota on fossil fuel production while meeting the energy requirements with a mix of other energy programs including alternative and renewable energy sources.
- Imposing a carbon tax based on GHG emissions and incentive plan for achieving a reduction in GHG

emissions from a facility. This will encourage
industries to:

- Invest into carbon capture and sequestration
- Invest in developing or adopting technologies
  for reducing GHG emissions
- Invest in research and development to improve
  energy conservation programs
- Invest in research and development for
  commercial and cost effective exploitation of
  renewable energy.
- Invest in alternative source of energy

CHAPTER-7
SUMMARY AND CONCLUSIONS

Based on the historical and recorded measurements and physical observations, scientific community is in agreement on the fact that the Earth is warming-up and anthropogenic greenhouse gas emissions are one of the major causes. Global community needs to understand the seriousness and urgency of the situation and should commit to play its part in efforts to control GHG emissions and in reducing the atmospheric concentrations of the greenhouse gases.

As discussed in section-5.2 agriculture can play a major role in the mitigation efforts. It can not only help in controlling or reducing the GHG emissions but can also serve as a vast sink and can help reduce the concentration level of greenhouse gases in the atmosphere over a period of time. This, however, requires better partnership between government institutions, education and research institutions and the farming community. Corporate sector can also play an important part by joining these efforts as investor, sponsor or research participant.

Governments can utilize conservation programs to encourage carbon sequestration and GHG reductions. GHG offsets factors should be used in setting priorities under environmental quality incentives program and the conservation reserve program. Routing methane to markets and providing grants for conservation innovation are some other measures that the governments can take to encourage GHG mitigation.

U.S. federal government is working with private sector, business and industries in partnership with farmers and land owners on several pilot projects for GHG reduction.

Table-7.1 below shows some examples of feasibility and pilot projects on soil carbon sequestration.

Table-7.1: Examples of feasibility and pilot projects on Soil Carbon Sequestration
Source: Rice, Capalbo, Hatfield (K-State Research & Extension) based on work done by Izaurradle (2004), Rice

Region	Land Use	Land Management Change
Saskatchewan, Canada	Crop Land	Direct seeding/ cropping intensification
Pacific Northwest, USA	Crop Land	Direct Seeding/ Crop Intensification
Midwest (Iowa, Kansas, Nebraska)	Cropland, Grass Planting	No Till, New Grass Planting
Oaxaca, Mexico	Crop/ Natural Fallow Secondary Forest	Fruit Tree Intercrops with annual crops/ Conservation Tillage
Pampas, Argentina	Crop Land	District Seeding
Kazakhstan	Crop Land	Agriculture to grassland

There is need for intensive research and educational initiatives to develop and implement measures that can provide long term benefits in efforts to reduce GHG emissions and concentration levels. There is also an immediate need to limit the emissions due to fossil fuel burning.

On industrial level focused effort is required to promote recovery and storage of carbon dioxide. Further research work is required to improve the performance of current amine-based systems to reduce the future cost of CO_2 capture. New or improved sorbents, lower regeneration heat requirements, and overall process optimization are some of the potential sources of cost reduction. Government-sponsored R&D efforts, together with industrial initiatives need to actively work on pursuing such goals.

The presence of acid gas impurities like SO_2 and NO_2 in power plant flue gas adversely affects the performance and cost of the CO_2 removal system. Adding or upgrading flue gas desulfurization (FGD) unit to remove SO_2 should be considered in such cases to minimize the cost of carbon mitigation.

As discussed in section 5.3, large energy requirements of CO_2 capture in case of retrofit units may lead to a more substantial loss of power plant capacity compared to a new plant affording better heat integration. Site-specific difficulties may further increase the capital cost

of a retrofit installation. Thus, the overall cost of CO_2 capture is likely to be greater for retrofit units than that of a new plant. An incentive program based on unit reduction of greenhouse gases and other pollutant would encourage old plants to take mitigation measures.

Information and experience gained from injection and/ or storage of CO_2 from a large number of existing enhanced oil recovery and acid gas projects as well as from Sleipner, Weyburn and In Salah projects confirm the feasibility of storing CO_2 in geologic formations as a CO_2 mitigation option.

According to IPCC, Special Report on Carbon Capture and Storage (2005), "The cost of geologic storage of CO_2 even though site specific is likely to be (about US$ 0.6-8.3 per tonne of CO_2) much less than cost of CO_2 capture (about US$13-74 per tonne).

Alternatively, captured CO_2 could be injected into the ocean at great depth where most of it would remain isolated from the atmosphere for centuries".

Anthropogenic CO_2 resides primarily in the upper ocean and has resulted in pH reduction. CO_2 can be injected as solid CO_2 hydrates or with mineral carbonates to increase retention. However, CO_2 may harm marine organism and may have some harmful effects on the ecosystem. Further studies need to be performed in this area to assess long term impact of CO_2 injection. For this reason chemical and biological monitoring of an injection project should be a key aspect to reduce long term environmental impact and win governmental and public acceptance.

Greenhouse gas emissions can also be reduced through several simple measures at individual, community and local governmental level. Small things such as changing light bulbs, properly inflating tires, reducing, reusing and recycling waste, better agricultural and land use practices can a go a long way in not only reducing greenhouse gas emissions but also reduce air pollution, reducing dependence on fossil fuels and money savings.

The burning of fossil fuel releases carbon dioxide (CO_2) into the atmosphere and contributes to climate change, but these emissions can be reduced by taking some simple measures such as the following:

a) Buy a vehicle which is fuel efficient
b) Improve driving habits by going easy on brakes, reducing frequency of accelerations (pedaling), vehicle idling
c) Take off unnecessary weight on the vehicle
d) Better vehicle maintenance and engine tune-up
e) Check tire pressure regularly
f) Car pool and/ or walk whenever possible
g) Encourage use of renewable fuel sources such as biodiesel and Ethanol based fuels

Making a few small changes in home and yard such as the following can lead to big reduction of greenhouse gas emissions and help save money:

a) Replace the conventional high energy bulbs to bulbs that have ENERGY STAR and consume less energy
b) Look for ENERGY STAR products when buying products for your home
c) Clean air filter regularly and have your heating and cooling system tuned up regularly
d) Seal and insulate your home, plug leaks in attics and basement, use ENERGY STAR window replacements.
e) Use green power that is generated from environmentally friendly sources
f) Use community recycle program, recycle newspapers, beverage containers, paper and other goods. Buy products that can be repaired, reused or recycled.
g) Use a push mower, use a mulching mower to reduce grass clippings
h) Conserve water especially hot water

Leading businesses should take steps to understand and manage their greenhouse gas emissions by preparing annual GHG inventories and setting long term targets to reduce emissions.

Businesses can promote educating themselves, customers, suppliers in particular and the community in general about GHG emissions, global warming and possible future climate changes. Businesses should try to improve energy efficiency which will not only reduce GHG emissions but would also help reduce operating costs.

State and local governments play an important role in reducing greenhouse gas emissions and greenhouse gas intensity. These agencies can participate and promote

national voluntary programs and initiatives, analyze cost
and benefits of mitigation measures and develop and apply
innovative programs and strategies that achieve wide
ranging benefits to environment, businesses and
communities.

There are, however, some gaps in currently available
or applied tools and methodologies for accurate measurement
of emissions and knowledge regarding some aspects of
implementation of carbon capture and storage. Enhancement
of knowledge in these areas and experience would reduce
uncertainties, improve accuracy and facilitate decision
making.

Significant growth has been seen in renewable energy
sector especially wind and solar energy, this trend needs
to continue to grow at a rapid rate to provide alternatives
that do not emit carbon dioxide.

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Appendix – A

TABLE OF UNITS

Unit	Symbol	Definition
Time		
second	sec	1 s
minute	min	60 s
hour	hour, hr or h	60 min
day	day or d	24 hr
Length or Distance		
millimeter	mm	1 mm
centimeter	cm	10 mm
meter	m	100 cm
kilometer	km	1000 m
inch	inch or in	2.54 cm
foot	ft	12 in or 30.48 cm
yard	yard or yd	3 ft or 36 inch
mile	mile	5280 ft or 1.609 km
Area		
Square Kilometer	sq km or km^2	1000000 m^2
Square Miles	sq mi	640 Acre
Acre	Acre	43560 ft^2
Square Meter	m^2	10000 cm^2
Square Yard	sq yd	9 ft^2
Square feet	ft^2	144 in^2
1 hectare	m^2	10000 m^2
Mass		
Gram	gm or g	1 gm or 1 g
Pound	lb or pound	453.6 gm
Kilogram	kg	1000 gm 2.204 lb
Metric Ton	MT or T	1000 kg or 2204 lb
Million Tonnes or Million Metric Tonnes	MMT	1000000 T or 10^6 T
Giga Tonnes	GT	1000000000 T or 10^9
Mega Grams	Mg	1000000 gm or 10^6 g
Terra Grams	Tg	1000000000000 gm or 10^{12} g

TABLE OF UNITS

Unit	Symbol	Definition
Mass		
Peta Grams	Pg	1000000000000000 gm or 10^{15} g
Temperature		
deg. Fahrenheit	deg. F or °F	1 deg.F or 1 °F (1.8* deg.C+32)
deg. Celsius	deg.C or °C	1 deg.C or 1 °C
Thermal Units		
Joule	J	1 N m
Calorie	Cal	4.184 J
British Thermal Unit	Btu	1 BTU or 1055.056 J
Million Btu	MMBtu	1000000 Btu
Kilojoule	KJ	1000 J
Mega Joule	MJ	1000000 J or 10^6 J
Giga Joule	GJ	10^9 J
Tera Joule	TJ	10^{12} J
Power Units		
Watt	W	1 J/s
Kilo Watt	KW	10^3 W
Mega Watt	MW	10^6 W
Giga Watt	GW	10^9 W
Concentration Levels		
Parts per million	ppm or PPM	1/1000000 or 10^{-6}
Parts per billion	ppb or PPB	1/1000000000 or 10^{-9}