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Carbon Sequestration

Instructor: Lee Layton, P.E

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5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone: 703-988-0088

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This course is based on a report by the United States Department of Energy titled "Carbon Sequestration Research and Development," December 1999.

Introduction

Predictions of global energy use in the 21st century suggest a continued increase in carbon emissions and rising concentrations of carbon dioxide (CO_2) in the atmosphere unless major changes are made in the way we produce and use energy—in particular, how carbon is managed.

The current level of carbon dioxide emissions generates about 9 billion-metric tons of carbon (GtC) per year and is expected to double by 2050. Although the effects of increased CO_2 levels on global climate are uncertain, many scientists agree that a doubling of atmospheric CO_2 concentrations could have a variety of serious environmental consequences.

> GtC is Giga-tons of carbon. 3.7 of carbon equals 1 GtC.

There are three ways to manage carbon emissions,

1. Reduce the need for fossil fuel combustion through increased energy efficiency.
2. Use alternative low-carbon and carbon-free fuels and technologies such as nuclear power and renewable sources.
3. Capture and securely store carbon emitted from fossil fuel combustion, which is known as carbon sequestration.

The United States has a coal supply that can supply electric generation for the next 400 years. However, the rush to eliminate carbon has caused policy planners to push for the abandonment of coal-fired generation. Carbon sequestration presents the opportunity to continue to use coal as the US transitions to other energy sources.

The purpose of *carbon sequestration* is to keep carbon emissions from reaching the atmosphere by capturing them, isolating them, and diverting them to secure storage. Any viable system for sequestering carbon must be safe, environmentally benign, effective, and economical. In addition, it must be acceptable to the public.

This concept is truly radical in a technological context. The development of today's fossil-energy-based system is rooted in the Industrial Revolution. For over 200 years, the development of energy technology has been focused on lowering costs through increased efficiency to support economic growth. Because of their abundance, availability, and high energy content, coal, oil, and natural gas have proved to be attractive energy sources to produce electricity, run industrial processes, propel transportation vehicles, and provide energy for residential and commercial applications. As fossil energy use increased and adverse environmental effects became apparent, energy technology also evolved to minimize them. However, all this enormous technological development has assumed that the free venting of CO_2 to the atmosphere was environmentally harmless.

Only recently has the increasing concentration of CO_2 in the atmosphere been considered to represent a serious environmental problem. The consequence is that we have developed an intricate, tightly coupled energy system that has been optimized over 200 years for economy, efficiency, and environmental performance, but not for the capture and sequestration of its largest material effluent, CO_2.

Why is carbon sequestration important? Given the magnitude of carbon reductions needed to stabilize the atmosphere, capture and sequestration could be a major tool for reducing carbon emissions to the atmosphere from fossil fuels; in fact, sequestration may be essential for the continued large-scale use of fossil fuels. It will allow greater flexibility in the future primary energy supply.

Several available technologies are used to separate and capture CO_2 from fossil-fueled power plant flue gases. The use of existing technology for removing CO_2 is projected to raise the cost of producing electrical power from coal-fired power plants. In fact, capture and sequestration could double the cost of electrical power generation from coal. Thus, although CO_2 is separated routinely, dramatic improvements are necessary to make the process economical. Techniques are needed to transform the captured CO_2 into materials that can be economically and safely transported and sequestered for a long time.

There are numerous options for the separation and capture of CO_2, and many of these are commercially available. However, none has been applied at the scale required as part of a CO_2 emissions mitigation strategy. Many issues remain regarding the ability to separate and capture CO_2 from sources on the scale required, and to meet the cost, safety, and environmental requirements for separation and capture. The three most promising methods of carbon storage include ocean sequestration, terrestrial ecosystem sequestration, and geologic formation sequestration.

The ocean represents a large potential storage location for carbon dioxide.   One solution is to inject a pure CO_2 stream that has been generated by a power plant directly into the deep ocean. The injected CO_2 may become trapped in ocean sediments or ice-like solids, called hydrates. Another option is to increase the net oceanic uptake from the atmosphere by enhancing the ocean's ability to absorb CO_2 with iron fertilization. Active experiments are already under way in iron fertilization and other tests of enhanced marine biological sequestration, as well as deep CO_2 injection. These approaches will require better understanding of marine ecosystems to enhance the effectiveness of applications and avoid undesirable consequences.

Terrestrial ecosystems, which are made up of vegetation and soils containing microbial and invertebrate communities, sequester CO_2 directly from the atmosphere.

The terrestrial ecosystem is a huge natural biological scrubber for CO_2 from all fossil fuel emissions sources, such as automobiles, power plants, and industrial facilities. The ability of the ecosystem to sequester carbon can be significantly increased over the next few years to provide critical "bridging technology" while other carbon management options are developed. The potential for terrestrial ecosystems to remove and sequester more carbon from the atmosphere could be increased by, for example, improving agricultural cultivation practices to reduce oxidation of soil carbon and enhancing soil texture to trap more carbon, and protecting wetlands.

Three principal types of geologic formations are widespread in the United States and have the potential for sequestering large amounts of CO_2. They are active and uneconomical oil and gas reservoirs, aqueous formations, and deep coal formations. Presently about 70 oil fields worldwide use injected CO_2 for enhanced oil recovery. CO_2 sequestration is already being practiced in a sub-seabed reservoir in the North Sea of Norway. The United States has sufficient capacity, diversity, and broad geographic distribution of potential reservoirs to use geologic sequestration in the near term. The primary uncertainty is the effectiveness of storing CO_2 in geological formations - how easily CO_2 can be injected and how long it will remain. Many important issues must be addressed to reduce costs, ensure safety, and gain public acceptance.

There are many technological issues to resolve before carbon sequestration will be a viable environmental option. In the following sections, we will look at the basics of the carbon cycle, carbon sequestration, and more details on the various methods of carbon sequestration.

Chapter 1
The Basics of Carbon Dioxide Storage and Sequestration

Carbon sequestration is tied to two carbon cycles— the natural and the fossil fuel cycles. Understanding aspects of both cycles provides a context for developing carbon sequestration options.

The Global Carbon Cycle

Oceans and terrestrial systems are *reservoirs* of CO_2. The *carbon budget* of a reservoir is its ability to retain CO_2. Decreasing atmospheric CO_2 concentrations by reducing CO_2 emissions or by changing the magnitude of the fluxes between reservoirs is controlled by the carbon budget of a reservoir. From a carbon sequestration perspective, understanding the potential to alter carbon budgets through the intervention of carbon sequestration technologies to reduce future atmospheric CO_2 concentrations is one of the principal challenges.

In recent years, human activities contributed an average annual emission of approximately 9.0 GtC into the atmosphere. The following information is from a 1995 report when the emissions were about 7.4 GtC of carbon. Most emissions were from fossil fuel combustion (and small amount from cement production.) Because of photosynthesis, plant growth, and additional storage in the oceans, only about 3.5 GtC of the additional CO_2 has entered the atmosphere.

Table 1 Global Carbon Flux (Based on 1995 data)				
Source	**GtC**	**Sink**	**GtC**	**Difference**
Respiration Land Use	60.0 1.4	Photosynthesis	61.7	-0.3
Fossil Fuels	6.0	-	-	6.0
Ocean release	90.0	Ocean uptake	92.2	-2.2
Source Total	157.4	Sink Total	153.9	
Net Difference				3.5

Looking at Table 1, you can see that the sources of CO_2 entering the atmosphere include human and animal respiration, fossil fuels, and release of decaying matter in the oceans. Also, changes in land use (e.g., deforestation) result in the release of CO_2 into the atmosphere. Offsetting the release of CO_2 is photosynthesis by plants and uptake by the world's oceans. The difference

between respiration and photosynthesis, including considering the change in land use results in a net reduction in CO_2 of 0.3 GtC. Fossil fuels and cement production release 6.0 GtC per year. The oceans absorb 2.2 GtC more CO_2 than they release. Summing the differences, we have 3.5 GtC of CO_2 per year that enters and remains in the atmosphere.

Figure 1 is a graphical view of the carbon cycle. The significance of understanding these complicated carbon exchanges is that developing the ability to alter these gross annual carbon exchanges of the global carbon cycle by a small percentage through carbon sequestration technologies would increase net storage of carbon in the major reservoirs and lessen atmospheric carbon concentrations.
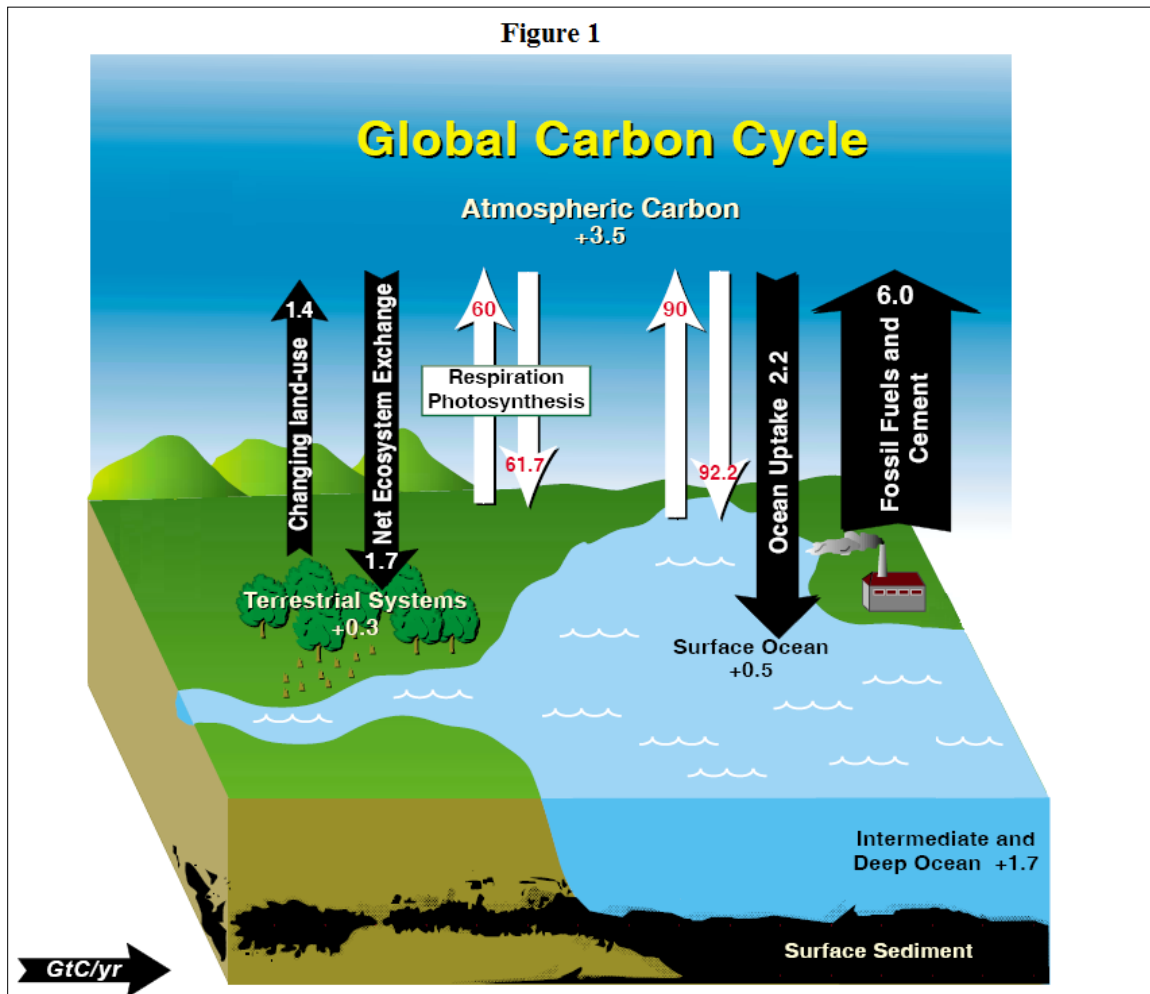
1995 data

About 75% of the world's commercial energy comes from fossil fuels. Given the advantages inherent in fossil fuels, such as their cost-competitiveness, their availability, their ease of transport and storage, and the large fossil resources, fossil fuels are likely to remain a major player in global energy supply for at least the next century.

Figure 2 shows the energy flows through the U.S. economy from fossil and other fuels. This diagram helps to identify places where CO_2 could be separated and captured, but there are energy and cost implications that must be considered. In the near term, most of the CO_2 captured is likely to come from electricity generated from fossil fuels, because large quantities of it could be processed at fixed locations and it represents about 30% of the total CO_2 emissions. However, other possibilities become more likely in the longer term. Fossil fuels, solid waste, or biomass can be "decarbonized" so that a higher energy-content and environmentally benign fuel is separated from CO_2. For example, either a fossil energy source or another carbon source such as solid waste or biomass could be pretreated to produce hydrogen and CO_2. These central pretreatment facilities could become other new sources of carbon for capture.
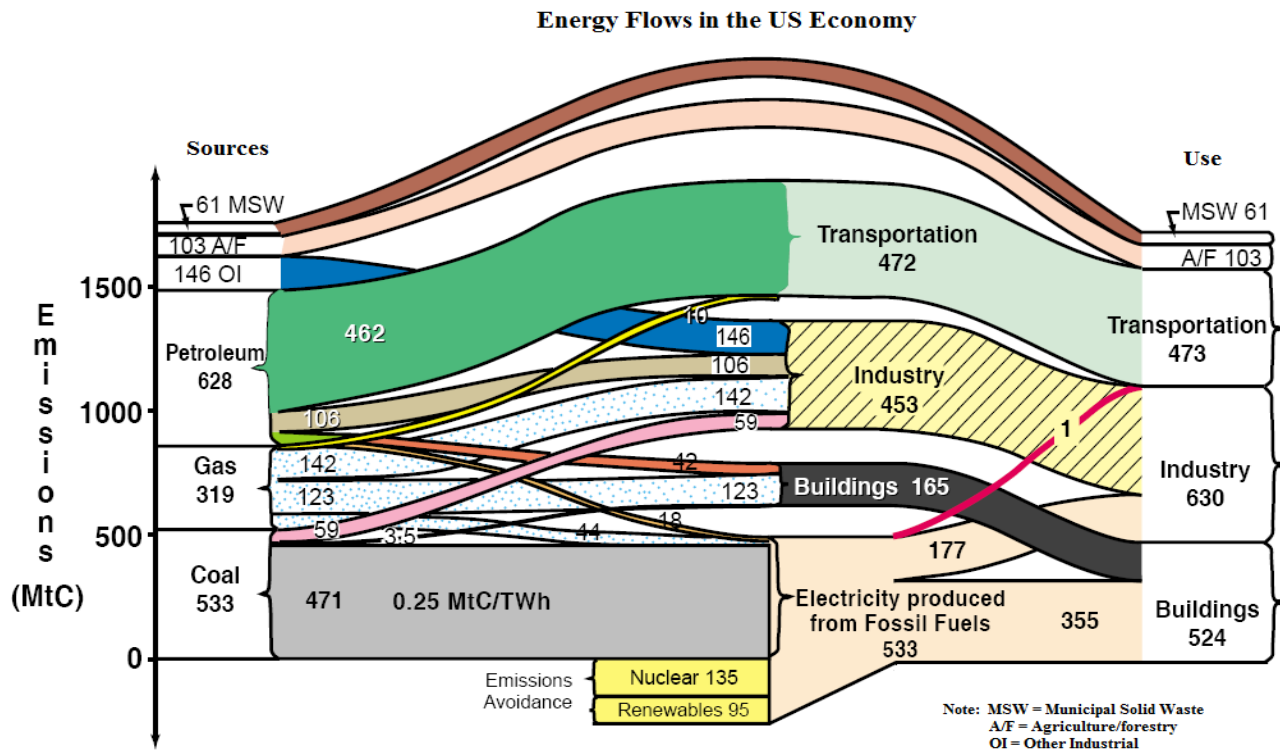
Energy Flows in the US Economy

Figure 2

Carbon Dioxide Sources

In this course we are only looking at the separation and capture of *anthropogenic* CO_2. The costs of separation and capture, including compression to the required pressure for the sequestration option used, are estimated to make up about three-fourths of the total costs of ocean or geologic sequestration. Power generation costs will increase significantly from CO_2 separation and capture. Using a base case

Anthropogenic CO_2 includes all forms of CO_2 that results from human activities as opposed to those occurring naturally.

pulverized coal plant with flue gas desulfurization for comparison, the cost of eliminating CO_2 emissions from advanced power generation plants ranged from \$35 to \$264 per ton of CO_2.   It is estimated that separation and capture approaches will increase power generation costs by about 20 to 30 mills/kWh.

Sources that appear to lend themselves best to separation and capture technologies include large-point sources of CO_2 such as conventional pulverized-coal steam power plants; natural-gas-fired combined cycle plants; and advanced power generation systems, including coal or natural gas combustion plants employing enriched air or oxygen to support combustion with CO_2 recycling, integrated coal gasification combined cycles, hydrogen turbines, and fuel cells. Many of the advanced systems will use enriched air or oxygen to support the combustion process. The reduction or elimination of the large volume of nitrogen in process and flue gases dramatically improves the opportunity for the separation and capture of CO_2 from these systems. The equipment used for combustion and processing will range from existing technology such as coal-fired steam plants and gas turbines to advanced technology such as production of hydrogen from fossil fuels.

In addition to power plants, numerous other high-CO_2-emitting industrial sources should consider the application of capture and sequestration technologies. In natural gas production, CO_2 is often generated as a by-product. Natural gas may contain significant amounts of CO_2, most of which must be removed to produce pipeline-quality gas. Therefore, sequestration of CO_2 from natural gas operations is a logical first step in applying CO_2 capture technology. Other significant industrial sources of CO_2 include oil refineries, iron and steel plants, and cement and lime producers. Although these sources contribute only a small fraction of total CO_2 emissions, separation and capture of these emissions are feasible and would contribute significantly to overall CO_2 emission reduction goals.

Dispersed sources of CO_2 emissions, particularly residential buildings and internal combustion engines are especially challenging sources for applying cost-effective separation and capture methods. However, the introduction of fuel cells for vehicular propulsion and power generation may occur and the need to use fossil fuels to produce hydrogen (H_2) for fuel cells could have a significant impact on CO_2 separation and capture. For example, if buses and vehicle fleets move toward on-board H_2 storage, central H_2 production facilities may be built that would allow CO_2 separation and capture.

Other advanced power systems, such as hydrogen turbines that would use H_2 as fuel, also have important implications with respect to the need for central H_2 production facilities and the opportunity for CO_2 separation and capture. Electric vehicles may also come into widespread use. Should that occur, separation and capture of CO_2 at the central power stations that produce the electricity for recharging electric vehicle batteries would indirectly reduce CO_2 emissions

from the transportation sector. However, one of the consequences of the deregulation of the electric power industry may be the introduction of a significant distributed power supply. Depending on the size and nature of these power generation plants, such a change might have a negative impact on the ability to separate and capture CO_2.

Carbon dioxide concentrations in effluent streams will range from approximately 5% for current power generation plants to almost 100% for some advanced technologies. All separation and capture feed streams are likely to contain small amounts of impurities such as oxygen, sulfur oxides, and nitrogen oxides from combustion of natural gas or advanced processing of fossil fuels to yield hydrogen. For some current and emerging technologies involving combustion of coal, the feed streams will contain large amounts of nitrogen, oxygen, water vapor, particulates, and volatile and semi-volatile chemical species as well. The feed stream may also be contaminated with chemicals used to remove other constituents such as sulfur and nitrogen oxides. Feed-stream pressures will range from ambient for current technologies to tens of atmospheres for some advanced processes. Feed-stream temperatures will range from very warm to extremely hot.

The goal of CO_2 separation and capture is to isolate carbon from its many sources in a form suitable for transport and sequestration. The technology required to perform this function depends on the nature of the carbon source and carbon forms that are suitable for subsequent steps leading to sequestration. Many forms are possible, including gaseous and supercritical CO_2 and even *clathrates*. High levels of purity are possible, but at significant cost.

> **Clathrates** are crystalline solids which look like ice and occur when water molecules from a cage-like structure around smaller "guest molecules." CO_2 can be a guest molecule in a clathrate.

The impurities in the product must be of sufficiently low concentrations so that transportation and sequestration operations are not compromised. The purity requirements imposed by sequestration operations are not known because sequestration technology is being developed concurrently. Some initial investigation to develop purity requirements will be necessary, will be reviewed, and modified as the requirements of various sequestration options become clear.

Potential Sequestration Technologies

The options currently identifiable for CO_2 separation and capture include,

1. Chemical and physical absorption
2. Physical and chemical adsorption
3. Low-temperature distillation
4. Gas-separation membranes

5. Mineralization and vegetation

For the CO_2 separation and capture methods identified, performance characteristics, including CO_2 product purity and operating conditions, differ because of operational or technical considerations. These characteristics of CO_2 separation and capture technologies are the basis for matching them with the technologies that are the sources of CO_2.

These were identified and included as probable options because of process simplicity, environmental impact, and economics. Currently, several CO_2 separation and capture plants use one or more of these methods to produce CO_2 for commercial markets.

1. Chemical and Physical Absorption

Carbon dioxide can be removed from gas streams by physical or chemical absorption. Physical absorption processes are governed by Henry's law (i.e., they are temperature and pressure dependent with absorption occurring at high pressures and low temperatures). Typically, these processes are used when the concentration is high (>525 kPa). The removal of 0.1 to 6% CO_2 from natural gas production wells by chemical absorption using amines can be deployed conveniently in remote fields. Currently, this approach represents the most widely deployed commercial technology for capture.

Chemical absorption is preferred for low to moderate CO_2 partial pressures. Because CO_2 is an acid gas, chemical absorption of CO_2 from gaseous streams such as flue gases depends on acid base neutralization reactions using basic solvents. Most common among the solvents in commercial use for neutralizing CO_2 are alkanolamines such as monoethanolamine (MEA), diethanolamine (DEA), and methyldiethanolamine (MDEA). Other chemical solvents in use are ammonia and hot potassium carbonate. Flue gases are typically at atmospheric pressure. Depending on the CO_2 content of the flue gas, the partial pressure of CO_2 can vary from 3.5 to 21.0 kPa. At such low partial pressures, alkanolamines are the best chemical solvents to enable good CO_2 recovery levels; however, use of these solvents must be balanced against the high energy penalty of regenerating them using steam-stripping.

Flue gases typically contain contaminants such as SO_x, NO_x, O_2, hydrocarbons, and particulates. The presence of these impurities can reduce the absorption capacity of amines as well as create operational difficulties such as corrosion. To avoid such problems, these contaminants are often reduced to acceptable levels using suitable pretreatment techniques. Some commercial processes manage these difficulties through pretreatment and/or the use of chemical inhibitors in the absorption process. However, these processes tend to be more expensive than conventional alkanolamine based absorption processes.

Typical operating problems encountered in using conventional trayed or packed columns for gas liquid contact are foaming, vapor entrainment of the solvent, and the need to replenish the solvent in low quantities. However, these problems have a small effect on the total system costs of the alkanolamine based absorption process. Membrane contactors that typically use polymeric membranes can offer advantages over conventional contactors, which are expected to be most advantageous where system size and weight need to be minimized. Potential benefits include the elimination of foaming and vapor entrainment, as well as the ability to maintain liquid and gas flow rates independently.

A concern is that the recovery of other volatile trace elements, such as mercury may not be consistent with an optimal strategy for CO_2 capture. Also, using current technologies, minimizing energy costs for CO_2 capture will not be compatible with a 100% CO_2 capture strategy.

2. Physical and Chemical Adsorption

Selective separation of CO_2 may be achieved by the physical adsorption of the gas on high-surface-area solids in which the large surface area results from the creation of very fine surface porosity through surface activation methods using, for example, steam, oxygen, or CO_2. Some naturally occurring materials, such as zeolites, have high surface areas and efficiently adsorb some gases. Adsorption capacities and kinetics are governed by numerous factors including adsorbent pore size, pore volume, surface area, and affinity of the adsorbed gas for the adsorbent.

A recent study evaluated physical adsorption systems based on zeolites operated in *pressure swing adsorption* (PSA) and *thermal swing adsorption* (TSA) modes. In PSA operation, gases are adsorbed at high pressures, isolated, and then desorbed by reducing the pressure. A variant of PSA, called vacuum swing adsorption, uses a vacuum desorption cycle. In TSA operation, gases are

> **Zeolites** are a crystalline, porous aluminosilicate material. Zeolites can perform ion exchange, filtering, chemical sieve, and gas absorption.

adsorbed at lower temperatures, isolated, and then desorbed by heating. These processes are energy-intensive and expensive. The study seems to indicate that PSA and TSA technologies are not attractive to the gas- and coal-fueled power systems. Nevertheless, PSA and TSA are commercially practiced methods of gas separation and capture and are used to some extent in hydrogen production and in removal of CO_2 from sub-quality natural gas. Therefore, these methods clearly are applicable for separation and capture of CO_2 from large-point sources.

4. Low-Temperature Distillation

Low-temperature distillation is widely used commercially for the liquefaction and purification of CO_2 from high purity sources.   In low-temperature distillation, a low-boiling-temperature liquid is purified by evaporating and subsequently condensing it. However, such processes are not used

for separating CO_2 from significantly leaner CO_2 streams. The application of distillation to the purification of lean CO_2 streams necessitates low temperature refrigeration (<0C) and solids processing below the *triple point* of CO_2.   A process to separate CO_2 from natural gas, providing liquid CO_2, is an example of such a low-temperature process.

Distillation has good economies of scale, as it is cost effective for large-scale plants, and it can produce a pure product. Distillation is most cost effective when feed gases contain components with widely separated boiling points, and when the feed gas is available at high pressure and most of the products are also required at high pressure. Low-temperature distillation enables direct production of liquid CO_2 that can be stored or sequestered at high pressure via liquid pumping. The major disadvantage of this process is that, if other components are present that have freezing points above normal operating temperatures, they must be removed before the gas stream is cooled to avoid freezing and eventual blockage of process equipment. Another disadvantage is the amount of energy required to provide the refrigeration necessary for the process.

> The **Triple Point** of a substance is the temperature and pressure at which three phases (gas, liquid, and solid) of the substance coexist in thermodynamic equilibrium. The triple point of CO_2 is -57C.

Most CO_2 emissions being considered for CO_2 capture are produced in combustion processes. Such streams contain water and other trace combustion by-products such as NO_x and SO_x, several of which must be removed before the stream is introduced into the low-temperature process. These by-products generated near atmospheric pressure. These attributes, coupled with the energy intensity of low-temperature refrigeration, tend to make distillation less economical than other routes. The application of low-temperature distillation, therefore, is expected to be confined to feed sources at high pressure and with high CO_2 concentrations.

4. Gas-Separation Membranes

There are many types of gas-separation membranes and although the efficacy of only a few of these types in separating and capturing CO_2 has been demonstrated, their potential is very good. Diffusion mechanisms in membranes are numerous and differ depending on the type of membrane used. Gas separation is accomplished via some interaction between the membrane and the gas being separated. For example, polymeric membranes transport gases by a solution-diffusion mechanism where the gas is dissolved in the membrane and transported through the membrane by a diffusion process. Polymeric membranes, although effective, typically achieve low gas transport flux and are subject to degradation. However, polymer membranes are inexpensive and can achieve large ratios of membrane area to module volume.

Palladium membranes are effective in separating H_2 from CO_2, but gas fluxes are typically very low, and palladium is subject to degradation in sulfur containing environments. Porous inorganic membranes, metallic or ceramic, are particularly attractive because of the many transport mechanisms that can be used to maximize the separation factor for various gas separations. Porous inorganic membranes can be 100 to 10,000 times more permeable than polymeric membranes. However, the cost for inorganic membranes is high, and the ratio of membrane area to module volume is 100 to 1,000 times smaller than that for polymer membranes. These factors tend to equalize the cost per membrane module. The inorganic membrane life cycle is expected to be much longer. Inorganic membranes can be operated at high pressures and temperatures and in

> **Permeance** is the volume of gas transported through a membrane per unit of surface area per unit of time per unit of differential pressure.

corrosive environments, yet still have very long-life cycles. They are also less prone to fouling and can be used in applications where polymer membranes cannot.

Zeolite-type materials may be well suited to achieve a membrane with molecular sieving characteristics. However, the permeance of such membranes tends to be lower than desired. These are high-cost membranes because the methods for fabricating them are expensive.

Inorganic membranes can be made with effective pore diameters as small as 0.5 nm and as large as desired. Membranes can be made with a wide range of materials, and pore size and material can be changed to improve permeance and separation factor. Large separation factors are essential to achieve desired results in a single stage. Inorganic membranes can be made to separate small molecules from larger molecules (molecular sieves) or to separate certain large molecules from smaller molecules (enhanced surface flow). This latter effect is important because it allows separation that will keep the desired gas either on the high-pressure or the low-pressure side of the membrane. Note that the operating conditions play an important role in determining the amount of the desired gas that can be recovered. There must be a partial pressure gradient of the desired gas across the membrane to achieve a flow of that gas through the membrane.

With all the design parameters available, it is likely that an inorganic membrane can be made that will be useful for separating CO_2 from almost any other gas if appropriate operating conditions can be achieved. However, for multiple gas mixtures, several membranes with different characteristics may be required to separate and capture high-purity CO_2.

5. Mineralization and Vegetation

The vegetation separation and some mineralization methods are also sequestration methods and are discussed in detail in Chapter 4.

Chapter 2
Geologic Sequestration

Geologic formations, such as oil fields, coal beds, and aquifers, are likely to provide the first large scale opportunity for concentrated sequestration of CO_2. In fact, CO_2 sequestration is already taking place at Sleipner West off the coast of Norway, where approximately one million tonnes of CO_2 are sequestered annually as part of an offshore natural gas production project. Developers of technologies for sequestration of CO_2 in geologic formations can draw from related experience gained over a century of oil and gas production, groundwater resource management, and, more recently, natural
gas storage and groundwater remediation. In some cases, sequestration may even be accompanied by economic benefits such as enhanced oil recovery, enhanced methane production from coal beds, enhanced production of natural gas from depleted fields, and improved natural gas storage efficiency using CO_2 as a "cushion gas" to displace methane from the reservoir.

Geologic Sequestration Mechanisms

CO_2 can be sequestered in geologic formations by three principal mechanisms. First, CO_2 can be trapped as a gas or supercritical fluid under a low permeability caprock, like the way that natural gas is trapped in gas reservoirs or stored in aquifers. This mechanism, commonly called *hydrodynamic trapping*, will be the most important for sequestration. Finding better methods to increase the fraction of space occupied by trapped gas will enable maximum use of the sequestration capacity of a geologic formation.

Second, CO_2 can dissolve into the fluid phase. This mechanism of dissolving the gas in a liquid such as petroleum is called solubility trapping. In oil reservoirs, dissolved CO_2 lowers the viscosity of the residual oil, so it swells and flows more readily, providing the basis for one of the more common oil recovery techniques. The relative importance of solubility trapping depends on a large number of factors, such as the *sweep efficiency* of CO_2 injection, the formation of fingers (preferred flow paths), and the effects of formation heterogeneity. Efficient solubility trapping will reduce the likelihood that CO_2 gas will quickly return to the atmosphere.

> **Sweep efficiency** is the efficiency of displacement of oil or water.

Finally, CO_2 can react either directly or indirectly with the minerals and organic matter in the geologic formations to become part of the solid mineral matrix. In most geologic formations, formation of calcium, magnesium, and iron carbonates is expected to be the primary mineral trapping processes. However, precipitation of these stable mineral phases is a slow process with poorly understood kinetics. In coal formations, trapping is achieved by preferential adsorption of CO_2. Developing methods for increasing the rate and capacity for mineral trapping will create

stable repositories of carbon that are unlikely to return to the biosphere and will decrease unexpected leakage of CO_2 to the surface.

To sequester CO_2 produced from the combustion of fossil fuels to generate electricity, CO_2 needs to be separated from the waste stream to a purity of at least 90%. CO_2 is then transported as a supercritical fluid by pipeline to the nearest geologic formation suitable for sequestration. The cost for transportation will be significant and must be included for any valid comparison among projects and ideas.

Capacity of Geologic Formations for Sequestration

Three principal types of geologic formations are widespread and have the potential to sequester large amounts of CO_2:

1. Active and depleted oil and gas reservoirs
2. Deep brine formations, including saline formations
3. Deep coal seams and coal-bed methane formations

Other geologic formations such as marine and arctic hydrates, CO_2 reservoirs, mined cavities in salt domes, and oil shales may increase sequestration capacity or provide site specific opportunities but are likely to be developed only after other sequestration targets are explored.

Estimates of sequestration capacity for each of these types of geologic formations are provided in Table 2. While the range and uncertainty in these estimates are large, they suggest that a significant opportunity exists for CO_2 sequestration in geologic formations.

Table 2 Sequestration Ability of Geologic Formations	
Geologic Formation	**Capacity (GtC)**
Deep saline aquifers	130
Natural gas reservoirs	10
Active gas fields	0.3/yr
Coal-bed methane	10

More specifically the United States has sufficient capacity, diversity, and broad geographic distribution of geological formations to pursue geologic sequestration confidently as a major

component of a national carbon management strategy. What is less certain is the ultimate capacity that geologic formations can contribute, over the centuries ahead, to sequestration of CO_2. Only through experience and application of systematic screening criteria will we gain enough knowledge to assess the ultimate sequestration capacity of geologic formations.

1. Sequestration in Oil and Gas Formations

Oil and gas reservoirs are promising targets for CO_2 sequestration for a number of reasons. First, oil and gas are present within structural traps and the oil and gas that originally accumulated in these traps did not escape over geological time. Thus, these reservoirs should also contain CO_2, if pathways to the surface or to adjacent formations are not created by over-pressuring of the reservoir, by fracturing out of the reservoir at wells, or by leaks around wells. Second, the geologic structure and physical properties of most oil and gas fields have been characterized extensively. While additional characterization—particularly of the integrity and extent of the caprock— may be needed, the availability of existing data will lower the cost of implementing CO_2 sequestration projects. Finally, very sophisticated computer models have been developed in the oil and gas industry to predict displacement behavior and trapping of CO_2 for oil recovery. These models consider the flow of oil, gas, and brine in three dimensions; phase behavior and CO_2 solubility in oil and brine; and the spatial variation of reservoir properties, to the extent it is known. These same processes are responsible for hydrodynamic and solubility trapping of CO_2.

The first and most viable option for CO_2 sequestration is to build upon the enormous experience of the oil and gas industry in oil recovery. Currently, about 80% of commercially used CO_2 is for oil recovery purposes. The technology for CO_2 injection is commercially proven and can be implemented without much difficulty. Enhanced oil recovery has the benefit of sequestering CO_2 while increasing production from active oil fields. In the long term, the volume of CO_2 sequestered as part of oil recovery projects may not be comparatively large, but valuable operational experience can be gained that will benefit geologic sequestration in other types of formations.

CO_2 could be sequestered in two types of natural gas fields: abandoned fields and depleted but still active fields where gas recovery could be enhanced by CO_2 injection. Abandoned gas fields are present in many parts of the United States. Deciding which abandoned gas fields could best be used in a CO_2 sequestration program would require a comprehensive review of the current conditions in abandoned fields and the economics of their rehabilitation. This would be a major program of investigation, but the necessary technology to conduct such a review is available and well known to the gas industry. Locating and sealing abandoned wells may be an ongoing challenge for sequestration in
abandoned gas fields.

In depleted gas fields, it is possible that injection could prolong the economic life of the field by maintaining reservoir pressures longer than would otherwise be possible. However, enhancing gas production through injection of another kind of gas while the field continues to operate has not been pursued in the United States.

2. Sequestration in Brine Formations

Brine formations are the most common fluid reservoirs in the subsurface, and large-volume formations are available anywhere. For sequestration, deep (>2000 ft) formations that are not in current use are the most logical targets. Suitable deep formations, which are usually filled with brackish or saline water, are located across most of the United States. Brine formations have the largest potential capacity and are the most challenging of the potential sequestration options.

Although there is little practical experience with CO_2 sequestration in brine formations, aquifer storage of natural gas provides a foundation of experience for identifying important technical issues. Operational experience from aquifer gas storage indicate that from an engineering perspective, the main issues for CO_2 disposal in aquifers relate to the disposal rate of CO_2; the available storage capacity; the presence of a caprock of low permeability, and potential CO_2 leakage through imperfect confinement; identification and characterization of suitable aquifer formations and caprock structures; uncertainty due to incomplete knowledge of subsurface conditions and processes; and corrosion resistance of materials to be used in injection wells and associated facilities.

The main trapping process affecting CO_2 sequestration in aquifers is well understood. Injection of CO_2 into a water-filled formation results in immiscible displacement of a brine phase by a less dense and less viscous gas phase. Because CO_2 is soluble in water, some of the CO_2 will dissolve in the water. The thermo-physical properties of water and CO_2 that determine flow behavior— such as density, viscosity, and solubility—are well known, as is their dependence on pressure, temperature, and salinity. Equilibrium solubility of CO_2 in water decreases by a factor of six between 10C and 150C, and it decreases with aquifer salinity. The rate at which gaseous CO_2 will dissolve in water depends on size and shape of the gas-water interfaces and may be subject to considerable uncertainty.

Uptake of CO_2 by water may be increased beyond what can be attributed to physical solubility by interactions with carbonate minerals. Minerals such as calcite would be dissolved in response to CO_2 injection. A larger increase in storage capacity is possible from heterogeneous reactions with aluminosilicates ("mineral trapping"). There are indications that kinetics of reactions with carbonates may be fast, while kinetics of silicate interactions is very slow, requiring tens or perhaps hundreds of years for substantial reaction progress.

Because CO_2 is less dense and viscous than water, CO_2 injection into aquifers will be prone to hydrodynamic instabilities. The viscosity contrasts will lead to viscous fingering and the density contrast will lead to gravity segregation. The specifics of each will depend on the spatial distribution of permeability at the actual site and on injection rates. The effect of these complexities may be important in controlling the relative importance of the three primary trapping mechanisms. Detailed characterization of these complexities will be difficult, but it may not be necessary for achieving engineering objectives.

Two key issues distinguish CO_2 sequestration in aquifers from sequestration in oil and gas reservoirs. First, oil and gas reservoirs occur by virtue of the presence of a structural trap. This same trap is likely to retain CO_2. Identification of such effective traps may be more difficult in brine formations and may require new approaches for establishing the integrity and extent of a caprock. Second, injection of CO_2 into a brine formation is unlikely to be accompanied by removal of water from the formation. Injection will therefore lead to an increase in formation pressure over a large area. Whether or to what extent large-scale pressurization will affect caprock integrity, create land surface deformation, and induce seismicity must be better understood to design safe and effective sequestration.

A final issue concerning sequestration in brine formations is the acceptable leakage rate from the formation to overlying strata. Leakage of CO_2 may not pose a safety hazard and may, in some cases, be desirable if leakage to overlying units increases the opportunity for enhanced solubility or mineral trapping. Evaluating general and site-specific acceptable leakage rates should be part of a long-term strategy for CO_2 sequestration in brine formations.

3. Sequestration in Coal Formations

Coal formations provide an opportunity to simultaneously sequester CO_2 and increase the production of natural gas. Methane production from deep un-mineable coal beds can be enhanced by injecting CO_2 into coal formations, where the adsorption of CO_2 causes the desorption of methane. This process has the potential to sequester large volumes of CO_2 while improving the efficiency and profitability of commercial natural gas operations.

The key technical and commercial criteria for successful application of this concept include favorable geology such as thick, gas-saturated coal seams, buried at suitable depths and located in simple structural settings, which have sufficient permeability; CO_2 availability, such as low-cost potential supplies of CO_2, either from naturally occurring reservoirs or from sources such as power plant flue gas; and gas demand, which includes an efficient market for utilization of methane, including adequate pipeline infrastructure, long-term end-users, and favorable wellhead gas prices.

Coal-bearing strata include both thin and thick coal seams and inter-layered sandstones, siltstones, and shales; and they are usually saturated with water. This complex inter-layered formation defines the coal-bed reservoir interval. Coal-bed stratigraphy and the structure of inter-layered and overlying strata are site-specific and will need to be individually characterized. Unlike in oil and gas reservoirs, however, the methane in coal beds is retained by adsorption rather than by trapping beneath an impermeable overlying seal. Therefore, the nature of overlying and adjacent strata becomes an important issue for retention of the CO_2 within the coal-bed reservoir interval until it is adsorbed and for retention of the displaced methane until it can be withdrawn. However, techniques to verify the capacity, stability, and permanence of CO_2 storage in coal-bed reservoir intervals are needed.

Concepts for Geologic Sequestration

The sequestration techniques described above draw heavily from current approaches used by industry for production of oil, gas, and coal-bed methane and for storage of natural gas. Although these techniques provide reasonable options for sequestration of CO_2, enhanced technology for CO_2 sequestration in geologic formations may significantly decrease costs, increase capacity, enhance safety, or increase the beneficial uses of CO_2 injection. Other such technologies are explained below.

One concept is enhanced mineral trapping with catalysts or other chemical additives. Conversion of CO_2 to stable carbonate minerals is expected to be very slow under the current scenarios envisioned for sequestration in geologic formations. Identification of chemical or biological additives that increase reaction rates could enhance the effectiveness of mineral trapping.

Sequestration in composite formations is another technology. Multilayer formations, all with imperfect caprocks, may result in highly dispersed plumes of CO_2. The greater the degree of dispersion, the greater the opportunity for efficient solubility and mineral trapping. Developing design criteria that account for acceptable leakage across multi-layer formations could increase the geographic distribution and capacity of geologic formations for sequestering CO_2.

Microbial conversion of CO_2 to methane is also promising. Microorganisms that generate methane from CO_2 (methanogens) are known to exist in a wide variety of   oxygen depleted natural environments. If sequestration sites could be chosen to take advantage of this naturally occurring process, an underground "methane factory" could be created. Alternatively, additives that stimulate methanogenesis could be injected along with CO_2 to promote methane formation.

Rejuvenation of depleted oil reservoirs could increase the available sequestration sites. Injection of CO_2 into active oil reservoirs is a widely practiced oil recovery technique. However, even

after the oil recovery process is no longer economically feasible, as much as 50% of the original oil in place may be left underground. CO_2 injection, followed by a quiescent period during which gravity drainage and gas cap formation redistribute the gas and liquid phases, may rejuvenate an oil formation that can no longer produce economically. The injected CO_2 is sequestered in the geological formation.

CO_2-enhanced production of methane hydrates will enhance production. Methane hydrates in ocean sediments and permafrost hold tremendous reserves of natural gas. Producing gas from these formations remains a challenge because of their complex structure, mechanical properties, and the thermodynamic behavior of hydrates. CO_2 injection into methane hydrate formations may enhance production while simultaneously sequestering CO_2.

Concerns with Geologic Sequestration

There are many unknowns with geologic sequestration. A few of the concerns are addressed below.

Hydrodynamic and solubility processes responsible for trapping CO_2 in geologic formations are well understood, especially over the time frame associated with oil recovery (<20 years). Mineral trapping is less well understood; particularly about how fast these reactions occur. Reactions between CO_2 and the microbial communities present in deep geologic formations are also poorly understood.

A high-purity, dry waste stream is the most desirable for sequestration in geological formations, based on considerations about volume reduction, costs for gas compression, and CO_2 handling issues. What is not understood is the effects of waste stream characteristics on trapping efficiency, economics, and safety of CO_2 sequestration.

Ongoing efforts related to oil and gas production and groundwater remediation have led to development of hydraulic, geophysical imaging, and geo-statistical techniques for characterizing the heterogeneity of sedimentary and fractured geological formations. These can be used to predict the sweep efficiency in brine formations, but additional needs specific to sequestration includes,

- Caprock characterization.
- Identification of leakage paths and rates.
- Evaluation of hydrologic isolation.
- Identification of mineral assemblages that influence mineral trapping.
- Water encroachment in dewatered formations.
- Reservoir compartmentalization.

- Evolution of joints and fracture networks.

Injection, drilling, and completion technology for the oil and gas industry has evolved to a highly sophisticated state so that it is possible to drill and complete vertical, slanted, and horizontal wells in deep formations and wells with multiple completions, as well as to manage corrosive fluids. Optimization of these for CO_2 sequestration may require methods of optimizing sequestration efficiency. The engineering and cost-related issues of transportation and compression of CO_2 have not been considered here but will need to be added, along with other engineering issues such as effects of contaminants in the CO_2 stream, before large-scale testing occurs.

Multiphase, multi-component computer simulators of subsurface fluid flow have been developed for oil and gas reservoirs, natural gas storage, groundwater resource management, and groundwater remediation. The accuracy of these simulators depends heavily on site- and project-specific calibration and improves by continual parameter adjustment over the project lifetime. Developing reliable tools for predicting, assessing, and optimizing CO_2 sequestration will require a similar level of experience under actual operating conditions.

Monitoring of CO_2 migration in the subsurface is needed for large-scale sequestration of CO_2. Tracking of the distribution of trapped CO_2 in the gaseous, dissolved, and solid phases is needed for performance confirmation, leak detection, and regulatory oversight. The spatial and temporal resolution of these methods is unlikely to be sufficient for performance confirmation and leak detection. Needs include,

- High-resolution mapping techniques for tracking migration of sequestered CO_2.
- Deformation and micro-seismicity monitoring.
- Remote sensing for CO_2 leaks and land surface deformation.

Gravity segregation, viscous fingering, and preferential flow along high permeability pathways will play a dominant role in CO_2 migration in the subsurface. These difficulties will be compounded by deformation accompanying adsorption-desorption processes and precipitation dissolution processes. A better fundamental understanding is needed to predict migration of CO_2 and to optimize sweep efficiency in geologic formations.

The partitioning of CO_2 between the brine, oil, gas, and solid phases is critical to understanding trapping mechanisms, as well as to predicting CO_2-enhanced oil recovery from petroleum formations and enhanced gas recovery from coal formations. Better understanding of the solid/fluid partitioning, particularly, is needed for optimizing enhanced gas recovery from coal-bed methane projects.

Although the principal reaction pathways between CO_2 and sedimentary formations are well understood (e.g., reactions of feldspars with acid to form calcite, dolomite, siderite, and clay; dissolution of carbonate minerals), the kinetics of CO_2 dissolution in the liquid phase and subsequent rock-water reactions are slow and poorly understood. If conversion of CO_2 to these stable mineral phases is to be an important component of sequestration in brine formations, understanding of the kinetics of these reactions and the processes controlling them is essential.

Production of oil and gas from geologic formations and subsequent sequestration of CO_2 into geologic formations will be accompanied by deformation of the reservoir formation. The influence of deformation on the hydraulic properties of the formation and integrity of the caprock must be better understood. In brine formations, unlike in oil and gas reservoirs where injection of CO_2 is accompanied by withdrawal of fluids, deformation is likely to be widespread as the pressure builds in the formation. The effects of deformation on the integrity of the caprock and its ability to induce seismic events must be better understood to ensure the long-term stability and safety of CO_2 sequestration.

Chapter 3
Ocean Sequestration

The ocean represents a large potential sink for sequestration of CO_2 emissions. Although the long-term effectiveness and potential side effects of using the oceans in this way are unknown, three methods of enhancing sequestration are discussed in this section:

- The direct injection of CO_2
- Enhancement of the natural ocean uptake from the atmosphere
- Other options that may require long time frames to be develop

For a given option the tradeoffs among cost, long-term effectiveness, and changes to the ocean ecosystem are discussed.

On average, the ocean is about 13,000 feet deep and contains 40,000 GtC of CO_2. It is made up of a surface layer (nominally 300 feet thick), a thermocline (down to about 3,000 feet deep) that is stably stratified, and the deep ocean below 3,000 feet. Its waters circulate between surface and deep layers on varying time scales from 250 years in the Atlantic Ocean to 1,000 years for parts of the Pacific Ocean. The amount of carbon that would cause a doubling of the atmospheric concentration would change the deep ocean concentration by less than 2%.

On a timescale of 1,000 years, about 85% of today's emissions of CO_2 will be transferred to the ocean. The strategy with ocean sequestration is to attempt to speed up this process to reduce both peak atmospheric CO_2 concentrations and their rate of increase.

Although the ocean's biomass represents about 0.05% of the terrestrial ecosystem, it converts about as much inorganic carbon to organic matter as do processes on land. The photosynthetic fixation of CO_2 by ocean organisms, followed by the sinking and slow re-mineralization of organic carbon, is a natural process for sequestering CO_2 in the deep sea. This process is often referred to as the "biological pump" and is shown graphically in Figure 3. The question is whether the deep sea can be used as a site for sequestration of additional CO_2.

Figure 3

Many people are wary of ocean sequestration because it is known that small changes in biogeochemical cycles may
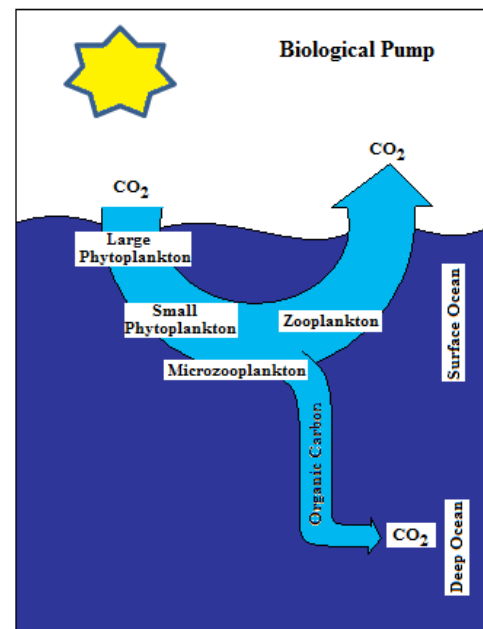
have large consequences, many of which are secondary and difficult to predict. Nevertheless, ocean carbon sequestration is occurring on a large scale today, and entrepreneurs are already trying to commercialize these technologies. Therefore, it is imperative to better understand the risks as well as the opportunities. The ocean plays an important role in sustaining the biosphere, so any change in ocean ecosystem function must be viewed with extreme caution.

How much carbon can the ocean sequester? Because of high pressures prevailing in deep ocean environments, a large quantity of CO_2 may be dissolved in deep ocean waters. However, a more realistic criterion needs to be based on an understanding of the biogeochemistry of the oceans. At present, we do not have enough information to estimate how much carbon can be sequestered without perturbing marine ecosystem structure and function.

Direct Injection of CO_2

The direct injection of CO_2 into the ocean requires starting with a concentrated stream of CO_2 and delivering it to locations in the ocean where it will be effectively sequestered for hundreds of years, if not longer. To accomplish this, CO_2 would be injected as a liquid below the *thermocline* at depths greater than 3,000 feet. One limitation of this approach is that it is best suited to large, stationary CO_2 sources with access to deep-sea sequestration sites—sources that may account for about 15 to 20% of our CO_2 emissions.

The technology is available to proceed with this option. However, we do not have the knowledge to optimize the costs, determine the effectiveness of the sequestration and understand the resulting changes in the biogeochemical cycles of the oceans.

> The **thermocline** is the portion of the ocean where the decrease in temperature with the increase in depth is the greatest. It separates the surface layer from the deep ocean. The thermocline is the range from 150 feet to 3000 feet.

There are many technical options for sequestration by direct injection of CO_2. For example, injections may occur at moderate depths (3,000– 6,000 feet), at deep depths (>9,000 feet), in depressions on the ocean floor, or even into the sub-oceanic crust of the earth. The CO_2 may be sequestered by dissolution in the water column or by the formation of CO_2 hydrates, which are solid, ice-like compounds. The delivery of the CO_2 may be by pipeline or tanker. One challenge is to determine how to use the buffering effect of bottom sediments (e.g., the ability of calcium carbonate to react with the CO_2) to increase the capacity and effectiveness of ocean sequestration. Another challenge is to understand the kinetics associated with the formation of CO_2 hydrates and to try to take advantage of their properties (e.g., increased density, lower mass transfer coefficient) for carbon sequestration. Finally, engineering analysis is required to estimate the costs of the various injection pathways.

Sequestration effectiveness will depend on the exact depth and location of the injection. In general, the deeper the CO_2 is injected, the more effectively it is sequestered; but injecting deeper requires more advanced technologies and may increase costs. Ocean general circulation models are required to quantify sequestration effectiveness by calculating the reduction in atmospheric CO_2 as a function of time because of various ocean sequestration strategies. However, the models must be improved to reduce the uncertainty associated with their results.

Environmental impacts near the injection point must be detailed, and the long-term, broad-scale impacts on the function of the ocean ecosystem must be understood. The most significant environmental impact is expected to be associated with lowered pH because of the reaction of CO_2 with seawater, although there could also be direct impact from the CO_2 itself. Non-swimming marine organisms residing at depths of about 3,000 feet or greater are most likely to be affected adversely by more acidic seawater; the magnitude of the impact will depend on both the level of pH change and the duration of exposure. The microbial community would also be affected, causing unknown impacts on biogeochemical processes that play a crucial role in the ocean carbon cycle. Local environmental impacts may be minimized by designing an injection system to disperse CO_2.

Led by offshore exploration and production activities of the oil and gas industry, great strides have been made in the development of undersea offshore technology. It is becoming routine to work in depths approaching 6,000 feet. Work at much deeper depths, even approaching 30,000 feet, is possible at reduced scales and/or time horizons, as has been shown in deep drilling and other scientific programs. However, many technical challenges still exist in going deep at large scales for extended times. Therefore, as a first step, the best strategy is to discharge the CO_2 below the thermocline at moderate depths of 3,000 to 6,000 feet.

To implement that strategy, several methods of injection have been proposed. One method is to transport the liquid CO_2 from shore in a pipeline and to discharge it from a manifold lying on the ocean bottom, forming a rising droplet plume. Another method is to transport the liquid CO_2 by tanker and then discharge it from a pipe towed by the moving ship as shown in Figure 4.

Once the CO_2 leaves the pipe, our current capabilities are much more limited. CO_2 hydrates may be formed from the injected CO_2. The thermodynamic behavior of hydrates is well understood, and their kinetics have been extensively investigated. However, scientists do not fully understand the kinetics that will control the formation and dissolution of hydrates in seawater, especially under the dynamic conditions in the plume.

Models are available to describe the fate of the injected CO_2 by modeling its behavior in the mid-field (up to a few hundred miles from the injection point) and in the far field (hundreds of miles from the injection point). These models can simulate broad characteristics of observed transient tracer fields, whose movements can be detected in the open ocean. However, for modeling the fate of a point source such

Deep Ocean Sequestration

Figure 4

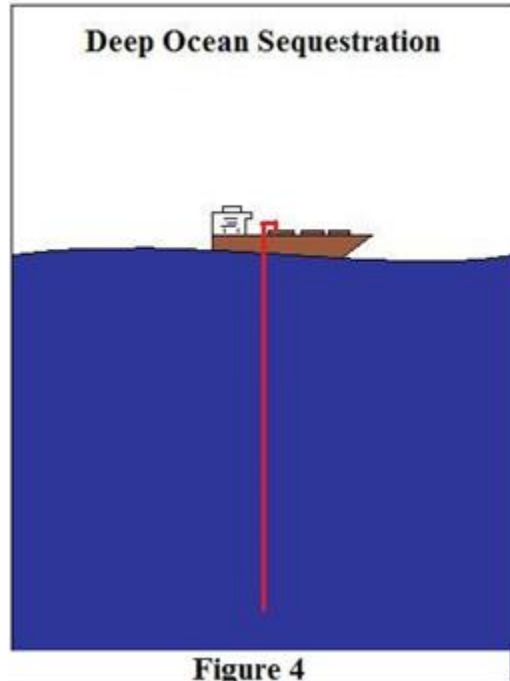as injected CO_2, the uncertainties are large, and the results will not be definitive.

The area where there is the least understanding is the environmental consequences of CO_2 injection. Scientists do not understand the ocean's capacity to neutralize the water that is acidified by injected CO_2. There are models to predict pH changes to around the injection point. However, there is very little knowledge of how the pH changes or other impacts due to CO_2 injection would affect the biogeochemistry and ecosystems in the deep ocean.

Natural Ocean Sequestration

The natural process of carbon fixation by phytoplankton occurs at a rate of 50 billion tonnes per year and results in sequestration of carbon in the deep ocean via the biological pump. The biological pump involves the gravitational settling, slow re-mineralization, and burial of biogenic debris formed in the upper levels of the ocean. Phytoplankton in surface waters are rapidly grazed by zooplankton, which in turn may be consumed by larger animals such as fish. While it is estimated that 70–80% of the fixed carbon is recycled in surface waters, the rest is exported as particulate organic carbon (POC) to the deep ocean, where it is slowly mineralized by bacteria. Fertilization of the oceans with micronutrients (such as iron) and macronutrients (such as nitrogen and phosphorus) is a strategy that is being considered to enhance drawdown of CO_2 from the atmosphere and thus accelerate the biological pump. Because certain areas of the ocean have low levels of phytoplankton yet a high concentration of nitrogen and phosphorus, it was realized that a lack of iron might limit phytoplankton growth. Initial short-term studies of iron

fertilization in high nutrient, low-chlorophyll waters have demonstrated that in situ fertilization of surface waters with iron to promote growth of phytoplankton is feasible.

Some commercial ventures are trying to capitalize on ocean fertilization for increasing their fish harvest. While these ventures have a primary goal other than carbon sequestration, the strategies of fertilization and potential for environmental impact are similar, and all activities using fertilization to enhance fish production also claim carbon sequestration as a secondary benefit. Commercial ventures are proceeding even though the potential ecological consequences of ocean fertilization are not yet known. Such consequences could range from changes in species diversity to induction of anoxia and significant adverse effects on community structure and function. The fundamental question that should be answered is whether any alterations in the ocean ecosystem are justified relative to the benefits to society.

An urgent need exists to determine the potential ecological consequences of large-scale ocean fertilization on the biosphere and on biogeochemical cycling. We need to be able to predict accurately how ecosystems will change in response to either short-term or sustained fertilization of the oceans.

We also need to understand overall natural carbon sequestration efficiency in the oceans. Moreover, the feasibility of ocean fertilization will depend on optimization of fertilizer design, delivery, and ecological monitoring. Long-term ecological monitoring may prove extremely costly, so robust, dynamic models that predict ecosystem response will be the key to designing an economical and effective monitoring strategy.

Small-scale ocean fertilization is feasible from both an engineering and an economic perspective. The technology for fertilizing surface waters is straightforward; it involves releasing micro-algae nutrients such as iron, phosphorus, or nitrogen from platforms such as boats or airplanes. Recent iron fertilization experiments demonstrated that a deficiency of iron limits photosynthesis in areas of the ocean where nitrogen and phosphorus are abundant. The application of 500 kg of iron to 72 square kilometers in the equatorial Pacific resulted in a 30-fold increase in phytoplankton biomass, a dramatic shift in species composition and elevated carbon fixation rates.

A number of technologies are available for monitoring ecosystem response to fertilization, including assays for primary and secondary production using radiotracer techniques. Determining ecosystem response below the euphotic zone (the zone where the net rate of photosynthesis is positive) could be used in situ filtration techniques that determine size distributions and chemistry of POC with minimal disturbance to the samples.

To verify the effectiveness of sequestration, an ocean carbon inventory survey will use improved technologies to characterize the dissolved and particulate organic and inorganic carbon pools, rates of transfer between carbon pools, and ecosystem function. To simulate the effectiveness of ocean fertilization as a CO_2 sequestration strategy, two challenges must be met. First, we must be able to predict the change in biological carbon export from the surface ocean to the deep ocean because of ocean fertilization. Second, we must be able to predict the fate of this carbon after it reaches the deep ocean.

The problem of predicting changes in carbon export from the surface ocean resulting from fertilization is a difficult one, because it depends on how difficult it is to predict changes in ecosystem structure. Surface ocean biology models have simulated biological carbon export at specific locations well, but these models have been "tuned" to match some observations at these locations. Work is under way to try to develop a single model that can be applied across the global ocean to predict carbon export from physical and nutrient conditions alone. Although much progress has been made in this area, this goal has not yet been attained. It will be important to monitor closely any ocean fertilization experiments to develop solid data sets for use in evaluating ocean biology and ecosystem models.

Predicting the fate of biogenic carbon after it is transported to the deep ocean is also difficult. An important component of this prediction is the estimation of the depth at which the organic carbon will be oxidized, and this depth will depend on whether the organic carbon is particulate or dissolved, the size of the particles, and other factors. Once the organic carbon has oxidized in the deep ocean, the problem is equivalent to the deep-ocean CO_2 injection problem—predicting ocean transport, CO_2 degassing, and sediment interactions. Several simulations of this aspect of the problem have already been made using assumptions about the change in ocean biological carbon export and the depth of its oxidation. These studies have concluded that the effectiveness of ocean fertilization as a CO_2 sequestration strategy is very sensitive to the rate of ocean mixing between the ocean's surface layers and its deep layers. If carbon in the deep layers is brought to the surface through mixing, then it could return to the atmosphere through degassing.

Other Approaches to Ocean Sequestration

Whereas most of the research in ocean CO_2 sequestration has been in the areas of deep-sea CO_2 injection and ocean fertilization, both concepts are new. Other technologies that may emerge in the future are discussed below.

Convert concentrated CO_2 at a power plant to strong carbonic acid, using the acid to dissolve carbonate minerals, and then release the dissolved carbonate and dissolved fossil-fuel CO_2 into the ocean. This technique would enhance ocean storage capacity and would eliminate concerns about changes in pH because the dissolved carbonate mineral would neutralize much of the

acidity of the carbonic acid. This approach would diminish eventual degassing back to the atmosphere, circumventing the need for pumping CO_2 to great distances and depths. Limitations of the concept include the need for large amounts of water and the need to transport more carbonate mineral than coal to the power plant.

Bury organic carbon in the ocean. Organic waste could be stored as a thick layer on the ocean bottom. Sources of this organic carbon could include farm waste, carbon-black from decarbonized fuel, or organic-rich dredged sediments. Biomass from fast growing sea grasses, kelp forests, or terrestrial plants could be harvested for burial in the ocean. Transportation of large volumes of biomass to the ocean depths, however, may prove too costly. Moreover, anoxia and the production of methane may present a serious problem with this approach.

Mine hydroxides and bicarbonates such as sodium hydroxide, potassium hydroxide, sodium bicarbonate, and dissolve them in the ocean. These minerals, when dissolved, will neutralize the acidity produced by CO_2 and will effectively sequester that CO_2 in the oceans. The limited availability of these materials in nature may preclude this approach.

Ocean Sequestration Concerns

There are a numerous unknowns with potentially using the ocean to sequester large amounts of additional CO_2.

The impact of long-term ocean fertilization on the structure and function of marine ecosystems is unknown. Changes in phytoplankton structure are an inevitable consequence of fertilization, and this would lead to changes in ocean food web structure and dynamics. Such changes could have long-term impacts on fisheries, many of which are already declining primarily because of over-fishing. Fertilization with iron and phosphorus in lake ecosystems selects for the growth of cyanobacteria over other types of phytoplankton; this proliferation could be a problem because certain species of cyanobacteria produce powerful toxins. While common marine cyanobacteria are nontoxic, further study is needed.

The impact of sustained fertilization on the natural biogeochemical cycles in the ocean is completely unknown. The biogeochemical cycles of carbon, nitrogen, phosphorus, silicon, sulfur, cobalt, zinc, and selenium in marine environments is highly complex and intertwined, and recent evidence suggests that they are regulated by the availability of iron on a global scale. A perturbation of one elemental cycle can have repercussions that are unanticipated.

 The potential risk of fertilization leading to eutrophication must be determined. Eutrophication causes oxygen depletion, which could kill species that require oxygen; in some cases, it can lead to the production of methane by microorganisms. On the other hand, lack of oxygen in the

sediments of the ocean floor could lead to an increase in the preservation of buried carbon due to slow rates of mineralization. The impact of fertilization on sediment dwelling organisms is unknown.

At present, there is not a good understanding of the effectiveness of ocean fertilization on a large scale. For instance, will enhanced carbon fixation in surface waters result in an increase in carbon sequestered in the deep ocean?

Chapter 4
Terrestrial Sequestration

The terrestrial biosphere is another potential avenue for sequestering carbon. The aim of developing enhanced carbon sequestration in the biosphere is to enable a rapid gain in withdrawal of CO_2 from the atmosphere over the next 50 years to allow time for implementation of other technological advances that will help mitigate CO_2 emissions.

Carbon sequestration in terrestrial ecosystems is either the net removal of CO_2 from the atmosphere or the prevention of CO_2 net emissions from terrestrial ecosystems into the atmosphere. Carbon sequestration may be accomplished by increasing photosynthetic carbon fixation, reducing decomposition of organic matter, reversing land use changes that contribute to global emissions, and creating energy offsets using biomass for fuels or beneficial products. The latter two methods may be viewed more appropriately as carbon management strategies.

The terrestrial biosphere is estimated to sequester large amounts of carbon, on the order of 2 GtC/year. There are two fundamental approaches to sequestering carbon in terrestrial ecosystems: protection of ecosystems that store carbon so that sequestration can be maintained or increased and manipulation of ecosystems to increase carbon sequestration beyond current conditions. In this section, we will review the inventories of carbon in terrestrial ecosystems and the roles of the biosphere in the global sequestration process and then estimate the potential for carbon sequestration in each of them.

Terrestrial Ecosystems

The world's terrestrial environment comprises a wide diversity of ecosystem types that can be categorized into several *biomes* to address unique aspects of their carbon sequestration potential.

> The term **Biomes** is used to describe distinct ecological communities of plants and animals in a particular climate. A desert is a biome.

The total amount of carbon "stored" in terrestrial ecosystems is large. Figure 3 shows estimates of the distribution of this carbon among the major ecosystems of the world. Carbon sequestration in these terrestrial ecosystems will be enhanced by increasing the amounts of carbon stored in living plant matter, roots, and soil carbon and in long-lived materials that contain woody matter, or by processing wood into long-lived carbon products. Net removal of CO_2 from the atmosphere by terrestrial ecosystems occurs when plant photosynthesis exceeds all processes of consumption and respiration, resulting in above-ground plant growth and increases in root and microbial biomass in the soil. Plant matter is consumed when it is eaten, dead or alive, by an animal. In addition, plants return stored carbon to the atmosphere through respiration, as do animals through their waste or death and decay. When a plant sheds its leaves and roots die, this organic material decays, adding carbon to the soil. Soil

carbon is lost to the atmosphere through decomposition by soil organisms. This process also mineralizes organic matter, making available the nutrients needed for plant growth. The total amount of carbon stored in an ecosystem reflects the long-term balance between plant production (inputs) and all respiration and decomposition.

Global Estimates of Terrestrial Carbon Stock
(billions of tonnes of Carbon)
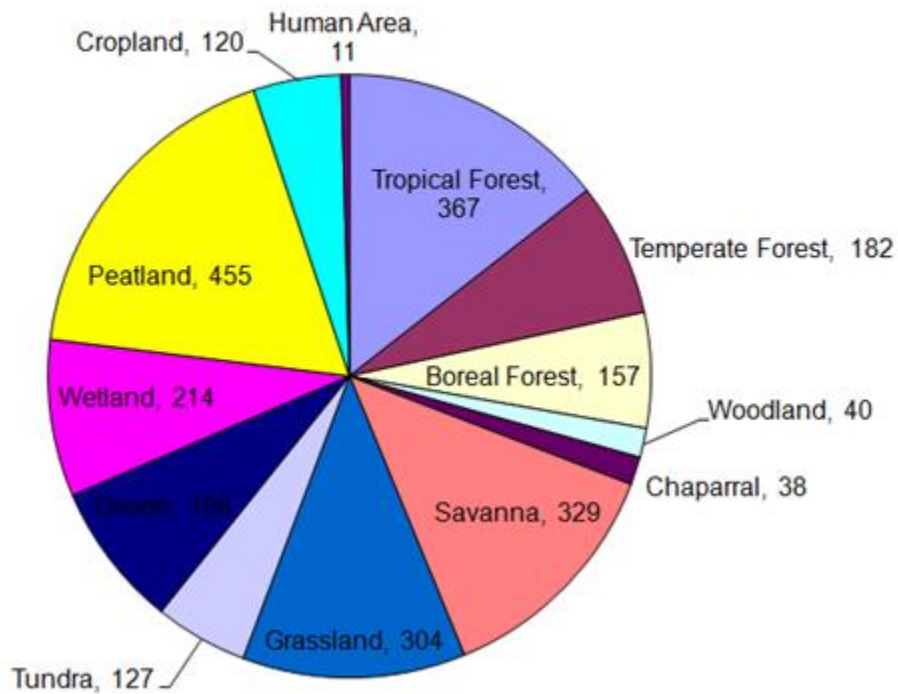
Biological transformation of carbon has been, and quite likely will continue to be, a primary mechanism for removing CO_2 from the atmosphere. This is reflected in the standing stock of vegetation and the accumulation of soil organic matter. Methods that rely on biological transformation can play a central role in the management of carbon sequestration in the future. This is a huge natural biological scrubber for emission sources from fossil fuel plants, cement plants, automobiles. The estimated value of CO_2 removed from the atmosphere each year by the earth's mantle of vegetation is the net ecosystem production. This value is uncertain because it is an estimated difference between photosynthesis and respiration—both very large fluxes and highly uncertain. We can "observe" the contemporary, worldwide *net difference* between global carbon uptake by photosynthesis and releases by respiration through measuring annual changes in atmospheric CO_2 and accounting for oceanic carbon dynamics. However, we cannot use this information to assess how the biosphere will regulate atmospheric CO_2 in the future. This is because the ratio of photosynthesis to respiration is highly sensitive to environmental variables

such as temperature, moisture, and nutrient availability and differs among ecosystems. If atmospheric CO_2 increases enough to cause climate change, the global ratio may change in ways that we cannot now predict accurately. Small changes in these large numbers could dwarf any carbon management strategy imposed by humans.

The Biomes

The biomes that make up the terrestrial ecosystem are categorized in Table 3. The estimates of potential carbon sequestration include the current natural rate of carbon sequestration, which totals about 2 GtC/year. Note that achieving the potential indicated in the table may imply an intensive management and/or manipulation of a significant fraction of the globe's biomes. The table also does not reflect estimates of economic, energy, social, or environmental costs to achieve such a rate, which could be unacceptably large for higher numbers. The values in this table are large and to achieve these values will require technological advances. It is important to remember that it is assumed that the technology will occur to allow us to optimize carbon sequestration beyond what is thought to be achievable with current best management practices.

Table 3 Potential Sequestration by Biomes	
Biomes	**GtC/yr**
Agricultural Croplands	0.9
Biomass Croplands	0.8
Grasslands	0.5
Rangelands	1.2
Forests	2.0
Deserts	1.3
Terrestrial Sediments	1.7
Wetlands	0.7
Total	9.1

Estimating the potential for increasing carbon sequestration in terrestrial ecosystems is difficult because the bio-geochemical dynamics that control the flow of carbon among plants, soils, and the atmosphere are poorly understood. Additionally, there will be socioeconomic issues, energy costs, and potential ecological consequences that would need to be compared with the benefits of sequestration or other carbon management options.

Strategies for sequestration a few decades from now will be implemented in a world different from todays. Human responses to climatic change and other environmental issues, population growth, economic development, and technological change may well lead to changes in patterns of land use, settlement, and resource management. It seems unlikely that carbon sequestration will be the highest-priority use for any land; instead, sequestration will have to be compatible with a host of other demands on ecosystem goods and services.

There are some limitations and uncertainties related to carbon sequestration potential in terrestrial ecosystems. First, it is critical at the outset to take a whole ecosystem approach. Having the capability to assess potential impacts on a particular ecosystem from an emphasis on sequestering carbon is a major need. For example, the dynamics of carbon storage and allocation are at present not well known under temperature, moisture, and nutrient conditions of a changing climate.

Second, carbon sequestration strategies may have consequences beyond simply increasing carbon storage. Increasing organic matter in wetlands could result in higher emissions of methane, a greenhouse gas with a 20 times higher contribution to global warming than CO_2, although hydrologic controls or increases in the fraction of recalcitrant organic matter could offset this process. Converting croplands to grasslands may increase emissions of nitrous oxide (N_2O), another greenhouse gas, to the atmosphere.

Third, land use and sequestration actions also could alter the flow of micronutrients. For example, because of controls on erosion, might the fluxes of phosphorous and nitrate in aquatic systems increase or decrease to levels that cause ecological impacts? Strategies to "improve" carbon sequestration in deserts through increases in drought-tolerant vegetation could lead to decreased fluxes of wind-blown nutrients such as iron, with possible adverse impacts on the ability of the ocean to sequester carbon through iron-fertilized phytoplankton.

Implementation of no-till practices, return of residues to soil, and the activities of the Conservation Reserve Program are increasing the amount of carbon in agricultural systems. (The main reason: the soil is less exposed to air, so less soil carbon is oxidized and carried off as CO_2.) Estimates suggest that the potential for soil carbon sequestration may be 8 to10 tera-grams per year. There is some evidence that levels of soil organic carbon have doubled over the past 20 years in the upper few inches of soil placed in the Conservation Reserve Program.

The cutting of forests of eastern North America in the previous century is now being replaced by forest re-growth, and North America might even be a sink for carbon at this time. Forests in the United States are being managed to maintain cover, increase water storage, and retain litter. Globally, however, there are still major challenges to slowing the rate of deforestation.

Although the use of biomass as an alternative fuel supply is not implemented yet on a large scale, this program is showing promise as a renewable energy technology. Sequestration of 0.5 to 0.8 GtC/year from crop-to-biofuel conversion could be achieved by converting 10 to 15% of agricultural cropland to energy crops. It is important to point out that the use of biomass products can have additional benefits beyond sequestration in carbon management. For example, they may replace a product that is energy-intensive to manufacture, or they may be more energy-efficient in performance.

For tundra and boreal forest, the trend is in the wrong direction. These areas are being impacted to become carbon sources rather than sinks. Desertification is increasing globally, and little emphasis is being placed on how to use these areas for carbon sequestration. Urbanization eliminated ten million hectares (ha) of agricultural and forested land in the United States between 1960 and 1980.

> **Desertification** is the degradation of arid land. It is the gradual loss of soil productivity and reduction in vegetation due to human activities and the impacts of climatic events such as droughts and floods.

These highly impacted environments offer interesting opportunities. The density of carbon under these "intensively managed" systems such as lawns with trees is high—attributable to the high rates of fertilization and irrigation, with nitrogen oxide pollutants playing a minor role. Ancillary benefits from urban forestation might include local cooling effects and water retention that would reduce emissions from fossil fuel use.

There are near-term beneficial practices that can be followed to recover some of the carbon lost from past practices and to protect important ecosystems. These should be implemented as much as is feasible. However, these alone cannot meet the vision for carbon sequestration.

Terrestrial Strategies

Terrestrial strategies include below ground carbon sequestration as well as above ground methods. In addition, there may be ways to increase the volume of certain types of land masses for sequestration.

Methods to increase below-ground carbon include:

- Increase the depth of soil carbon
- Increase the density of carbon in the soil
- Increase the mass and/or depth of roots
- Decrease the decomposition rate of soil carbon

One key link to another technology system is the possible use of byproducts created by advanced chemical or biological methods as soil additions to increase organic content, water retention, and protection of organic matter, and to improve the texture of the soil so that it can hold more carbon. An example might be creation of "smart fertilizers" or the use of mixtures of minerals (e.g., carbonates, silicates, and oxides) formed at fossil fuel power plants blended with bio-solids such as sewage sludge.

Methods to increase above-ground carbon include:

- Increase the rate of accumulation of above-ground biomass
- Increase the density of total biomass per area and/or the density of carbon in the above ground biomass
- Increase the longevity of biomass carbon (decrease decomposition rate)
- Increase beneficial use of biomass carbon in long-lived products

An important component for the above-ground carbon is the use of biomass products. Increasing the density of total biomass or the accumulation rate offers high carbon sequestration potential. However, storage due to increased plant productivity is most efficient if the carbon is moved to a long-term pool, such as long-lived woody biomass or soils. Another alternative is to substitute products manufactured from biomass for products that are made using fossil fuels, addressing both sequestration and management. Obvious examples that address both carbon management and sequestration include biofuels and wood products.

Less obvious but important examples that are focused on carbon sequestration might include the use of biomass products in structural materials or combined with other materials to create new soils.

The amount of land area can have a significant impact. As seen by the large areas in Table 3, in some ecosystems, a small change in carbon content could result in large increases in total carbon sequestered. Although the total land area of the world cannot be increased, research might allow the land area to increase total carbon sequestration by optimization across the following:

- Social drivers
- Economic drivers
- Ecosystem management drivers

Optimization among ecosystems for carbon sequestration will be a complex function. Research in this area includes issues such as transforming land from low carbon sequestration uses to high carbon sequestration uses, as well as reversing land use changes that have made land areas into sources of CO_2 emissions.

The overriding objective for terrestrial ecosystem carbon sequestration is to optimize net ecosystem exchange and ensure that the increased carbon is stored in long lived vegetation, soil, or products.

A rational strategy to sequester carbon must consider all the components of the terrestrial ecosystem. Single tree species cannot be considered in isolation from other plant species or from soil because of the interactions and interdependencies among species in an ecosystem. Likewise,

soil management cannot be separated from plant productivity. This integrative strategy element—ecosystem dynamics—is driven by four basic needs.

The first is to balance decomposition of biomass and soil organic matter as a source of carbon loss to the atmosphere against decomposition as a source of nutrients essential to plant growth. Sequestration strategies that attempt to decrease decomposition rates may inadvertently result in lower ecosystem carbon storage because, without decomposition, insufficient nutrients are available for plant growth. Plants, soil, and nutrient cycling must be considered together.

The second strategy is to balance instantaneous or optimum plant productivity with the desire for long-term, stable productivity. An ecosystem that is managed for a single species will not maintain productivity under a wide range of conditions, such as climatic anomalies or disease outbreaks, without intensive management inputs. Target species, species diversity, and ecosystem resilience must be considered together.

The third strategy includes design strategies that are compatible with other human demands on land and natural resources. It is necessary to understand both the impacts of carbon management on other ecosystem services and ways to design carbon management strategies that work in concert with other goals for terrestrial ecosystems, such as production of food, fuel, and fiber; clean water; climate moderation; or aesthetic or cultural value.

The fourth strategy is to determine the potential feedback from carbon sequestration actions. What is the impact of carbon sequestration on the production or consumption of trace gases that affect radiative forcing (N_2O and CH4) or that otherwise have significant roles in atmospheric chemistry (CO and NO)? For example, increased organic matter content in wetlands might increase net methane emission. Will increased reservoirs of organic matter in soils significantly affect weathering and subsequent transport in rivers of iron, silica, and other micronutrients? If so, in what direction might changes occur, and what are the potential impacts? What consequences would an emphasis on desert carbon sequestration have on an eolian transport of iron and other metals or nutrients to the oceans or other terrestrial ecosystems?

There are three specific strategies for increasing terrestrial sequestration. They are:

1. Manage crops and lands
2. Improve soil
3. Select and engineer species.

These are closely coupled, and they must be implemented and assessed at the scale of whole ecosystems.

1. Improve soil

A variety of detailed strategies could be implemented or developed to increase the carbon content of soil, increasing below-ground carbon directly and above-ground carbon indirectly. One of the key questions is whether soil texture, topographic position, and climate determine the carbon content of a soil or whether it can be changed by manipulation. We know little about the processes of humification (formation of humus, which consists of decayed organic matter that provides nutrients for plants and increases the soil's retention of water) or stabilization of decomposable organic carbon in soils. However, our current level of understanding is adequate to begin to address the questions: To what degree can these processes of stabilization be managed? What would be the consequences for plant productivity and ecosystem functions? Opportunities for innovation exist in the following areas.

How can the amount of water required be minimized, or use water of lower quality to increase carbon accumulation? For example, groundwater of marginal quality could be used for restoration of large tracts of degraded lands. Urban forests and grasslands would benefit from utilization of "gray" water from homes, businesses, or cities rather than irrigation using potable water supplies. Surface treatments or soil amendments that improve retention of water in soil between rain events and irrigation would also be of great benefit. Could desalination be linked to irrigation and carbon sequestration via production of carbonates with brines and CO_2?

Can the efficiency at which nutrients are taken up by plants through novel microbial manipulations or soil amendments be improved? Can we determine and enhance the role of mycorrhiza (a mutual association between a fungus and the root of a seed plant it invades) in carbon fixation and plant productivity? The availability of other critical nutrients and trace elements, not just nitrogen and phosphorous, must be addressed.

Can the formation of strongly-adsorbing and highly recalcitrant organic macromolecules be enhanced through soil amendments, microbial manipulation, or genetic selection of biomass? Can soil organic carbon profiles be deepened to provide a greater mass of soil available for carbon sequestration? Can inorganic carbon formation be enhanced in an arid system?

Beyond no-till agriculture, what methods can be used to minimize soil erosion? Are there soil additions or surface treatments that will significantly inhibit the susceptibility of soil to water erosion? Are there engineering innovations to at least trap organic matter that might be released from erosion (e.g., sediment trapping to enhance wetlands)? Can the current, approximately 0.5 GtC, trapped in sediments each year behind dams be permanently sequestered?

Can waste byproducts (e.g., fly ash, concrete, sewage sludge) be used alone or mixed with other materials to improve soil characteristics safely and economically to help the retention of carbon?

Can materials created from byproducts be used to reclaim degraded lands, or even help mitigate land subsidence while at the same time sequestering carbon?

2. Manage crops and land

Opportunities for increasing carbon sequestration by management practices vary in intensity and are specific to each ecosystem. There are also complexities to implementing some strategies. For example, no-till practices reduce oxidation of soil organic matter but do not necessarily promote increased incorporation of surface organic matter into the soil to potentially enhance soil organic carbon in the long term. There are opportunities to use natural biodiversity as well. For example, a shift from annual to perennial grains would benefit soil carbon sequestration. Management of agricultural ecosystems by planting trees and legumes mixed with crop plants can add organic carbon to soil. Proposed strategies include:

- Converting marginal crop and pastureland into woodlands
- Crop rotation, residue management
- Forest management such as reducing deforestation
- Range land management
- Precision farming focused on soil management
- Management for pest and disease control and control of invasive species
- Decrease urbanization and land conversion of forests to agricultural use

3. Select and engineer species

Opportunities to select or genetically engineer species for carbon sequestration behavior can directly impact both above-ground and below ground carbon. It will be important to understand carbon partitioning into biomass as we attempt to engineer or select carbon sequestration traits.

There are methods to indirectly make more land area available for carbon sequestration such as by improving food production per hectare so that more land is available for carbon sequestration. This strategy should require research on plants and microbial communities with a focus on near-term biotechnology options and species selection using extant knowledge and relevant fundamental research on functional genomics that will have impacts in later years.

For research in plant genetics, genes must be available for insertion into the plant of choice. Many genes in agriculture have come from a small set of annual plants for which information on gene function is easily obtained. Most of the genes found in such plants would not have direct value to a carbon sequestration strategy because genes for long-term carbon storage may have little agronomic value. Thus, to enable use of genetic engineering for carbon sequestration, there is a need to discover genes in perennial plants that allocate more carbon to below-ground

components, that code for higher content of extractives (components desired from the plant), or that provide resistance to microbial degradation. To enable the discovery of such genes, a functional genomics effort must precede the genetic engineering efforts.

It is not always necessary to start with functional genomics to modify the plant genome. For

> **Lignin** is a complex polymer that hardens and strengthens the cell walls of plants and that does not decompose easily.

example, genes for producing higher lignin content in maize have been bred out of current varieties. Genetic stocks possessing higher lignin content exist, and these could be reintroduced if the objective were to produce this characteristic for carbon sequestration. Altering the Rubisco enzyme to increase biomass production through a more efficient uptake of carbon might have huge potential benefits.

Strategies central to this theme include developing methods to,

- Increase standing biomass
- Maximize lignin content for longevity of woody biomass
- Increase pest and disease resistance
- Improve photosynthetic efficiency
- Extend growing seasons of plants
- Increase root: shoot ratios
- Increase carbon allocation in below-ground components of less decomposable carbon compounds (e.g., lignin, phenolics)
- Engineer new plants that have improved water efficiency, nutrient utilization, salt tolerance, and pH tolerance.

Carbon sequestration in terrestrial ecosystems will provide significant near-term benefits with the potential for even more major contributions in the long-term. There are many ancillary positive benefits from carbon sequestration in terrestrial ecosystems, which are already a major biological scrubber for CO_2. The potential for carbon sequestration could be large for terrestrial ecosystems (5–10 GtC/year). However, this value is speculative, and research is needed to evaluate this potential and its implications for ecosystems. In addition, economic and energy costs were not fully considered in the analysis to estimate the carbon sequestration potential. As carbon sequestration strategies are developed, a whole ecosystem approach under changing climate conditions must be considered.

Summary

Carbon capture and sequestration will become an important topic as the United States attempts to modify greenhouse gas emissions. Coal is the most predominate natural energy resource in the United States and it will continue to be a major component in the energy mix for electric power generation for many years. Carbon sequestration will likely cause energy costs to rise sharply.

Carbon sequestration is presently being used in sample scale applications, but it is unproven on the scale needed to manage the CO_2 emissions for fossil fueled power plants. However, geologic, terrestrial, and ocean sequestration of CO_2 are all promising technologies that must be considered. Significant research is needed to find ways to transport and safely sequester CO_2.

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