Sequestering Carbon Emissions in the Terrestrial Biosphere

The Washington
Advisory
Group LLC

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EXECUTIVE SUMMARY

Projected estimates of global surface climate warming have led to the view that actions to reduce carbon dioxide emissions from fossil fuel production are required. The Bush Administration has withdrawn from the Kyoto Protocol because it would require deep reductions in carbon dioxide emissions with attendant significant adverse economic consequences and because of the uncertainty in the climate projections.

Most scientists have come to the view that carbon dioxide emissions from all sources can be offset to a significant degree by the sequestration of carbon in terrestrial ecosystems comprising soils, croplands, grazing lands and forestlands, if these ecosystems are properly managed.

Adoption of recommended management practices can enhance the soil carbon pool, and improve soil quality and productivity. The opportunities to enhance soil carbon include: increasing the soil organic carbon concentration by applying quantities of biomass to the soil and improving water and nutrient use efficiencies and improving biomass productivity. Soil and vegetation management approaches provide ways of enhancing biomass productivity and returning more biomass both above and belowground to the soil. Losses of soil organic carbon caused by accelerated soil erosion; mineralization and leaching can be arrested. Grazing lands offer similar opportunities for carbon sequestration through improved species, integrated nutrient management and controlled grazing. Restoring degraded soils is an important option to sequester carbon and improve the environment.

Managing forests to increase their capacity for sequestering carbon provides opportunities to offset considerably more carbon dioxide emissions. Reforestation and afforestation present many opportunities. Among these opportunities are the support and fostering of the storage of the emitted carbon dioxide in trees by increasing in situ tree growth, increasing the area planted to forests, increasing use and permanence of forest products, and decreasing the loss of current forests.

These concepts are elaborated in the text that follows, as well as possible avenues for collaboration between government agencies, universities and industry participants in a carbon sequestration initiative.

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PREFACE

The Washington Advisory Group, LLC provides strategic counsel and management consulting to companies, universities, governments, and not-for-profit organizations around the world. Since its founding in 1996, The Advisory Group has largely served clients that are engaged in science, technology, and higher education.

The following paper, prepared by The Advisory Group for the Western Fuels Association and the Greening Earth Society, describes the status of carbon sequestration science and recommends approaches to typical terrestrial biomes that the Western Fuels Association and its industry affiliates might consider to offset their carbon dioxide emissions.

Advisory Group Principal Dr. Robert M. White led the project, assisted by several terrestrial carbon sequestration experts. Dr. White advises on environment, energy, and climate change, and development and management of organizations and research programs. He was President of the National Academy of Engineering from 1983–1995. Previously, he was the first Administrator of the National Oceanic and Atmospheric Administration.

The experts included Norman J. Rosenberg, Ph.D. (Senior Staff Scientist, Joint Global Change Research Institute), Rattan Lal, Ph.D. (Professor, School of Natural Resources, The Ohio State University), and Rosina Bierbaum, Ph.D. (Dean, School of Natural Resources, University of Michigan). The project was staffed by Leslie Ricketts and Elaine Robinson.

We examined the results of key Department of Energy conferences on carbon sequestration, the deliberations of the Intergovernmental Panel on Climate Change, and other references as the basis for this document, which outlines both the potential and the uncertainties of terrestrial biospheric carbon sequestration. In some cases, the references include text written by us that are direct extracts. These are too numerous to identify; selected references are listed in Appendix I. A glossary of terms used in this report and a definition of units of measure are found in Appendices II and III.

Robert M. White

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1.0 INTRODUCTION

Climate warming is expected to follow from the increasing emission of carbon dioxide to the atmosphere. Carbon is accumulating in the atmosphere in the form of carbon dioxide (CO_2) as the result of fossil fuel combustion, land use change, and tropical deforestation.

The Intergovernmental Panel on Climate Change (IPCC)[1] the highly respected international climate analysis group, has projected that the global surface temperature will warm between 1.4-5.8 degrees centigrade in the course of this century as a consequence of the industrial burning of fossil fuels and land use change. The wide spread of temperature projections reflects the broadly different future economic, technological and sociological scenarios used by the panel. Although subject to controversy, recent estimates by James Hansen suggest much lower surface temperature change of 0.75° c + 0.25° c by the year 2050 and 2° c by 2100.[16]

Global surface temperatures have been measured and have increased by approximately 0.6 degrees centigrade in the past century. Observations of the retreat of glaciers, lengthening of the growing season, rising minimum temperatures and other phenomena have been interpreted by many scientists as manifestations of an enhanced greenhouse effect or human-induced global warming.

There is great potential to decrease atmospheric carbon concentrations through biospheric sequestration. Biosphere carbon sequestration can contribute to many ancillary environmental benefits which will redound to the favorable public perception of the Greening Earth Society (GES), such as development of urban forests, greenbelts, reforestation projects, land reclamation, promotion of biomass energy, and greenways. It is important to recognize that there are many carbon sequestration approaches other than in the terrestrial biosphere. For example, research is underway to determine if carbon can be captured at the point of generation and deposited in deep geological strata. Carbon can also be sequestered in the ocean and other bodies of water. This paper does not consider oceanic or geological disposal of carbon.

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One of the major uncertainties in estimating the uptake and longevity of carbon by the terrestrial biosphere is that processes like fire, insect infestations and land use changes are rarely taken into account, and in many cases can slow the rates or even reverse the direction of terrestrial carbon sequestration. Even without these major disturbances, carbon sequestration in terrestrial systems is not permanent, because the stored carbon is released when the plants die, the trees or crops are harvested, or the soil is tilled and subjected to erosional processes.

In recognition of the concern that climate changes such as those projected by IPCC and other sources may occur, the nations of the world met in Kyoto, Japan in 1997 and agreed to a protocol to reduce carbon dioxide and other greenhouse gas emissions. The burden of emissions reductions agreed in the Kyoto Protocol falls on industrialized countries. Developing countries were excused from reducing their emissions for the present. The United States committed to a reduction of emissions of greenhouse gases of 7% below the levels of 1990, when the U.S. emitted about 1.6 gigatons (GT). In view of expectations for the actual energy needs of the U.S. in the 2008-2012 Kyoto target period, it is estimated that such a reduction of carbon dioxide and other greenhouse gas emissions would require approximately a 40% reduction in the use of fossil fuels over what would be expected under a business-as-usual scenario. The impact of such a reduction on the economy of the U.S. in this case could be severe.

The Bush Administration has withdrawn from the Kyoto Protocol citing its expected economic consequences, the fact that only industrialized countries bear the burden, and the continued existence of scientific uncertainties about climate change projections. The Administration has announced steps to slow the increase in U.S. emissions and examine alternatives to mandatory emission reductions. It has focused on the trading of CO_2 emission rights, and opportunities provided by the sequestration of carbon in the biosphere, in the oceans, and in underground geological strata. A strong focus and support of the Administration is for development of energy generation technologies that are less carbon intensive. These will take decades to develop and implement.

The Administration has come forward with alternative proposals for emission reductions as a substitute for those called for in the Kyoto Protocol.[5] The U.S. now proposes that emissions be related to economic

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conditions. Only when the growth of carbon dioxide emissions exceeds the growth of the gross domestic product (GDP) would mandatory emission reductions be required. The focus of actions to reduce emissions would be on the intensity of carbon emissions, i.e. the amount of CO_2 per unit of GDP, rather than the absolute amount of emissions. This alternative U.S. view postulates that economic growth and new technology can rein in the emissions of carbon dioxide and other greenhouse gases. Critics point out that, while decreased energy intensity of GDP is a desirable goal, the likely increase in GDP by the 2008-2012 time period will nonetheless increase overall emissions considerably above what they are today and very much above what they were in 1990. Thus, despite all the attendant uncertainties, strategies must be sought to lower emissions or to mitigate them.

2.0 THE STATE OF THE SCIENCE [3, 6, 7, 8, 17]

The atmospheric concentration of CO_2 has increased by about 32% from approximately 280 parts per million by volume (ppmv) at the beginning of the industrial revolution (ca. 1850) to about 370 ppmv today. More than 8 GT (billion metric tons) of carbon are presently emitted as CO_2 into the atmosphere each year from all sources. The U.S. today contributes about 23% (1.8 GT) of the total global carbon emissions.

Although carbon dioxide is the primary greenhouse gas of concern with regard to global warming, it is also important to recognize that carbon dioxide is the building block of photosynthesis. The process of photosynthesis converts sunlight into energy necessary to convert carbon in the atmosphere into the organic compounds of which trees, grasses and plants, and agricultural crops are constituted. The converted carbon in turn releases carbon dioxide to the atmosphere when trees are cut down and plants and crops of the biosphere are harvested or decay. Elevated CO_2 concentrations stimulate photosynthesis and growth in plants of the kind exhibited by legumes, small grains and most trees and decreases transpiration, or water use. Transpiration of moisture is also reduced in tropical grasses such as maize, sorghum, and sugar cane. Together, these phenomena comprise the CO_2-fertilization effect.[2]

With proper management, terrestrial biosphere carbon sequestration shows great promise for absorbing a significant fraction of the carbon dioxide emissions that result from the combustion of fossil fuels[3,4] and for slowing the rate of climate change. It is a form of carbon storage that can be implemented rapidly. For example, forests have the potential to sequester approximately 0.75 GT of carbon per year on a global basis, a significant fraction of the global carbon dioxide emissions of about 8.0 GT of carbon emitted to the atmosphere. Forest clearing for agriculture and for building and energy use, on the other hand, contribute to the atmospheric carbon dioxide load at the rate of about 1.6 GT of carbon per annum.

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Soil, the repository for decayed plant matter, is by far the largest terrestrial storehouse of carbon, and soil management becomes of central importance. Soil is currently estimated to contain about 70% of all terrestrial carbon. Soil can be a source of carbon by plowing, biomass burning and droughts among others. Management of many of these processes and activities can aid in increasing the capacity of the biosphere to store carbon. As a minimum, terrestrial biospheric sequestration can buy time for other energy technologies to take place that can provide less carbon intensive energy generation.

Carbon dioxide is in continuous exchange between soils and the atmosphere. The balance between carbon input to soils from plant and animal residues and carbon emissions to the atmosphere due to organic matter decomposition, and respiration of the roots and microbes, largely determine the amount of carbon stored in soils. Carbon sequestration generally is effected by: 1) minimizing soil disturbance and erosion; 2) maximizing the return of crop residue to soils; 3) maximizing water and nutrient use efficiencies in crop production; and 4) growing plants with a large capacity to store carbon in above ground and below ground biomass. In fact, the U.S. submission to The Hague Conference of Parties in 1999 noted that most of the carbon offset of about 0.3 GT or about 16% of U.S. emissions were going to be from forests, about 0.02 GT (about 1%) from cropland and about 0.01 GT (about 0.6%) from grazing land. However, the achievable potential from croplands and grazing lands, with adoption of recommended practices, is an order of magnitude higher.[32]

The Department of Energy has formulated 50-year roadmaps for biosphere carbon sequestration. The roadmaps are illuminating for the potential for carbon sequestration in various biomes and also suggest approaches to accomplishing biosphere carbon sequestration. The roadmaps summarize many limitations and uncertainties related to carbon sequestration potential in terrestrial ecosystems.

The roadmaps also call for extensive research. Presently the dynamics of carbon sequestration are not well understood under the varying temperature, moisture and nutrient conditions of a changing climate. Some reverse climate effects need to be considered. For example, increasing organic matter in wetlands could result in higher emissions of the greenhouse gas methane. Conversion of croplands to grasslands, on the other hand, may decrease the emissions of another greenhouse gas, nitrous oxide, to the atmosphere.

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Biomass, which includes trees, crops, grasses, and other plant and animal material above and below ground, has potential as a cleaner partial alternative to fossil fuels. It is a renewable energy source such that the carbon dioxide emitted by biomass when it is burned as a fuel is restored or reconstituted as biomass again. Fossil energy sources emit carbon dioxide that is dispersed for approximately a century into the atmosphere. It may be possible to sequester as much as 0.5-0.8 GT of carbon per year by transforming biomass to biofuels.

There are many approaches to implementing carbon sequestration research and actions. No tillage ("no till") practices return residues to soil and increase the amount of carbon in agricultural systems. Forests cut in eastern North America in the previous century are now being replaced by forest regrowth. The recent estimates indicate that North America might even be an increasing storehouse for carbon at this time. It is important to understand the potential of various approaches and costs of carbon sequestration.

The addition of plant or animal litter to soil provides a myriad of living organisms, such as bacteria and fungi, with the energy and nutrients required for their growth and functioning. Gradually, the plant and animal debris decompose to yield a rather stable brown to black material called "humus." The content of organic carbon soil (SOC) reflects the action and interaction of the major factors of soil formation—climate, vegetation, topography, parent material and age. Soil carbon losses of up to 50% (30 to 40 Mg/ha) have been reported in temperate regions 30-70 years after conversion of forests and grasslands to agriculture. In subtropical and tropical environments, the losses have been as great or greater than those observed under temperate conditions but may occur over a 5 to 20 year period. The loss of soil carbon is estimated at 3 to 5 GT for soils of the U.S. and 66 to 90 GT for soils of the world.[8] A large fraction of this historic carbon loss can be resequestered by adopting recommended management practices and restoring degraded soils.

2.1 THE HISTORICAL CARBON TRAJECTORY

The global organic carbon pool consists of terrestrial, aquatic and atmospheric components. The size of these components varies widely, from ~720 GT in the atmosphere to ~38,000 GT in the deep oceans. Of the approximately 2,200 GT of carbon found on land (1550 GT in 1-m deep soil and 620 GT in the biota), about 70% is in the form of soil organic matter while the remainder is made up of plant and tree matter. The processes of photosynthesis by plants and their respiration determine how much carbon is stored in vegetation, trees, and soils and exchanged annually between the atmosphere and land.

The growth of forests and their management offers one of the most promising sources of carbon sequestration in the biosphere. When Europeans colonized the U.S., the land may have held 110-115 GT of carbon. However, it lost carbon continuously from the time of European settlement until about the turn of the 20th century, as forests were cut and replaced by agricultural land which holds much less carbon. By the 1920's, agricultural expansion had slowed almost to a stop. Since that time, farmland has been slowly declining in areal coverage, wildfires have been suppressed, and brush and forests have re-established on abandoned farmland in the U.S. Between 1700 and 1945, perhaps 27 GT of carbon had been released from land use.[19] However, net sequestration of carbon has been the rule since then, adding a total of about 2 GT to U.S. lands through 1990.[19] Estimates for 1999 indicate that forest ecosystem management and growth in the U.S. were enough to offset 15% of the country's CO_2 emissions.[20] With proper management, forests can continue and can substantially increase their net sequestration of carbon.

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2.2 A GLOBAL CO_2 CONCENTRATION TARGET

The potential importance of carbon sequestration is illustrated in Figure 1. A level of CO_2 concentration of 550 parts per million (ppm) has been suggested as an acceptable target. Many scientists believe that if adopted it is important that the target be achieved at a slow rate of change to allow time for societies and ecosystems to adjust. The figure shows, as an example, one scenario for limiting the atmospheric CO_2 concentration by the end of the century to 550 ppm from its present concentration of 370 ppm. According to this scenario, by the year 2035 carbon sequestration is the dominant mode of limiting the atmospheric accumulation of CO_2, allowing time for energy intensity and fuel mix technology to permit the attainment of the goal of 550 ppm.

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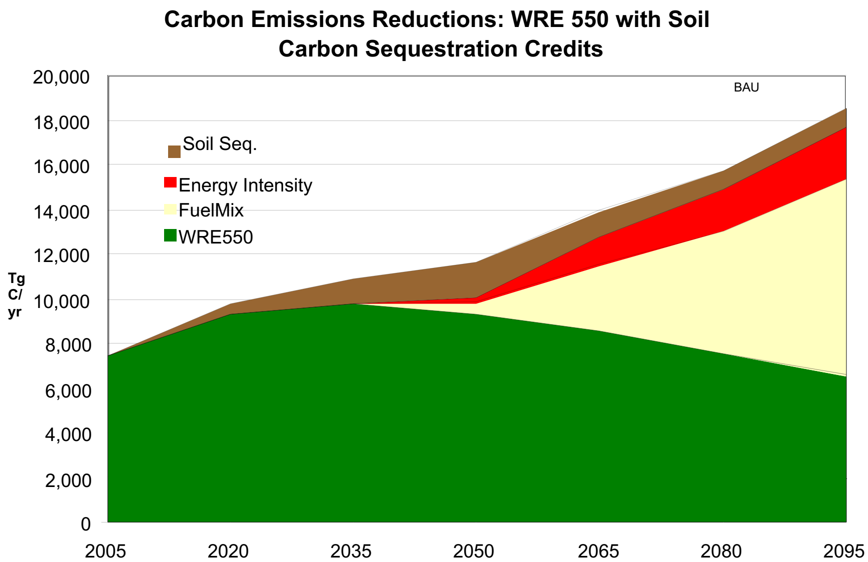

Figure 1. Global carbon emissions trajectories in the 21st century according to the IPCC (1990) business as usual scenario (top line) and the Wigley-Richels-Edmonds scenario (bottom line) required to limit atmospheric CO_2 concentration to 550 ppmv (Wigley et al., 1996). This figure shows a hypothetical path to carbon emission reductions under a scenario in which credit for soil carbon sequestration is allowed. Soil carbon sequestration alone achieves the necessary net carbon emission reduction in the early part of the century. From the middle of the century on, further emission reductions must come from energy system changes such as fuel switching and decreased total energy consumption. (1000 Teragrams (Tg) = 1 Gigaton (GT))

It is estimated that soil carbon sequestration alone could make up the difference between the expected and desired emissions trajectories in the first three to four decades of the 21st century. The calculations shown in Figure 1 are based on the assumption that in the twenty-first century, agricultural soils will sequester carbon at global annual rates ranging from 0.4 to 0.8 GT, with rates twice as great in the initial years and half as great in the later years.

It is further assumed that the potential of soil carbon sequestration is realized without additional net cost to the economy — not unreasonable in view of the known benefits of organic matter in soils. Additionally, by allowing time for new technologies to be developed and for existing facilities to live out their design lifetimes, the costs of an avoided ton of carbon emissions during the next century can be cut approximately in half.

3.0 MANAGING SOILS, CROPLANDS AND GRAZING LANDS FOR CARBON SEQUESTRATION [2, 8, 9, 10, 11, 12, 13, 18]

Soil carbon sequestration depends on the amount of crop/forage residue and other biosolids applied to the soil. The amount of carbon in the soil increases in direct proportion to its residence time. The carbon sequestration potential of agricultural ecosystems is primarily centered in the soil. Historically, grasslands have been converted to croplands and have suffered a net loss of carbon, following conversion of the native ecosystem to croplands. An estimate of the relative global potential in 2010 in carbon stocks through improved management and land use change is shown in Table 1.

Table 1. Global potential in 2010 for net change in carbon stocks through improved management and land use change [36]

Activity	Area Mha	Assumed area in activity by 2010 (%)	Estimated net change in C stocks in 2010 GT per year
Cropland management	1300	30	.125
Grazing land management	3400	10	.240
Cropland to grassland	1500	3	.038
Restoring severely degraded lands	280	5	.003

Improved land management has the potential to sequester about 0.4 GT per annum by 2010.[31]

As a first approximation, it appears that a potential exists to offset significant amounts of CO_2 emissions by sequestering carbon in the soils of lands now in agricultural production. This may provide enough capacity given dedicated management, to hold the atmospheric CO_2 rise to a trajectory consistent with 550 ppmv described earlier for a few decades. There is additional carbon sequestration potential in the soils of managed forests, grasslands and degraded and desertified lands (discussed elsewhere in this report).

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Improved management of croplands, grazing lands, and soils in recent years seems to have stabilized the overall carbon levels and these levels have begun to rise.[35] These changes are attributable to reduced tillage intensity; genetically induced productivity increases and increased inputs of fertilizers, pesticides and irrigation. These specific inputs have hidden carbon costs,[33] and with indiscriminate use can be potentially harmful to the environment. Other management practices include increased crop rotation and set-asides of marginal croplands for perennial vegetation.

Pasturelands have the greatest opportunities for increasing soil carbon with improved practices such as planting appropriate species, rotational grazing and application of fertilizers. Rangelands are principally managed by manipulating grazing intensity. Opportunities to increase soil carbon on extensively managed pasture lands should be based largely on restoring degraded, poorly managed areas through control of invasive species, elimination of severe overgrazing and active restoration of severely degraded rangelands.

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An important objective in managing croplands and grazing lands is to reduce decomposition. Many grass and crop species have slow decomposition rates at cooler temperatures. Soil organic matter typically shows longer life with greater depth due to the lower rates of decay at depths associated with lower temperatures. Thus developing and using deeper rooting plants can increase the soil carbon pool. The rates of soil carbon sequestration with no-till farming range from 200 in the dry and warm regions to 600 kg/ha/yr in humid and cold regions. These rates can be higher (300 kg/ha/yr to about 1 Mg/ha/yr) with incorporation of appropriate cover crops in the rotation cycle. As previously indicated, development of reduced or zero tillage systems for a wider variety of crops and environments is an important strategy, recognizing that the benefits of no-till agriculture begin to disappear upon cessation of the practice.

Grazing lands comprised of pasture and rangelands represent the largest and most diverse single land resource in the U.S. and in the world. Grazing land comprises more than half of the land surface in the world and 55% of the total land in the U.S. As with croplands, the magnitude of the carbon input to the soil in grazing lands depends on several management approaches such as residue management, fertilization and manuring, stocking rate, and controlled burning. Soils under grazing management have more soil organic carbon than those under cropping. This can be attributed to the lower frequency and intensity of soil disturbance.

3.1 OPPORTUNITIES FOR SOIL CARBON SEQUESTRATION IN CROPLANDS AND GRAZING LANDS[9, 32]

There are numerous opportunities for increasing soil the carbon pool in croplands. The strategy is to adopt recommended management practices that lead to intensification of agriculture. Recommended management practices involve maximizing use efficiencies of all inputs (e.g., energy use, fertilizer and chemical use, irrigation etc.). The objective is to conserve soil and water and recycle nutrients, and minimize losses due to erosion, leaching, volatilization and evaporation. These objectives are achievable through adoption of mulch farming techniques, including no till or conservation tillage, integrated nutrient management and precision farming, and use of cover crops in the rotation cycle. Specific options for carbon sequestration in croplands are discussed below.

Increase the soil organic carbon concentration or density: The soil organic carbon concentration can be enhanced by applying large quantities of biomass to the soil and improving water and nutrient use efficiencies. Agricultural practices that return biomass to the soil include mulch farming, conservation tillage, use of composts and farmyard manure. Crop rotation, agro-forestry systems, and application of bio-solids to the soil also increase soil organic carbon. The degree of soil disturbance through tillage operations adversely impacts soil aggregation, exacerbates residue decomposition and reduces the ultimate retention of carbon in soil. In this context, no-till agriculture, among the most significant technological innovations of the last thirty years, allows farmers to grow crops economically while reducing erosion and improving both quantity and quality of soil organic material (SOM). Conversion of plow till to no till, in combination with growing cover crops and applying farmyard manure or compost, has a large potential to sequester carbon in cropland soils.

Agricultural practices that return biomass to the soil include mulch farming, conservation tillage, use of composts and farmyard manure.

Improve biomass productivity: Soil and vegetation management practices could be adopted as a way of enhancing biomass productivity and returning more biomass, both above and belowground, to the soil. Deep-rooted cover crops and forages (e.g., alfalfa, switch grass, fescue) increase carbon pool in the sub-soil[34] enhances the organic carbon pool in the subsoil. Judicious application of essential nutrient elements such as nitrogen, phosphorous and zinc is crucial to enhancing the soil organic pool through improvements in humification efficiency of the residue returned to the soil.

Addition of nutrients to soil via fertilizers, whether organic or synthetic, is essential for maintaining or improving soil fertility and, hence, soil organic matter. Integrated nutrient management (INM) and precision farming or soil-specific management are critical to soil carbon sequestration.

Restore degraded soils of ecosystems: A clear opportunity also exists in restoring degraded soils of ecosystems. This is an important strategy to resequester part of the soil organic carbon that has been depleted by land misuse and soil mismanagement. There are a number of techniques that could be used for restoring degraded soils and ecosystems. Important among these are establishing vegetation cover for erosion control, conservation tillage, mulch farming, establishing winter cover crops, and eliminating summer fallow. Increasing soil fertility and replenishing depleted nutrients through judicious application of fertilizers, integrated nutrient management, biological nitrogen fixation, manuring and recycling of nutrients through application of bio solids are among the numerous options.

A clear opportunity also exists in restoring degraded soils of ecosystems.

Attempts at restoring mined soils have increased the rate of soil organic carbon significantly and may be an appealing opportunity to WFA. One way in which this can be done is by the application of municipal sewage to mined lands. One of the techniques in restoring eroded and drastically mined soils can be to sow them with fast growing trees and grasses which, in addition to sequestering carbon in soil, also have the potential of being used as a bio-fuel. Such bio-fuels can be burned directly in many power plants. Large areas of highly eroded lands can be converted to bio-fuel plantations.

Opportunities in grazing lands include: growing species with high biomass productivity and deep root systems, controlled/rotational grazing with low stocking rates, and the management of soil fertility and fire frequency. The restoration of degraded soils such as those that are eroded or mined are important strategies for enhancing biomass production and sequestering soil carbon. It should be noted that fire management is important because controlled burning can improve biomass production and excessive intense fires can acerbate losses and adversely affect productivity. Rangelands also have a potential of sequestering inorganic carbon as secondary carbonates. Soil biotic processes accentuate biosequestration of carbonates.

Growing improved species of grasses: An opportunity for a generic pilot project could include growing improved species of grasses on rangelands in the western U.S. Mesquite continues its century-long invasion of the degraded rangelands in this region. As a woody shrub, mesquite can sequester more carbon in soil and biomass, yet replacing mesquite with herbaceous grasses is an important strategy to improve rangeland quality, biomass productivity, and sequestering of carbon. There are many grasses that are suited for these environments.

Convert to bio-fuel plantations: Opportunities also exist in other generic projects. Rangelands that have become deserts in the western U.S. can be converted to bio-fuel plantations by growing drought tolerant trees. The strategy would be to plant multipurpose trees for shelter, windbreaks, and bio-fuel production and thus increase carbon sequestration. A number of tree varieties can be converted to fast growth, such as neem, leucaena, acacia, gumtree, casurina, cassia and tamerisk though their requirement for irrigation water may be a concern.

The potential for soil carbon sequestration depends upon the choices of land use, the soil, and crop and vegetation management. It should be noted that the rate of soil carbon sequestration is a function of the large variability in the soil profile characteristics, such as moisture and temperature regimes, land uses, and other uncertainties. The potential of the soil as a sink for carbon depends on numerous soil factors and ecosystem characteristics. Important among these characteristics are the clay content and mineralogy of the soil, the availability of water and nutrients, the effect of rooting depth and mean temperature, precipitation and growing degree-days.

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Ultimately an individual farm would need a monitoring and evaluation system. Detailed soil maps of the farm would need to be developed and changes in soil carbon would need to be measured or estimated using remote sensing and GIS (Geographic Information Systems) technologies. At the landscape scale involving multiple farms, it would be necessary to establish rates of soil organic carbon sequestration for principal soil types. The rates of soil organic carbon sequestration would need to be checked at a few locations. Use of remote sensing techniques involving aerial photography and satellite imagery and use of soil management practices would assist in estimating the soil organic carbon pool. Using solid agricultural practices, the potential for carbon sequestration on croplands in the U.S. is about 0.08-0.2 GT of carbon per year and on U.S. grazing lands is about 0.02-0.09 GT of carbon per year. [32, 9] The restoration of degraded lands would contribute significantly to the carbon sequestration.

There is also a potential for sequestration of inorganic carbon in rangelands and irrigated lands in arid and semi-arid regions of south and southwestern USA. The potential of inorganic carbon sequestration as secondary carbonates is more in irrigated ecosystems, especially if the irrigation water is of a high quality and contains low salt concentration. The formation of secondary carbonates is accentuated in management systems that also receive biosolids (e.g., compost, manure).

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4.0 MANAGING FORESTS FOR CARBON SEQUESTRATION

Forests cover about one-third of the U.S., totaling about 750 million acres. There are many different types of forests, stretching from the subtropical forests along the Florida coast to the boreal forests in Alaska, and from the deciduous forests in the eastern U.S. to the conifer forests of the West. The growth of forests and their management offers one of the most promising sources of carbon sequestration in the biosphere.

The concept of offsetting carbon dioxide emissions by sequestering the CO_2 in forests is not new. The IPCC thoroughly reviewed the available literature on the concept in 1995[21] and again in 2000.[22] Those reviews concluded that globally, changes in forest management could induce future carbon sequestration adequate to offset an additional 15-20% of CO_2 emissions. Forest management can clearly play a substantial role in increasing carbon storage in forests. For example, the biomass density has nearly doubled in eastern U.S. forests since the early 1950's, attributable in large part to the trend toward managed growth on private lands.[20]

The concept of offsetting carbon dioxide emissions by sequestering the CO_2 in forests is not new.

Forests in the U.S. stored about 38 GT of carbon in 1997.[20] They sequestered a net of approximately 0.9 GT of CO_2 in 1999. Perhaps, more importantly, carbon stored in forests is much more easily maintained for a long-term of many years.

Conversion of forestlands to non-forest use reduces reforestation potential. The conversion of forestlands to non-forest use usually means permanent loss of all or a substantial part of the biomass and a reduction of organic matter in the soils of the forest floor. Finally, sequestration can be increased in wood and paper products depending on how these products are made, used and disposed of. Specifically the objectives must be to increase and maintain the area of forest cover, maximize biomass accumulation, and maximize the average standing stock of biomass.

A rapidly growing forest in temperate regions absorbs on average 2.24 Mg of carbon per hectare per year (1 ton per acre per year).[22] Clearly, this annual uptake of carbon varies greatly from year to year, depending on weather and the developmental state of forests, and from place to place, depending on the character of the forests and soils. For example, from one year to the next, uptake of carbon by U.S. forests has been estimated to vary by 100%,[23] from less than 0.1 GT to over 0.2 GT/year (approximately 0.4-0.7 GT of CO_2) between 1980-1993. The uptake of carbon increases from "0" at forest establishment to a maximum annual increment which ranges from to 1.6 Mg per hectare, 35-40 years after planting in the Rocky Mountains, to 4.5 Mg per hectare, 20-25 years after planting in the south central U.S.[24] Young trees take up carbon at the fastest rate, but older trees hold more total carbon.

4.1 OPPORTUNITIES FOR INCREASING CARBON SEQUESTRATION IN TREES AND FORESTS

The most successful tactics for sequestering and retaining increasing amounts of carbon from the atmosphere in forests vary widely with the types of trees. Favorable opportunities for management actions follow:

Increase in *situ* tree growth. Opportunities include the common forest management techniques aimed at increasing wood production. Forest thinning and selective harvesting, by removing small stems at several different developmental ages, permits the remaining trees to grow much larger, and forests of large trees store more carbon than forests of small trees. In addition, thinning removes "ladder fuels" which permit small, smoldering ground fires to climb into the forest canopy and become intense, stand-destroying fires, which release carbon already stored. The addition of nitrogen fertilizers, especially in nitrogen-poor evergreen forests, also increases forest growth and carbon storage, in the U.S., up to 0.45 Mg of carbon/hectare/year.[25] In all, Nabuurs et al. (2000)[28] calculate the annual forest increment could be enhanced by 25% with these techniques.

Thinning removes "ladder fuels" which permit small, smoldering ground fires to climb into the forest canopy and become intense, stand-destroying fires, which release carbon already stored.

Increase area planted to forests. This set of opportunities involves increasing the incentives to shift current non-forest land uses to forests, and rapid reestablishment of forests following harvests. The amount of wastelands and marginal agricultural lands increases in the U.S. every year, as new techniques produce greater crop yields, and as the focus shifts to the best croplands. The planting of forests of rapidly growing species, such as aspen, for either carbon storage or for harvest as biofuels can sequester up to 4.5 Mg of carbon/hectare/year on these lands.[25]

In many cases, planting along riparian areas can reduce erosion and flooding while cultivating a fast growing biomass tree crop such as poplar. Another approach to this problem is to grow trees at the same location as crops are being grown, that is, the practice of agro forestry. Although it is most extensive in tropical areas, agro forestry is practiced as far north as the Arctic Circle. Many pasture and crop plants of temperate regions can be cultivated in plantations of widely-spaced trees with little loss in crop productivity, and with potential eventual carbon storage of 13.4 - 179.2 tons of carbon/hectare.[25] Obviously the utility of all these afforestation efforts to carbon sequestration can be significant as well as profitable. The creation of tax incentives at local and state levels for planting forests, and for retaining planted forests could be key to implementing these strategies.

...planting along riparian areas can reduce erosion and flooding while cultivating a fast growing biomass tree crop such as poplar.

Increase use and permanence of forest products. These strategies are centered on encouraging greater use of forest products, in the expectation that some of the uses will more permanently store carbon (e.g., substitution of wood for other building materials), some will substitute directly for fossil fuels (e.g., use of biofuels), and all will be followed by forest replanting to continue taking up atmospheric carbon. The substitution of forest products for aluminum, steel, concrete and brick has the added advantage of reducing the fossil fuel use expended in production of these latter raw materials. This indirect effect on carbon sequestration can be greater than the effect of the carbon stored directly in the wood products.

The substitution of biofuels for fossil fuels, based on crops (sugar cane in Brazil, corn in the U.S.) and wood products, may potentially replace up to 3.5 GT/year of fossil fuels by 2050.[25] The use of short rotation woody crops for both construction and biofuels could average 0.3 GT of carbon/year in the U.S. prorated over a 50 year period of such projects, with 75% of the carbon sequestered from fossil fuel displacement rather than from direct carbon sequestration.[26]

Decrease losses of current forests. The 20th century in the U.S. is characterized by growth of forests on lands freed from agricultural uses, and a lesser decrease of forests as they are replaced by urban and suburban uses. Indeed, during the period from 1990 to 1999, net annual carbon sequestration in the U.S. averaged approximately 0.3 GT, but the rate of annual sequestration declined by about 10% from increasing harvests and land use changes.[22] One means to reduce the loss of forests is to increase the rotation period of forests, such that forests harvested every 30 years are retained for 40 or even 50 years. This technique alone can add about 0.45 additional Mg of carbon/hectare/year.

Other opportunities. Techniques to reduce the impact on carbon stocks of forest harvests, by "low impact forestry" need to be adopted. These techniques range from selective harvests that leave large trees and a large portion of the forest community behind, to minimizing disturbance to soil and the remaining vegetation.[22]

Another approach aims at reducing losses to common forest disturbances such as wildfire and pest infestations. During the past 10 years, an average of 1.34 million hectares of forests have burned in the U.S.,[27] releasing about 0.2 GT of CO_2 in the year 2000, alone. Nabuurs et al. (2000) calculate these disturbance losses at about 60% of the annual carbon increment. Fire losses can be reduced by enhanced fire suppression, and by increased removal of accumulating fuels.

Similarly, pest management techniques can reduce losses to forest pests which kill thousands of acres of trees in the U.S. every year, resulting in emission of the carbon stored there over the subsequent several years and decades. The two kinds of disturbances are related; large, stand-replacing fires are much more likely where insects have killed large portions of the forest, while fire damages to individual trees provide entry points for the build-up of pest populations to epidemic levels.

...pest management techniques can reduce losses to forest pests which kill thousands of acres of trees in the U.S. every year...

5.0 CARBON SEQUESTRATION RESEARCH

Carbon restoration involves a search for ways to effect greater, more rapid, and longer-lasting sequestration. Promising lines of research are evolving in coordinated research activities such as CSiTE (Carbon Sequestration in Terrestrial Ecosystems) and CASMGS (Consortium for Agricultural Soils Mitigation of Greenhouse Gases) that could lead to an improved understanding of soil carbon dynamics and the subsequent development of superior carbon sequestration methods.

Carbon restoration involves a search for ways to effect greater, more rapid, and longer-lasting sequestration.

CSiTE is a research consortium established by the U.S. Department of Energy's Office of Science - Biological and Environmental Research to discover acceptable methods to enhance carbon sequestration in terrestrial ecosystems. CASMGS is a university-based consortium sponsored by the U.S. Department of Agriculture to provide the information and technology necessary to develop, analyze and implement carbon sequestration strategies

CSiTE and CASMGS research underway seeks, among other objectives:

- To improve the understanding of the mechanisms of carbon stabilization and turnover in soil aggregates;
- To improve the description of the various carbon pools and the transfer among them to allow more realistic modeling of the dynamics of soil organic matter;
- To improve understanding of landscape effects on carbon sequestration and how it might be controlled through precision farming;
- To apply genetic engineering to enhance plant productivity and to favor carbon sequestration;
- To improve understanding of the environmental effects of soil carbon sequestration on erosion, nutrient leaching, and emissions of other greenhouse gases; and
- To develop mechanisms to estimate and verify changes in soil carbon and greenhouse-gas emissions that result from changes in land use and management, and in the context of likely changes in policy and land use.

Improving carbon sequestration in forests implies a large number of research and development needs. Participants in a terrestrial carbon sequestration initiative could become involved with the government in supporting such work. The opportunities range from developing genetically improved plantation species to maximize wood growth and density, to the development of silviculture practices to maximize biomass accumulation. Some of these practices include stocking control, management and proscribed burning. Another facet of research and development activities involve the enhancement of wood and paper product characteristics that increase sequestration and a better understanding of the attraction between natural disturbances and management practices and forest protection. In addition, there are many belowground carbon increases that could benefit from research and development. Finally, there is the assessment of the impact of changes that might result from adoption of various strategies on ecosystem functions, as well as evaluating the risk of disturbances to forests from fires, pests and climate change.

Improving carbon sequestration in forests implies a large number of research and development needs.

6.0 ECONOMIC OPPORTUNITIES

Agricultural and rangeland practices should be weighed and include estimates of energy use and carbon emissions for primary fuels, electricity, fertilizers, lime, pesticides, irrigation, seed production, and farm machinery. Thus, a net carbon sequestration value can be calculated by subtracting the carbon cost associated with the alternative production methods from the gross soil carbon sequestration calculated from direct measurements. Finally, a marginal analysis should be conducted to compare the carbon cost of the alternative practice with that of the conventional one. This type of analysis should be comprehensive and include the global warming potential of other gases released or absorbed by agricultural fields such as nitrous oxide and methane. There are examples in the literature of this type of analysis but much more remains to be done for an effective evaluation of agricultural practices with regard to carbon sequestration.

One estimate of the economic value of soil carbon sequestration is displayed in Figure 2 below, which, for the stabilization case shown in Figure 1, indicates that soil carbon sequestration alone can reduce present discounted costs by nearly 45%.

The enhanced sequestration of carbon in forests is a potentially effective means to reduce the impacts of increasing greenhouse gas concentrations on climate, ecosystems and human activities. These impacts have their own costs and benefits, recently estimated by UNEP at a net loss of several hundred billion dollars per year. However, implementing the techniques and approaches to enhancing carbon sequestration in forests, as in the examples mentioned above, can also be profitable in terms of economic, ecologic, and human concerns. Creation, growth, and preservation of forests not only preserves land from erosion, and protects valued species of plants and animals, but also maintains the trees that remove particulate and gaseous pollutants from the atmosphere, and that sustain the watersheds from which the majority of Americans derive their fresh water supplies.

The enhanced sequestration of carbon in forests is a potentially effective means to reduce the impacts of increasing greenhouse gas concentrations on climate, ecosystems and human activities.

These ecosystem services have direct, substantial economic value. Substituting wood products for other raw building materials can reduce building costs, as well as reducing use of fossil fuels. Reduction in forest disturbances through pest and fire management techniques enhances the economic value of forest products, and reduces the high costs of suppressing fires and pest epidemics, which are usually much more expensive than the management techniques needed to avoid the disturbances. In short, enhanced carbon sequestration in forests is simply good business sense.

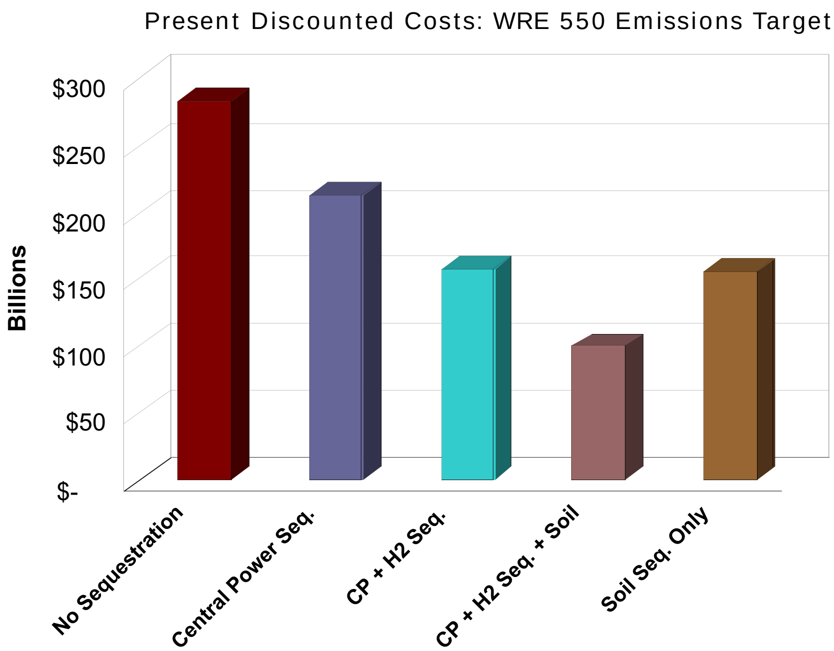

Figure 2. Present Discounted Costs: WRE 550 Emissions Target. This figure compares the present discounted costs (from now to 2100 at 5%/yr) of meeting the WRE 550 carbon emissions constraint under various assumptions about the possibility of carbon sequestration, as determined from a hypothetical scenario from the MiniCAM model. The cases shown from left to right are: no sequestration considered; sequestration of CO2 captured at sites of central power production (CP); CP plus hydrogen fuel production (H2); CP + H2 plus soil carbon sequestration (SCS) and SCS only. Soil sequestration alone could reduce the discounted costs by about 45%.

6.1 ACTIONS NOW UNDERWAY

Despite uncertainty on many levels, soil carbon sequestration projects are underway. Some utilities and other emitters of greenhouse gases, anticipating a future in which reductions in CO_2 emissions may be mandatory, already are searching for cost-effective ways to offset or otherwise meet imposed limits. Transactions already are being made: in October 1999, the Trans Alta Corporation, a member of the Greenhouse Emissions Management Corporation (GEMCo, an association of energy utilities in Western Canada), announced an agreement to purchase up to 0.003 GT of carbon emission reduction credits (CERCs) from farms in the U.S. The IGF insurance company has solicited the CERCs from eligible farmers or landowners in Iowa.

Despite uncertainty on many levels, soil carbon sequestration projects are underway.

On 15 January 2002, members of the Pacific Northwest Direct Seed Association (PNDSA) agreed with the utility corporation Entergy to hold carbon in soil accrued as a result of no-till practices and receive, in exchange, a certain monetary compensation for their services. The non-profit environmental organization Environmental Defense has agreed to facilitate this agreement. The lease agreement transfers the liability of emitting CO_2 from the energy company to the farmer for 10 years. During this period, the utility has voluntarily committed to develop or adopt other forms of carbon sequestration or to reduce CO_2 emissions in some other way.

The electric utility industry's ongoing efforts were reported by the Energy Information Administration in its report of February 2002.[14] The Energy Information Report indicates that some electric utilities are presently voluntarily involved in carbon sequestration projects by afforestation and reforestation. The efforts involve urban forestry projects as well as those in rural or wilderness areas. The number of reported projects has increased from 78 to 494 between 1994 and 2000 and resulted in about .01 GT of carbon dioxide being sequestered in the year 2000.

7.0 OPPORTUNITIES FOR A CARBON SEQUESTRATION INITIATIVE

A host of opportunities as described in the previous sections present themselves for consideration. Capitalizing on the opportunity for offsetting carbon emissions from fossil fuel generating plants through terrestrial biosphere carbon sequestration offers considerable opportunity for a carbon sequestration initiative. As indicated earlier, this may buy the time necessary to adopt new technologies that can make operations more cost effective and also reduce the carbon intensity of energy generation activities. The Association and its utilities are in an excellent position to move ahead almost immediately with attempts to offset carbon dioxide emissions through approaches to terrestrial biosphere carbon sequestration. Approaches to carbon sequestration explained in previous sections of this report are well known. The uncertainties can be resolved over time by joining with government and other interested agencies to support key research activities.

The possibility that carbon may become a tradable commodity has not gone unnoticed in the agriculture and forestry communities. Beneficial land-management practices might be encouraged if a market develops through which farmers are rewarded for employing practices that increase carbon stores on agricultural lands. But uncertainty about costs, benefits, and risks of new technologies to increase carbon sequestration could impede adoption. To address farmers' reluctance to adopt carbon sequestration practices, financial incentives could be used to encourage practices such as conservation tillage. Government payments, tax credits, and/or emissions trading within the private sector also could be employed.

A program could be formulated consisting of both research and actual implementation. The program should be easily understandable by farmers, rangeland and forestry managers, by adopting a program title such as "Reducing Climate Warming Through Agriculture and Forestry" and clear objectives. The objectives also need to be easily grasped by the general public, the Administration, the Congress and the press. All of these sectors must be enlisted to foster the program of a carbon sequestration initiative.

A program could be formulated consisting of both research and actual implementation.

The program would have other benefits besides increasing biosphere carbon storage capacity to offset emissions. The program could serve to enlist the aid of organizations that have hitherto been deeply concerned about carbon dioxide emissions and climate warming. Such a program could seek to enlist the active assistance of other environmental organizations. Such a program would serve to cement relations with representatives in state and federal government.

The companies of the Greening Earth Society, Center for Energy and Economic Development, and the Western Fuels Association may wish to emulate the actions of other energy companies. Some have begun to report their carbon emissions and their plans to reduce them to shareholders and the public in “social accountability” or “sustainability” reports. One energy company, Royal Dutch/Shell, will include its environmental sustainability report with its annual report for the first time this year. Shell’s report will supposedly show a reduction in carbon emissions of 10 percent from 1990 levels.[29] British Petroleum CEO John Browne announced recently in a speech at Stanford University a similar goal.[30]

It is visualized that a carbon sequestration initiative could consist of two parts: the first would be devoted to research to reduce the uncertainties that presently exist in terrestrial biospheric carbon sequestration. The research program will have to be very broad based. It will have to include both basic and applied theoretical laboratory and field-based research. It will be necessary to have some reasonably early field scale investigations. Such research could be done in conjunction with the extensive program now sponsored by the federal government through the Departments of Energy, Agriculture and other agencies. Specific projects in other fields jointly sponsored by the private sector and the U.S. Government have been successful, for example by the Electric Power Research Institute (EPRI).

The second element of the program would be implementation, where the operating utilities working in conjunction with the Department of Agriculture and specialists from the university community could fund demonstration projects to illustrate to farmers, rangeland managers and foresters the benefits of taking certain management steps to increase sequestration of carbon in soils as well as carbon in the biosphere, in general.

APPENDIX I

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APPENDIX II

GLOSSARY

Afforestation: Planting of new forests on lands that have not been recently forested.
Biofuels: Liquid fuels and blending components produced from biomass (plant) feedstocks, used primarily for transportation.
Biomass: Materials that are biological in origin, including organic material (both living and dead) from above and below ground, e.g., trees, crops, grasses, tree litter, roots, and animals and animal waste.
Carbon sink: A reservoir that absorbs or takes up released carbon from another part of the carbon cycle. The four sinks, which are regions of the Earth within which carbon behaves in a systematic manner, are the atmosphere, terrestrial biosphere (usually including freshwater systems), oceans, and sediments (including fossil fuels).
Deforestation: The net removal of trees from forested land.
Emissions: Anthropogenic releases of gases to the atmosphere. In the context of global climate change, they consist of radiatively important greenhouse gases (e.g., the release of carbon dioxide during fuel combustion).
Emission reduction: A decrease in annual greenhouse gas emissions.
Fossil fuel: An energy source formed in the Earth's crust from decayed organic material. The common fossil fuels are petroleum, coal, and natural gas.
Fuel cycle: The entire set of sequential processes or stages involved in the use of fuel, including extraction, transformation, transportation, and combustion. Emissions generally occur at each stage of the fuel cycle.
Greenhouse effect: The result of water vapor, carbon dioxide, and other atmospheric gases trapping radiant (infrared) energy, thereby keeping the Earth's surface warmer than it would otherwise be. Greenhouse gases within the lower levels of the atmosphere trap infrared radiation that would otherwise escape into space, and subsequent re-radiation of some of the energy back to the Earth maintains higher surface temperatures than would occur if the gases were absent. See Greenhouse gases.
Greenhouse gases: Those gases, such as water vapor, carbon dioxide, nitrous oxide, methane, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride, that are transparent to solar (short-wave) radiation but opaque to long-wave (infrared) radiation, thus preventing long-wave radiant energy from leaving Earth's atmosphere. The net effect is a trapping of absorbed radiation and a tendency to warm the planet's surface.
Intergovernmental Panel on Climate Change (IPCC): A panel established jointly in 1988 by the World Meteorological Organization and the United Nations Environment Program to assess scientific information related to climate change and to formulate realistic response strategies.
Ozone: A molecule made up of three atoms of oxygen. In the stratosphere, ozone occurs naturally and provides a protective layer shielding the Earth from harmful ultraviolet radiation. In the troposphere, it is a chemical oxidant, a greenhouse gas, and major component of photochemical smog.

Photosynthesis: The manufacture of carbohydrates and oxygen by plants from carbon dioxide and water in the presence of chlorophyll, with sunlight as the energy source. Carbon is sequestered and oxygen and water are released in the process.
Reforestation: Replanting of forests on lands that have recently been harvested.
Sequestered carbon: Carbon that is removed from the atmosphere and retained in a carbon sink (such as a growing tree) or in soil.
Sequestration: The fixation of atmospheric carbon dioxide in a carbon sink through biological or physical processes, such as photosynthesis.
Sink: See Carbon sink.

The entries above were excerpted from the Voluntary Reporting of Greenhouse Gases 2000 report (February 2002) published by the Energy Information Administration, Office of Integrated Analysis and Forecasting, U.S. Department of Energy, Washington, DC. www.eia.doe.gov/oiaf/1605/vrrpt/pdf/0608(00).pdf

APPENDIX III

UNITS OF MEASURE

GT = gigaton = petagram = 1000 MMT= 1 billion tons

Mg = million grams

MMT = million metric tons

MMTC = million metric tons of carbon

MT = metric ton = 1000 kg = 1 Mg

Pg = petagram = 10^{15} g = 1000 MMT = GT

Tg = teragram – 10^{12} g

Ha = hectare = 10,000 square meters = 2.47 acres

C = carbon – comprises 12/44 of the mass of carbon dioxide (CO_2); thus to convert from CO_2 equivalent to C equivalent, one multiplies by 12/44 (0.273). In this paper, emissions are expresses in terms of gigatons (GT).

Metric (SI) multipliers

Prefix	Abbreviation	Value
Giga	G	10^9
Mega	M	10^6
Kilo	k	10^3