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REDUCING GLOBAL WARMING THROUGH FORESTRY AND AGRICULTURE

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PLAIN ENGLISH GUIDE
4

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Plain English Guide No. 4

Reducing Global Warming Through Forestry and Agriculture

BY STEVEN R. SCHROEDER, PH.D. AND KENNETH GREEN, D.ENV.

Executive Summary

Elevated levels of carbon dioxide and other “greenhouse” gases may be contributing to higher global average temperatures in recent years, a trend frequently referred to as global warming. Some scientists predict that such warming could increase sea levels, stimulate weather that is more violent, alter patterns of disease, and have other potentially damaging effects. Carbon, a constituent of all the main greenhouse gases, is believed to play a pivotal role in the regulation of the earth’s temperature.

The major human activities that cause greenhouse gases to build up are the burning of wood and fossil fuels, and changes in land use that result in fewer plants capturing less carbon dioxide from the atmosphere. Since the beginning of the industrial revolution (around 1750), carbon dioxide in the air has risen more than 30 percent, from 278 to 368 parts per million, and other carbon-containing greenhouse gas concentrations have increased even more. Methane concentrations, for example, have risen by nearly 120 percent since the beginning of the 19th century, from approximately 790 parts per billion in 1850, to the present level of over 1,725 parts per billion.

Concerns over potentially negative effects of prolonged global warming have stimulated interest in restraining the buildup of greenhouse gases in the atmosphere. Proponents of immediate action favor measures aimed at slowing or stopping the buildup of greenhouse gases by using less fossil fuel, or using it more efficiently. An alternate approach that is gaining more attention shifts the focus away from slowing generation of greenhouse gases to removing greenhouse gases from the atmosphere and storing, or “sequestering,” them in a variety of ways. This study focuses on those efforts.

Advocates of sequestration point to numerous benefits of this approach, including lower costs of carbon dioxide control, reduced impact on lifestyles of people in developed countries, and greater ability to achieve domestic greenhouse gas reductions without transferring wealth or technology abroad.

There are three major ways to store additional carbon in forests (including soil):

1. *Preventing Long-term Deforestation.* In some cases, forested areas are harvested but not replanted, or land is converted to non-forestry or non-agricultural use. This limits the Earth's natural ability to regulate greenhouse gases, including carbon dioxide. This can be offset by reducing long-term or permanent deforestation.
2. *Increasing Tree-planting.* More trees can be planted on marginal land, such as less-productive agricultural land. This directly removes additional carbon dioxide from the atmosphere, and locks it away in the woody tissue of the trees.
3. *Improving Forest Management.* Advanced forest management practices can be adopted more quickly and uniformly, particularly in developing countries where they have not yet taken hold. With such techniques, forests can be managed for long-term health and carbon storage as well as for wood production.

Carbon can also be stored in agricultural soils, which can retain as much carbon as forest soil. Practices that maximize both plant growth and carbon-retention in soils (called conservation tillage) can be used for cotton and most grain crops. Specific conservation-tillage practices that can increase carbon-retention by agricultural soils include:

1. *No-till Cultivation.* Tilling agricultural soils liberates trapped carbon, and is not always necessary for crop cultivation.
2. *Maximizing Carbon Retention Through Fertilizer and Herbicide Use.* Changing the way that fertilizers and herbicides are used can alter the way that agricultural soils store carbon-bearing matter underground, maximizing the retention of carbon.
3. *Planting of "Cover Crops."* Fields with fewer cover crops are more likely to undergo degradation of sub-surface carbon-bearing. Cover crops can be planted on "fallow" agricultural lands to preserve soil nutrients and carbon content between primary crop periods.

Many farmers are already adopting these practices to achieve higher production (and usually lower costs), allowing additional marginal land to be retired and reforested.

Finally, some forest and agricultural land can be used to grow trees and crops for "biomass." Biomass is a term used to encompass the many different types of carbon-bearing plant matter that are not ultimately used for food production. Biomass includes unusable portions of agricultural crops, such as crop stubble, wheat stalks, and corn stalks. Biomass can be burned directly, or can be converted to fuels such as methanol, and has the potential to replace a significant amount of petroleum-derived fossil fuels.

While burning fossil fuels such as oil and coal adds carbon to the atmosphere, biomass avoids this by recycling the same carbon over and over again. Although carbon is released to the atmosphere when biomass fuel is burned, the carbon is pulled out of the atmosphere when the crops are re-planted.

Global carbon dioxide emissions contained about 8.2 gigatons of carbon in 2000 and, with "business as usual," could reach 14.5 gigatons in 2050.[1] Based on evaluation of published studies, potential amounts of emissions that could be stored in plants and soil or avoided by using biomass fuel, and their approximate costs, can be summarized as follows:

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[1] A gigaton (Gt) is a billion metric tons. A metric ton is 2,204.6 pounds.

1. *Changes in Forest Management.* This could result in about 2 gigatons of carbon stored per year, at an average cost around $4 per ton of carbon stored.
2. *Changes in Agricultural Management.* This could result in about 1 gigaton per year in soil, with operational savings offsetting most of the costs.
3. *Use of Biomass Fuels.* This could substitute for 2 gigatons of annual fossil fuel emissions at a cost similar to the replaced fossil fuels.

Summing up these three areas, a projected potential annual savings of 5 gigatons would offset or avoid 35 percent of the “business as usual” emissions in 2050. Savings would grow toward this annual rate as sequestration efforts are established, be maintained for 30 to 50 years, and then slowly taper off as forests and soils approach their carbon capacity.

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Part 1

Introduction

A. Greenhouse Gases and Climate Concerns

The Earth’s natural greenhouse effect keeps the overall global temperature warm enough to sustain life because, as sunlight warms the earth’s surface, greenhouse gases trap escaping heat. The major greenhouse gases are carbon dioxide, methane, nitrous oxide, halocarbons (most of which are man-made, and include chlorofluorocarbons, or CFCs), and ozone.[2] Human activities increase the concentrations of almost all greenhouse gases, which concerns climate watchers since the Earth’s temperature equilibrium could be altered. Global average temperatures have been rising since around 1900, and damaging impacts which have been predicted include rising sea levels, more violent storms, and expansion of diseases into new areas.[3]

Two major areas of human activities cause greenhouse gases to be emitted:

1. *Fossil Fuel and Cement Production.* These directly emit greenhouse gases. Fossil fuel combustion forms carbon dioxide from atmospheric oxygen and carbon in fuel, which releases carbon that ordinarily would remain underground.[4]

2. *Land-use Changes.* These, occurring from forest to cropland, produce a complex chain of continuing emissions, including some “negative” emissions in which changes in land use lead to greater sequestration of carbon dioxide or reduced emissions of greenhouse gases such as methane. An initial pulse of carbon dioxide emissions occurs when trees are harvested, burned, or killed. As the land erodes, decaying soil organic matter emits more carbon dioxide, but the net emission rate usually declines to nearly zero after a few decades. Crops and soil may emit other greenhouse gases such as methane and nitrous oxide. If cropland is abandoned, trees start regrowing and the new carbon storage from regrowth is counted as negative emissions.

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[2] Almost all halocarbons are man-made. Ozone has complex greenhouse effects. Near the surface, increasing ozone pollution traps heat, but stratospheric ozone depletion cools the stratosphere and eventually cools the lower atmosphere. Besides these greenhouse gases, other processes and chemicals play a role in regulating Earth’s heat retention, including water vapor, aerosols, volcanic eruptions, solar output variations, and more. Aerosols include soot particles, which absorb heat, and reflective particles (derived from sea salt, sulfate pollution, volcanos, or dust storms) which also reflect heat, mostly by enhancing the formation of clouds.

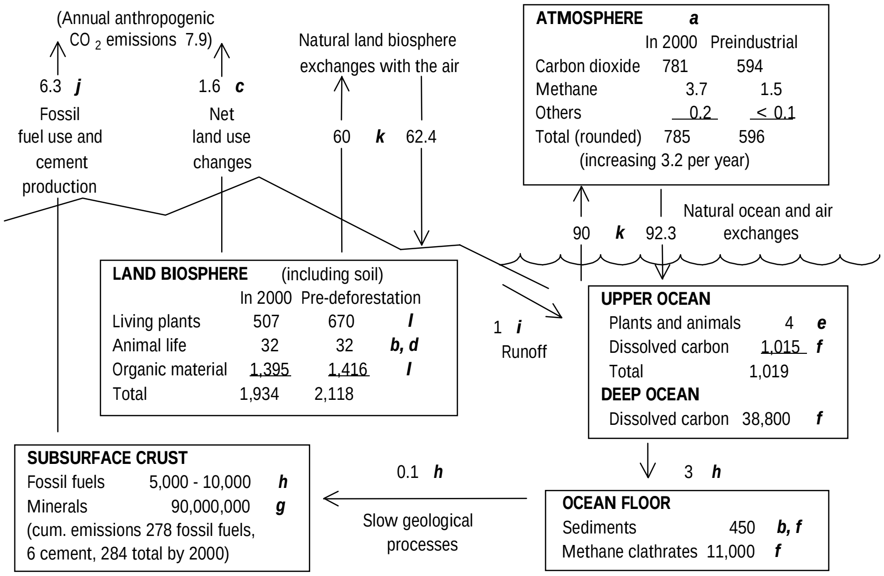
[3] Though temperatures have been rising since 1900, the latest report of the Intergovernmental Panel on Climate Change (IPCC) suggests that human activity has only been a factor in the warming of the last 50 years, with previous warming resulting from natural climate variability.

[4] Emissions from fossil fuels also include gases escaping or evaporating during production. Cement production drives off carbon dioxide from calcium carbonate to form calcium oxide. See Charles D. Keeling, “Industrial Production of Carbon Dioxide from Fossil Fuels and Limestone,” *Tellus*, vol. 25, no. 2 (1973), p. 191. Ozone is generally not emitted, but is produced daily by chemical reactions involving sunlight and previously-emitted air pollutants.

B. The Carbon Cycle

All greenhouse gases listed above, except nitrous oxide and ozone, contain carbon. About 45 percent of the weight (water excluded) of organic material is carbon. Plants obtain carbon from carbon dioxide, and animals obtain carbon from food.[5] Carbon is a stable element that circulates through the environment in solid, liquid, and gaseous forms such as carbon dioxide, methane, and organic compounds in living things. The carbon cycle, summarized in Figure 1, ties together living and non-living processes that cause greenhouse gases to be added to or removed from the air.

Figure 1: The Global Carbon Cycle From 1990 to 2000[6]



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[5] The cells of animals are fueled by breaking down sugar in the presence of oxygen, which produces carbon dioxide. Plant cells obtain energy from the sun and build their tissues by taking in carbon dioxide, converting it into sugars through the process of photosynthesis, which releases oxygen.

[6] Notes: Boxes show estimated sizes of reservoirs in 2000, in gigatons of carbon. Numbers by arrows are average annual flows in the 1990s, in gigatons of carbon. Bold italic letters indicate sources, listed below: ***a*** Computed from concentrations of each gas. Sources are listed in the text descriptions of Figures 2 and 3. ***b*** W. B. Whitman, D. C. Coleman, and W. J. Wiebe, "Prokaryotes: The Unseen Majority," *Proc. Natl. Acad. Sci.* USA, vol. 95, no. 12 (9 June 1998), pp. 6578-6583. The quantity of insects is extrapolated from termites. ***c*** Robert T. Watson et al., ed., *Land Use, Land-Use Change, and Forestry* (Cambridge, UK: Cambridge Univ. Press, 2000), Table 2. Estimate for 1989-1998 is assumed to apply throughout 1990s. ***d*** B. Bolin, et al., *The Global Carbon Cycle* (Chichester, UK: Wiley, 1979), p. 157; population updated to 6.0 billion.***e*** V. V. Dobrovolsky, *Biogeochemistry of the World's Land* (Boca Raton, Florida: CRC Press, 1994), p. 163. ***f*** R. J. Scholes et al., "Biogeochemistry of Terrestrial Ecosystems," in B. Walker et al., ed., *The Terrestrial Biosphere and Global Change: Implications for Natural and Managed Ecosystems* (Cambridge, UK: Cambridge Univ. Press, 1999), p. 298. ***g*** W. L. Chameides and E. M. Perdue, *Biogeochemical Cycles* (New York: Oxford, 1997), p. 121. ***h*** Houghton, *Global Warming: The Complete Briefing*, p. 23. ***i*** E. K. Berner and R. A. Berner, "Biogeochemistry," in *McGraw-Hill Encyclopedia of Science and Technology*, 8th ed., (New York: McGraw-Hill, 1997), vol. 2, pp. 664-665. ***j*** Gregg Marland, Tom Boden, and Robert J. Andres, "Global CO2 Emissions from Fossil-Fuel Burning, Cement Manufacture, and Gas Flaring: 1751-1997," (Oak Ridge, TN: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Dec 2000, http://cdiac.esd.ornl.gov/ftp/ndp030/global97.ems). Estimates for 1998-99 except cement production are based on growth from 1997 in http://www.eia.doe.gov/emeu/iea/carbon.html. ***k*** Nominal emissions of 60 and 90 gigatons, with sinks larger in proportion to R. Houghton, "The Annual Net Flux of Carbon to the Atmosphere from Changes in Land Use 1850-1990," *Tellus*, vol. 51B, no. 2 (April 1999), eq. 2.***l*** Houghton, "The Annual Net Flux of Carbon to the Atmosphere from Changes in Land Use 1850-1990," Fig. 3, with some additional losses of carbon estimated from the beginning of deforestation to 1850.

Figure 1 depicts both natural and human-influenced (anthropogenic) components of the carbon cycle.[7] Carbon in the air is known accurately since carbon-containing greenhouse gases are well-mixed in the lower and upper atmosphere. Other reservoirs are uncertain. For example, the land biosphere is estimated elsewhere to contain over 25 percent more carbon than is indicated in Figure 1.[8] Some numbers are not measured, but are specified to balance with other components, since carbon is not created or destroyed, but moves from one reservoir to another.

While the atmospheric carbon reservoir is of concern because of its greenhouse effects, other carbon reservoirs are much larger. Carbon in trees, plants, and soil on land (1,934 gigatons) is over twice the amount in the air (785 gigatons), and oceanic carbon (roughly 40,000 gigatons) is about 50 times as abundant. Fossil fuel deposits, including coal, oil, and gas (5,000 to 10,000 gigatons) and oceanic methane trapped in sediments (possibly 11,000 gigatons), contain over 20 times the amount of carbon in the air.[9]

Natural carbon dioxide flows are about 20 times the human input to the air. Each year, plants on land exchange about 60 gigatons of carbon with the air, and oceans exchange about 90 gigatons with the air. Human emissions of carbon dioxide averaged about 7.9 gigatons of carbon per year in the 1990s, and were 8.2 gigatons in 2000.[10]

C. Human Changes to the Carbon Cycle

The recently observed carbon dioxide buildup has been caused by a continuing imbalance from human emissions. Effects on the carbon cycle will be discussed from three perspectives: atmospheric concentration trends, emission trends, and the proportion of emissions that stay in the air.

1. Atmospheric Concentrations

Figures 2 and 3 show carbon dioxide and methane levels from 1850 to 2000. For several thousand years before industrialization (which began about 1750), concentrations varied only a few percent. Carbon dioxide

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[7] Because of the large scale of the global carbon cycle, all quantities are expressed as gigatons. A gigaton (Gt) is a billion (10^9) metric tons or 1 petagram (Pg), which equals 10^{15} grams. A metric ton is 2204.6 pounds. A gigaton of water fills a cube 1 kilometer (3,280 feet) on a side. Based on fairly complex calculations, the mass of carbon in one part per million of carbon dioxide is about 2.12 gigatons (A square 14 miles on a side is about one-millionth of the earth's area. Imagine replacing the air over that area with carbon dioxide, and then weighing the carbon.).

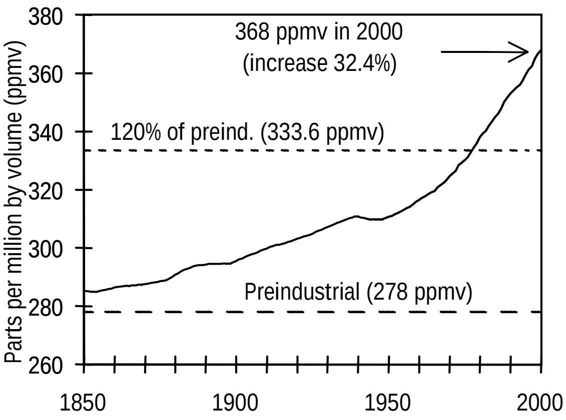
[8] Watson et al, *Land Use, Land-Use Change, and Forestry*, p. 31.

[9] Fossil fuel is estimated in John T. Houghton, *Global Warming: The Complete Briefing* (Cambridge, United Kingdom: Cambridge University Press, 1997), p. 23. Ocean methane is estimated by R. J. Scholes et al., "Biogeochemistry of Terrestrial Ecosystems," in B. Walker et al., eds., *The Terrestrial Biosphere and Global Change: Implications for Natural and Managed Ecosystems* (Cambridge, United Kingdom: Cambridge University Press, 1999), p. 298.

[10] Fossil fuel and cement production emissions are estimated annually from 1751 to 1997 in Gregg Marland et al., http://cdiac.esd.ornl.gov/ftp/ndp030/global97.ems (statistics since 1950 are probably accurate within 10 percent). The estimates are projected to 2000. Annual land-use emission estimates (uncertainty is around 50 percent, but trends should be qualitatively correct) are in Richard A. Houghton and Joseph L. Hackler, *Carbon Flux to the Atmosphere from Land-Use Changes: 1850-1990* (Oak Ridge, Tennessee: Carbon Dioxide Information Analysis Center, February 2001), http://cdiac.esd.ornl.gov/epubs/ndp/ndp050.html). Net emissions from land-use change in 1990 to 2000 are assumed to be 1.6 gigatons per year based on Watson et al., *Land Use, Land-Use Change, and Forestry*, p. 5. These emissions exclude gases other than carbon dioxide. Methane emissions were slightly above 0.4 gigaton of carbon per year in the early 1990s (0.12 gigaton natural, 0.28 gigaton anthropogenic), according to J. T. Houghton, *Global Warming: The Complete Briefing*, p. 35. Other greenhouse gas flows are much smaller than 0.01 gigaton of carbon per year.

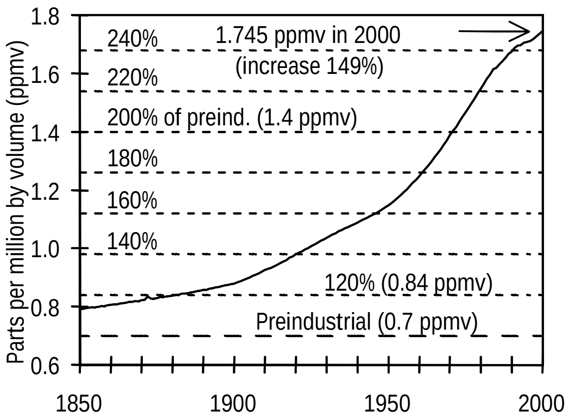
rose over 32 percent from the pre-industrial level by 2000, and methane rose nearly 150 percent.[11] The air contained 781 gigatons of carbon in the form of carbon dioxide, and only 3.7 gigatons of carbon in other gases, but other greenhouse gases have more heating effect per molecule than carbon dioxide. The rise in all greenhouse gases by 2000 is equivalent to carbon dioxide growth of more than 60 percent.[12] Industrial-era growth in greenhouse gases is slightly larger than the rise as the last ice age ended, but occurred more than 10 times as fast and has raised carbon dioxide and methane to levels not found in the warm periods between the last four ice ages.[13]

Figure 2: Annual Carbon Dioxide Concentrations



Source: http://www.giss.nasa.gov/data/si99/ghgases

Figure 3: Annual Methane Concentrations



Source: http://www.giss.nasa.gov/data/si99/ghgases

2. Emissions

The upper panel of Figure 4 shows annual carbon dioxide emissions from 1930 to 2000, and the annual buildup in the air (discussed below), all in gigatons of carbon.[14] Since 1960, total emissions (the solid line)

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[11] Greenhouse gas concentrations are expressed here in parts per million by volume of dry air (water vapor excluded, since water vapor is extremely variable), which is equivalent to a proportion of molecules (For example, 300 ppmv is the same as 300 molecules per million molecules of dry air). Global average gas concentrations are based on precise measurements (errors are under 1 percent for major gases). Air bubbles trapped in ice caps allow accurate measurements of concentrations for the last several hundred thousand years (errors are probably under 10 percent). Figures 2 and 3 start in 1850, but the rise in concentration from pre-industrial times to 1850 was small. Annual greenhouse gas concentrations from 1850 to 1998 are listed by Goddard Institute for Space Studies in http://www.giss.nasa.gov/data/si99/ghgases. Estimates for 1999 and 2000 are projected. Preindustrial averages are in John T. Houghton et al., *Climate Change 1995, The Science of Climate Change* (Cambridge, United Kingdom: Cambridge University Press, 1996), p. 92. Other greenhouse gas changes are measured or estimated as follows: nitrous oxide has risen about 15 percent from 0.275 to 0.316 parts per million, and tropospheric ozone has risen about 60 percent from 0.025 to 0.04 parts per million (a very imprecise estimate). Almost all halocarbons (about 0.00142 parts per million) are man-made.

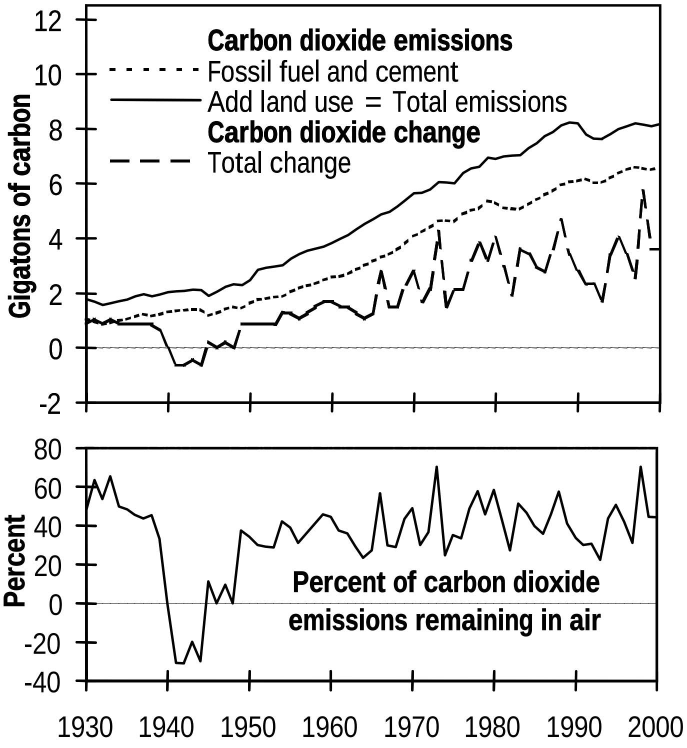
[12] Updated to 2000 from Houghton, *Global Warming*, pp. 41–42.

[13] Ice-age values are averages of ice-core measurements dated 20,000 to 30,000 years ago in Thomas A. Boden et al., *Trends '93: A Compendium of Data on Global Change* (Oak Ridge, Tennessee: Carbon Dioxide Information Analysis Center, 1994, http://cdiac.esd.ornl.gov), pp. 9, 231, 383. Average ice age concentrations of carbon dioxide, methane, and nitrous oxide were 197, 0.4, and 0.19 parts per million respectively. Halocarbons are almost entirely man-made, and there could have been 0.02 parts per million of trophospheric ozone, but there are no published ice age ozone estimates. Carbon dioxide and methane concentrations for the last four glacial-interglacial cycles are in J. R. Petit et al., "Climate and Atmospheric History of the Past 420,000 Years from the Vostok Ice Core, Antarctica," *Nature*, vol. 399, no. 6735 (June 3, 1999), pp. 429–436.

[14] This paragraph discusses only emissions and atmospheric growth of carbon dioxide, not other gases, because historical emissions of other greenhouse gases are not accurately estimated. Sources are in footnote 10. The annual buildup of carbon dioxide is computed from the concentrations in Figure 2. The buildup has been more variable from year to year

rose from about 3.8 to 8.2 gigatons of carbon per year, or from 1.26 to 1.35 tons per capita (after a peak of 1.59 tons in 1988).[15] Total emissions have been nearly constant since the late 1980s, mostly due to reduced deforestation; fossil fuel emissions (the dotted line) rose more slowly in the 1990s. In the United States, carbon dioxide emissions rose from 0.712 gigatons of carbon in 1960 (19 percent of the world total, or 3.94 tons per person) to 1.48 gigatons in 2000 (18 percent of the world total, or 5.24 tons per person, after a recent peak of 5.52 tons in 1979).[16]

Figure 4: Carbon dioxide emissions and change (top panel, gigatons of carbon), percent of emissions remaining in atmosphere (lower panel)



Upper panel: Annual carbon dioxide emissions (solid line is total anthropogenic emissions) and change in mass of carbon dioxide from preceding year (gigatons of carbon).

Source: Emissions from http://cdiac.esd.ornl.gov/ftp/ndp030/global97.ems, and concentrations from http://www.giss.nasa.gov/data/si99/ghgases, converted to gigatons of carbon. Lower panel: Percent computed from annual change and annual total emissions in top panel.

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since the early 1960s both because accurate measurements are available and because El Niño events have become stronger. During El Niño, warmer temperatures encourage plant growth, which temporarily removes carbon from the air. The "buildup" was negative in the early 1940s, possibly resulting from the prolonged El Niño of 1939 to 1943. See D. M. Etheridge et al., "Natural and Anthropogenic Changes in Atmospheric CO_2 over the Last 1000 Years from Air in Antarctic Ice and Firn," *Journal of Geophysical Research*, vol. 101, no. D2 (February 20, 1996), pp. 4115–4128.

[15] Global population estimates are available at http://www.census.gov/ipc/www/worldpop.html.

[16] United States carbon emissions from fossil fuel and cement production are in Marland et al., http://cdiac.esd.ornl.gov/ftp/ndp030/nation97.ems, and from land-use changes are in R. A. Houghton, J. L. Hackler, and K. T. Lawrence, "The U. S. Carbon Budget: Contributions from Land-Use Change," *Science*, vol. 285, no. 5427 (July 23, 1999), pp. 574–578. In most years until the late 1800s, United States per-capita emissions exceeded 10 tons of carbon due to rapid deforestation. Since 1945, forest re-growth has exceeded deforestation in the United States. Fossil fuel and cement emissions rose from 0.797 to an estimated 1.503 gigatons from 1960 to 2000. United States population estimates are at http://www.census.gov/population/estimates/nation/popclockest.txt, but 1991 to 2000 estimates were revised to fit the 2000 census count of 281.4 million.

3. Proportion Remaining in the Air.

Only 42 percent of the carbon dioxide emissions from 1960 to 2000 remain in the air, due to natural removal processes. The lower panel of Figure 4 shows the carbon dioxide buildup as a percent of annual emissions. Cumulative carbon emissions from fossil fuels and cement were 284 gigatons through 2000.[17] Land-use changes emitted about 200 gigatons.[18] The carbon dioxide buildup, 187 gigatons of carbon, is 39 percent of total emissions of 484 gigatons. Since the proportion staying in the air has only risen to 42 percent since 1960, carbon dioxide removal processes continue to be effective. Much "missing" carbon dioxide is dissolved in the oceans, and the rest has apparently been stored by faster tree growth in undisturbed forests.

For other greenhouse gases, the proportion that stays in the air depends on the speed of the removal processes. Methane is removed fairly rapidly, and emissions are nearly constant, so its buildup has slowed down. Some halocarbons may persist for around 50,000 years, but most CFCs will be removed in the next 50 to 100 years as their emissions decline rapidly.

The fact that the environment absorbs over half of human carbon dioxide emissions suggests that natural processes can be enhanced.

Future greenhouse gas concentrations depend on future emission trends, which cannot be forecast except by forecasting human behavior. Scenarios have been generated by groups including the Intergovernmental Panel on Climate Change to explore alternative paths of development. More than 50 scenarios covering 1990 to 2100 have been developed, all assuming substantial economic growth.

The widely-used "business as usual" scenario projects improved efficiency but still expects annual carbon dioxide emissions to grow from 7.4 gigatons of carbon in 1990 to 8.4 gigatons in 2000, 9.9 gigatons in 2010, 12.2 gigatons in 2025, 14.5 gigatons in 2050, and 20.3 gigatons in 2100.[19] Emissions would total 1424 gigatons from 2001 to 2100, nearly 3 times the 484 gigatons by 2000. The carbon dioxide level in 2100 may be 708 parts per million, over 2.5 times the pre-industrial average and nearly twice the level in 2000.[20]

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[17] Marland et al., http://cdiac.esd.ornl.gov/ftp/ndp030/global97.ems, with projections from 1998 to 2000.

[18] Watson et al., *Land Use, Land-Use Change, and Forestry*, p. 4, estimates a release of 136 gigatons of carbon from 1850 to 1998. Assume 4 gigatons were emitted in 1999 and 2000. About 60 gigatons were released before 1850, according to R. S. DeFries et al., "Combining Satellite Data and Biogeochemical Models to Estimate Global Effects of Human-induced Land Cover Change on Carbon Emissions and Primary Productivity," *Global Biogeochemical Cycles*, vol. 13, no. 3 (September 1999), pp. 803–815. In Figure 1, the land biosphere has lost about 184 instead of 200 gigatons of carbon. The discrepancy is due to natural regrowth and the imprecision of data estimates.

[19] J. T. Houghton, B. A. Callander, and S. K. Varney, eds., *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment* (Cambridge, United Kingdom: Cambridge University Press, 1992), p. 91. IPCC is the United Nations Intergovernmental Panel on Climate Change, which has comprehensively reviewed the state of knowledge of climate change each five years since 1990. The "business as usual" scenario is also called "IS92a." The estimate for 2010 (the middle of the Kyoto Protocol commitment period) is a proportional change between the 2000 and 2025 projections. The projection for 2000 (made in the early 1990s) slightly exceeds the latest estimate of 8.2 gigatons. Emissions in 2100 are estimated to be 1.80 tons per person. From pp. 80 and 91, estimated emissions from 2001 to 2100 include fossil fuels (1386 gigatons from 1990 to 2100), plus deforestation (77 gigatons), plus cement (48 gigatons computed from p. 91 but omitted on p. 80), minus total emissions from 1990 to 2000 (87 gigatons in 11 years).

[20] J.T. Houghton et al., *Climate Change 1995*, p. 23. Projected levels depend on the assumed rate of carbon dioxide removal. With 708 parts per million of carbon dioxide in 2100, there would be 1,503 gigatons of carbon (excluding other gases such as methane), an increase of 722 gigatons from 2000, implying that about 51 percent of the emitted carbon would stay in the air.

The Kyoto Protocol to the United Nations Framework Convention on Climate Change, a treaty signed by President Clinton but not yet ratified by the United States Senate, directs developed countries to reduce net greenhouse gas emissions by about 5 percent below 1990 levels during 2008 to 2012. Net emissions may be controlled through a combination of reducing the amount of carbon dioxide emitted and agriculture and forestry changes to increase the amount of carbon dioxide that is pulled out of the atmosphere.

The fact that the environment absorbs over half of human carbon dioxide emissions suggests that natural processes can be enhanced. Flows of carbon dioxide into oceans do not seem to be adjustable by human action, but vegetation and soil should be able to store a major part of the currently non-sequestered human emissions. The carbon storage capacity will probably be reached in 50 to 100 years, but that time will allow a transition to less carbon-intensive technologies.

Part 2

Carbon Sequestration and Forestry

A. The Role of Forests in the Carbon Cycle

Before deforestation (which started several thousand years ago) and industrialization, carbon in plants slightly exceeded carbon in the air.[21] Trees still contain over 94 percent of the world's living plant biomass.[22] Carbon exchanges between plants and the air, about 60 gigatons per year in each direction, vary annually as weather and growing conditions change, but are nearly balanced overall.[23] Without human disturbance, slightly more carbon would be stored (by net plant growth) than released by plants and soil (as carbon dioxide from decay) to balance soil carbon lost by runoff into oceans.

The carbon stored in a forest varies with climate and soil conditions. Some typical values, in metric tons of carbon per hectare, are 370 in a rain forest (250 in plants and 120 in soil), 296 in a high-latitude forest (90 in plants, 206 in soil), 281 in a temperate forest (147 in plants, 134 in soil), 80 in a savanna (30 in plants, 50 in soil), and, for comparison, 196 in a prairie (7 in plants, 189 in soil).[24] The global emissions from fossil fuels and cement in 2000 (6.6 gigatons of carbon) could be stored in a temperate forest about the size of Minnesota or a prairie slightly smaller than North and South Dakota.

Natural forests are affected by disturbances such as forest fire, storms, or insect outbreaks, but such disturbances are rarely catastrophic. For example, a forest fire in Alaska typically removes most of the carbon in trees and part of the soil carbon, leaving about 40 percent of the original carbon.[25] In many forests, low-intensity forest fires every few years clear out underbrush and small trees, causing only temporary small carbon losses and reducing the frequency of catastrophic fires that would kill large trees.

When a forest regrows, carbon storage does not occur evenly over time. A typical Oregon forest loses carbon for about 20 years because growth is slower than the decay of debris. The trees grow rapidly for about 60 more years, then slowly for about 120 years until the trees are about 200 years old, with little additional carbon

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[21] An estimate of carbon in biomass (plants and trees) is in Richard A. Houghton, "The Annual Net Flux of Carbon to the Atmosphere from Changes in Land Use 1850-1990," *Tellus*, vol. 51B, no. 2 (April 1999), Table 3, updated to 2000. The mass of carbon in the air is computed from greenhouse gas concentrations as in footnote 7.

[22] Computed from J. S. Amthor et al., *Terrestrial Ecosystem Responses to Global Change: A Research Strategy*. ORNL/TM-1998/27 (Oak Ridge, Tennessee: Oak Ridge National Laboratory, 1998). This includes woodlands and savannas, where trees are smaller or farther apart than in forests.

[23] P. P. Tans and J. White, "In Balance, with a Little Help from the Plants," *Science*, vol. 281, no. 5374 (July 10, 1998).

[24] R.A. Houghton, "The Annual Net Flux of Carbon to the Atmosphere from Changes in Land Use 1850–1990," p. 301. A hectare is a square 100 meters on a side, or 2.47 acres. A square mile contains 640 acres or about 259 hectares.

[25] E. S. Kasischke, N. L. Christensen, Jr., and B. J. Stocks, "Fire, Global Warming, and the Carbon Balance of Boreal Forests," *Ecological Applications*, vol. 5, no. 2 (1995), pp. 437–451.

storage after 200 years as old trees die and new trees grow.[26] With shorter-lived trees, the life cycle is similar but more rapid. A typical pine forest in the southeastern United States stores about 2 tons of carbon per hectare per year for the first 10 years (instead of losing carbon in that period), rising to 7 tons per hectare per year until the trees are 50 years old, followed by slowing growth.[27]

A typical pine forest in the southeastern United States stores about 2 tons of carbon per hectare per year for the first 10 years, rising to 7 tons per hectare per year until the trees are 50 years old, followed by slowing growth.

B. Human Effects on Forests

The current forested area of the Earth is about 4.1 billion hectares (16.6 million square miles, about the size of North and South America).[28] Without deforestation, global forestation would be around 1.1 billion hectares (the size of Europe plus all of Turkey) larger.

Compared to a forest, typical cropland has little living vegetation and about 25 to 30 percent less soil carbon. Conventional cropland stores about 24 percent as much carbon as a rain forest, 36 to 39 percent as much as a temperate forest, or 55 percent as much as a boreal (northern) forest.[29] In Figure 1, 184 gigatons of carbon have been lost from the land biosphere since deforestation, including 23 percent of the original live biomass and 4 percent of soil organic material.[30] Dividing this loss into categories using typical loss rates, forests lost about 151 gigatons of carbon, and forest soils lost about 37 gigatons, by tree removal.[31]

It is difficult to estimate the annual rate of emissions from explicit land-use changes around the world. Land-observing satellites have allowed global surveys of land uses since the mid-1970s. Earlier estimates are based on recorded surveys of land use, or estimated factors (such as cropland per person) if no historical data are available. Even recent estimates are uncertain, since land uses do not always fit neatly into categories.

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[26] W. B. Cohen et al., "Two Decades of Carbon Flux from Forests of the Pacific Northwest," *BioScience*, vol. 46, no. 11 (December 1996), pp. 836–844. Plots of land with different amounts of time since they were logged or had a forest fire were compared to construct the hypothetical life cycle of a single forest that re-grows after a harvest or fire.

[27] R. G. Newell and R. N. Stavins, *Climate Change and Forest Sinks: Factors Affecting the Costs of Carbon Sequestration*, Discussion Paper 99-31 (Washington, DC: Resources for the Future, April 1999), p. 31.

[28] The current forested area is in S. Brown et al., "Management of Forests for Mitigation of Greenhouse Gas Emissions," in Robert T. Watson et al., eds., *Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change* (Cambridge, United Kingdom: Cambridge University Press, 1996), p. 776. The deforested area is computed from V. Cole et al., "Agricultural Options for Mitigation of Greenhouse Gas Emissions," in *ibid*., p. 751. It is assumed that cropland converted from all forest soil, 5 percent of grassland soil, 80 percent of wetland soil, 90 percent of volcanic soil, and 10 percent of other soil was originally forest (these total 1.005 billion hectares), and an additional 10 percent of former forest land (0.1 billion hectares) is not cropland. All numbers are approximate because the boundary between forests and areas with sparse trees is gradual.

[29] Per hectare, typical cropland has 5 tons of vegetation, compared to 90 to 250 tons in a forest, and soil carbon loss of 30 to 50 tons, in R.A. Houghton, "The Annual Net Flux of Carbon to the Atmosphere from Changes in Land Use," p. 301

[30] Organic material lost only 1.5 percent (from 1416 to 1395 gigatons) but organic material in 2000 includes a gain of 31 gigatons of wood products (such as buildings) and debris that are not part of soil organic carbon.

[31] These add up to 188 gigatons, not 184. There were probably 12 gigatons of carbon lost from other vegetation, 15 gigatons lost in other soil (these categories are mainly grassland converted to agriculture), and a gain of 31 gigatons of carbon in wood products mentioned in footnote 30.

Until about 1907, deforestation emitted more carbon dioxide than fossil fuel use.[32] Since the early 1900s in most of North America and Europe, forests have started to recover as economies shifted away from wood, but deforestation in the tropics has accelerated since the 1950s. In the 1990s, almost all net deforestation (about 1.5 of the 1.6 billion gigatons of carbon emissions per year) occurred in the tropics.

Human actions may have subtle effects on the carbon cycle that affect all plant life. Accounting for all known carbon sources and "sinks" (including flows between air and oceans), each year an average of about 60 gigatons of carbon are emitted from and 62.4 gigatons are stored in the land biosphere.[33] The discrepancy of 2.4 gigatons is called a "missing sink" because it is not accounted for by land-use changes. The missing sink may represent enhanced plant growth from longer growing seasons, carbon dioxide fertilization (faster growth with more carbon dioxide), nitrogen fertilization (moderate increases of nitrous oxide act as nitrogen fertilizer), and reduced losses from forest fire suppression.[34]

There is much political controversy about where the "missing sink" is located. Some studies find regrowth mainly in North America and Europe.[35] One study suggests that North American regrowth stores enough carbon to offset all North American emissions, while another finds substantial carbon storage in Central and South America.[36] Since net carbon storage is the small difference between two very large quantities (plant growth and respiration), disagreements between studies are not surprising. In fact, regrowth in existing United States forests (not including reestablished forests) absorbs 10 to 30 percent of United States emissions, about 0.15 to 0.45 gigatons of carbon per year.[37]

There are three principle means of improving carbon storage in forests: stop net deforestation, establish or reestablish forests, and improve management of existing forests.

C. Studies of Potential Forestry Approaches to Maximizing Sequestration

There are three principle means of improving carbon storage in forests: stop net deforestation, establish or reestablish forests, and improve management of existing forests. This section also describes the potential for biomass fuel, whether the biomass is obtained from forests or cropland.

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[32] Compare land-use emissions in J.T. Houghton and J.L. Hackler, *Carbon Flux to the Atmosphere from Land-Use Changes: 1850 to 1990*, with fossil fuel and cement production emissions in Marland et al., http://cdiac.esd.ornl.gov/ftp/ndp030/global97.ems.

[33] A "source" emits carbon to the air. A "sink" extracts carbon from the air.

[34] R.A. Houghton, "The Annual Net Flux of Carbon to the Atmosphere from Changes in Land Use," p. 310.

[35] One example is P. J. Rayner et al., "Reconstructing the Recent Carbon Cycle from Atmospheric CO_2, $\delta^{13}C$, and O_2/N_2 Observations," *Tellus*, vol. 51B, no. 2 (April 1999), pp. 213–232. This study also found a sudden global increase in carbon storage on land starting in 1988 (from 0.3 to 1.1 gigatons per year).

[36] S. Fan et al., "A Large Terrestrial Carbon Sink in North America Implied by Atmospheric and Oceanic Carbon Dioxide Data and Models," *Science*, vol. 282, no. 5388 (October 16, 1998), pp. 442-446, and O. L. Phillips et al., "Changes in the Carbon Balance of Tropical Forests: Evidence from Long-Term Plots," *Science*, vol. 282, no. 5388 (October 16, 1998), pp. 439–442.

[37] Houghton et al., "The U. S. Carbon Budget: Contributions from Land-Use Change," pp. 574–578.

Many studies have examined the possibilities for increasing carbon storage in forests. Extrapolations can suggest the global carbon storage potential. This discussion is very general, and each sequestration effort must be designed for local conditions to be effective. For comparison purposes, potential carbon storage is expressed as a proportion of projected "business as usual" emissions.

1. Two programs (Conservation Reserve Program and Wetland Reserve Program) convert vulnerable cropland to grass or forests. Forests on 7.5 million hectares (1 percent of the continental United States area) in these programs could offset about 0.25 percent of global "business as usual" emissions from 2010 to 2040.[38] While this is a very small part of the emission reductions that may be needed, much more land in the continental United States (32 to 90 million hectares) and other countries may be suitable for reforestation.[39]
2. A recent report of the United Nations Intergovernmental Panel on Climate Change (IPCC) projects carbon flows centered on 2010, the middle of the Kyoto Protocol commitment period.[40] Per year, deforestation may emit 1.8 gigatons of carbon, but reforestation would store 0.2 to 0.6 gigatons. Forestry activities to comply with the Kyoto Protocol could store about 0.6 gigatons per year (6 percent of global emissions around 2010), reducing net land-use change emissions to 0.4 to 1.0 gigatons per year.
3. A 1995 IPCC report analyzed the global potential for carbon storage in forests.[41] Slower tropical deforestation, tropical forest regeneration, and reforestation on 700 million hectares (nearly the size of the continental United States, but only 17 percent of the global forest area) could store 60 to 87 gigatons of carbon in 55 years. Carbon storage could be over 2 gigatons per year by 2050, about 14 percent of "business as usual" emissions. Costs would average $2 to $8 (United States dollars) per ton of carbon stored.
4. Trees are expected to grow faster with increased carbon dioxide. In North Carolina, trees in a young forest were exposed to 60 percent added carbon dioxide for two years, and they grew 25 percent faster than nearby trees without extra carbon dioxide.[42] However, tree ring studies show no detectable faster growth from the global rise in carbon dioxide.

Carbon storage in forests is compatible with harvesting, if damage to soil and unharvested trees is minimized. A simulation of a southeastern United States pine forest compares harvesting each 45 years with no harvest for 100 years.[43] With no harvest, little carbon is added after 60 years. A harvest leaves about 25 percent of the tree carbon. If carbon losses from erosion are minimized, soil carbon builds up with each generation of trees. This forest may eventually contain more carbon than a never-harvested forest because of the large accumulation of soil carbon, even if part of the forest is harvested each year.

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[38] J. R. Barker et al., "Carbon Dynamics of the Conservation and Wetland Reserve Programs," *Journal of Soil and Water Conservation*, vol. 51, no. 4 (July–August 1996), pp. 340–346.

[39] L. S. Heath and R. A. Birdsey, "Carbon Trends of Productive Temperate Forests of the Coterminous United States," *Water, Air, and Soil Pollution*, vol. 70, nos. 1–4 (October 1993), pp. 279–293.

[40] Based on Tables 3 and 4 of Watson et al., *Land Use, Land-Use Change, and Forestry*, pp. 12 ("Global Total" portion of table) and 14 ("Global Estimates" portion of table).

[41] Brown et al., "Management of Forests for Mitigation of Greenhouse Gas Emissions," pp. 773–798.

[42] Evan H. DeLucia et al., "Net Primary Production of a Forest Ecosystem with Experimental CO_2 Enrichment," *Science*, vol. 284, no. 5417 (May 14, 1999), pp. 1177–1179. Carbon dioxide was emitted from towers surrounding groups of about 100 trees to raise the concentration to about 560 parts per million (control groups had similar towers emitting unaltered air), and the growth of trees, plant debris, and roots was monitored in each group.

[43] Newell and Stavins, *Climate Change and Forest Sinks: Factors Affecting the Costs of Carbon Sequestration*, p. 31.

Biomass fuel can substitute for fossil fuels. The carbon savings of using biomass fuel is not the carbon emitted from the fuel, but is instead carbon in the fossil fuel that would have been used in its place (minus fossil fuel, if any, used in production). Biomass energy has been significant since the discovery of fire, although much of the energy is used for subsistence cooking and heating. For simplicity, biomass fuel benefits are summarized here rather than in Part 4, even though biomass fuel can be obtained from crops.

One study shows a potential for biomass to avoid about 3.5 gigatons of carbon emissions per year by 2050 (24 percent of business as usual emissions).[44] However, the 1995 IPCC projections are slightly lower, including 29 gigatons of carbon emissions avoided by biomass fuel from forests from 1995 to 2050 (0.9 to 1.2 gigatons per year after 2040), plus 20 to 75 gigatons avoided by biomass fuel crops (0.4 to 1.5 gigatons per year).[45] The total avoided emissions, 1.3 to 2.7 gigatons of carbon per year, still represent 9 to 19 percent of business as usual emissions from 2040 to 2050, and could be sustained indefinitely.

The cost of forest sequestration varies widely depending on the location, specific activities, assumed "time value of money" for future expenses and revenues, local wages and costs, and impact on the economy. Income from harvesting or tourism can help offset the costs. Projects examined by the IPCC reported costs from $0.40 to $15 per ton of carbon stored, with many projects costing under $3 per ton.[46] The cost is usually low because most projects make only small adjustments to natural growth processes.

The cost of forest sequestration varies widely depending on the location, specific activities, assumed "time value of money" for future expenses and revenues, local wages and costs, and impact on the economy.

D. The Potential for Carbon Sequestration through Forestry

Forestry actions to enhance carbon storage focus on stopping deforestation, encouraging reforestation, and improving forest management. Additional tree growth removes carbon dioxide from the air. Harvesting removes some of the stored carbon, but maintains vigorous growth for a large percentage of the time and can allow continuous accumulation of soil carbon. Some of the wood and vegetation harvested from forestry sequestration projects may also be used as biomass that can substitute for fossil fuels.

After trees are planted, carbon storage rises slowly (if at all) for a few years, then increases rapidly while the trees are growing vigorously, and gradually levels off as the forest matures. Depending on the rate of establishing forestry projects on most of the suitable land worldwide, the maximum carbon storage rate will

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[44] D. O. Hall, J. I. House, and J. I. Scrase, "Introduction: Overview of Biomass Energy," in *Industrial Uses of Biomass Energy,* F. Rosillo-Calle, S. Bajay, and H. Rothman, eds. (London: Taylor and Francis, 2000), p. 277.

[45] The forest biomass projection is in Table 24-5 of Brown et al., "Management of Forests for Mitigation of Greenhouse Gas Emissions," pp. 773–798. The agricultural biomass projection is in the "Fossil C Offsets" part of Table 23-5 of V. Cole et al., "Agricultural Options for Mitigation of Greenhouse Gas Emissions," in *ibid.*, pp. 757–764, after correcting an error. The "Biofuel Production from Crop Residues" line is blank and values are filled in to get the correct totals in the "Total Potential CO_2 Mitigation" line.

[46] *Ibid*, p. 787.

probably occur around 2050, with a significant tapering off of additional carbon storage by 2100 as most forests mature.

Summarizing the available studies, additional forestry projects could store about 0.6 gigatons of carbon per year by 2010 (about 6 percent of "business as usual" emissions) and about 2 gigatons per year by 2050 (14 percent of "business as usual"). Cumulative storage in trees and soil of 60 to 87 gigatons of carbon by 2050, and possibly 50 additional gigatons by 2100 (assuming a declining net growth rate) would replace over half of the forest carbon lost up to 2000. In addition, biomass fuel, including both trees and biomass crops, should be able to replace about 2 gigatons a year of carbon emissions by 2050, another 14 percent of projected fossil fuel emissions.

Additional forestry projects could store about 0.6 gigatons of carbon per year by 2010 (about 6 percent of "business as usual" emissions) and about 2 gigatons per year by 2050 (14 percent of "business as usual").

For activities that do not require intensive management, typical costs would be on the order of $4 per ton of carbon sequestered (not adjusted for inflation after the late 1990s). For comparison, estimated costs of carbon reduction through fuel use reductions or alternative fuels average about $100 per ton.[47] Costs of biomass fuel vary widely but, with additional development, are expected to be similar to the costs of the fossil fuels they replace.

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[47] This is a "representative" figure, but actual published estimates are scarce and vary widely. Simple conservation measures to reduce fuel consumption may have a negligible cost, while developing alternative fuels is much more expensive. At recent efficiency levels, one ton of carbon emissions would be avoided by reducing electricity use by 3,100 kilowatt hours (kwh) generated by coal, 5,000 kwh generated by oil, or 6,600 kwh generated by natural gas, or by not using 8.5 barrels of crude oil, 410 gallons (1560 liters) of gasoline, 360 gallons (1,370 liters) of diesel or heating oil, or 1.4 short tons (1,270 kilograms) of coal, or by not flying 32,000 miles (51,600 km) in a Boeing 737–800 that is 75 percent full. For comparison with activities using renewable resources, 10.5 years of human metabolism at 2,700 calories per day or burning 2.5 metric tons of wood would emit one ton of carbon. At recent United States retail prices, any of these alternatives would cost well over $100 per ton, so a $100 cost to avoid the use of this amount of energy would be a savings. (Carbon emissions from electricity generation are computed from Figure 19-1 of H. Ishitani and T. B. Johansson, eds., "Energy Supply Mitigation Options," in Watson et al., *Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change*, pp. 587–647. Other carbon emissions are computed using carbon emission factors and heat contents given in Appendix A of EIA, *Emissions of Greenhouse Gases in the United States 1987-1992*, DOE/EIA–0573 (Washington: Energy Information Administration, October 1994), http://www.eia.doe.gov/oiaf/1605/87-92rpt/cover.html and appa.html. The heat content for coal (14,000 btu/pound for bituminous coal) is obtained from B. D. Hong and E. R. Slatic, "Carbon Dioxide Emission Factors for Coal," *Quarterly Coal Report*, No. 94/Q1 (January–April 1994), pp. 1–8, http://www.eia.doe.gov/cneaf/coal/quarterly/co2_article/co2.html. Airplane fuel use uses fuel consumption factors (10,550 pounds, at 6.75 pounds per gallon, per 1,000-mile flight segment) from http://www.boeing.com/commercial/bbj/quickref.html, a Boeing 737–800 capacity of 189 passengers from http://www.boeing.com/commercial/737-800/product.html, and jet fuel carbon characteristics from the EIA source above. Fuel wood averages 39.8 percent carbon and contains heat energy of 6,400 btu/pound (J. Ausubel, A. Grübler, and N. Nakicenovic, "Carbon Dioxide Emissions in a Methane Economy," in *Climatic Change*, vol. 12, no. 3 [June 1988], pp. 245–263). For human metabolism, the global average per capita food supply in 1986 was 2,710 calories (Food and Agriculture Organization, *FAO Statistical Pocketbook* [Geneva: FAO, 1988], p. 2), divided by calories into 15.7 percent protein (6 calories per gram, 45.6 percent carbon), 21.8 percent fat (9 calories per gram, 76.1 percent carbon), and 62.5 percent carbohydrates (4 calories per gram, 42 percent carbon).

Part 3

Carbon Sequestration and Agriculture

A. The Role of Agriculture in the Carbon Cycle

The global cultivated area is 1.7 billion hectares (6.6 million square miles, larger than South America), 1 billion hectares (3.9 million square miles, about the size of Europe) of which was converted from forests.[48] Most carbon storage on cropland occurs in soil in the form of organic plant matter and inorganic carbonates, since crops themselves contain only a few tons of carbon per hectare during the growing season. Converting grassland or forest to cropland releases 30 to 50 tons of soil carbon per hectare over a few years or decades by decay of organic material.[49] Agricultural soils have lost about 48 gigatons of carbon since cultivation began (10 percent of all cumulative human carbon dioxide emissions).[50]

Both traditional and modern practices cause erosion that depletes soil carbon. In “slash and burn” farming, ashes from trees provide nutrients that are depleted in a few years. The farmers move to other land, but if severe erosion occurs, the soil does not fully recover. Until recently, agricultural research emphasized raising yields using chemical fertilizers and pesticides, with little concern for soil quality. Plowing seems environmentally sound because it buries weeds and crop residues, which release nutrients as they decay, reducing the need for agricultural chemicals. However, most of the released nutrients run off and the loose soil is subject to wind and water erosion. (Pastures are not discussed in this guide since they usually do not lose soil carbon, unless overgrazing leads to substantial erosion.)

Some progress has already been made in improving soil management, at least in developed countries. Windbreaks (rows of trees between fields) and changes in plowing have nearly eliminated dust storms in the central United States since the Dust Bowl of the 1930s, even though droughts still occur. Soil management techniques can be further improved to provide more carbon storage. Research has led to methods that maintain or increase crop yields, use less fertilizer and pesticides, and preserve soil organic material.

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[48] Cole et al., “Agricultural Options for Mitigation of Greenhouse Gas Emissions,” p. 751.

[49] R.A. Houghton, “The Annual Net Flux of Carbon to the Atmosphere from Changes in Land Use,” p. 301.

[50] Cole et al., “Agricultural Options for Mitigation of Greenhouse Gas Emissions,” p. 751, reports a loss of 55 gigatons, but here the loss is 48 gigatons (35 gigatons from former forest soil and 13 from former grassland or other soil) to be consistent with land biosphere losses in Figure 1.

The "green revolution" increased crop yields worldwide through more productive crop varieties, greater use of fertilizers, and a minor degree of better soil management. The production of biomass in crops can significantly exceed the annual growth of trees on the same land, although most biomass is removed and the residue decays quickly. On one corn field in Missouri cultivated with regularly updated techniques, annual production rose from 3 to 4 tons of carbon per hectare from the early 1900s to 9.5 to 11 tons in the 1990s.[51]

In the United States, increased productivity has allowed retirement of much marginal land, and some has been reforested, as mentioned in Part 3. Continental United States cropland decreased from 158 to 133 million hectares (from 21.6 to 18.2 percent of the land area) between 1932 and 1999.[52] Corn cropland dropped 23 percent from 40.7 million hectares in 1919-28 (the size of Illinois, Indiana, and Iowa) to 31.1 million hectares in the 1990s (the size of Illinois and Iowa), while production more than tripled from 58.7 to 219.2 million metric tons per year (2.31 to 8.63 billion bushels).[53]

Windbreaks (rows of trees between fields) and changes in plowing have nearly eliminated dust storms in the central United States since the Dust Bowl of the 1930s, even though droughts still occur.

Some practices that increase productivity also improve soil. Harvesting (cutting stalks) and threshing (removing grain from the stalks) formerly were separate activities. Stalks were threshed away from the field, and the residue was usually not returned (some nutrients were returned in the form of manure). Combines, increasingly used since the 1940s, perform both activities, extracting grain and leaving the residue. Since crop residues are left in the field, soil carbon has built up, in some cases nearly to the level of prairie.[54]

However, other agricultural practices have a carbon cost.[55] Groundwater used for irrigation to increase production on semiarid land often releases a large amount of dissolved carbon dioxide. Applying nitrogen fertilizer to increase production results in carbon dioxide (and nitrous oxide) emissions during production and use.

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[51] G. A. Buyanovsky and G. H. Wagner, "Carbon Cycling in Cultivated Land and Its Global Significance," *Global Change Biology*, vol. 4, no. 2 (February 1998), pp. 131–141. Production includes the entire plant, including roots. The ranges (such as 9.5 to 11 tons) show variations due to wet and dry years. Compare this production rate with 7 tons per hectare per year in a pine forest, as stated in Part 3.

[52] The planted area of principal crops is in United States Department of Agriculture, *Crop Production Historical Track Records* (Washington, DC: National Agricultural Statistical Service, USDA, June 2000), http://www.usda.gov/nass/pubs/trackrec/track00a.html. Before 1983, 4 percent is added because some planted but unharvested area was excluded. The land area of the continental U. S. is 731.4 million hectares. The crop area was about 130 million hectares in 1909, 153 million hectares in 1981, and 128 million hectares in 1987. The maximum crop area is about equal to the land area from the Dakotas to the Pacific Coast (North Dakota, South Dakota, Montana, Wyoming, Idaho, Washington, and Oregon), while the area retired is about as large as Idaho.

[53] *Ibid*. Corn production includes only the corn kernels. Some of the planted area is harvested for silage (stalks converted to livestock feed) if unfavorable weather prevents ears from developing fully.

[54] Buyanovsky and Wagner, "Carbon Cycling in Cultivated Land and Its Global Significance," pp. 131–141.

[55] W. H. Schlesinger, "Carbon Sequestration in Soils," *Science*, vol. 284, no. 5423 (June 25, 1999), p. 2095. Some groundwater contains over 1 percent carbon dioxide, over 25 times the concentration in the air.

B. Studies of Potential Agricultural Approaches to Sequestration

There have been many studies of carbon benefits of various agricultural practices, but few calculate potential global benefits based on that research. Three significant categories of effort are erosion control, conservation tillage, and rice cultivation. Other areas of effort have carbon implications but are not described in detail here, including recycling of agricultural wastes and modifying livestock diet to reduce methane emissions. As with forestry projects, each agricultural project must be customized for the climate and crop conditions.

1. Erosion Control and Restoration of Degraded Land

Erosion control methods also store carbon, including vegetative cover, rows of trees as windbreaks, and land contouring. Restoration can also store carbon on degraded lands, including high-salinity soil, strip-mined land, and contaminated soil.[56] Restoration is customized to deal with the particular type of degradation and mixture of toxins, and establishes plant cover that tolerates or even ingests contaminants. Plants may be used as biomass fuel to dispose of organic contamination, processed as "ore" to remove heavy metals, or left in place.

The "green revolution" increased crop yields worldwide through more productive crop varieties, greater use of fertilizers, and a minor degree of better soil management.

2. Conservation Tillage

Conservation tillage (including no-till cultivation) reduces water and wind erosion by leaving a specified amount of crop residue on the surface.[57] It is most effective when combined with modern technology, such as using computer monitoring to customize the treatment of small sectors of a field. Conservation tillage is not feasible with crops that are dug up to be harvested, such as potatoes or peanuts, but is usually recommended for grain and cotton. In the United States, conservation tillage grew from about 1 percent of cropland in 1963 to 26 percent in 1989 and 37 percent in 1998 (with 16 percent, the area of Nebraska, using no-till cultivation).[58]

Conservation tillage has several benefits. First, it reduces costs, since precise applications of seeds, fertilizer, and pesticides reduce the amount of these agricultural inputs, as well as the labor and fuel to make repeated trips over fields. Second, reduced erosion lowers the amount of pollution from runoff. Third, less-disturbed fields improve wildlife habitat. Finally, soil carbon builds up because less carbon dioxide is emitted.

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[56] R. Lal et al., "Managing U. S. Cropland to Sequester Carbon in Soil," *Journal of Soil and Water Conservation*, vol. 54, no. 1 (first quarter 1999), p. 376.

[57] See "Definitions," Conservation Technology Information Center (Lafayette, Indiana). To protect from water erosion, at least 30 percent of the crop residue must remain on the surface. To protect from wind erosion, at least 1000 pounds per acre (1.12 metric tons per hectare) must remain. No-till cultivation does not disturb the soil except to directly inject seeds and fertilizer. (http://kyw.ctic.purdue.edu/Core4/CT/Definitions.html)

[58] Noel Duri, "Global Climate Change and the Effect of Conservation Practices in U. S. Agriculture," *Environmental Geology*, vol. 40, no. 2 (December 2000), pp. 41–52.

In one study, converting 76 percent of United States cropland to no-till cultivation could offset 0.7 to 1.1 percent of United States fossil fuel emissions from 1990 to 2020 by storing about 0.28 to 0.45 gigatons of soil carbon. A broad analysis estimates that conservation tillage and related actions in the United States could store 0.06 to 0.17 gigatons of carbon per year, about 4 to 11 percent of total United States carbon emissions in 2000.[59] Attaining these benefits, however, requires adoption by many individual farmers.

Some studies estimate potential global carbon storage from agricultural improvements. In one study, intensive agricultural management of agricultural lands, deserts, degraded lands, grasslands, and rangelands could sequester 3.35 to 3.9 gigatons of carbon per year, and could sustain this rate for at least 25 to 50 years. This estimate is likely to be high because it includes natural carbon storage which is already occurring. The 1995 IPCC estimate for carbon sequestration by agricultural improvements is storage of 0.45 to 0.9 gigatons of carbon per year (25 to 51 gigatons in 55 years, half to all of the 48 gigatons of global soil carbon losses to date), or 3 to 6 percent of "business as usual" emissions in 2050.[60]

3. Management of Rice Cultivation

Rice paddies are a seasonal wetland, so efficient cultivation resembles conservation tillage while the rice paddy is drained and wetland management while it is flooded. A major tradeoff is the concern that storing carbon can lead to the release of methane, which is about 21 times as strong a greenhouse gas as carbon dioxide. It is possible (but not always economically feasible) to reduce carbon dioxide, methane, and nitrous oxide emissions simultaneously by draining the fields at specific rice growth stages and using fertilizers designed to reduce methane generation.[61] Annual methane emissions from rice cultivation are estimated at 0.02 to 0.04 gigatons of carbon, and better management practices could reduce emissions by 0.006 to 0.026 gigatons (equivalent to reducing carbon dioxide emissions by 0.13 to 0.5 gigatons of carbon annually, or 1.5 to 6 percent of total carbon dioxide emissions in 2000).

C. The Potential for Carbon Sequestration through Agriculture

Measures to store carbon in agricultural soil result in high carbon storage rates within the first few years, but such high rates can be maintained for only 25 to 50 years. Conservation tillage must continue indefinitely to avoid release of the accumulated carbon.

Not including biomass fuels (whose sequestration possibilities are discussed in Part 2), a rough "consensus" of attainable carbon sequestration in soil by agricultural improvements is about 0.5 gigatons per year by 2025 and about 1 gigaton per year by 2050 (about 6 percent of "business as usual" fossil fuel emissions), with reduced new storage after that time as optimal practices are applied on almost all suitable land. It is most likely that the cumulative added carbon storage in soil will not exceed the 48 gigatons that have been lost through 2000. Generally, these practices have little net cost because of reduced operating expenses and maintained or increased production.

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[59] Lal et al., "Managing U. S. Cropland to Sequester Carbon in Soil," p. 379.

[60] Cole et al., "Agricultural Options for Mitigation of Greenhouse Gas Emissions," pp. 745–771.

[61] *Ibid*, pp. 759760.

Part 4

Summary

Currently, human generated (or anthropogenic) emissions of carbon dioxide and other greenhouse gases total about 8.2 gigatons of carbon per year (about 1.35 metric tons per capita). The Kyoto Protocol to the United Nations Framework Convention on Climate Change, a treaty signed by President Clinton (but not yet ratified by the United States Senate), directs developed countries to reduce emissions by about 5 percent below 1990 levels by 2008 to 2012. Emissions can be reduced by the conventional approach of decreasing fossil fuel use, but such reductions are likely to cause significant economic disruption. If appropriate agriculture and forestry changes are made that increase the amount of carbon dioxide pulled out of the atmosphere by plant and tree growth, net amounts of greenhouse gas emissions can also be reduced.

Evaluation of the effectiveness of a proposed forestry or agricultural improvement activity requires understanding the carbon cycle (see Part 1), a complex pathway carbon follows as it cycles through the environment. Annual natural carbon exchanges are about 60 gigatons between air and plants and 90 gigatons between air and oceans. While the human emission rate is small compared to the natural flows, the human emissions are unbalanced and build up in the air. The major activities that emit greenhouse gases are fossil fuel use and cement production, which directly emit greenhouse gases, and land-use changes (mainly deforestation), which directly emit greenhouse gases as the trees are cut down and indirectly emit greenhouse gases by reducing the number of trees that store carbon.

Not all of the greenhouse gases emitted by humans stay in the air. The environment absorbs over half of the carbon dioxide emissions, dissolving it in oceans and storing it in plants on land. Flows of carbon dioxide into oceans do not appear to be adjustable, but a major part of the currently non-sequestered human emissions could be stored using present technology, by encouraging forest growth and storage of carbon in soil.

In this section, potential benefits are compared to “business as usual” carbon dioxide emissions in 2050, projected to be about 14.5 gigatons of carbon per year.

- As discussed in Part 2, forestry actions can be divided into three primary areas: Stopping net deforestation (particularly in the tropics), emphasizing reforestation (such as on abandoned farms), and management of existing and new forests. Because additional carbon storage tapers off in a forest after the trees are mature, most forests should be harvested except in remote or sensitive areas. Wood supplies can increase, and with careful harvesting, soil carbon builds up with each generation of trees. Conservatively, carbon storage in 2050 could be about 2 gigatons of carbon annually (14 percent of business as usual emissions) through forestry changes on 700 million hectares (17 percent of global forests, about the size of the continental United States). A similar rate of carbon storage probably can be maintained for about 50 years until forest growth slows down. The cost of storing carbon is projected to be about $4 per ton, with a wide variation depending on remoteness and intensity of management. Costs of harvesting would generally be paid for by lumber sales.

- In agriculture, conservation tillage can be used to enhance sequestration. Conservation tillage involves many site-specific practices to maximize production and minimize soil disturbance. These practices are already being adopted to achieve increased production and usually lower costs. Marginal farmland can be retired and converted to forests. Around 2050, conservation tillage and related practices probably can store slightly over 1 gigaton of carbon per year in the soil, about 7 percent of projected emissions in 2050. Such a high rate of net carbon storage probably can be maintained for 30 to 50 years.
- Biomass fuel from wood and crops or residue is not included in the above estimates, where projected carbon savings are the net amount of emissions avoided by not using fossil fuel. Around 2050, biomass fuel could be realistically grown in sufficient quantities to replace about 2 gigatons per year of carbon emissions from fossil fuel, about 14 percent of projected emissions in 2050. Such substitution could be maintained indefinitely. The cost of biomass fuel is expected to be similar to the fuels it replaces.

If appropriate agriculture and forestry changes are made that increase the amount of carbon dioxide pulled out of the atmosphere by plant and tree growth, net amounts of greenhouse gas emissions can also be reduced.

Individual sequestration efforts must be appropriately designed for local technological and cultural conditions to avoid hindering economic growth or causing other unwanted effects. Some parameters must be taken into account when designing projects or evaluating whether projected savings are attainable. First, these estimates assume that plants are not expected to grow larger even if they may grow faster in response to carbon dioxide and nitrogen fertilization. Second, the estimates assume that no major die-off occurs due to climate changes. Third, verifiable accounting must evaluate a large area to consider tradeoffs, such as whether protecting one forest will cause people to deforest or otherwise degrade another forest.

In summary: by around 2050, forestry changes could store about 2 gigatons of carbon per year, agricultural changes could store about 1 gigaton per year in soil, and biomass fuels could substitute for 2 gigatons of annual fossil fuel emissions. The total savings of 5 gigatons per year is around 35 percent of the projected “business as usual” emission rate in 2050. This carbon savings rate probably can be maintained for 30 to 50 years around the middle of this century, with a smaller saving rate before and after that time. While these savings would not completely offset the increase in emissions expected by 2050, the avoided or stored emissions will buy time to allow development of alternative energy-related technologies.

About the Authors

Steven Schroeder received his Ph.D. in meteorology from Texas A&M University in 1998 after a United States Air Force career in meteorology and operations research. His postdoctoral research interests at Texas A&M University involve historical and modern climate change issues, including investigating whether water vapor changes will amplify or partly offset warming caused by the ongoing buildup of greenhouse gases.

Kenneth Green, D.Env., is Director of the Environmental Program at Reason Public Policy Institute and an expert reviewer for the Intergovernmental Panel on Climate Change (IPCC)'s most recent report on climate change. Dr. Green has published several peer-reviewed policy studies on climate change for RPPI, including *A Plain English Guide to the Science of Climate Change, Climate Change Policy Options and Impacts*, *Evaluating the Kyoto Approach to Climate Change*, and *A Baker's Dozen: 13 Questions People Ask About the Science of Climate Change*. He received his doctorate in environmental science and engineering from UCLA in 1994.

Related RPPI Studies

Exploring the Science of Climate Change, Kenneth Green, Plain English Guide No. 3, August 2000.

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A Baker's Dozen: 13 Questions People Ask About the Science of Climate Change, Kenneth Green, October 1998.

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