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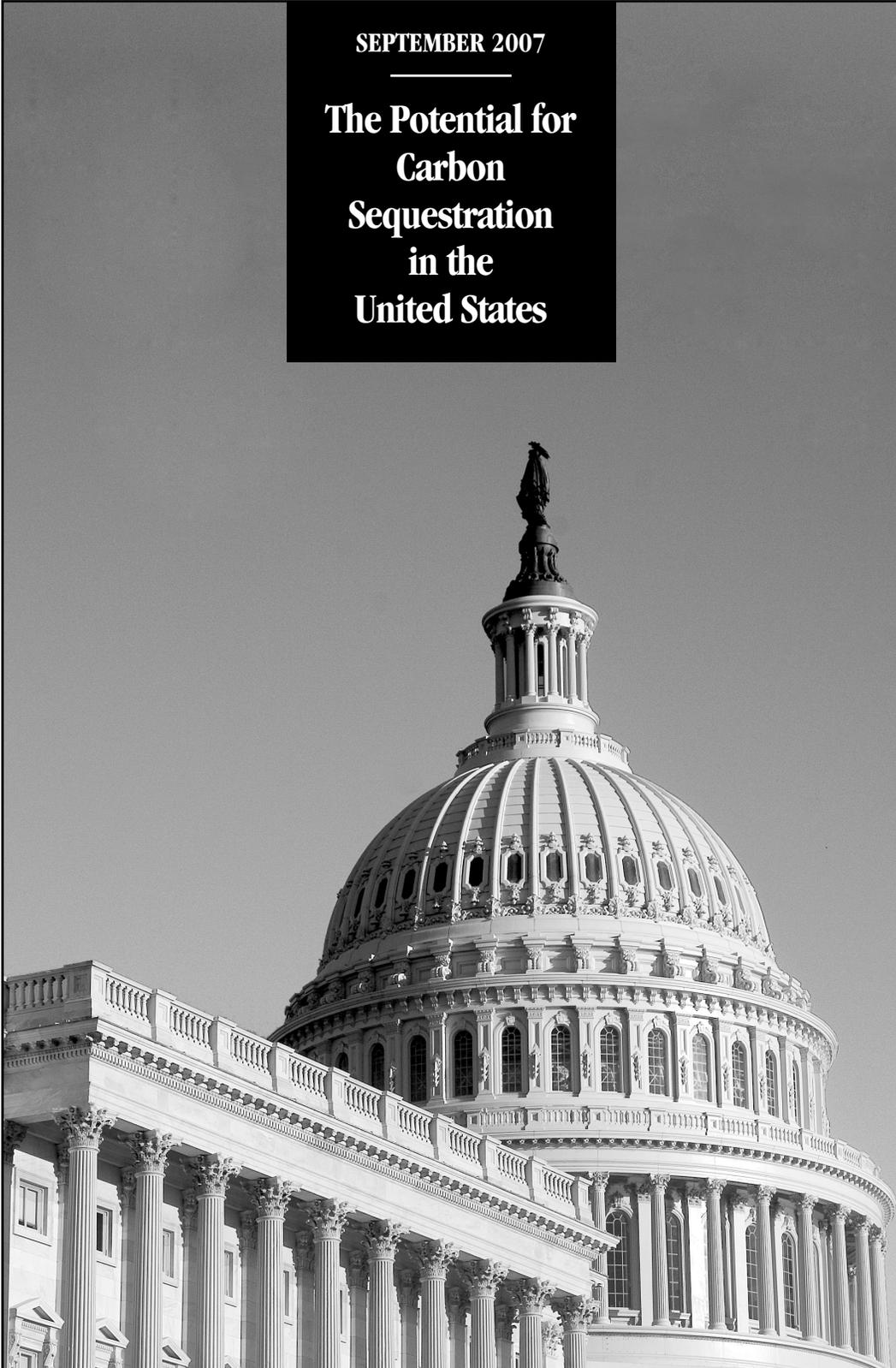
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The Potential for Carbon Sequestration in the United States

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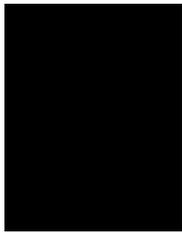# The Potential for Carbon Sequestration in the United States

September 2007

Preface

The atmospheric concentration of greenhouse gases—notably carbon dioxide (CO_2)—has gradually increased over the past century and is warming the Earth's climate. Various analyses suggest that starting to stabilize or reduce that concentration to avoid some future climate-related damage would have greater benefits than costs. Ways to lower the atmospheric concentration of CO_2 include not only reducing emissions but also encouraging carbon sequestration—the capture and storage of CO_2 to prevent its release into the atmosphere, and the absorption of atmospheric CO_2 by vegetation and soil.

This Congressional Budget Office (CBO) paper—prepared at the request of the Chairman of the Subcommittee on Private Sector and Consumer Solutions to Global Warming and Wildlife Protection of the Senate Committee on Environment and Public Works—examines the methods, technological potential, and possible costs of carbon sequestration in the United States. In accordance with CBO's mandate to provide objective, impartial analysis, the paper makes no recommendations.

Natalie Tawil of CBO's Microeconomic Studies Division wrote the paper, under the supervision of Joseph Kile and David Moore. Terry Dinan, Justin Falk, Mark Lasky, Robert Shackleton, and G. Thomas Woodward of CBO provided helpful comments, as did Donald Marron (formerly of CBO), James J. Dooley of the Joint Global Change Research Institute, and Keith Paustian of Colorado State University. (The assistance of external reviewers implies no responsibility for the final product, which rests solely with CBO.)

Christian Howlett edited the paper, and Loretta Lettner proofread it. Maureen Costantino designed the cover and prepared the report for publication. Angela McCollough prepared drafts of the paper. Linda Schimmel coordinated the print distribution, and Simone Thomas prepared the electronic version for CBO's Web site (www.cbo.gov).

Peter R. Orszag
Director

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Introduction and Summary

Human activity emits roughly 32 billion metric tons of carbon dioxide (CO_2)—the primary greenhouse gas—into the atmosphere each year. Worldwide, about 80 percent of those emissions come from the combustion of oil, coal, natural gas, and other fossil fuels; the remaining 20 percent comes from deforestation.[1] (Because plants take in CO_2, removing them releases some or all of that carbon.) Currently, in any given year, the equivalent of about half of total CO_2 emissions are absorbed by the world's oceans, soil, and vegetation, which (together with the atmosphere and fossil carbon deposits) make up the natural reservoirs through which carbon flows over time. The other half of those emissions remain in the atmosphere, contributing to the rising atmospheric concentration of CO_2 and the gradual warming of the Earth's climate.[2]

Various analyses suggest that avoiding future climate-related damage by starting to reduce the atmospheric concentration of CO_2 would have greater benefits than costs. Options for doing that include not only curbing activities that generate emissions but also sequestering CO_2—for example, by encouraging its absorption from the atmosphere into vegetation and soil (biological sequestration) and by trapping CO_2 at power plants and industrial facilities before it is emitted and injecting it into underground storage sites (a process known as carbon dioxide capture and storage, or CCS). This paper looks at the methods, potential scale, and possible costs of both types of carbon sequestration.[3] It also examines the particular role that sequestration could play in the context of the full range of possible actions to mitigate greenhouse-gas emissions.

Types of Carbon Sequestration and Their Technological Potential

Biological sequestration encompasses various ways of using land to enhance the natural uptake of atmospheric carbon in plants and soil. Examples include planting or

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1. For more information about the sources of CO_2 emissions, see Environmental Protection Agency, "Carbon Sequestration in Agriculture and Forestry—Global Scale: Forestry and Agriculture in the Global Carbon Cycle" (October 19, 2006), available at www.epa.gov/sequestration/ccyle.html; and Intergovernmental Panel on Climate Change, Working Group I, *Climate Change 2007: The Physical Science Basis* (Cambridge, England: Cambridge University Press, 2007), available at http://ipcc-wg1.ucar.edu/wg1/wg1-report.html.

2. Greenhouse gases from human activity differ in the extent to which they contribute to global warming. The gases with the greatest potential to contribute to global warming over 100 years are, by order of importance, carbon dioxide, methane, nitrous oxide, and halocarbons. Together, emissions of those gases, weighted by their global-warming potential, rose by 24 percent between 1990 and 2004. CO_2 emissions grew by 28 percent during that period and made up 77 percent of greenhouse-gas emissions from human activity in 2004. See Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2005,* 430-R-07-002 (April 2007), available at www.epa.gov/climatechange/emissions/downloads06/07ES.pdf; and Intergovernmental Panel on Climate Change, Working Group III, *Climate Change 2007: Mitigation of Climate Change—Summary for Policymakers* (Cambridge, England: Cambridge University Press, 2007), available at www.ipcc.ch/SPM040507.pdf.

3. Although the potential for carbon sequestration exists in many parts of the globe (particularly in tropical regions, in the case of biological sequestration), this analysis focuses on sequestration in the United States.

preserving trees, altering how farmers sow crops, planting vegetation in areas prone to soil erosion, and changing the way in which grazing lands are managed. In the United States, those practices might be used to offset a fraction of projected CO_2 emissions over several decades. However, biological sequestration faces implementation challenges, in part because it can be easily reversed by common natural disturbances, such as fires, or by changes in land use and management.

Carbon dioxide capture and storage involves capturing CO_2 emissions for long-term storage in geologic formations such as oil or natural gas fields, coal seams that cannot be mined economically, or deep saline formations. Such sites offer the potential for much larger and more-secure storage than biological sequestration does. (Another possibility is to inject CO_2 deep into the ocean, but that option raises significant ecological concerns.) Some techniques for capturing CO_2 are a routine part of industrial processes, but CCS is still at the experimental stage in the United States for large-scale emission sources (such as electricity-generating plants) and storage sites.

In all, the United States accounts for roughly one-quarter of global CO_2 emissions from fossil-fuel combustion, or about 6 billion metric tons per year. However, its current land-use and forestry practices have the net effect of removing the equivalent of about 0.8 billion metric tons of CO_2 from the atmosphere annually.[4]

Studies estimate that biological sequestration has the technological potential to sequester about 40 billion to 60 billion metric tons of CO_2 in the United States over the course of 50 years and another few tens of billions of tons over the following half-century.[5] The total capacity for storing captured CO_2 emissions in geologic formations is estimated at roughly 1.2 trillion to 3.6 trillion metric tons.[6] Thus, the United States has the technological potential to offset roughly a decade's worth of its current CO_2 emissions through biological sequestration and

a few hundred years' worth of emissions through carbon dioxide capture and storage.[7]

Economic Potential of Carbon Sequestration

The extent to which the United States exploits its technological potential for biological sequestration and CCS will depend on the costs and value of those practices. If a policy was established to limit the atmospheric concentration of CO_2, it would effectively put a price on CO_2 emissions—with a corresponding value for CCS and perhaps also for biological sequestration. The specific details of the policy would determine the price. The range of recently debated policies and literature on the economic costs of reducing greenhouse-gas emissions suggest a CO_2 price of about $5 to $65 per metric ton by 2020. Some economists' estimates of the socially optimal price for CO_2 emissions—the price that balances the incremental cost of countering climate change with the

4. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. Carbon in vegetation and soil is generally quantified in terms of carbon mass, not carbon dioxide (although when that carbon is removed from, or released into, the atmosphere, it is mainly in the form of carbon dioxide). One metric ton of carbon is equivalent to 3.67 metric tons of carbon dioxide.

5. Estimates of technological potential are highly dependent on underlying assumptions, particularly land-use scenarios. This estimate is conservative in that it draws on sources that tend not to assume large-scale changes in land use. See, for example, R. Lal and others, *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect* (Ann Arbor, Mich.: Ann Arbor Press, 1998), pp. 18–21; R.F. Follett and others, *The Potential of U.S. Grazing Land to Sequester Carbon and Mitigate the Greenhouse Effect* (Boca Raton, Fla.: CRC Press, 2001), pp. 401–430; and Kenneth E. Skog and Geraldine A. Nicholson, "Carbon Sequestration in Wood and Paper Products," and R. Birdsey, Ralph Alig, and Darius Adams, "Mitigation Activities in the Forest Sector to Reduce Emissions and Enhance Sinks of Greenhouse Gases," in Linda A. Joyce and Richard Birdsey, eds., *The Impact of Climate Change on America's Forests: A Technical Document Supporting the 2000 USDA Forest Service RPA Assessment*, General Technical Report RMRS-GTR-59 (Department of Agriculture, Forest Service, 2000), pp. 79–88 and 112–131. The first study estimates the potential for restoring soil carbon lost to agricultural activity; the second estimates the potential associated with reserving grazing land for conservation purposes, restoring grazing land and soil, and using better management practices; and the final studies offer projections of the forestry-related net removal of carbon from the atmosphere.

6. Department of Energy, National Energy Technology Laboratory, *Carbon Sequestration Atlas of the United States and Canada* (March 2007). That estimate includes geologic storage capacity in Canada as well as the United States.

7. Department of Energy, Energy Information Administration, *Emissions of Greenhouse Gases in the United States, 2005,* DOE/EIA-0573(2005) (November 2006), Chapter 2, available at www.eia.doe.gov/oiaf/1605/ggrpt/carbon.html.

incremental damage of allowing it to occur—also fall within that range.[8]

Although biological sequestration practices have a relatively small technological potential in the United States, they could be put in place by landowners immediately and are fairly inexpensive. Economic analyses estimate that a CO_2 price of $5 per metric ton would prompt enough changes in forest and cropland-soil management to sequester between 0.5 billion and 25 billion metric tons of CO_2 over 100 years (in addition to the 0.8 billion metric tons already removed annually by plants and soil in the United States).[9] That range equals about 5 million to 250 million metric tons per year—or up to 4 percent of the nation's CO_2 emissions from human activity in 2005.[10] Roughly speaking, those levels of biological sequestration might account for, at most, less than half of the technological potential. A CO_2 price of $50 per metric ton might prompt enough changes to fully exploit the technological potential of forest and cropland-soil strategies, sequestering more than 60 billion metric tons of CO_2 over a century.

Any policy to promote biological sequestration, however, would have to address significant implementation challenges. For example, in accounting for sequestration activities voluntarily undertaken by landowners in response to a policy, authorities would have to determine

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8. For example, in a recent paper, economist William Nordhaus concluded that the socially optimal price for a metric ton of CO_2 would be $7.35, rising steadily (at 2 percent to 3 percent a year) to about $10.15 by 2020; see Nordhaus, *The Challenge of Global Warming: Economic Models and Environmental Policy* (New Haven, Conn.: Yale University, July 24, 2007), available at http://nordhaus.econ.yale.edu/dice_mss_072407_all.pdf. Also see Intergovernmental Panel on Climate Change, Working Group II, *Climate Change 2007: Impacts, Adaptations, and Vulnerability—Summary for Policymakers* (Cambridge, England: Cambridge University Press, 2007), p. 16, available at www.ipcc.ch/SPM13apr07.pdf.

9. Unless otherwise stated, the values for CO_2 prices in this paper can be thought of in terms of 2005 dollars, which is what most of the underlying studies used for their estimates. (Some of the studies did not specify the nature of their dollar values, but those analyses were conducted in the low-inflation environment of the early 2000s and do not reflect a level of precision that would make an assumption of 2005 dollar values inappropriate.)

10. Department of Energy, *Emissions of Greenhouse Gases in the United States, 2005*.

whether the actions were attributable to the policy or would have occurred even in its absence.

CO_2 capture and storage, which has a fairly large technological potential, has not yet been demonstrated on the scale envisioned for mitigating CO_2 emissions. It is also more costly than biological sequestration. Analysts estimate that the CO_2 price would need to be in the range of $15 to $90 per metric ton (depending on the type of electricity plant at which the CO_2 was captured) to cover the anticipated costs of CCS and exploit the full potential for geologic storage. That potential corresponds to several hundred years' worth of CO_2 emissions at current U.S. levels.

Interactions Among Various Climate-Change Strategies

To refine estimates of the extent to which the United States might use carbon sequestration practices, those practices need to be considered in the context of a broader range of strategies for mitigating climate change (taking as a given that the benefits of action to counter climate change exceed the costs of inaction). Other strategies include increasing the nation's reliance on renewable or alternative sources of energy (including biofuels), using energy more efficiently, and reducing emissions of other greenhouse gases (such as methane and nitrous oxide). The relative importance of those different strategies is apt to vary over time with changes in the price for CO_2.

Analysis suggests that limits on CO_2 emissions would be likely to spur an increasing, and relatively large, reliance on carbon dioxide capture and storage for some time. By contrast, the economic potential for biological sequestration would start to decline after some point. Not only is that approach's physical potential fairly limited, but more important, restrictions on emissions would encourage landowners to cultivate biofuel crops as CO_2 prices rose, including on forestland not being valued for its sequestration services. Recent studies suggest that such land-use changes argue for the importance of having any policy target for climate change cover the full terrestrial stock of biological carbon. Otherwise, releases of carbon associated with those land-use changes would partly offset the reductions in atmospheric carbon associated with narrower limits on greenhouse-gas emissions, such as limits that applied only to fossil-fuel-related emissions.

Biological Sequestration

Biological sequestration involves using and managing land in ways that enhance the natural absorption of atmospheric carbon by vegetation and soil. Plants and soil absorb and lose carbon through various natural processes. For example, plants take in atmospheric CO_2 through photosynthesis and incorporate it into their biomass as carbon. When plants decay, some of that carbon is released into the atmosphere, and some is deposited in the soil as organic carbon. Soil microorganisms transform decomposing vegetation into inorganic compounds (such as mineral nutrients and CO_2), which may be absorbed by new vegetation or returned to the atmosphere. The amount of carbon that is sequestered in plants and soil reflects the long-term balance between carbon absorption and release mechanisms.[11]

The long-term storage potential—or carbon stock equilibrium—of soil and vegetation is limited by characteristics such as location, climate, soil type, and plant species. The extent to which that storage potential is realized depends partly on how land is used and managed. On land used for crops in the continental United States, the equilibrium level of carbon in an acre of soil varies from the equivalent of 56 metric tons of CO_2 to 120 metric tons, averaging about 80 metric tons.[12] Pasture, range-land, and agricultural land that is reserved for conservation purposes store carbon at higher equilibrium levels: Those levels range from 73 to 159 metric tons of CO_2 per acre and average 113 metric tons. Mature, never-harvested forests have even higher equilibrium levels per acre, varying from 286 to 1,179 metric tons of CO_2 and averaging 465 metric tons.[13] Harvesting forests decreases the equilibrium level of carbon. The average stand of timber harvested on a 30-year rotation holds the equivalent

of 203 metric tons of CO_2 per acre at the beginning of the rotation (that is, at the start of its regrowth) and 256 metric tons at the end of the rotation.[14]

Agricultural Land Management Practices

Various agricultural practices, such as reducing or eliminating tillage and altering the mix of crops, can enhance carbon sequestration. Tillage (ploughing and harrowing to produce a seed bed) releases carbon into the atmosphere by disturbing the soil and increasing the exposure of soil carbon to the air. Tillage also removes plant residue from the previous crop that would have protected and increased carbon in the soil. Those effects can be lessened through no-tillage practices, in which farmers sow crops by cutting narrow slots in the soil for seeds and do not remove residue from earlier crops. In addition, as farmers rotate which crops they grow on which parts of their land from year to year, they can foster sequestration through frequent use of cover crops—particularly those, like hay, that do not require tillage and that fix carbon in the soil through their extensive root systems. Other practices that help sequester carbon include planting grasses on the edges of cropland and streams to prevent soil erosion and changing grazing management on rangeland and pasture (for example, by rotating grazing areas and using improved plant species).[15]

Numerous studies have examined how much additional carbon would be sequestered on land where those

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11. Globally, carbon stocks in soil are about four times greater than carbon stocks in vegetation. In particular ecosystems, the ratio of soil carbon to carbon in vegetation ranges from about 1 to 1 in tropical forests to 5 to 1 in boreal forests, 15 to 1 in wetlands, 33 to 1 in grasslands, and 43 to 1 in croplands. See Intergovernmental Panel on Climate Change, *Land Use, Land-Use Change, and Forestry—Summary for Policymakers* (Geneva, Switzerland: IPCC, 2000), Part 1, Table 1, available at www.grida.no/climate/ipcc/land_use/003.htm.

12. Carbon stocks on cropland are primarily contained in the soil. Although the crops themselves absorb large amounts of carbon annually, much of it leaves the land in harvested agricultural products. The remaining crop residues decompose fairly quickly.

13. Carbon sequestration occurs in four parts of a forest: soil, trees, the forest floor, and understory vegetation. The share of total sequestration attributable to each part differs greatly depending on the region, the type and age of the forest, the quality of the site, and previous land use. On average, soil contains 59 percent of the carbon stored in a forest, trees contain 31 percent, forest litter holds 9 percent, and understory vegetation accounts for 1 percent. See Richard A. Birdsey, *Carbon Storage and Accumulation in United States Forest Ecosystems,* General Technical Report W0-59 (Department of Agriculture, Forest Service, August 1992).

14. Ruben N. Lubowski, Andrew J. Plantinga, and Robert N. Stavins, "Land-Use Change and Carbon Sinks: Econometric Estimation of the Carbon Sequestration Supply Function," *Journal of Environmental Economics and Management,* vol. 51, no. 2 (March 2006), pp. 135–152, Appendix C, available at www.econ.iastate.edu/jeem/supplement/MS15019.pdf.

15. In addition to those practices for lands that are in use, sequestration can be enhanced by retiring land (such as by using conservation set-asides, converting drained land to wetland, and changing cropland into grassland or forest).

practices were used. Estimates of the increase associated with changing from conventional tillage to no tillage range from the equivalent of 0.64 to 1.05 metric tons of CO_2 per acre per year.[16] Altering the mix of crops might sequester the equivalent of 0.12 to 0.47 metric tons of CO_2 per acre annually.[17] Permanent plantings along waterways might yield the equivalent of 0.4 to 1.0 metric ton of CO_2 per acre per year, and changes in grazing management on rangeland and pasture might sequester the equivalent of 0.07 to 1.90 metric tons of CO_2 per acre per year.[18] Those practices would cause land to reach its carbon stock equilibrium in an estimated 15 to 20 years for no tillage and 25 to 50 years for crop-mix changes and grazing management.[19] After that, continuing those practices would maintain the carbon stock equilibrium but would not sequester any additional carbon on that land.

Forestry Practices

Carbon sequestration can also be enhanced by planting new trees and reducing the destruction of existing forests. Afforestation—planting trees on land previously used for other purposes—raises annual sequestration by the equivalent of 2.2 to 9.5 metric tons of CO_2 per acre for 120 years, studies estimate.[20] For reforestation—planting trees on land recently devoted to forestry (such as severely burned land)—the increase in sequestration is slightly smaller: 1.1 to 7.7 metric tons per acre.[21]

Sequestration can also be increased through certain management practices on timberland, such as choosing particular tree species, timing harvests, and managing pests and fires. Estimates of those increases range from 2.1 to 3.1 metric tons of CO_2 per acre per year.[22] Increases from timber management do not have a fixed time horizon because of the carbon content of the associated wood products.[23]

16. That range comes from Tristram O. West and Wilfred M. Post, "Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation: A Global Data Analysis," *Soil Science Society of America Journal,* vol. 66 (November–December 2002), pp. 1930–1946. It was independently confirmed in Keith Paustian and others, *Climate Change and Greenhouse Gas Mitigation: Challenges and Opportunities for Agriculture,* Task Force Report No. 141 (Ames, Iowa: Council for Agricultural Science and Technology, May 2004). The range is smaller in studies that focus exclusively on the United States: 0.15 to 0.89 metric tons per acre per year. See Lal and others, *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect,* pp. 18–21; R. Lal and others, "Managing U.S. Cropland to Sequester Carbon in Soil," *Journal of Soil and Water Conservation*, vol. 54 (First Quarter 1999), pp. 374–381; and R.F. Follett, "Soil Management Concepts and Carbon Sequestration in Cropland Soils," *Soil & Tillage Research*, vol. 61 (August 2001), pp. 77–92.

17. That range comes from West and Post, "Soil Organic Carbon Sequestration Rates." Studies that look only at the United States estimate a slightly smaller range: 0.15 to 0.45 metric tons per acre annually. See Lal and others, *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect,* and "Managing U.S. Cropland to Sequester Carbon in Soil."

18. The highest rates achieved with management changes come from converting grazing land to perennial grasses. See Environmental Protection Agency, *Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture,* EPA 430-R-05-006 (November 2005); and Paustian and others, *Climate Change and Greenhouse Gas Mitigation.*

19. West and Post, "Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation"; and Environmental Protection Agency, *Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture.*

20. R.A. Birdsey, "Regional Estimates of Timber Volume and Forest Carbon for Fully Stocked Timberland, Average Management After Final Clearcut Harvest," in R.N. Sampson and D. Hair, eds., *Forests and Global Change,* vol. 2, *Forest Management Opportunities for Mitigating Carbon Emissions* (Washington, D.C.: American Forests, 1996), pp. 309–334. Those estimates are for afforestation in the United States, which is largely a temperate region. Recent research suggests that in the tropics, afforestation would have a greater impact on climate change, whereas at high latitudes, afforestation would be counterproductive because vegetation would darken the landscape and cause it to absorb more sunlight, more than offsetting the benefits of carbon sequestration; see G. Bela and others, "Combined Climate and Carbon-Cycle Effects of Large-Scale Deforestation," *Proceedings of the National Academy of Sciences,* vol. 104, no. 16 (April 17, 2007), pp. 6550–6555.

21. Birdsey, "Regional Estimates of Timber Volume and Forest Carbon for Fully Stocked Timberland."

22. C. Row, "Effects of Select Forest Management Options on Carbon Storage," in Sampson and Hair, eds., *Forest Management Opportunities for Mitigating Carbon Emissions.*

23. A share of the carbon contained in the salable portion of harvested timber is sequestered in wood and paper products (including recycled products) during their usable lives and afterward in landfills. Estimates of that share range from 20 percent to about 45 percent. See Lubowski, Plantinga, and Stavins, "Land-Use Change and Carbon Sinks," Appendix C; and, for a discussion of the uncertainties of such estimates, Ross W. Gorte, *Carbon Sequestration in Forests,* CRS Report for Congress RL31432 (Congressional Research Service, March 29, 2007).

Technological Potential of Biological Sequestration

In all, the United States could sequester an estimated 40 billion to 60 billion metric tons of CO_2 over 50 years using the agricultural and forestry practices described above.[24] That amount is equivalent to 0.8 billion to 1.2 billion metric tons per year—or roughly 13 percent to 20 percent of the nation's CO_2 emissions in 2005. Over the succeeding half-century, the United States could probably sequester another few tens of billions of tons of CO_2.

Biological carbon sequestration is easily reversible, however. Altering or abandoning the practices undertaken to increase sequestration would release some of the stored carbon, as would natural disturbances (such as fires or pest outbreaks) and perhaps global warming.

The effects of climate change could also have an impact on the overall technological potential for biological sequestration. Higher levels of CO_2 in the atmosphere and greater releases of nitrogen from decomposition accelerated by warming could increase biological sequestration by acting as fertilizers. As the climate continued to warm, however, those effects would be increasingly offset by a rise in plant and soil respiration, which would boost the release of carbon from the land. Recent modeling suggests that with higher temperatures, net absorption of carbon will at some point be significantly reduced or even reversed because of increased respiration and limits on plant growth imposed by the availability of nutrients and water.[25]

Economic Potential of Biological Sequestration

The extent to which the United States realizes the technological potential of biological sequestration will depend

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24. Lal and others, *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect*; Follett and others, *The Potential of U.S. Grazing Land to Sequester Carbon and Mitigate the Greenhouse Effect*; Skog and Nicholson, "Carbon Sequestration in Wood and Paper Products"; and Birdsey, Alig, and Adams, "Mitigation Activities in the Forest Sector to Reduce Emissions and Enhance Sinks of Greenhouse Gases."

25. Andrei P. Sokolov and others, *Consequences of Considering Carbon/Nitrogen Interactions on the Feedbacks Between Climate and the Terrestrial Carbon Cycle,* Report No. 151 (Cambridge, Mass.: Massachusetts Institute of Technology Joint Program on the Science and Policy of Global Change, June 2007).

on the costs of altering land-use practices and the economic incentives for doing so. Policies to limit greenhouse-gas emissions would effectively create a price for emitting a ton of CO_2—and potentially for offsetting those emissions by sequestering carbon. The level of that price would affect the amount of biological sequestration undertaken in the United States. In addition, the specific mix of different strategies for limiting the atmospheric concentration of greenhouse gases—such as biological sequestration, carbon dioxide capture and storage, greater reliance on renewable and alternative sources of energy, and energy-efficiency efforts—will depend on the relative real (inflation-adjusted) costs of employing each of those strategies.

Afforestation. According to various studies, a price of $5 per metric ton of CO_2 would prompt enough new forests to be planted in the United States to sequester the equivalent of between 2 million and about 50 million metric tons of CO_2 annually over 100 years (a period that would generally cover a forest's full growth). The top end of that range equals almost 1 percent of the United States' current annual CO_2 emissions from human activity. If the price of CO_2 was $50 per metric ton, enough afforestation would occur to sequester an estimated 500 million to 800 million metric tons per year over the same period (see Figure 1)—or as much as 13 percent of annual U.S. emissions of CO_2.

In deciding whether to engage in sequestration activities, landowners would consider two types of costs: direct costs and opportunity costs. Direct costs are those associated with the activity itself—the cost of planting trees, for example. Opportunity costs are the forgone returns associated with alternative uses of the land that the owner did not choose—for instance, land used to grow trees cannot also be used to grow biofuel crops.

The estimates cited above come from studies whose models account for both direct costs and opportunity costs. Those "sector optimization models" assume that landowners seek to maximize their profits through their responses to forest, agriculture, and CO_2 prices. The models acknowledge to some degree the competition that exists between the different land uses from which people can choose (including different strategies for mitigating

Figure 1.

Estimates of the Amount of Carbon That Would Be Sequestered Annually Through Afforestation in the United States at Different CO_2 Prices
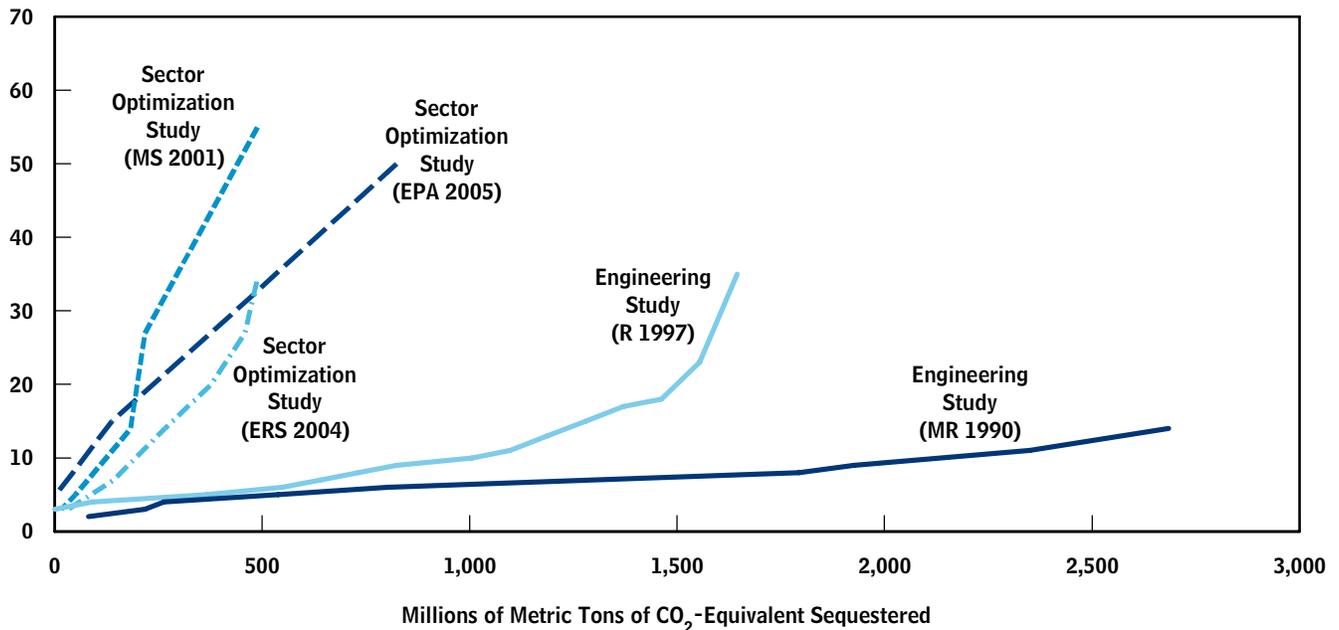
(Dollars per metric ton of CO_2)

Millions of Metric Tons of CO_2-Equivalent Sequestered

Source: Congressional Budget Office based on the studies listed below.

Notes: CO_2 = carbon dioxide.

EPA 2005 = Environmental Protection Agency, *Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture,* EPA 430-R-05-006 (November 2005).

ERS 2004 = Jan Lewandrowski and others, *Economics of Sequestering Carbon in the U.S. Agricultural Sector,* Technical Bulletin 1909 (Department of Agriculture, Economic Research Service, March 2004).

MS 2001 = Bruce A. McCarl and Uwe A. Schneider, ''Greenhouse Gas Mitigation in U.S. Agriculture and Forestry,'' *Science,* vol. 294 (December 21, 2001), pp. 2481–2482.

R 1997 = Kenneth R. Richards, *Estimating Costs of Carbon Sequestration for a United States Greenhouse Gas Policy* (Boston: Charles River Associates, 1997).

MR 1990 = Robert J. Moulton and Kenneth R. Richards, *Costs of Sequestering Carbon Through Tree Planting and Forest Management in the United States,* General Technical Report WO-58 (Department of Agriculture, Forest Service, 1990).

Sector optimization studies account for both direct costs and opportunity costs in modeling landowners' decisionmaking; engineering studies take into account only direct costs. Other engineering studies that CBO examined yielded estimates within the range defined by the results of MR 1990 and R 1997; thus, they are not included here. Those studies are Daniel J. Dudek and Alice LeBlanc, ''Offsetting New CO_2 Emissions: A Rational First Greenhouse Policy Step,'' *Contemporary Policy Issues,* vol. 8, no. 3 (July 1990), pp. 29–42; Kenneth R. Richards, Robert J. Moulton, and Richard A. Birdsey, ''Costs of Creating Carbon Sinks in the U.S.,'' *Energy Conservation and Management,* vol. 34, nos. 9–11 (1993), pp. 905–912; Richard M. Adams and others, ''Sequestering Carbon on Agricultural Land: Social Costs and Impacts on Timber Markets,'' *Contemporary Policy Issues,* vol. 11, no. 1 (January 1993), pp. 76–87; and Peter J. Parks and Ian W. Hardie, ''Least-Cost Forest Carbon Reserves: Cost-Effective Subsidies to Convert Marginal Agricultural Land to Forests,'' *Land Economics,* vol. 71, no. 1 (February 1995), pp. 122–136.

All of the estimates shown here reflect the annualized net present value of the mitigation. Where necessary, CBO used adjusted results to reflect a discount rate of 4 percent to 5 percent (with the exception of the MS 2001 study, which does not specify the discount rate used). All of the studies (except possibly MS 2001) account for carbon in all four components of the forest ecosystem: soil, trees, the forest floor, and understory vegetation.

CO_2 emissions) and the market responses associated with those choices.[26]

Other studies of the economic potential of carbon sequestration through afforestation use "engineering models" that take into account only direct costs. Those models produce higher estimates (see Figure 1), but the estimates are less reliable because the models examine only the option of afforestation. They do little to account for the effects of an afforestation strategy on land and other markets.

Cropland Soil. Studies have also used sector optimization models to examine the economic potential of sequestration in cropland soil (see Figure 2).[27] That potential is greater than for afforestation at low CO_2 prices but the reverse at higher prices. With a CO_2 price of $5 per metric ton, cropland management would sequester the equivalent of about 3 million to 200 million metric tons per year in the United States over a 100-year period, the studies estimate. The high end of that range is equivalent to about 3 percent of the nation's current yearly CO_2 emissions from human activity. At a CO_2 price of $50 per metric ton, the range of estimates is about 90 million to 200 million metric tons a year over that time frame.

Above a certain point, a higher price for CO_2 does not induce greater amounts of sequestration through crop-

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26. Of the three sector optimization studies shown in Figure 1, MS 2001 looked at carbon mitigation associated with afforestation, agricultural soil, livestock operations, and biofuel production; ERS 2004 considered carbon mitigation associated with afforestation, agricultural soil, and grasslands; and EPA 2005 examined carbon mitigation associated with afforestation, forest management, agricultural soil, biofuels, grassland, livestock operations, and fossil-fuel use in crop production. That last study also included mitigation options for two other greenhouse gases commonly associated with agricultural operations: methane and nitrous oxide.

27. All of the studies shown in Figure 2, which are sector optimization studies, examined changes in tillage and (with the possible exception of MS 2001) changes in crop mix. In addition, M 2007 looked at biofuels, grassland, decreases in fertilizer use (which affects the greenhouse gas nitrous oxide), changes in other crop production inputs, and livestock operations and other activities (such as converting irrigated land to dry land and reducing rice acreage) that affect levels of methane and nitrous oxide. (The various policies included in MS 2001, ERS 2004, and EPA 2005 are described in the previous footnote.)

land management because other carbon-mitigation strategies—such as using land to cultivate biofuel crops—become more attractive as CO_2 prices rise. In fact, higher CO_2 prices are projected to cause a decline in sequestration from cropland management as landowners shift to more profitable mitigation strategies (see Figure 2).

A Limitation of the Estimates of Economic Potential. An important caveat about the estimates shown in Figure 1 and Figure 2 is that they do not reflect the effects of whatever regulatory system might be used to implement CO_2 pricing for biological sequestration. Such regulation would probably be relatively complex. To be effective, it would have to address the fact that biological sequestration is not necessarily permanent. And it would need to take into account that biological sequestration measures used on one piece of land could influence the use of other land in ways that could increase greenhouse-gas emissions. Moreover, in measuring biological sequestration for compensation purposes, regulators would have to factor in the amount of sequestration that would have occurred anyway. (For more about the implementation issues associated with biological sequestration, see Box 1.)

Carbon Dioxide Capture and Storage

Carbon dioxide capture and storage involves capturing CO_2 emitted by power plants and large-scale industrial facilities and storing it in underground reservoirs (or possibly in the oceans). CO_2 capture is already used on a small scale as part of various industrial processes. Its use on a scale that could help reduce the atmospheric concentration of greenhouse gases is still experimental and is likely to be fairly expensive. Nevertheless, CCS appears to have the technological potential to store very large quantities of CO_2 relatively securely. The power generators (and perhaps large industrial plants) that are possible candidates to eventually employ CCS produced well over 40 percent of the United States' CO_2 emissions associated with human activity in 2005.[28]
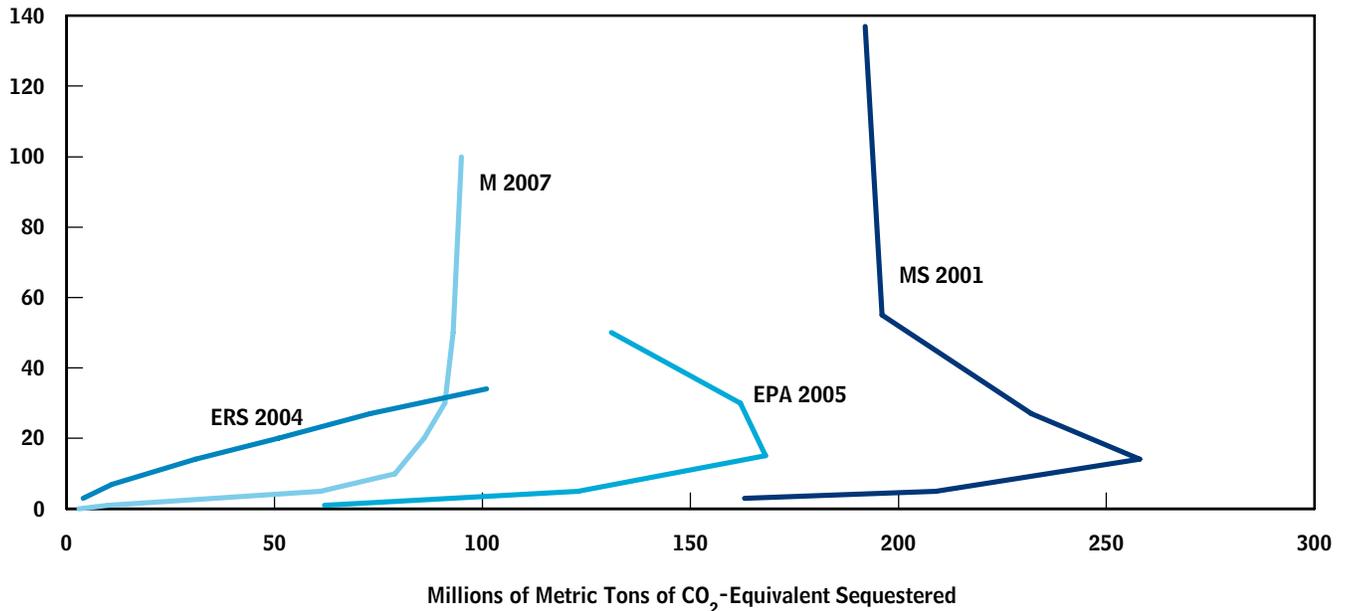
Capture

Carbon dioxide can be captured before or after fossil fuel is burned. Either approach is likely to confine about

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28. Department of Energy, *Emissions of Greenhouse Gases in the United States, 2005.*

Figure 2.

Estimates of the Amount of Carbon That Would Be Sequestered Annually in Cropland Soil in the United States at Different CO_2 Prices

(Dollars per metric ton of CO_2)

Millions of Metric Tons of CO_2-Equivalent Sequestered

Source: Congressional Budget Office based on the studies listed below.

Notes: CO_2 = carbon dioxide.

M 2007 = Bruce A. McCarl, ''Agriculture in the Climate Change and Energy Price Squeeze, Part 2: Mitigation Opportunities'' (presentation given at the Fourth USDA Greenhouse Gas Conference, Baltimore, February 6–8, 2007).

EPA 2005 = Environmental Protection Agency, *Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture,* EPA 430-R-05-006 (November 2005).

ERS 2004 = Jan Lewandrowski and others, *Economics of Sequestering Carbon in the U.S. Agricultural Sector,* Technical Bulletin 1909 (Department of Agriculture, Economic Research Service, March 2004).

MS 2001 = Bruce A. McCarl and Uwe A. Schneider, ''Greenhouse Gas Mitigation in U.S. Agriculture and Forestry,'' *Science,* vol. 294 (December 21, 2001), pp. 2481–2482.

All of the studies shown here are sector optimization studies, which account for both direct costs and opportunity costs in modeling landowners' decisionmaking. The reduction in sequestration at higher CO_2 prices reflects the fact that alternative uses of land (such as for growing biofuel crops) become more cost-effective at higher CO_2 prices.

Implementation Issues for a Biological Sequestration Policy

According to analysts, any policy for reducing atmospheric concentrations of carbon dioxide (CO_2) that explicitly accounted for carbon sequestered in agricultural land or forests would have to address three measurement issues:

■ Permanence—biological sequestration does not necessarily last forever;

■ Leakage—the policy could prompt changes in economic activities that would increase CO_2 emissions in other places or from other sectors, thus countering the effects of the sequestration; and

■ Additionality—measurements would need to factor in the amount of biological sequestration that would have occurred without the policy.[1]

Different methods have been proposed to account for the fact that biological sequestration may be impermanent. One method would be to credit biological sequestration projects as carbon was stored and debit them as it was released into the atmosphere. A second approach would be to discount the value attributed to biological sequestration projects based on expectations about the amount and timing of any release of sequestered carbon into the atmosphere. A third approach would be to treat CO_2 credits associated with biological sequestration projects as though they had to be redeemed in the future. Credits could carry expiration dates, at which time they would have to be regenerated by continuing the sequestration project, establishing a new project, or otherwise achieving a permanent reduction in emissions.

The problems of leakage and additionality can be defined according to the specific architecture of the policy being considered. Current policy discussions focus on what types of biological sequestration actions could or could not be used to meet an emissions target that was defined in terms

of CO_2 released from fossil-fuel combustion. Those discussions do not include bringing the full terrestrial stock of biological carbon within a policy target. Under the current focus of those discussions, leakage might occur when, for example, a landowner opted not to harvest timber in order to sequester carbon. That action would reduce the supply of lumber but leave demand unchanged. Other suppliers might then choose to produce more lumber, increasing the amount of carbon they released and countering the sequestration effort. A policy that allowed for biological sequestration only through credits to parties who voluntarily engaged in certain actions would raise concerns about that potential countereffect.[2] But a policy that covered all potential emissions and absorptions of CO_2 would account for that effect.

Additionality is important to determine because policies to counter climate change seek to encourage new CO_2-reduction activities beyond those that would have occurred anyway. Under a biological sequestration policy that credited certain voluntary actions, there would be two main difficulties in determining "baseline" changes in CO_2 (those not attributable to the climate change policy). First, parties engaged in the voluntary actions would have an incentive to understate the baseline because doing so would increase the value associated with their efforts. Second, many uncertainties exist in trying to estimate the future path of carbon sequestration in the absence of a sequestration project. Given the many random events that could affect decisions and influence natural systems, it is very difficult to predict what landowners' future actions would otherwise have been. Again, establishing a policy target that covered the full terrestrial stock of biological carbon would subsume those difficulties under the more general challenge of finding proven ways to measure and monitor changes in that stock.

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1.   The information in this box comes from Brian C. Murray, Brent Sohngen, and Martin T. Ross, "Economic Consequences of Consideration of Permanence, Leakage, and Additionality for Soil Carbon Sequestration Projects," *Climatic Change,* vol. 80 (January 2007), pp. 127–143; and John M. Reilly and Malcolm O. Asadoorian, "Mitigation of Greenhouse Gas Emissions from Land Use: Creating Incentives Within Greenhouse Gas Emissions Trading Systems," *Climatic Change,* vol. 80 (January 2007), pp. 173–197.

2.   Studies suggest that leakage associated with carbon sequestration in agricultural soil would range from less than 10 percent for working land to 20 percent for retired land, whereas leakage associated with forest conservation could reach 90 percent. See Murray, Sohngen, and Ross, "Economic Consequences of Consideration of Permanence, Leakage, and Additionality for Soil Carbon Sequestration Projects"; and Brian C. Murray, Bruce A. McCarl, and Heng-Chi Lee, "Estimating Leakage from Forest Carbon Sequestration Programs," *Land Economics,* vol. 80, no. 1 (February 2004), pp. 109–124.

90 percent of a plant's CO_2 emissions.[29] In postcombustion capture, plant operators cool flue gases, treat them for contaminants, and pass them through reusable chemical solvents that trap CO_2. Heat is then used to extract the CO_2. The higher the CO_2 content and pressure of the flue gases, the less energy-intensive and less costly the process. Among the types of electric power plants that might employ postcombustion capture, the CO_2 content of flue gases ranges from 3 percent to 6 percent for natural gas combined-cycle plants and from 10 percent to 12 percent for pulverized-coal plants.[30] (Certain industrial processes, such as making cement, release a much higher proportion of CO_2 in their flue gases. However, those processes account for only a small fraction of U.S. emissions of CO_2 caused by human activity.)[31]

Postcombustion capture is being considered as a way to reduce CO_2 emissions from conventional coal-fired electricity generators in the United States. For example, a 180-megawatt power plant in Maryland uses the process to capture CO_2, which is then sold to the food industry.

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29. See John Deutch, Ernest J. Moniz, and others, *The Future of Coal: Options for a Carbon-Constrained World* (Cambridge, Mass.: Massachusetts Institute of Technology, 2007), available at http://web.mit.edu/coal/The_Future_of_Coal.pdf; Intergovernmental Panel on Climate Change, *Carbon Dioxide Capture and Storage— Summary for Policymakers and Technical Summary* (Cambridge, England: Cambridge University Press, 2005), available at www.ipcc.ch/activity/ccsspm.pdf; Nisheeth Singh, "A Systems Perspective for Assessing Carbon Dioxide Capture and Storage Opportunities" (master's thesis, Massachusetts Institute of Technology, May 2004), available at http://sequestration.mit.edu/pdf/Nisheeth_Singh_thesis_June2004.pdf ; and B. Bock, P. Goldberg, and R. Rhudy, *Economic Evaluation of CO_2 Storage and Sink Enhancement Options* (Tennessee Valley Authority, Department of Energy, and Electric Power Research Institute, December 2002).

30. Department of Energy, "Carbon Capture Research" (August 7, 2007), available at www.fe.doe.gov/sequestration/capture/index.html. Natural gas and coal are the resources most widely used for electricity generation in the United States; they accounted for 20 percent and 49 percent, respectively, of net generation in 2006. See Department of Energy, Energy Information Administration, "Net Generation by Energy Source" (May 11, 2007), Table 1.1, available at www.eia.doe.gov/cneaf/electricity/epm/table1_1.html#_ftn3.

31. Department of Energy, *Emissions of Greenhouse Gases in the United States, 2005*. Calcining, a process involving the intense heating of limestone that is used in cement and lime production, accounts for the majority of those non-fossil-fuel-related industrial emissions. It releases CO_2 at concentrations of 14 percent to 33 percent. See Singh, "A Systems Perspective for Assessing Carbon Dioxide Capture and Storage Opportunities."

(Carbon dioxide is an important input in many manufacturing processes, including the production of carbonated beverages.) Operators of a 5-megawatt plant in Wisconsin hope to demonstrate the technology there by fall 2007. If the demonstration is successful, current plans call for applying postcombustion capture at two larger coal-fired power plants, in West Virginia and Oklahoma, over the following few years.[32]

In precombustion capture, by contrast, natural gas, oxygen, and sometimes steam are used to produce CO_2 and hydrogen (generally for commercial purposes).[33] Although the process usually employs natural gas, it can be applied to any gasified fossil fuel (such as coal) or to biomass. Precombustion techniques release CO_2 at higher pressures and higher concentrations than in the flue gases of conventional power plants that run on pulverized coal. That means that the process can use physical solvents for CO_2 capture, which merely require reducing pressure to release CO_2—a less energy-intensive method than generating the heat needed for the chemical solvents used in postcombustion capture. Precombustion techniques also require less equipment because of the higher pressure of the CO_2 releases.

Precombustion capture, which is a routine part of some industrial processes, is also being considered for use in electricity-generating plants. It is well suited to integrated gasification combined-cycle (IGCC) power plants, which convert coal or other fuels into syngas and use it to produce electricity.[34] IGCC technology is currently being used to generate electricity from coal at two U.S. plants, and at least 34 more IGCC coal plants have been proposed in the United States. (According to the Energy Information Administration, under current policies, none of the plants expected to be built between now and 2030 will have carbon dioxide capture and storage capabilities.) Precombustion capture has not yet been employed with

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32. Daniel Cusick, "Climate: French Company Sees Fortunes Rise with Talk of U.S. Emission Curbs," *Greenwire* (May 15, 2007), available at www.eenews.net/Greenwire/2007/05/15#1.

33. The hydrogen that is produced with that technique is used mainly to make ammonia and fuels. The CO_2 that is produced supplies the commercial market for carbon dioxide.

34. Syngas (synthesis gas) is the name given to the substance that results when a fuel containing carbon is transformed into a gas product that releases energy when burned. The concentration of CO_2 in the gas of an IGCC plant fueled by coal can be as high as 50 percent.

IGCC on a commercial scale. To demonstrate that technology, the Department of Energy's FutureGen project aims to produce hydrogen and electricity from coal while capturing CO_2 for sequestration.[35]

Transport

Once captured, CO_2 intended for sequestration must be compressed (to make it easier to transport) and then moved to a storage site. Since the early 1980s, various companies have transported CO_2 through pipelines (especially oil companies, which use carbon dioxide to enhance the recovery of oil at existing production sites).[36] Today, over 2,500 kilometers of dedicated pipeline—most of it in the United States—carries more than 40 million metric tons of CO_2 per year. Smaller amounts, including those that need to travel long distances overseas, are transported on tanker ships.[37]

Storage

Carbon dioxide emissions could be stored underground in geologic formations, such as deep saline formations, oil and gas fields, and coal beds that cannot be mined economically because of their depth or the thickness of the seam. Analysts estimate that in the United States and Canada combined, such reservoirs could hold a total of 1.2 trillion to 3.6 trillion metric tons of CO_2 emissions—many times the potential of biological sequestration.[38] Some analysts have also suggested that significant potential for CO_2 storage exists in the world's oceans (for more details, see Box 2).

Deep saline formations account for 80 percent of the low-end estimate of geologic storage capacity in the

United States and Canada (919 billion metric tons out of 1.2 trillion).[39] Such formations are filled with highly saline water not fit for industrial or agricultural use. The pressures in those formations indicate that they could withstand the injection of CO_2. Some of the CO_2 injected into them would dissolve in the water; the rest would migrate to the top of the formation. Certain deep saline formations in the United States are already used for storage of liquid hazardous wastes.[40] In addition, a Norwegian oil company uses a saline formation 800 meters below the bed of the North Sea to store CO_2 recovered from natural gas operations.

Oil and gas reservoirs—both those in production and those that are or will soon be abandoned—account for about 7 percent (82 billion metric tons) of the low-end estimate of geologic storage capacity in the United States and Canada. Carbon dioxide is already injected into oil fields as part of a process called enhanced oil recovery. Once injected into a reservoir, CO_2 expands and pushes oil toward the extraction well. Moreover, given adequate pressure, CO_2 mixes with oil and makes it flow more easily. That technique allows operators to recover up to 25 percent of the oil that remains in an active reservoir after other techniques have been exhausted. It has been used in more than 70 operations worldwide, mostly in the United States (particularly in the Permian Basin of Texas and New Mexico). With enhanced oil recovery, some of the injected CO_2 is eventually pumped up with the oil, but the rest remains in the oil field, where it can be stored once the field stops producing and the wells are sealed. Current research is focused on increasing the amount of CO_2 that is stored. For example, Canada's Weyburn Field is hosting a large pilot project for

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35. Some observers worry that if investors wait to see whether Future-Gen is successful before proceeding with commercial-scale investment in IGCC carbon dioxide capture and storage, adoption of the technology will be delayed by at least 5 to 10 years. See Ken Berlin and Robert M. Sussman, *Global Warming and the Future of Coal* (Washington, D.C.: Center for American Progress, May 2007).

36. Singh, "A Systems Perspective for Assessing Carbon Dioxide Capture and Storage Opportunities."

37. Intergovernmental Panel on Climate Change, *Carbon Dioxide Capture and Storage.*

38. The difference between the low and high figures results almost entirely from differing estimates of the capacity for storage in deep saline formations. See Department of Energy, *Carbon Sequestration Atlas of the United States and Canada.*

39. The numbers cited here for the storage capacity of deep saline formations, unminable coal seams, and oil and gas reservoirs come from Department of Energy, *Carbon Sequestration Atlas of the United States and Canada.*

40. More than 400 U.S. wells exist for injecting industrial wastes into saline formations. The Mount Simon reservoir—which underlies Illinois, Indiana, Michigan, Kentucky, and Pennsylvania (a region with numerous fossil-fuel power plants)—has been approved by the Environmental Protection Agency for disposal of industrial waste. See U.S. Climate Change Technology Program, *Technology Options for the Near and Long Term* (August 2005), p. 3.1-4, available at www.climatetechnology.gov/library/2005/tech-options/tor2005-311-313.pdf.

Storing Carbon Dioxide in Oceans

About one-third of the carbon dioxide (CO_2) released into the atmosphere by human activity over the past two centuries has been stored in the oceans through natural processes. That storage might be increased by directly injecting CO_2 into the deep ocean, although doing so would probably have negative consequences for ocean ecosystems.

Research on different approaches to ocean storage of CO_2 has included modeling, laboratory experiments, engineering development, and limited field experiments. Among the issues being studied are the pace and level at which injected CO_2 would eventually reach equilibrium with the atmosphere. Some data and modeling indicate that ocean storage would retain 65 percent to 100 percent of injected CO_2 for at least 100 years and 30 percent to 85 percent for at least 500 years, depending on the depth and location of the injection.[1]

The potential storage capacity of the world's oceans is largely unknown. It depends on the partial pressure of CO_2 in the atmosphere and on the salinity, alkalinity, and temperature of seawater. Some researchers suggest that the total capacity could be on the order of trillions of metric tons.[2] However, climate change could affect the potential to use the oceans for carbon sequestration and absorption. One recent study suggests that the Southern Ocean—which accounts for 15 percent of the Earth's carbon-absorbing reservoirs—is losing its ability to take in carbon dioxide.[3]

Injecting CO_2 into the oceans would add to the changes in ocean chemistry that are currently occurring because of natural processes and human-induced increases in the atmospheric concentration of CO_2. The oceans would grow more acidic, which would be likely to harm their inhabitants. When CO_2 reacts with seawater, it forms carbonic acid, which corrodes shells and skeletons made of calcium carbonate (such as those of algae, mollusks, and reef-building corals). The resulting damage could disrupt large parts of the marine food chain.[4]

1. Intergovernmental Panel on Climate Change, *Carbon Dioxide Capture and Storage—Summary for Policymakers and Technical Summary* (Cambridge, England: Cambridge University Press, 2005), available at www.ipcc.ch/activity/ccsspm.pdf.

2. Ibid.

3. Corinne Le Quere and others, "Saturation of the Southern Ocean CO_2 Sink Due to Recent Climate Change," *Science Express* (published online, May 17, 2007).

4. Kathy Tedesco and others, "Impacts of Anthropogenic CO_2 on Ocean Chemistry and Biology," *NOAA Research* (October 3, 2005), available at www.research.noaa.gov/spotlite/spot_gcc.html; and Richard A. Feely and others, "Impact of Anthropogenic CO_2 on the $CaCO_3$ System in the Oceans," *Science,* vol. 305 (July 16, 2004), pp. 362–366.

enhanced oil recovery that analysts anticipate will sequester 20 million tons of CO_2 over its lifetime.[41]

Carbon dioxide can also be pumped into natural gas reservoirs to reinvigorate production, although there is less call for that enhanced recovery technique because initial recovery processes at gas fields usually remove most of the original gas in place. One of the largest CO_2 sequestration projects yet undertaken is part of the development of the In Salah natural gas fields in Algeria, where CO_2 removed from the gas that is produced is reinjected into the depleted gas reservoir for storage.

Unminable coal seams account for the other 13 percent (156 billion metric tons) of the low-end estimate of geologic storage capacity in the United States and Canada. Coal seams might be able to store several times more CO_2 than natural gas reservoirs of the equivalent volume because of the large surface area of the coal. Typically,

41. Climate Action Network Europe, Climate Technology Assessment Project, *Storage in Depleted Oil and Gas Fields,* Climate Technology Sheet No. 4 (November 2003), available at www.climnet.org/CTAP/techsheets/CTAP04_eor.pdf.

Box 3.

Implementation Issues for a Policy of Carbon Dioxide Capture and Storage

Any policy that addressed the capture and storage of carbon dioxide (CO_2) would have to account for the possibility that geologic storage, although expected to be relatively secure, might not be permanent.[1] Important regulatory concerns include properly determining the suitability of storage reservoirs, monitoring their structural integrity over the long term, assuming long-term financial responsibility for such verification and monitoring, and assuming potential liability for any damage from leakage.

Implementing geologic sequestration would also raise issues of surface and subsurface property rights. Surface property rights include rights to the land at the injection site and above the reservoir in general, as well as easements for the pipelines that would transport CO_2. Subsurface rights include mineral and water rights. In situations somewhat analogous to that of geologic sequestration, at least two approaches have been taken to address potential conflicts over subsurface property rights. In some states, landowners have been allowed to inject a substance below the surface even if the substance migrates below another party's land. Alternatively, landowners in certain states can negotiate an agreement that supersedes individual property rights and establishes a common interest in a reservoir beneath adjacent lands; participation in such an established agreement can also be compelled by law.

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1. The information in this box comes from Midwest Regional Carbon Sequestration Partnership, *Characterization of Geologic Sequestration Opportunities in the MRCSP Region, Phase I Task Report, October 2003–September 2005* (2005), Chapter 6, available at http://198.87.0.58/PhaseIReport.aspx.

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methane-rich gas (generated as part of the geologic process that transforms plant material into coal) adheres to the surface of the coal. Commercial efforts to recover that methane generally depressurize the coal bed by pumping out water, but methane can also be displaced by injecting CO_2 into the coal bed. The CO_2 remains sequestered in the coal bed, where it adheres to the surface of the coal at about twice the rate that methane does.[42] Limited field tests have demonstrated the use of CO_2 to recover coal-bed methane. The process is being employed in the San Juan basin of New Mexico as well as in Canada and Poland, although it faces some technological hurdles.[43]

According to the Intergovernmental Panel on Climate Change, well-selected, -designed, and -managed geologic storage sites could trap CO_2 for millions of years and would be likely to retain over 99 percent of their injected CO_2 for at least 1,000 years.[44] Below 800 meters underground, pressure turns CO_2 into a relatively dense liquid, making it less likely to escape a storage reservoir. Still, oil and gas wells could be pathways for CO_2 leakage if they were not properly plugged, and overpressurizing storage reservoirs would risk causing fractures that could damage their structural integrity. In addition, injecting CO_2 into deep saline formations could acidify their contents, dissolving minerals and possibly creating new pathways for CO_2-rich fluid to escape a reservoir.

Economic Potential of Carbon Dioxide Capture and Storage

For CCS to be economically feasible, the price of CO_2 would have to be high enough to cover the incremental costs of CO_2 capture and compression (at power plants

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42. Department of Energy, "Geologic Sequestration Research" (April 17, 2007), available at www.fe.doe.gov/programs/sequestration/geologic/index.html.

43. One obstacle to that technique is that most coal seams not amenable to mining have low permeability, which makes it difficult to inject a compressed gas such as CO_2. Further, as CO_2 adheres to the coal, it can lead the coal seam to swell, closing the seam's pores and inhibiting both injection and extraction.

44. Intergovernmental Panel on Climate Change, *Carbon Dioxide Capture and Storage*.

designed for that purpose), transport, and storage.[45] Analysts' estimates of that price vary from $15 to $90 per metric ton of CO_2.[46] If all of the sources that could eventually employ CCS did so, and if their emissions remained at 2005 levels, it would take roughly 500 to 1,500 years to fully exploit the capacity of potential geologic storage sites in the United States and Canada.[47]

Analysts estimate the incremental (additional) costs of CO_2 capture and compression using an engineering approach (one that considers only direct costs, not opportunity costs). They generally compare the costs of producing electricity at similar plants with and without CO_2 capture, taking into account the added greenhouse-gas emissions that result from the energy required for the capture and compression processes. Analysts then add estimates of transport costs, based on the distance to a potential storage site, and storage costs, based on the type of storage reservoir. As with estimates of the economic potential of biological sequestration, estimates of the economic potential of CCS do not include the effects of the regulatory system that might be set up to implement carbon dioxide capture and storage (see Box 3).

The type of plant used to compare the costs of producing electricity with and without CO_2 capture has a major impact on the resulting cost estimates (see Figure 3).[48] Most studies of CO_2 capture in the electricity industry use integrated gasification combined-cycle plants for the comparison. Estimates based on those plants are generally lower than estimates based on natural gas combined-cycle (NGCC) power plants or on pulverized-coal plants

(either new ones or existing plants modified to include capture capabilities).

Ultimately, the relevant incremental cost of carbon dioxide capture and storage depends on what types of plants would be built in the absence of a limit on CO_2 emissions. That decision depends on the relative cost of producing electricity at different types of plants at different times—which in turn depends on the prices of natural gas and coal. For example, although the incremental *cost of capture* is estimated to be lowest at integrated gasification combined-cycle plants, in recent years natural gas combined-cycle plants have been the most common type of power plant built. Both with and without CO_2 capture capabilities, the *cost of generating power* is lower at those natural gas plants than at IGCC plants.[49] The price of natural gas is climbing, however, so IGCC plants may be an appropriate reference for evaluating the incremental costs of capture in the long term, because the coal supplies that they use are relatively secure.[50]

Estimates of the costs of transporting CO_2 depend largely on the distance to a potential storage site. Given the strong overlap between the locations of existing sources of CO_2 emissions and potential geologic storage sites,

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45. In most estimates, capture and compression account for at least three-quarters of CCS costs. See Singh, "A Systems Perspective for Assessing Carbon Dioxide Capture and Storage Opportunities."

46. Bock, Goldberg, and Rhudy, *Economic Evaluation of CO_2 Storage and Sink Enhancement Options;* Deutch, Moniz, and others, *The Future of Coal;* Gemma Heddle, Howard Herzog, and Michael Klett, *The Economics of CO_2 Storage* (Cambridge, Mass.: Massachusetts Institute of Technology, Laboratory for Energy and the Environment, August 2003), available at http://sequestration. mit.edu/pdf/LFEE_2003-003_RP.pdf; Intergovernmental Panel on Climate Change, *Carbon Dioxide Capture and Storage;* and Singh, "A Systems Perspective for Assessing Carbon Dioxide Capture and Storage Opportunities."

47. Department of Energy, *Emissions of Greenhouse Gases in the United States, 2005.*

48. Another option for electricity generation that does not produce CO_2 emissions is nuclear power.

49. With underlying natural gas prices of roughly $3 per gigajoule (about 950,000 British thermal units) and coal prices of roughly $1.25 per gigajoule, estimates of the cost of generating power at NGCC plants range from 3.3 to 3.7 cents per kilowatt hour without CO_2 capture and from 4.8 to 5.5 cents with capture. Equivalent estimates for IGCC plants are 4.1 to 5.0 cents per kilowatt hour without capture and 5.4 to 6.7 cents with capture. For pulverized-coal plants, estimates range from 4.2 to 4.6 cents per kilowatt hour without capture and from 7.3 to 7.7 cents with capture. See Jeremy David and Howard Herzog, *The Cost of Carbon Capture* (Cambridge, Mass.: Massachusetts Institute of Technology, 2001); Intergovernmental Panel on Climate Change, *Carbon Dioxide Capture and Storage;* Department of Energy, National Energy Technology Laboratory, and Concurrent Technologies Corporation, *Evaluation of Fossil Fuel Power Plants with CO_2 Recovery* (February 2002); and Singh, "A Systems Perspective for Assessing Carbon Dioxide Capture and Storage Opportunities."

50. The Department of Energy's projections for the cost of electricity generation in 2015 are 5.61 cents per kilowatt hour for IGCC plants, 0.08 cents more than for NGCC plants. With CO_2 capture included, the projected cost for IGCC plants is 7.37 cents per kilowatt hour, 0.22 cents less than for NGCC plants. See Department of Energy, Energy Information Administration, *Annual Energy Outlook 2007, With Projections to 2030,* DOE/EIA-0383(2007) (February 2007).

Figure 3.

Range of Cost Estimates for Carbon Dioxide Capture and Storage, by Type of Power Plant and Storage Location

(Dollars per metric ton of CO_2)
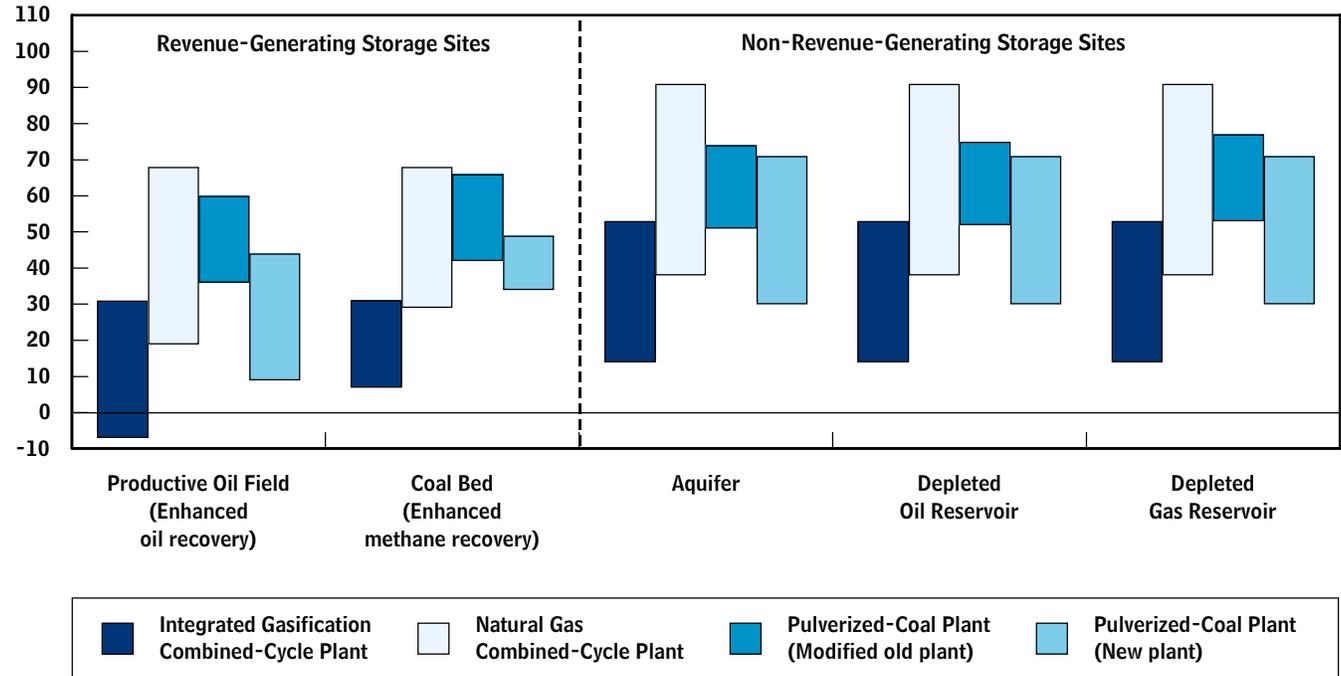
Source: Congressional Budget Office based on B. Bock, P. Goldberg, and R. Rhudy, *Economic Evaluation of CO₂ Storage and Sink Enhancement Options* (Tennessee Valley Authority, Department of Energy, and Electric Power Research Institute, December 2002); Intergovernmental Panel on Climate Change, *Carbon Dioxide Capture and Storage—Summary for Policymakers and Technical Summary* (Cambridge, England: Cambridge University Press, 2005); Nisheeth Singh, "A Systems Perspective for Assessing Carbon Dioxide Capture and Storage Opportunities" (master's thesis, Massachusetts Institute of Technology, May 2004); John Deutch, Ernest J. Moniz, and others, *The Future of Coal: Options for a Carbon-Constrained World* (Cambridge, Mass.: Massachusetts Institute of Technology, 2007); and Gemma Heddle, Howard Herzog, and Michael Klett, *The Economics of CO₂ Storage* (Cambridge, Mass.: Massachusetts Institute of Technology, Laboratory for Energy and the Environment, August 2003).

Notes: CO_2 = carbon dioxide.

Broadly speaking, in the studies shown here, integrated gasification combined-cycle plants were assumed to run at 80 percent to 85 percent of their roughly 500-megawatt capacity and to capture between 85 percent and 100 percent of their CO_2 emissions. Natural gas combined-cycle plants were assumed to run at 50 percent to 95 percent of their 400- to 800-megawatt capacity and to capture between 85 percent and 100 percent of their CO_2 emissions. Pulverized-coal plants were assumed to run at 65 percent to 85 percent of their 300- to 800-megawatt capacity and to capture between 85 percent and 90 percent of their CO_2 emissions. Coal was assumed to cost between \$1 and \$1.50 per gigajoule and natural gas between \$2.50 and \$4.50 per gigajoule.

The power plants used in these analyses were all assumed to be purpose-built for carbon dioxide capture and storage, except for old pulverized-coal plants, which were assumed to be modified to include CO_2 capture capabilities. Adding CO_2 capture technology to an existing pulverized-coal plant is not straightforward; options range from standard retrofitting to rebuilding the plant to include capture capabilities while also upgrading its basic technology. Each option involves a number of complications. Coal-based power plants generate about half of the electricity produced in the United States. Roughly half of the coal they consume is used by plants that are less than 30 years old, with substantial remaining service lives.

transport costs make up a small proportion of overall CCS costs in most studies' estimates.[51]

Estimates of storage costs vary by the type of storage site. Storage is cheapest when it can generate revenues by facilitating the recovery of energy resources, such as oil. But the potential to take advantage of sites that use enhanced oil recovery or enhanced coal-bed methane recovery is limited. Although the electricity sector represents the largest potential demand for CCS, other sources of emissions (such as cement producers) that have higher CO_2 contents in their emission streams are likely to adopt CCS before electricity generators do.[52] Those other sources might utilize most of the revenue-generating opportunities for CO_2 storage. In addition, there could be a mismatch between the nearly continuous emissions of large amounts of CO_2 from a power plant and the more limited and episodic use of CO_2 in enhanced oil or methane recovery.

Estimates of the incremental costs of carbon dioxide capture and storage for IGCC plants, when using non-revenue-generating geologic storage sites, range from about $15 to $50 per metric ton (see Figure 3). When those plants can take advantage of opportunities for enhanced oil or methane recovery, the range of costs declines to between -$5 per metric ton (meaning that CCS would save a plant money) and $30 per metric ton. Cost estimates are higher for NGCC plants: about $40 to $90 per metric ton with non-revenue-generating storage and about $20 to $70 per metric ton with enhanced oil or methane recovery. As shown in Figure 3, the lowest estimates for NGCC plants are roughly comparable to the higher-end IGCC estimates, and the highest estimates for NGCC plants greatly exceed IGCC estimates. Estimates of the incremental costs of carbon dioxide capture and storage at pulverized-coal plants—particularly existing plants modified to add CO_2 capture capabilities—are much higher than estimates for IGCC plants.

However, low-end estimates for new pulverized-coal plants built to include CO_2-capture technology are comparable to midlevel estimates for IGCC plants.

In the end, the additional cost of carbon dioxide capture and storage will depend on the types of plants that would be built in the absence of limits on CO_2 emissions, which would vary with the relative cost of producing electricity at different types of plants at different points in time.

Carbon Sequestration in the Context of Broad Strategies for Reducing Greenhouse Gases

Curbing greenhouse-gas emissions to counter climate change would involve action on multiple fronts, and the contribution from each front would probably change depending on the price for CO_2. As noted in the discussions of biological sequestration and carbon dioxide capture and storage, the CO_2 price influences the extent to which different practices are used. For example, the sector optimization models shown in Figure 2 on page 9 estimate that sequestration in cropland soil would initially increase as the CO_2 price rose but then would decline at higher CO_2 prices as other uses of the land became more profitable.

Similar changes in the balance of practices are evident when the analysis is broadened to include other approaches for countering climate change—such as shifts in the mix of energy sources (including emission-free ways to produce energy, such as nuclear power and hydropower); improvements in energy efficiency; and reductions in greenhouse gases other than CO_2. The change in the prevalence of different approaches is demonstrated by models that simulate how the economy as a whole would respond to increases in the price for CO_2 over time.

Carbon sequestration in soil might make its most substantial contribution to overall mitigation when CO_2 prices were low. At higher prices, afforestation, forest management, and the use of land to grow biofuel crops would become relatively more attractive to landowners.[53] The importance of afforestation and forest management

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51. Of the 500 largest point sources of CO_2 in the United States, 95 percent are within 50 miles of a potential storage reservoir. See J.J. Dooley and others, *Carbon Dioxide Capture and Geologic Storage: A Core Element of a Global Energy Technology Strategy to Address Climate Change* (College Park, Md.: Global Energy Technology Strategy Program, April 2006), available at www.pnl.gov/gtsp/docs/ccs_report.pdf; and Department of Energy, *Carbon Sequestration Atlas of the United States and Canada,* pp. 10, 13–15.

52. Dooley and others, *Carbon Dioxide Capture and Geologic Storage.*

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53. Biofuels help reduce greenhouse gases primarily by replacing fossil fuels in the generation of heat and power and the production of liquid fuels. (Complementary potential exists for carbon sequestration in soil and for CCS when making biofuels.)

Figure 4.

Reduction of Annual U.S. Greenhouse-Gas Emissions Associated with Different Mitigation Strategies and CO_2 Prices

(Billions of metric tons of CO_2-equivalent)

Initial CO_2 Price of $10 per Metric Ton (Rising by 4 percent annually)
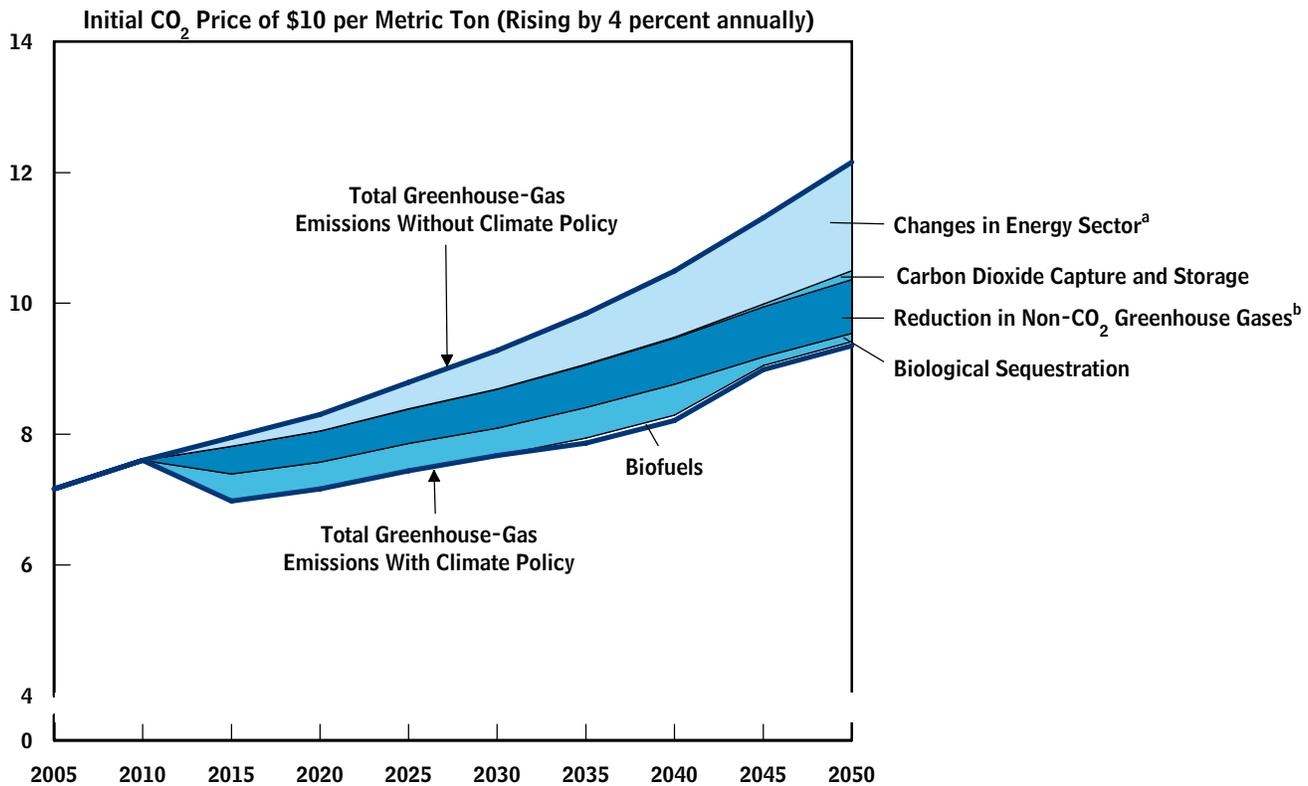
Continued

would eventually decline, however, as those practices were constrained by the scale of biofuel production and as forests eventually approached the limit of their physical capacity to absorb carbon.[54] That dynamic is reflected in Figure 4, which shows how the projected mix of strategies to curb greenhouse-gas emissions in the United States would change if the price for CO_2 started at either $10 or $30 per metric ton in 2015 and then rose at a real rate of 4 percent per year.[55] With the lower price profile, biofuels would kick in (with a very small contribution) only

after about 15 years. They would be more important with the higher price profile, accounting for almost 10 percent of annual greenhouse-gas reductions (relative to projected emissions without a climate change policy) by 2050. As the reliance on biofuels grew, the importance of biological sequestration would decline.

In the analysis whose results are shown in Figure 4, all of the mitigation strategies were subject to a rising CO_2

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54. Bruce A. McCarl and Ronald D. Sands, "Competitiveness of Terrestrial Greenhouse Gas Offsets: Are They a Bridge to the Future?" *Climatic Change,* vol. 80 (January 2007), pp. 109–126; and Environmental Protection Agency, *Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture,* EPA 430-R-05-006 (November 2005).

55. Ronald D. Sands, "Application of Second Generation Model (SGM) to U.S. Cap and Trade Reference Scenarios" (presentation given at the Nicholas Institute conference "Economic Modeling of Federal Climate Legislation: Advancing Model Transparency and Technology Policy Development," Washington, D.C., July 18, 2007). That analysis is an extension of McCarl and Sands, "Competitiveness of Terrestrial Greenhouse Gas Offsets."

Figure 4.

Continued

(Billions of metric tons of CO_2-equivalent)
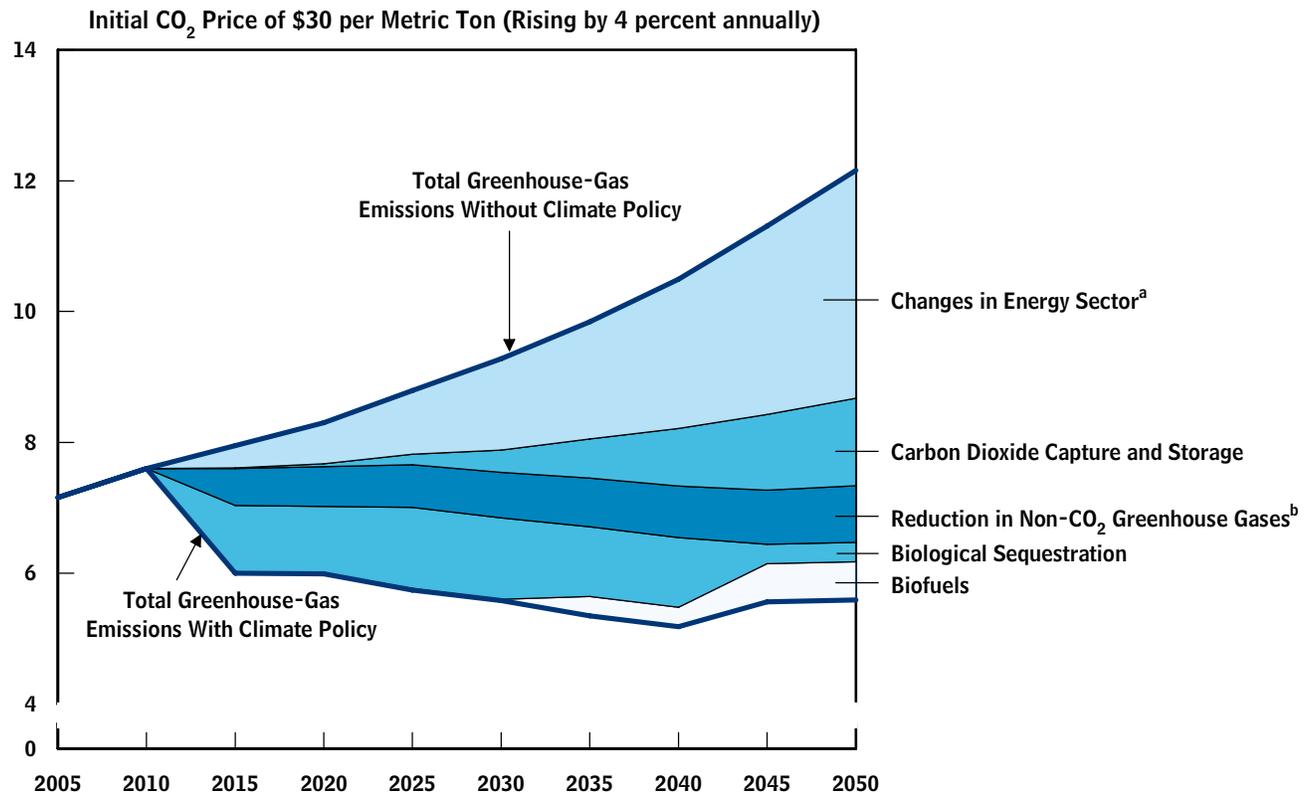
Initial CO_2 Price of \$30 per Metric Ton (Rising by 4 percent annually)

Source: Congressional Budget Office based on Ronald D. Sands, "Application of Second Generation Model (SGM) to U.S. Cap and Trade Reference Scenarios" (presentation given at the Nicholas Institute conference "Economic Modeling of Federal Climate Legislation: Advancing Model Transparency and Technology Policy Development," Washington, D.C., July 18, 2007). That analysis is an extension of Bruce A. McCarl and Ronald D. Sands, "Competitiveness of Terrestrial Greenhouse Gas Offsets: Are They a Bridge to the Future?" *Climatic Change,* vol. 80 (January 2007), pp. 109–126.

Note: CO_2 = carbon dioxide.

a. Changes in the energy sector include switching between fossil fuels with different carbon contents, generating electricity from nuclear power and hydropower (which do not produce CO_2 emissions), and improving energy efficiency.

b. Mainly methane and nitrous oxide.

price except biological sequestration. Because of methodological limitations, that set of approaches was subject to a constant CO_2 price. As a result, the relative contribution of biological sequestration may be underestimated in the analysis. Moreover, other analyses have shown that when models of climate-change mitigation do not apply CO_2 pricing to changes in the biological stock of carbon, biofuel production is allowed to increase at the expense of forest land without taking into account the associated losses in carbon storage.[56] The implication is that policies

that addressed only carbon emissions from the energy sector could lead to a pace of biofuel production that

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56. U.S. Climate Change Science Program, *Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations* (July 2007), available at www.climatescience.gov/Library/sap/sap2-1/finalreport/default.htm; and Ronald D. Sands and Marian Leimbach, "Modeling Agriculture and Land Use in an Integrated Assessment Framework," *Climatic Change*, vol. 56 (January 2003), pp. 185–210.

would offset its own gains through deforestation.[57] Overcoming the implementation challenges of a biological sequestration policy would not only allow the United States to take near-term advantage of relatively small but low-cost contributions to climate-change mitigation but also help address the risk that incentives for biofuel production could undermine that mitigation by encouraging deforestation.

At comparatively low prices for CO_2, the contribution of carbon dioxide capture and storage to climate-change mitigation in the United States might be largely overshadowed by biological sequestration, reductions in other greenhouse gases (such as methane and nitrous oxide), and energy-sector approaches, including changes in the mix of energy sources and improvements in energy efficiency (see Figure 4).[58] If the CO_2 price started at $10 per metric ton in 2015 and rose by 4 percent a year, CCS would make a small entry into the strategy mix after about 30 years (as the CO_2 price reached about $30 per metric ton). By 2050, CCS would account for just 5 percent of the total yearly reduction in greenhouse-gas

emissions. In comparison, other changes in the energy sector would account for nearly 60 percent of annual reductions by 2050, and cuts in greenhouse gases other than CO_2 would account for almost 30 percent. However, biofuel production—which would also enter the strategy mix late in the game—would has even less impact than carbon dioxide capture and storage: just 2 percent by 2050.

Greenhouse-gas mitigation policies that affected the price of CO_2 could have an impact on turnover in the capital stock at CCS-eligible facilities and on CCS research and development. The dynamic analysis reflected in Figure 4 captures those influences.[59] If the CO_2 price began at $30 per metric ton, carbon dioxide capture and storage would enter the strategy mix within a decade. By 2050, it would account for more than 20 percent of annual greenhouse-gas reductions—second only to other energy-sector mitigation activities, which would contribute about 50 percent of annual reductions. Cuts in greenhouse gases other than CO_2 would have a smaller relative impact than in the lower price profile (13 percent of overall reductions), but biofuels would make a much larger contribution (nearly 10 percent). For more details about the role of biological sequestration and CCS with different CO_2 price profiles, see the appendix.

No one mitigation strategy will single-handedly meet the challenge of alleviating climate change, and considering any one strategy in isolation is likely to overstate its potential contribution. Examining mitigation strategies as a group highlights the fact that their collective potential falls short of the sum of their independent potentials and alters their relative importance. Ultimately, society can achieve more at a lower cost with a wider mix of approaches—taking advantage of the least costly options early on and, when those are exhausted, exploiting more expensive options as CO_2 prices rise.

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57. In the United States, more than 20 million acres of forest were cut down between 1982 and 1997, releasing tens of millions of tons of carbon each year. Under current conditions, even without a policy to mitigate greenhouse gases, analysts project that more than 60 million U.S. acres will be deforested over the next 100 years. Ralph J. Alig, "Deforestation Research in the United States: Evidence to Inform the Avoided Deforestation Discussion" (presentation given at the Forestry and Agriculture Greenhouse Gas Modeling Forum, Shepherdstown, W. Va., March 8, 2007), available at http://foragforum.rti.org/papers/index.cfm.

58. The three principal sources of methane emissions in the United States are energy production and consumption, waste management (landfills and wastewater treatment plants), and agriculture (ruminant animals and animal waste). The largest U.S. source of nitrous oxide emissions related to human activity is the use of nitrogen fertilizers on agricultural land. Another major source of nitrous oxide emissions is energy consumption by vehicles, homes, businesses, factories, and electric utilities. Handling animal waste and burning crop residues also release nitrous oxide. (See Department of Energy, *Emissions of Greenhouse Gases in the United States, 2005.*) Options for reducing emissions other than CO_2 are generally less capital-intensive than energy-sector options.

59. In the underlying model, industry-specific capital stocks are grouped together for each five-year period. Older stocks are assumed to be less responsive to changes in prices than newer stocks are.

Appendix:
The Role of Biological Sequestration and CCS at Various CO$_2$ Prices

The main text of this paper describes the possible roles that biological sequestration and carbon dioxide capture and storage (CCS) would play in reducing U.S. emissions of greenhouse gases under two assumptions about carbon dioxide (CO$_2$) prices. In the first assumption, the price of CO$_2$ starts at $10 per metric ton in 2015 and rises at a real (inflation-adjusted) rate of 4 percent each year thereafter. In the second assumption, CO$_2$ is initially priced at $30 per metric ton in 2015 and then increases at the same 4 percent annual rate.

This appendix expands on that analysis by showing the relative contributions of biological sequestration and CCS over time under a broader set of pricing profiles. CO$_2$ prices in those profiles start at either $10, $20, $30, $40, or $50 in 2015 before growing at a real rate of 4 percent per year. Under those profiles, in 2030, biological sequestration would account for 26 percent to 35 percent of the reduction in U.S. greenhouse-gas emissions, whereas CCS would contribute no more than 11 percent of that reduction (see Table A-1). In 2050, by contrast, biological sequestration would account for no more than about 7 percent of the reduction in greenhouse-gas emissions, while the contribution of CCS would range from 5 percent to 20 percent, depending on the price of CO$_2$.

Table A-1.

Impact of Biological Sequestration and Carbon Dioxide Capture and Storage Over Time at Different CO_2 Prices

	CO_2 Price in 2015 (Dollars per metric ton)[a]				
	10	**20**	**30**	**40**	**50**
2030					
CO_2 Price (Dollars per metric ton)	18	36	54	72	90
Biological Sequestration					
Millions of metric tons of CO_2 sequestered	419	804	1,243	1,501	1,758
Percentage of total reduction in U.S. greenhouse-gas emissions	26.2	31.1	33.7	33.8	35.1
Carbon Dioxide Capture and Storage					
Millions of metric tons of CO_2 sequestered	2	71	340	489	515
Percentage of total reduction in U.S. greenhouse-gas emissions	0.2	2.7	9.2	11.0	10.3
2050					
CO_2 Price (Dollars per metric ton)	39	79	118	158	197
Biological Sequestration					
Millions of metric tons of CO_2 sequestered	127	257	294	422	549
Percentage of total reduction in U.S. greenhouse-gas emissions	4.5	5.0	4.5	5.8	7.1
Carbon Dioxide Capture and Storage					
Millions of metric tons of CO_2 sequestered	134	998	1,339	1,327	1,190
Percentage of total reduction in U.S. greenhouse-gas emissions	4.8	19.5	20.4	18.2	15.4

Source: Congressional Budget Office based on Ronald D. Sands, "Application of Second Generation Model (SGM) to U.S. Cap and Trade Reference Scenarios" (presentation given at the Nicholas Institute conference "Economic Modeling of Federal Climate Legislation: Advancing Model Transparency and Technology Policy Development," Washington, D.C., July 18, 2007). That analysis is an extension of Bruce A. McCarl and Ronald D. Sands, "Competitiveness of Terrestrial Greenhouse Gas Offsets: Are They a Bridge to the Future?" *Climatic Change,* vol. 80 (January 2007), pp. 109–126.

Note: CO_2 = carbon dioxide.

a. In this analysis, the CO_2 price is assumed to increase at a real rate of 4 percent a year after 2015.

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