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The atmospheric concentration of greenhouse gases—notably carbon dioxide (CO₂)—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 CO₂ include not only reducing emissions but also encouraging carbon sequestration—the capture and storage of CO₂ to prevent its release into the atmosphere, and the absorption of atmospheric CO₂ 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.)

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Peter R. Orszag
Director

September 2007
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The Potential for Carbon Sequestration in the United States

Introduction and Summary
Human activity emits roughly 32 billion metric tons of carbon dioxide (CO₂)—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 CO₂, removing them releases some or all of that carbon.) Currently, in any given year, the equivalent of about half of total CO₂ 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 CO₂ 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 CO₂ would have greater benefits than costs. Options for doing that include not only curbing activities that generate emissions but also sequestering CO₂—for example, by encouraging its absorption from the atmosphere into vegetation and soil (biological sequestration) and by trapping CO₂ 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


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 CO₂ 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 CO₂ 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 CO₂ deep into the ocean, but that option raises significant ecological concerns.) Some techniques for capturing CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂, it would effectively put a price on CO₂ 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 CO₂ price of about $5 to $65 per metric ton by 2020. Some economists’ estimates of the socially optimal price for CO₂ 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.


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.

incremental damage of allowing it to occur—also fall within that range.\footnote{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).\footnote{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.\footnote{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 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.


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.)

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.\textsuperscript{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.\textsuperscript{12} Pasture, rangeland, 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.\textsuperscript{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.\textsuperscript{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).\textsuperscript{15}

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

\textsuperscript{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, \textit{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.

\textsuperscript{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.

\textsuperscript{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, \textit{Carbon Storage and Accumulation in United States Forest Ecosystems}, General Technical Report WO-59 (Department of Agriculture, Forest Service, August 1992).


\textsuperscript{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 CO₂ per acre per year.16 Altering the mix of crops might sequester the equivalent of 0.12 to 0.47 metric tons of CO₂ per acre annually.17 Permanent plantings along waterways might yield the equivalent of 0.4 to 1.0 metric ton of CO₂ 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 CO₂ 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.


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.


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 CO₂ 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 CO₂ 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


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. 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.

Economic Potential of Biological Sequestration

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

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Figure 1.

Estimates of the Amount of Carbon That Would Be Sequestered Annually Through Afforestation in the United States at Different CO₂ Prices

(Dollars per metric ton of CO₂)

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

Notes: CO₂ = carbon dioxide.

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.
CO₂ 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 CO₂ prices but the reverse at higher prices. With a CO₂ 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 CO₂ emissions from human activity. At a CO₂ 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 CO₂ does not induce greater amounts of sequestration through crop-

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.)

Carbon Dioxide Capture and Storage

Carbon dioxide capture and storage involves capturing CO₂ emitted by power plants and large-scale industrial facilities and storing it in underground reservoirs (or possibly in the oceans). CO₂ 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 CO₂ 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’ CO₂ 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

Figure 2.

Estimates of the Amount of Carbon That Would Be Sequestered Annually in Cropland Soil in the United States at Different CO₂ Prices

(Dollars per metric ton of CO₂)

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

Notes: CO₂ = carbon dioxide.


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 CO₂ prices reflects the fact that alternative uses of land (such as for growing biofuel crops) become more cost-effective at higher CO₂ prices.
Implementation Issues for a Biological Sequestration Policy

According to analysts, any policy for reducing atmospheric concentrations of carbon dioxide (CO₂) 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ would account for that effect.

Additionality is important to determine because policies to counter climate change seek to encourage new CO₂-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 CO₂ (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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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 CO₂ emissions. In postcombustion capture, plant operators cool flue gases, treat them for contaminants, and pass them through reusable chemical solvents that trap CO₂. Heat is then used to extract the CO₂. The higher the CO₂ 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 CO₂ 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. (Certain industrial processes, such as making cement, release a much higher proportion of CO₂ in their flue gases. However, those processes account for only a small fraction of U.S. emissions of CO₂ caused by human activity.)

Postcombustion capture is being considered as a way to reduce CO₂ 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 CO₂, which is then sold to the food industry.

In precombustion capture, by contrast, natural gas, oxygen, and sometimes steam are used to produce CO₂ and hydrogen (generally for commercial purposes). 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 CO₂ 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 CO₂ capture, which merely require reducing pressure to release CO₂—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 CO₂ 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. 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...
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 CO₂ for sequestration.³⁵

**Transport**

Once captured, CO₂ 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 CO₂ 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 CO₂ 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 CO₂ emissions—many times the potential of biological sequestration.³⁸ Some analysts have also suggested that significant potential for CO₂ 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 CO₂. Some of the CO₂ 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 CO₂ 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, CO₂ expands and pushes oil toward the extraction well. Moreover, given adequate pressure, CO₂ 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 CO₂ 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 CO₂ 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 FutureGen 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.

enhanced oil recovery that analysts anticipate will sequester 20 million tons of CO\textsubscript{2} over its lifetime.\footnote{Climate Action Network Europe, Climate Technology Assessment Project, \textit{Storage in Depleted Oil and Gas Fields}, Climate Technology Sheet No. 4 (November 2003), available at www.climnet.org/CTAP/techsheets/CTAP04_eor.pdf.}

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\textsubscript{2} sequestration projects yet undertaken is part of the development of the In Salah natural gas fields in Algeria, where CO\textsubscript{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\textsubscript{2} than natural gas reservoirs of the equivalent volume because of the large surface area of the coal. Typically,
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 CO₂ into the coal bed. The CO₂ remains sequestered in the coal bed, where it adheres to the surface of the coal at about twice the rate that methane does. Limited field tests have demonstrated the use of CO₂ to recover coalbed 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.

According to the Intergovernmental Panel on Climate Change, well-selected, -designed, and -managed geologic storage sites could trap CO₂ for millions of years and would be likely to retain over 99 percent of their injected CO₂ for at least 1,000 years. Below 800 meters underground, pressure turns CO₂ into a relatively dense liquid, making it less likely to escape a storage reservoir. Still, oil and gas wells could be pathways for CO₂ leakage if they were not properly plugged, and overpressurizing storage reservoirs would risk causing fractures that could damage their structural integrity. In addition, injecting CO₂ into deep saline formations could acidify their contents, dissolving minerals and possibly creating new pathways for CO₂-rich fluid to escape a reservoir.

Economic Potential of Carbon Dioxide Capture and Storage

For CCS to be economically feasible, the price of CO₂ would have to be high enough to cover the incremental costs of CO₂ capture and compression (at power plants...
designed for that purpose), transport, and storage. Analysts’ estimates of that price vary from $15 to $90 per metric ton of CO₂. 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. Analysts estimate the incremental (additional) costs of CO₂ 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 CO₂ 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 CO₂ capture has a major impact on the resulting cost estimates (see Figure 3). Most studies of CO₂ 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 CO₂ 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 CO₂ capture capabilities, the cost of generating power is lower at those natural gas plants than at IGCC plants. 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.

Estimates of the costs of transporting CO₂ depend largely on the distance to a potential storage site. Given the strong overlap between the locations of existing sources of CO₂ emissions and potential geologic storage sites,

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.”


48. Another option for electricity generation that does not produce CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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).
Range of Cost Estimates for Carbon Dioxide Capture and Storage, by Type of Power Plant and Storage Location

(Dollars per metric ton of CO₂)


Notes: CO₂ = 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ capture capabilities. Adding CO₂ 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 CO2 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 CO2 storage. In addition, there could be a mismatch between the nearly continuous emissions of large amounts of CO2 from a power plant and the more limited and episodic use of CO2 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 CO2 capture capabilities—are much higher than estimates for IGCC plants.

However, low-end estimates for new pulverized-coal plants built to include CO2-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 CO2 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 CO2. As noted in the discussions of biological sequestration and carbon dioxide capture and storage, the CO2 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 CO2 price rose but then would decline at higher CO2 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 CO2. 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 CO2 over time.

Carbon sequestration in soil might make its most substantial contribution to overall mitigation when CO2 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


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

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.)
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.\textsuperscript{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.\textsuperscript{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$_2$


Figure 4.
Continued

(Billions of metric tons of CO₂-equivalent)

Initial CO₂ Price of $30 per Metric Ton (Rising by 4 percent annually)


Note: CO₂ = 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 CO₂ 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 CO₂ 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 CO₂ 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

would offset its own gains through deforestation.\(^{57}\) Over-
coming 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 pro-
duction 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 over-
shadowed 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 effi-
ciency (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 per-
cent 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. How-
ever, biofuel production—which would also enter the
strategy mix late in the game—would have 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 green-
house gases other than CO\(_2\) would have a smaller relative
impact than in the lower price profile (13 percent of over-
all reductions), but biofuels would make a much larger
contribution (nearly 10 percent). For more details about
the role of biological sequestration and CCS with differ-
ent 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 poten-
tial 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” (pre-
sentation given at the Forestry and Agriculture Greenhouse Gas
Modeling Forum, Shepherdstown, W. Va., March 8, 2007), avail-

58. The three principal sources of methane emissions in the United
States are energy production and consumption, waste manage-
ment (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 Depart-
ment of Energy, Emissions of Greenhouse Gases in the United States,
2005.) Options for reducing emissions other than CO\(_2\) are gener-
ally 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 CO₂ 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 (CO₂) prices. In the first assumption, the price of CO₂ 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, CO₂ 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. CO₂ 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 CO₂.
Table A-1.
Impact of Biological Sequestration and Carbon Dioxide Capture and Storage Over Time at Different CO₂ Prices

<table>
<thead>
<tr>
<th>CO₂ Price in 2015 (Dollars per metric ton)</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>2030 CO₂ Price (Dollars per metric ton)</td>
<td>18</td>
<td>36</td>
<td>54</td>
<td>72</td>
<td>90</td>
</tr>
<tr>
<td>Biological Sequestration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Millions of metric tons of CO₂ sequestered</td>
<td>419</td>
<td>804</td>
<td>1,243</td>
<td>1,501</td>
<td>1,758</td>
</tr>
<tr>
<td>Percentage of total reduction in U.S. greenhouse-gas emissions</td>
<td>26.2</td>
<td>31.1</td>
<td>33.7</td>
<td>33.8</td>
<td>35.1</td>
</tr>
<tr>
<td>Carbon Dioxide Capture and Storage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Millions of metric tons of CO₂ sequestered</td>
<td>2</td>
<td>71</td>
<td>340</td>
<td>489</td>
<td>515</td>
</tr>
<tr>
<td>Percentage of total reduction in U.S. greenhouse-gas emissions</td>
<td>0.2</td>
<td>2.7</td>
<td>9.2</td>
<td>11.0</td>
<td>10.3</td>
</tr>
<tr>
<td>2050 CO₂ Price (Dollars per metric ton)</td>
<td>39</td>
<td>79</td>
<td>118</td>
<td>158</td>
<td>197</td>
</tr>
<tr>
<td>Biological Sequestration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Millions of metric tons of CO₂ sequestered</td>
<td>127</td>
<td>257</td>
<td>294</td>
<td>422</td>
<td>549</td>
</tr>
<tr>
<td>Percentage of total reduction in U.S. greenhouse-gas emissions</td>
<td>4.5</td>
<td>5.0</td>
<td>4.5</td>
<td>5.8</td>
<td>7.1</td>
</tr>
<tr>
<td>Carbon Dioxide Capture and Storage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Millions of metric tons of CO₂ sequestered</td>
<td>134</td>
<td>998</td>
<td>1,339</td>
<td>1,327</td>
<td>1,190</td>
</tr>
<tr>
<td>Percentage of total reduction in U.S. greenhouse-gas emissions</td>
<td>4.8</td>
<td>19.5</td>
<td>20.4</td>
<td>18.2</td>
<td>15.4</td>
</tr>
</tbody>
</table>


Note: CO₂ = carbon dioxide.

a. In this analysis, the CO₂ price is assumed to increase at a real rate of 4 percent a year after 2015.