27. Mitigation

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Key Messages

1. **There are long time lags between actions taken to reduce carbon dioxide emissions and their effects on its atmospheric concentration. Mitigation efforts that only *stabilize* global emissions will therefore not reduce atmospheric concentrations of carbon dioxide, but will only limit their rate of increase.**
2. **To meet the rapid emissions reduction (B1) scenario used in this assessment, global mitigation actions would, within the next 25 years, need to limit global greenhouse gas emissions to a peak of around 44 billion tons of carbon dioxide per year. In 2011, global emissions were around 37 billion tons, and have been rising about 0.9 billion tons per year for the past decade. The world is therefore on track to exceed this level within a few years.**
3. **Over recent decades, the U.S. economy has emitted less carbon dioxide per dollar of gross domestic product (GDP) for many reasons. However, U.S. population and economic growth have outweighed these trends, and in the absence of additional public policies greenhouse gas emissions are expected to continue to rise.**
4. **Carbon storage in land ecosystems, especially forests, has offset around 13% of U.S. fossil fuel emissions of greenhouse gases over the past several decades, but this carbon "sink" is projected to become smaller as forests age.**
5. **Even absent a comprehensive national greenhouse gas policy, both voluntary activities and a variety of policies and means at federal, state, and local levels are currently in place that lower emissions. While these efforts represent significant steps towards reducing greenhouse gases, and often result in additional co-benefits,**

they are not close to sufficient to reduce total U.S. emissions to a level consistent with the B1 scenario analyzed in this assessment.

Mitigation refers to actions that reduce the human contribution to the planetary greenhouse effect. Mitigation actions include lowering emissions of greenhouse gases like carbon dioxide and methane, and particles that have a warming effect. Increasing the net uptake of carbon dioxide by land-use change and forestry can make a contribution as well. As a whole, the human contribution to emissions results in higher global concentrations of greenhouse gases and to a warming of the planet – and the effect is increased by various self-reinforcing cycles in the Earth system (such as the way melting sea ice results in more dark ocean water, which absorbs more heat, and leads to more sea ice loss). Also, the absorption of increased carbon dioxide by the oceans is leading to increased ocean acidity. Engineering a reduction of incoming solar radiation could limit the effect of increased greenhouse gas concentrations but would not help alleviate the acidity problem.

Four mitigation-related topics are assessed in this chapter. First, it presents an overview of greenhouse emissions and their climate influence, to provide a context for discussion of mitigation efforts. Second, the chapter provides an analysis of activities contributing to U.S. emissions of carbon dioxide and other greenhouse gases, considering both industrial and land-use activities. Third, it provides a summary of current government and voluntary efforts to manage these emissions of carbon dioxide and other greenhouse gases. Finally, there is an assessment of the adequacy of these efforts relative to the magnitude of the problem and a discussion of preparation for potential future action. While the chapter presents a brief overview of mitigation issues, it does not provide a comprehensive discussion of policy options, nor does it attempt to review or analyze the range of technologies available to reduce emissions. These topics have been the subject of other assessments, including those by the National Academy of Sciences (NRC 2010b) and the U.S. Department of Energy (US DOE 2011).

Emissions, Concentrations, and Climate Forcing

Setting mitigation objectives requires knowledge of the Earth system processes that determine the relationship among emissions, atmospheric concentrations and, ultimately, climate. Human-caused climate change results mainly from the increasing atmospheric concentrations of greenhouse gases (IPCC 2007). These gases cause radiative "forcing" – an imbalance of heat trapped by the atmosphere compared to an equilibrium state. Atmospheric concentrations of greenhouse gases are the result of the history of emissions and of processes that remove them from the atmosphere, for example by "sinks" like growing forests (Plattner et al. 2008). The fraction of emissions that remains in the atmosphere, which is different for each greenhouse gas, also varies over time as a result of Earth system processes.

The impact of greenhouse gases depends partly on how long each one persists in the atmosphere (Denman et al. 2007). Reactive gases like methane and nitrous oxide are destroyed chemically in the atmosphere, so the relationships between emissions and atmospheric concentrations are determined by the rate of those reactions. The term "lifetime" is often used to describe the speed with which a given gas is removed from the atmosphere. Methane has a relatively short lifetime (largely removed within a decade or so, depending on conditions), so reductions in emissions can lead to a fairly rapid decrease in concentrations as the gas is oxidized in the atmosphere

(Cicerone and Oremland 1988). Nitrous oxide has a much longer lifetime, taking more than 100 years to be substantially removed (IPCC 1995), so reductions in its emissions will take a longer time to affect its atmospheric concentration. Other gases in this category include industrial gases, like those used as solvents and in air conditioning, some of which persist in the atmosphere for hundreds or thousands of years.

Carbon dioxide (CO_2) is not reactive, so it does not, strictly speaking, have a "lifetime" (Moore and Braswell 1994). Instead, the relationship between emissions and concentrations year to year is determined by patterns of release (for example, through burning of fossil fuels) and uptake (for example, by vegetation and by the ocean) (Schimel 1995). Once CO_2 is emitted from any source, a portion is removed from the atmosphere over time by plant growth and absorption by the oceans, after which it continues to circulate in the land-atmosphere-ocean system until it is finally converted into stable forms in soils, deep ocean sediments, or other geological repositories.

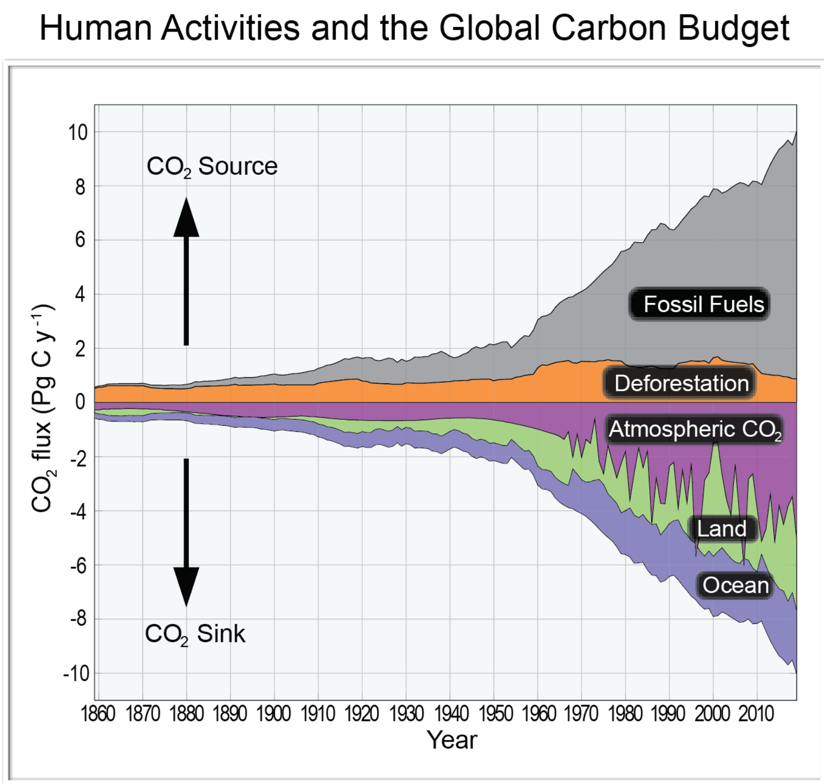

Figure 27.1: Human Activities and the Global Carbon Budget, 1859-2012.

Caption: Figure shows human-induced changes in the global carbon budget roughly since the beginning of the Industrial Revolution. Emissions from fossil fuel burning are the dominant cause of the steep rise in carbon dioxide shown here from 1950-present. (Canadell et al. 2007; Global Carbon Project 2011; Le Quere et al. 2009).

About half the carbon dioxide emitted at any one time is removed from the atmosphere in a century. However, around 20% of carbon released as emissions from fossil fuel burning continues to circulate and to affect atmospheric concentrations for thousands of years (Archer 2010). Stabilizing or reducing atmospheric carbon dioxide concentrations, therefore, requires very deep reductions in future emissions to compensate for past emissions that are still circulating in the Earth system. Avoiding future emissions, or capturing and storing them in stable geological storage, would prevent carbon dioxide from entering the atmosphere, and would have very long-lasting effects on atmospheric concentrations.

In addition to greenhouse gases, there can be climate effects from particulate matter in the atmosphere. An example is black carbon (soot), which is released from coal burning, diesel engines, cooking fires, wildfires, and other combustion sources. These particles have a warming influence, especially when they absorb solar radiation low in the atmosphere (Grieshop et al. 2009). Other particles, such as those formed from sulfur dioxide released during coal burning, have a cooling effect by reflecting some of the sun's radiation back to space, or by increasing the brightness of clouds.

The importance of each gas or type of particle is related to both how long it lasts in the atmosphere (the longer it lasts, the greater its influence) and its potency in trapping heat. The warming influence of different gases can be compared using "global warming potentials" (GWP), which combine these two effects, usually added up over a 100-year time horizon. GWPs are referenced to carbon dioxide—which is defined as having a GWP of 1.0— and the combined effect of multiple gases is denoted in carbon dioxide equivalents, or CO_2-e.

The relationship between emissions and concentrations can be modeled using Earth System Models (Plattner et al. 2008). Such models apply our understanding of biogeochemical processes that remove greenhouse gas emissions from the atmosphere to predict their future concentrations. These models show that stabilizing CO_2 emissions would allow atmospheric concentrations to increase approximately linearly, and would not stabilize its atmospheric concentration. Stabilizing atmospheric concentrations of CO_2 would require reducing emissions far below present-day levels. Concentration and emissions scenarios, such as the recently developed Representative Concentration Pathways (RCPs) and scenarios developed earlier by the Intergovernmental Panel on Climate Change's (IPCC) Special Report on Emissions Scenarios (SRES), are used in Earth System Models to study potential future climates. The RCPs span a range of atmospheric targets for use by climate modelers (Moss et al. 2010; van Vuuren et al. 2006) as have the SRES cases. These global analyses form a framework within which the climate contribution of U.S. mitigation efforts can be assessed. In this report, special attention is given to the SRES A2 scenario (similar to RCP8.5), which assumes continued increases in emissions, and the SRES B1 scenario (close to RCP4.5), which requires a rapid reduction of emissions (Ch. 2: Our Changing Climate).

Box: Geoengineering

Geoengineering has been proposed as a third option for addressing climate change in addition to, or alongside, mitigation and adaptation. Geoengineering refers to intentional modifications of the Earth system as a means to address climate change. Two types of activities have been proposed: carbon dioxide removal (CDR), which boosts CO_2 removal from the atmosphere by various means, such as fertilizing ocean processes that help take up carbon; and solar radiation management (SRM, or sunlight reflection methods), which reflects a small percentage of sunlight back into space to offset warming from greenhouse gases (Shepherd 2009).

Current research suggests that SRM or CDR might diminish the impacts of climate change by reducing changes in temperature and precipitation. However, once undertaken, sudden cessation of SRM would exacerbate the climate effects on human populations and ecosystems, and some CDR might interfere with oceanic and terrestrial ecosystem processes (Russell et al. 2012). SRM undertaken by itself would not address additional rises in CO_2 atmospheric concentrations, and would therefore also fail to address ocean acidification. Furthermore, no international institutions exist to manage such a global intervention. The risks associated with such purposeful perturbations to the Earth system are thus poorly understood, suggesting the need for caution and comprehensive research, including consideration of the implicit moral hazards.

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U.S. Emissions and Land-Use Change

Industrial Emissions

Aggregate U.S. industrial greenhouse gas emissions rose from just under 5,500 million tons CO_2-e in 1970 to 7,300 million tons CO_2-e in 2007, before falling in the 2009-2010 recession (EC-JRC/PBL 2011). Carbon dioxide made up just over 80% of these emissions, with methane (10%) and nitrous oxide (5%) second and third. Emissions of industrial gases (hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride) grew slowly prior to 1994, but exhibit a marked acceleration thereafter because they are largely substitutes for ozone-destroying gases controlled by the Montreal Protocol (UNEP 2009).

Forty percent of carbon dioxide emissions are attributable to liquid fuels (petroleum), followed closely by solid fuels (principally coal), and to a lesser extent gaseous fuels such as natural gas (Marland et al. 2008). The two dominant sectors in producing these emissions are electric power generation (coal and gas) and transportation (petroleum). Flaring and cement manufacture together account for less than 2% of total emissions historically and less than 1% today.

The historical patterns of greenhouse gas emissions derive from four driving forces: rising population, per-capita gross domestic product (GDP) growth, a reduction in the energy needed to produce each unit of GDP, and a falling CO_2 content of energy. The decrease in energy intensity is associated with several changes in the economy: substitution responses to energy prices (such as substituting natural gas for coal as natural gas prices have declined); both autonomous and price-induced technological change to improve efficiency; and changes in the composition of the capital stock as well as the mix of sectors in the economy (Metcalf 2008; Sue Wing 2008). Over this period, emissions increased by 29%, resulting from growth in both population and output per person that outweighed reductions attributable to energy intensity and carbon intensity.

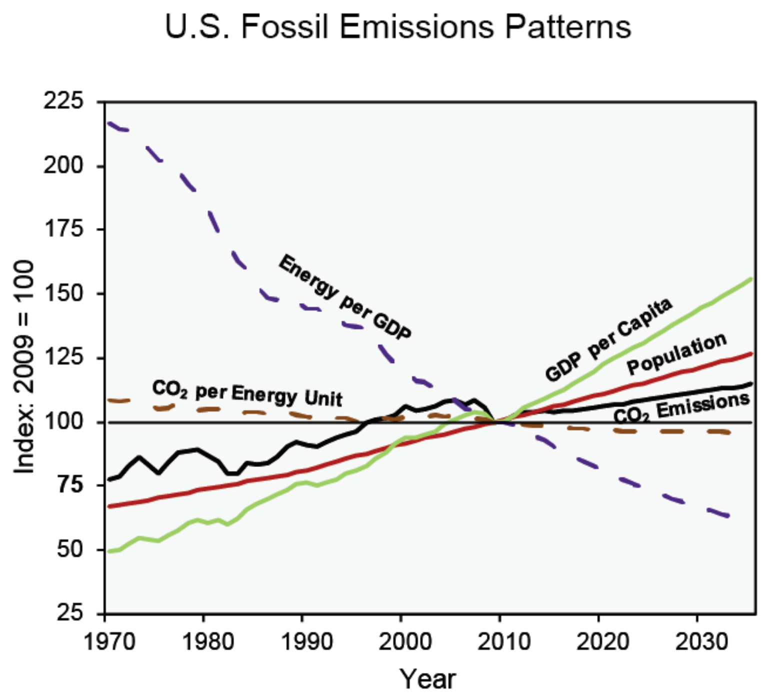

Figure 27.2. U.S. Fossil Emissions Patterns

Caption: While energy use as a percentage of gross domestic product has dropped significantly, total carbon dioxide emissions and population continue to rise. The chart shows observed patterns from 1970 to 2009, and forecasts through 2035. (Snead and Jones 2010).

These trends are expected to continue in the future, though more recent projections show a slower rate of emissions growth than the figure implies. Compared to 2010, projections for the year 2035 show 25% and 62% increases in population and per-capita GDP (respectively), a 42% decline in the energy-GDP ratio, and continued reductions in the emission intensity of energy use, with the net result being a 2% increase in energy-related CO_2 emissions over the period (EIA 2012)

Land Use & Agriculture

Estimates of carbon stocks and fluxes for U.S. lands are based on land inventories augmented with data from ecosystem studies and production reports (EPA 2010; USDA 2011). Stocks of the main carbon pools (biomass, dead wood, litter, soil, and harvested products) are estimated periodically and their rate of change, or flux, calculated as the average annual difference between two time periods.

U.S. lands were estimated to be a net sink of between approximately 640 and 1,074 million tons CO_2-e in the late 2000s (Pacala et al. 2007; USDA 2011). Estimates vary depending on choice of datasets, models, and methodologies (See Ch. 15: Biogeochemistry, Carbon Sink box for more discussion). This net land sink effect is the result of sources (from crop production, livestock production, and grasslands) and sinks (in forests, urban trees, and wetlands). Sources of carbon have been relatively stable over the last two decades, but sinks have been more variable. Long-term trends suggest significant emissions from forest clearing in the early 1900s followed by a sustained period of net uptake from forest regrowth over the last 70 years (Birdsey et al. 2006). The amount of carbon taken up by U.S. land sinks is dominated by forests, which have annually absorbed 7% to 24% (with a best estimate of about 13%) of fossil fuel CO_2 emissions in the U.S. over the past two decades.

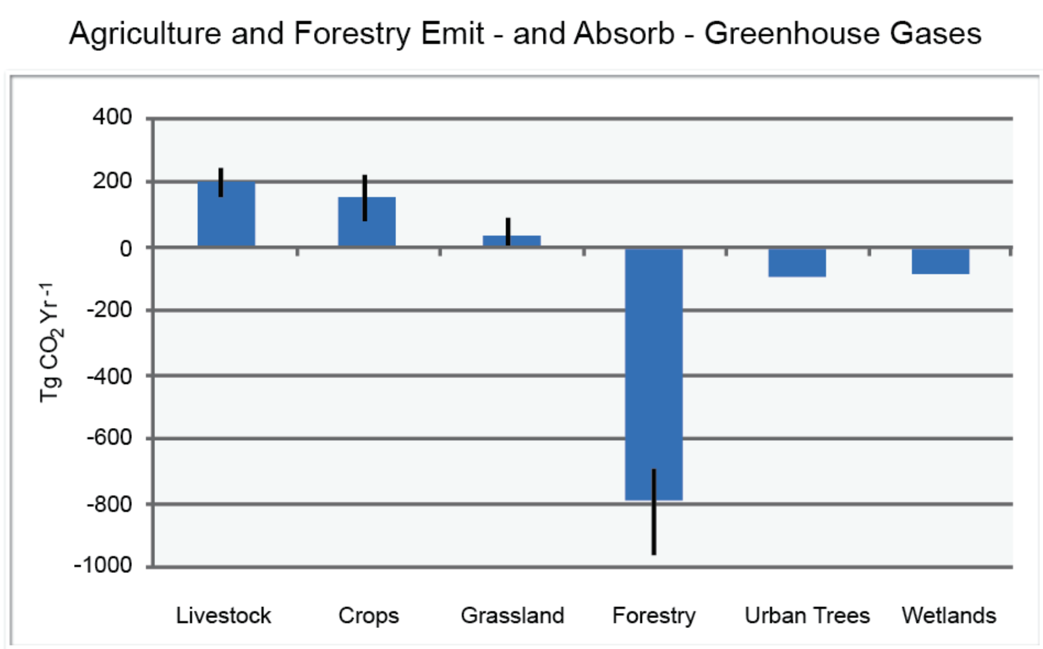

Figure 27.3: Agriculture and Forestry Emit – and Absorb – Greenhouse Gases

Caption: Chart shows greenhouse gas emissions from livestock and crop production, but does not include fossil fuels used in agricultural production. Forests are a significant "sink" that absorbs carbon dioxide from the atmosphere. (Pacala et al. 2007; USDA 2011).

The land sink, driven substantially by forest re-growth after agricultural land abandonment and recovery from harvesting, may not be sustainable for more than a few more decades (Pan et al. 2011; Williams et al. 2012). Deforestation continues to cause an annual loss of 877,000 acres (137,000 square miles) of forest land, offset by a larger area gain of new forest of about 1.71 million acres (268,000 square miles) annually (Masek et al. 2011). Since most of the new forest is on relatively low productivity lands of the Intermountain West, and much of the deforestation occurs on high productivity lands in the East, the net impact of recent land-use changes on carbon stocks is negative (Zheng et al. 2011). The effects of fertilization by increasing CO_2 concentration and nitrogen deposition are not likely to be as large as effects of land use and disturbances (Zhang et al. 2012). In some regions, longer growing seasons may increase annual productivity (Richardson et al. 2010). There is a lack of consistency in published results about the relative effects of disturbance and non-disturbance factors (for example, Caspersen et al. 2000; Pan et al. 2009; Zhang et al. 2012).

Droughts and other disturbances, such as fire and insect infestations, have already turned some U.S. land regions from carbon sinks into carbon sources (Zhang et al. 2012). The future persistence of the land sink depends on the relative effects of several interacting factors: recovery from historical land-use change, atmospheric CO_2 and nitrogen deposition, natural disturbances, and the effects of climate variability and change, particularly drought and effects on the length of the growing season.

Current Activities Affecting Emissions

Rapid and large reductions in global emissions would be necessary to reach the tighter targets (such as the B1 scenario; see Ch. 2: Our Changing Climate) analyzed in this assessment. Voluntary efforts and governmental actions in city, state, regional, and federal programs are underway that have the effect of reducing the U.S. contribution to total global emissions. Many, if not most, public programs affecting U.S. greenhouse gas emissions are designed to address other policy issues: energy, transportation, housing safety, and many others. Efforts directed specifically at greenhouse gas emissions include:

- Reduction in CO_2 emissions from energy end-use and infrastructure through the adoption of energy-efficient components and systems – including buildings, vehicles, manufacturing processes, and electric grid systems;
- Reduction of CO_2 emissions from energy supply through the promotion of renewables (wind, solar, bioenergy), nuclear energy, and coal and natural gas electric generation with carbon capture and storage, and
- Reduction of emissions of non-CO_2 greenhouse gases, for example, by lowering methane emissions from energy and waste, and cutting methane and nitrous oxide emissions from agriculture.

Federal Actions

The Federal government has implemented a number of measures that promote energy efficiency, clean technologies, and alternative fuels (The White House 2012; The White House 2010a, 2010b; DOE 2009b; GAO 2011). A sample is provided in Table 27.2. These actions fall into two general categories: research and development, to accelerate the development of innovative equipment and systems; and commercialization and deployment, including information dissemination, voluntary standards-setting, tax and other financial incentives, and rules and regulations.

At the national level, the Environmental Protection Agency has authority to regulate greenhouse gas emissions under the Clean Air Act. The Department of Energy provides most of the funding for energy research, development, and demonstration activities, and the Agency has the authority to regulate the efficiency of appliances and building codes for manufactured housing. In addition, most of the other federal agencies – importantly including Defense, Housing and Urban Development, Transportation, and Agriculture – have programs related to greenhouse gas mitigation.

City, State, and Regional Actions

Jurisdiction for greenhouse gases and energy policies is shared between the federal government and the states (for an overview see NRC 2010b). For example, states regulate economic activity and energy distribution, while the Federal Energy Regulatory Commission regulates wholesale sales and transportation of natural gas and electricity. In addition, many states have adopted climate initiatives as well as energy policies that reduce greenhouse gas emissions. For a survey of many of these state activities, see Table 27.1[1]. Many cities are taking similar actions.

The most ambitious is California's Global Warming Solutions Act (AB 32), which sets a state goal to reduce its greenhouse gas emissions to 1990 levels by 2020. The state program will cap emissions and use a market-based system of trading in emissions credits (cap-and-trade), as well as a number of regulatory actions. The most well-known, multi-state effort has been the Regional Greenhouse Gas Initiative (RGGI), formed by ten northeastern and mid-Atlantic states (though New Jersey exited in 2011). RGGI is a cap-and-trade system applied to the power sector with revenue from allowance auctions directed to investments in efficiency and renewable energy.

Voluntary Actions

A host of voluntary actions are being carried out by corporations, individuals, and non-profit organizations. Four examples give the flavor of the range of efforts:

- The Carbon Disclosure Project has the largest global collection of self-reported climate change and water-use information. The system enables companies to measure, disclose, manage, and share climate change and water use information. Some 650 U.S. signatories include banks, pension funds, asset managers, insurance companies, and foundations.
- Many local governments are undertaking initiatives to reduce greenhouse gas emissions within and outside of their organizational boundaries (Krause 2011; Pitt 2010). For example, over 1,055 municipalities from all 50 states have signed the U.S. Mayors Climate Protection Agreement (U.S. Mayors Climate Protection Agreement 2012), and many of these communities are actively implementing strategies to reduce their greenhouse gas footprint.

[1] For this paper version of the text, the entry page of the website is attached as a table.

- Under the American College and University Presidents' Climate Commitment (ACUPCC), 677 institutions have pledged to develop plans to achieve net-neutral climate emissions through a combination of on-campus changes and purchases of emissions reductions elsewhere.
- Federal voluntary programs include Energy STAR, a labeling program that identifies energy efficient products for use in residential homes and commercial buildings and plants, and programs and partnerships devoted to reducing methane emissions from fossil fuel production and landfill sources and high GWP emissions from industrial activities.

Box: Co-Benefits for Air Pollution and Human Health

Actions to reduce greenhouse gas emissions yield co-benefits for objectives apart from climate change, such as energy security and biodiversity. The co-benefits for reductions in air pollution have received particular attention. Because air pollutants and greenhouse gases share common sources, particularly in fossil fuel combustion, actions to reduce greenhouse gas emissions also reduce air pollutants. While some greenhouse gas measures might increase other emissions, broad programs to reduce greenhouse gases across an economy or a sector can reduce air pollutants markedly (Bell et al. 2008; van Vuuren et al. 2006).

There is significant interest in quantifying the air pollution and human health co-benefits of greenhouse gas mitigation, particularly from the public health community (World Health Organization and Davis 1997), as the human health benefits are immediate and local, in contrast to the long-term and widespread effects of climate change. Many of these studies have found that the monetized health and pollution control benefits could offset a significant portion of the direct mitigation cost (e.g., Burtraw et al. 2003). Methane reductions have also been shown to generate health benefits from reduced ozone, estimated to justify a 20% reduction of human-induced methane emissions (West et al. 2006). Similarly, in developing nations, reducing black carbon from household cook stoves has been shown to substantially reduce air pollution-related illness and death (Shindell et al. 2012; Wang and Smith 1999).

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Preparation for Potential Future Mitigation Action

Current voluntary and governmental efforts do lower U.S. greenhouse gas emissions, but they are not close to sufficient to yield the U.S contribution to the reductions needed to meet the lower emissions scenario (B1) used in this assessment. The Annual Energy Outlook prepared by the DOE Energy Information Administration attempts to take account of these activities, yet it projects continued growth in energy-related U.S. CO_2 emissions through 2035 (EIA 2012). To meet the rapid emissions reduction (B1) scenario under reasonable assumptions about managing costs, annual *global* CO_2 emissions would need to peak at around 44 billion tons within the next 25 years or so and decline steadily for the rest of the century. The current U.S. share of global CO_2 emissions is about 20%. At the current rate of emissions growth, the world is on a track to exceed the 44 billion ton level within a decade (see Box). More aggressive greenhouse concentration targets, such as those associated with a frequently-discussed limit of a 2ºC (3.6ºF) temperature increase above pre-industrial levels (UFNCCC 2009) would require an even more dramatic reduction in global emissions (Webster et al. 2011).

Box: Emissions Scenarios and the RCPs

The Representative Concentration Pathways (RCPs) specify alternative limits to human influence on the Earth's energy balance, stated in watts per square meter (W/m^2) of the Earth's surface (Moss et al. 2010; van Vuuren et al. 2011b). The A2 emissions scenario used in this assessment implies atmospheric concentrations with radiative forcing slightly lower than the highest RCP, which is 8.5 W/m^2. The lower limits, at 6.0, 4.5 and 2.6 W/m^2, imply ever-greater mitigation efforts. The B1 scenario (rapid emissions reduction) also used in this assessment is close to the 4.5 W/m^2 RCP (Thomson et al. 2011) and to a similar case (Level 2) analyzed in a previous federal study (Clarke et al. 2007). Those assessments find that, to manage the economic costs, annual global fossil and industrial CO_2 emissions need to peak by 2035 to 2040 at around 44 billion tons of CO_2, and decline thereafter. The scale of the task can be seen in the fact that these global emissions were already at 37 billion tons in 2011, and for the past decade they have been rising at around 0.93 billion tons CO_2 per year (BP 2012). The lowest RCP would require an even more rapid turnaround and negative net emissions—that is, removing CO_2 from the air—in this century (van Vuuren et al. 2011b).

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Achieving the B1 emissions path would require substantial decarbonization of the global economy by century's end, implying a fundamental transformation of the global energy system. Details of the energy mix along the way differ among analyses, but the implied involvement by the U.S. can be seen in a three-model study carried out under the U.S. Climate Change Science Program (Clarke et al. 2007). In this study, direct burning of coal without carbon capture is essentially excluded from the power system, and the same holds for natural gas toward the end of the century – to be replaced by some combination of coal or gas with carbon capture and storage, nuclear generation, and renewables. Biofuels and electricity are projected to substitute for oil in the transport sector. A substantial component of the task is accomplished with demand reduction, through efficiency improvement, conservation, and shifting to an economy less dependent on energy services.

The challenge is great enough even starting today, but delay by any of the major emitters makes meeting any such target even more difficult and may altogether rule out some of the more ambitious goals (Clarke et al. 2007). A study of the climate change threat and potential responses by the U.S. National Academies therefore concludes that there is "an urgent need for U.S. action to reduce greenhouse emissions" (NRC 2010a). The NRC goes on to suggest alternative national-level strategies that might be followed, including an economy-wide system of price penalties on greenhouse emissions and a portfolio of possible regulatory measures and subsidies. Deciding these matters will be a continuing task, and U.S. Administrations and the Congress face a long sequence of choices about whether to take additional mitigation actions, and how best to do it. Two supporting activities will help guide this process: opening future technological options and development of ever-more-useful assessments of the cost and effectiveness of policy choices.

Many technologies are potentially available to accomplish emissions reduction. They include: ways to increase the efficiency of fossil energy use and facilitate a shift to low-carbon energy sources; sources of improvement in the cost and performance of renewables (wind, solar, bioenergy) and nuclear energy; ways to reduce the cost of carbon capture and storage; and means to expand terrestrial sinks through management of forests and soils, and increased agricultural productivity (DOE 2011). In addition to the research and development carried out by private sector firms with their own funds, the federal government traditionally supports major programs to advance these technologies. This is accomplished in part by credits and deductions in the tax code, and in part by federal expenditure. For example, the 2012 federal budget devoted approximately $6 billion to clean energy technologies (OMB 2012). Success in these ventures, lowering the cost of greenhouse gas reduction, can make a crucial contribution to future policy choices (NRC 2010b).

Because they are in various stages of research and development, the costs and effectiveness of many of these technologies remain uncertain; continuing study of their performance is important to understanding their role in future mitigation decisions (Edmonds et al. 2000, 2007). In addition, evaluation of broad policies and particular mitigation measures requires frameworks that combine information from a range of disciplines. Study of mitigation in the near future can be done with energy-economic models that do not assume large changes in the mix of technologies or changes in the structure of the economy. Analysis over the time spans relevant to stabilization of greenhouse gas concentrations, however, requires Integrated Assessment Models, which consider all emissions drivers, and representations of how they are related to the larger economy and features of the climate system (Clarke et al. 2007; Clarke et al. 2009; Janetos et al. 2009; Prinn 2012; DOE 2009a). This type of analysis also is useful for exploring the relations between mitigation and measures to adapt to a changing climate.

Box: Interactions Between Adaptation and Mitigation

There are various ways in which mitigation efforts and adaptation measures are interdependent. For, example, the use of plant material as a substitute for petroleum-based transportation fuels, or directly as a substitute for burning coal or gas for electricity generation, has received substantial attention (for example, EIA 2012). But land that is used for mitigation purposes is potentially not available for food production, even as the global demand for agricultural products continues to rise (DeFries and Rosenzweig 2010; Melillo et al. 2009; Thomson et al. 2010). The converse of this is that land that is required for adaptation strategies, like setting aside wildlife corridors or expanding the extent of conservation areas, is potentially not available for mitigation involving the use of plant material, or active management practices to enhance carbon storage in vegetation or soils. These potential interactions are poorly understood but potentially important, especially as climate change itself affects vegetation and ecosystem productivity and carbon storage.

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Continued development of these analytical capabilities can help support decisions about national mitigation and the U.S. position in international negotiations. In addition, as shown above, mitigation is being undertaken by individuals and firms as well as by city, state, and regional governments. For many of these efforts, the needed analysis of cost and effectiveness is limited, so additional support for studies of these activities is needed to insure that resources are efficiently employed.

Research Needs

- Development of cost-effective energy use technologies (devices, systems, and control strategies) and energy supply technologies that produce little or no CO_2 or other greenhouse gases.
- Better understanding of the relationship between emissions and atmospheric greenhouse gas concentrations is needed to more accurately predict how the atmosphere and climate system will respond to mitigation measures.
- The processes controlling the land sink of carbon in the U.S. require additional research, including analysis of economic decision-making about the fate of land and how it is managed, as well as the inherent ecological processes and how they respond to the climate system.
- Uncertainties in model-based projections of greenhouse gas emissions, and of the effectiveness and costs of policy measures, need to be better quantified. Exploration is needed of the effects of different model structures, assumptions about model parameter values, and uncertainties in input data.
- Social and behavioral science research is needed to inform the design of mitigation measures for maximum participation and to prepare a consistent framework for assessing costs and effectiveness of both voluntary mitigation efforts and regulatory and subsidy programs.

Table 27.1. State Climate and Energy Initiatives

STATE CLIMATE AND ENERGY INITIATIVES

Most states have implemented programs to reduce greenhouse gases (GHG's) or adopt increased energy efficiency goals. Examples of greenhouse gas policies include:

◙ Greenhouse Gas Reporting and Registries
http://www.c2es.org/us-states-regions/policy-maps/ghg-reporting

◙ Greenhouse Gas Emissions Targets
http://www.c2es.org/us-states-regions/policy-maps/emissions-targets

◙ CO_2 Controls on Electric Powerplants
http://www.edf.org/sites/default/files/state-ghg-standards-03132012.pdf

◙ Low-Carbon Fuel Standards
http://www.c2es.org/us-states-regions/policy-maps/low-carbon-fuel-standard

◙ Climate Action Plans
http://www.c2es.org/us-states-regions/policy-maps/action-plan

◙ Cap-and-Trade Programs
http://arb.ca.gov/cc/capandtrade/capandtrade.htm

◙ Regional Agreements
http://www.c2es.org/us-states-regions/regional-climate-initiatives#WCI

Also, states have taken a number of energy measures, motivated in part by greenhouse gas concerns. For example:

◙ Renewable Portfolio Standards
[http://www.dsireusa.org/documents/summarymaps/RPS_map.pdf]

◙ Energy Efficiency Resource Standards
http://www.dsireusa.org/documents/summarymaps/EERS_map.pdf

◙ Property Tax Incentives for Renewables
http://www.dsireusa.org/documents/summarymaps/PropertyTax_map.pdf

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Table 27.2. Sample Federal Mitigation Measures

Caption: A number of federal laws and regulations target ways to reduce future climate change by decreasing greenhouse gas emissions emitted by human activities

Greenhouse Gas Regulations
Emissions Standards for Vehicles and Engines -- For light-duty vehicles, rules establishing tightened standards for 2012-2016 model years and 2017-2025 model years. -- For heavy- and medium-duty trucks, a rule establishing standards for 2014-2018 model years.
Carbon Pollution Standard for New Power Plants -- A proposed a rule setting limits on CO_2 emissions from future power plants.
Stationary Source Permitting -- A rule setting GHG emissions thresholds for permits under the New Source Review Prevention of Significant Deterioration and Title V Operating Permit programs are required for new and modified industrial facilities.
Greenhouse Gas Reporting Program -- A program requiring annual reporting of GHG data from large emission sources and suppliers of products that emit greenhouse gases if released or combusted.
Other Rules and Regulations with Climate Co-benefits
Oil and Natural Gas Air Pollution Standards -- A rule revising New Source Performance Standards and National Emission Standards for Hazardous Air Pollutants for certain components of the oil and natural gas industry.
Mobile Source Control Programs -- Particle control regulations affecting mobile sources, especially diesel engines, that reduce black carbon by controlling direct particle emissions. -- The requirement to blend increasing volumes of renewable fuels.
National Forest Planning -- Identify and evaluate existing information relevant to the plan area for a baseline assessment of carbon stocks. -- Reporting of net carbon stock changes on forest land is required.

Standards and Subsidies
<u>*Appliance and Building Efficiency Standards*</u> -- Energy efficiency standards and test procedures for residential, commercial, industrial, lighting, and plumbing products. -- Model residential and commercial building energy codes, and technical assistance to state and local governments, and NGOs.
<u>*Financial Incentives for Efficiency and Alternative Fuels and Technology*</u> -- Weatherization assistance for low-income households, tax incentives for commercial and residential buildings and efficiency appliances, and support for state and local efficiency programs. -- Tax credits for biodiesel and advanced biofuel production, alternative fuel infrastructure, and purchase of electric vehicles -- Loan guarantees for innovative energy or advanced technology vehicle production and manufacturing; investment and production tax credits for renewable energy production.
Support for Research, Development, Demonstration, and Deployment
-- Loan guarantees for innovative energy or advanced technology vehicle production and manufacturing; investment and production tax credits for renewable energy production.
Federal Agency Practices and Procurement
-- Executive orders and federal statutes requiring federal agencies to reduce building energy and resource consumption intensity, and to procure alternative fuel vehicles. -- Agency-initiated programs in most departments oriented to lowering energy cost and greenhouse gas emissions.

Traceable Accounts

Chapter 27: Mitigation

Key Message Process: Evaluation of literature by Coordinating Lead Authors

Key message #1/5	**There are long time lags between actions taken to reduce carbon dioxide emissions and reductions in its atmospheric concentration. Mitigation efforts that only *stabilize* global emissions will therefore not reduce atmospheric concentrations of carbon dioxide, but will only limit their rate of increase.**
Description of evidence base	The message is a restatement of conclusions derived from the peer-reviewed literature over nearly the past 20 years (see Section I of chapter). Publications have documented the long lifetime of CO_2 in the atmosphere, resulting in long time lags between action and reduction (Archer 2010; Schimel 1995), and Earth System Models have shown that stabilizing emissions won't immediately stabilize atmospheric concentrations, which will continue to increase (Plattner et al. 2008).
New information and remaining uncertainties	There are several important uncertainties in the current carbon cycle, especially the overall size, location, and dynamics of the land-use sink (Archer 2010; Schimel 1995). Simulating future atmospheric concentrations of greenhouse gases requires both assumptions about economic activity, stringency of any greenhouse gas emissions control, and availability of technologies, as well as a number of assumptions about how the changing climate system affects both natural and anthropogenic sources.
Assessment of confidence based on evidence	**Very High**. Observations of changes in the concentrations of greenhouse gases are consistent with our understanding of the broad relationships between emissions and concentrations.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 27: Mitigation

Key Message Process: Please see KM #1 for description of process.

Key message #2/5	**To meet the rapid emissions reduction (B1) scenario used in this assessment, global mitigation actions would, within the next 25 years, need to limit global greenhouse gas emissions to a peak of around 44 billion tons per year. In 2011, global emissions were around 37 billion tons, and have been rising about 0.9 billion tons per year for the past decade. The world is therefore on track to exceed this level within a few years.**
Description of evidence base	A large number of emissions scenarios have been modeled, with a number of publications showing what would be required to limit CO_2 (Clarke et al. 2007; Moss et al. 2010; Thomson et al. 2011; van Vuuren et al. 2011a) to any predetermined limit. At current concentrations and rate of rise, the emissions of CO_2 would need to peak around 44 billion tons within the next 25 years in order to stabilize concentrations as in the B1 scenario. This limit is projected to be surpassed (BP 2012).
New information and remaining uncertainties	Uncertainties about the carbon cycle could affect these calculations, but the largest uncertainties are the assumptions made about the strength and cost of greenhouse gas emissions policies.
Assessment of confidence based on evidence	The confidence in the conclusion is **high**. This is a contingent conclusion, though – we do not have high confidence that this will actually occur, simply that if we do choose to limit concentrations as in the B1 scenario, emissions will need to peak soon and then decline.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 27: Mitigation

Key Message Process: Please see KM #1 for description of process.

Key message #3/5	**Over recent decades, the U.S. economy has emitted less carbon dioxide per dollar of GDP for many reasons. However, U.S. population and economic growth have outweighed these trends, and in the absence of additional public policies greenhouse gas emissions are expected to continue to rise.**
Description of evidence base	Trends in greenhouse gas emissions intensity are analyzed and published by governmental reporting agencies (EC-JRC/PBL 2011; EPA 2010; Marland et al. 2008; UNEP 2009; USDA 2011). Published, peer-reviewed literature cited in Section II of the Mitigation Chapter supports the conclusions about why these trends have occurred (Metcalf 2008; Sue Wing 2008), and government agency calculations support the statement about how population and economic growth are expected to counterbalance these trends (EIA 2012).
New information and remaining uncertainties	Economic forecasts are highly uncertain.
Assessment of confidence based on evidence	**High**. The statement is a summary restatement of published analyses by government agencies and interpretation from the reviewed literature.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 27: Mitigation

Key Message Process: Please see KM #1 for description of process.

Key message #4/5	**Carbon storage in land ecosystems, especially forests, has offset around 13% of U.S. fossil fuel emissions of greenhouse gases over the past several decades, but this carbon "sink" is projected to become smaller as forests age.**
Description of evidence base	Underlying data come primarily from US Forest Service Forest Inventory and Analysis plots, supplemented by additional ecological data collection efforts. Modeling conclusions come from peer review literature. All references are in Section II of the Mitigation Chapter. Studies have shown that there is a large land-use carbon sink in the US (Birdsey et al. 2006; Pacala et al. 2007; USDA 2011). Many publications attribute this sink to forest re-growth, and the sink is projected to decline as a result of forest aging (Pan et al. 2011; Williams et al. 2012; Zhang et al. 2012) (Zheng et al. 2011) and factors like drought, fire, and insect infestations (Zhang et al. 2012) reducing the carbon sink of these regions.
New information and remaining uncertainties	FIA plots are measured extremely carefully over long time periods, but do not cover all US forested land. Other US land types must have carbon content estimated from other sources. Modeling relationships between growth and carbon content, and taking CO_2 and climate change into account have large scientific uncertainties associated with them.
Assessment of confidence based on evidence	**High**. Evidence of past trends is based primarily on government data sources, but these also have to augmented by other data and models in order to incorporate additional land-use types. Projecting future carbon content is consistent with published models, but these have intrinsic uncertainties associated with them.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Chapter 27: Mitigation

Key Message Process: Please see KM #1 for description of process.

Key message #5/5	**Even absent a comprehensive national greenhouse gas policy, both voluntary and governmental efforts to reduce emissions are under way. While these efforts have other co-benefits, they are not close to sufficient to reduce total U.S. emissions to a level consistent with the B1 scenario analyzed in this assessment**
Description of evidence base	The identification of state, local, regional, federal, and voluntary programs that will have an effect of reducing greenhouse gas emissions is a straightforward accounting of both legislative action and announcements of the implementation of such programs. Some of the programs include the Carbon Disclosure Project (CDP), the American College and University Presidents' Climate Commitment (ACUPCC), U.S. Mayors Climate Protection Agreement (U.S. Mayors Climate Protection Agreement 2012), and many other local government initiatives (Krause 2011; Pitt 2010). Several states have also adapted climate policies including California's Global Warming Solutions Act (AB 32) and the Regional Greenhouse Gas Initiative (RGGI). The assertion that they will not lead to a reduction of US CO_2 emissions is supported by calculations from the US Energy Information Administration.
New information and remaining uncertainties	There are no uncertainties about the existence of the programs identified. The major uncertainty in the calculation about future emissions levels is whether comprehensive national policy is implemented.
Assessment of confidence based on evidence	**Very High**. There is no uncertainty about whether programs exist or not, although there is recognition that their implementation may differ from how they are originally planned, and that institutions can always choose to leave voluntary programs (as is happening with RGGI, noted in the chapter). The statement about the future of US CO_2 emissions cannot be taken as a prediction of what will happen – it is a conditional statement based on an assumption of no comprehensive national legislation or regulation.

CONFIDENCE LEVEL			
Very High	**High**	**Medium**	**Low**
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

References

Archer, D., 2010: The Global Carbon Cycle (Princeton Primers in Climate) Princeton University Press.

Bell, M.L., D.L. Davis, L.A. Cifuentes, A.J. Krupnick, R.D. Morgenstern, and G.D. Thurston, 2008: Ancillary human health benefits of improved air quality resulting from climate change mitigation. *Environmental Health*, **7,** 41

Birdsey, R., K. Pregitzer, and A. Lucier, 2006: Forest carbon management in the United States: 1600–2100. *Journal of Environmental Quality*, **35,** 461–1469

BP: BP Statistical Review of World Energy, June 2012. [Available online at http://www.bp.com/sectionbodycopy.do?categoryId=7500&contentId=7068481]

Burtraw, D., A. Krupnick, K. Palmer, A. Paul, M. Toman, and C. Bloyd, 2003: Ancillary benefits of reduced air pollution in the US from moderate greenhouse gas mitigation policies in the electricity sector. *Journal of Environmental Economics and Management*, **45,** 650-673

Canadell, J.G., C. Le Quéré, M.R. Raupach, C.B. Field, E.T. Buitenhuis, P. Ciais, T.J. Conway, N.P. Gillett, R. Houghton, and G. Marland, 2007: Contributions to accelerating atmospheric CO2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proceedings of the National Academy of Sciences*, **104,** 18866-18870

Caspersen, J.P., S.W. Pacala, J.C. Jenkins, G.C. Hurtt, P.R. Moorcroft, and R.A. Birdsey, 2000: Contributions of Land-Use History to Carbon Accumulation in U.S. Forests. *Science*, **290,** 1148-1151 doi: 10.1126/science.290.5494.1148, [Available online at http://www.sciencemag.org/content/290/5494/1148.abstract]

Cicerone, R.J. and R.S. Oremland, 1988: Biogeochemical aspects of atmospheric methane. *Global Biogeochemical Cycles*, **2,** 299-327

Clarke, L., J. Edmonds, H. Jacoby, H. Pitcher, J. Reilly, and R. Richels, 2007: Scenarios of Greenhous Gas Emissions and Atmospheric Concentrations–US Climate Change Science Program Synthesis and Assessment Product 2.1 a

Clarke, L., J. Edmonds, V. Krey, R. Richels, S. Rose, and M. Tavoni, 2009: International climate policy architectures: Overview of the EMF 22 International Scenarios. *Energy Economics*, **31,** S64-S81

DeFries, R. and C. Rosenzweig, 2010: Toward a whole-landscape approach for sustainable land use in the tropics. *Proceedings of the National Academy of Sciences*, **107,** 19627-19632

Denman, K.L., G. Brasseur, A. Chidthaisong, P. Ciais, P.M. Cox, R.E. Dickinson, D. Hauglustaine, C. Heinze, E. Holland, D. Jacob, U. Lohmann, S. Ramachandran, P.L. da Silva Dias, S.C. Wofsy, and X. Zhang, 2007: Couplings Between Changes in the Climate System and Biogeochemistry. *Climate Change 2007: The Physical Science Basis*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, Eds., Cambridge University Press, 499-587. [Available online at http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter7.pdf]

DOE, 2009a: The National Energy Modeling System: An Overview 2009, Energy Information Administration, Office of Integrated Analysis and Forecasting 83 pp. [Available online at http://www.eia.doe.gov/oiaf/aeo/overview/]

——, 2009b: . Strategies of the Commercialization and Deployment of Greenhouse Gas Intensity-Reducing Technologies and Practices. DOE/PI-000, the Committee on Climate Change Science and Technology Integration 190 pp. [Available online at http://www.climatetechnology.gov/Strategy-Intensity-Reducing-Technologies.pdf]

DOE, 2011: Report of the First Quadrennial Technology Review, U.S. Department of Energy 168 pp. [Available online at http://energy.gov/sites/prod/files/QTR_report.pdf]

EC-JRC/PBL: EDGAR version 4.2. [Available online at http://edgar.jrc.ec.europa.eu/]

Edmonds, J., M. Wise, J. Dooley, S. Kim, S. Smith, P. Runci, L. Clarke, E. Malone, and G. Stokes, 2000: Global Energy Technology Strate

gy: Addressing Climate Change. Battelle.

——, 2007: Global Energy Technology Strategy: Addressing Climate Change: GTSP Phase II Results. Battelle.

EIA, 2012: Annual Energy Outlook 2012 (Early Release Overview). [Available online at http://www.eia.gov/forecasts/aeo/er/]

——: Annual Energy Outlook 2012 with Projections to 2035. [Available online at http://www.eia.gov/forecasts/aeo/]

EPA, 2010: Inventory of US greenhouse gas emissions and sinks: 1990-2008.

GAO, 2011: Climate Change: Improvements Needed to Clarify National Priorities and Better Align Them with Federal Funding Decisions. GAO-11-317, U.S. Government Accountability Office 95 pp. [Available online at http://www.gao.gov/assets/320/318556.pdf]

Global Carbon Project: Ten Years of Advancing Knowledge on the Global Carbon Cycle and its Management. [Available online at http://www.globalcarbonproject.org/global/pdf/GCP_10years_med_res.pdf]

Grieshop, A.P., C.C.O. Reynolds, M. Kandlikar, and H. Dowlatabadi, 2009: A black-carbon mitigation wedge. *Nature Geoscience*, **2,** 533-534

IPCC, 1995: *The Science of Climate Change: Summary for Policymakers. Technical Summary of the Working Group I Report.*

——, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change

Janetos, A., L. Clarke, B. Collins, K. Ebi, J. Edmonds, I. Foster, J. Jacoby, K. Judd, R. Leung, and R. Newell, 2009: Science challenges and future directions: Climate change integrated assessment research. Report PNNL-18417 from the US Department of Energy, Office of Science.

Krause, R.M., 2011: Symbolic or substantive policy? Measuring the extent of local commitment to climate protection. *Environment and Planning C: Government & Policy*, **29,** 46-62

Le Quere, C., M.R. Raupach, J.G. Canadell, and G. Marland, 2009: Trends in the sources and sinks of carbon dioxide. *Nature Geoscience*, **2,** 831-836 doi: 10.1038/ngeo689, [Available online at http://www.nature.com/ngeo/journal/v2/n12/full/ngeo689.html]

Marland, G., B. TA, and R. Andres, 2008: Global, Regional, and National Fossil Fuel CO2 Emissions. *trends: a Compendium of data on Global Change*

Masek, J.G., W.B. Cohen, D. Leckie, M.A. Wulder, R. Vargas, B. de Jong, S. Healey, B. Law, R. Birdsey, and R. Houghton, 2011: Recent rates of forest harvest and conversion in North America. *Journal of Geophysical Research*, **116,** G00K03

Melillo, J.M., J.M. Reilly, D.W. Kicklighter, A.C. Gurgel, T.W. Cronin, S. Paltsev, B.S. Felzer, X. Wang, A.P. Sokolov, and C.A. Schlosser, 2009: Indirect emissions from biofuels: How important? *Science*, **326,** 1397-1399 doi: DOI: 10.1126/science.1180251

Metcalf, G.E., 2008: An empirical analysis of energy intensity and its determinants at the state level. The Energy Journal, 29, 1-26

Moore, B. and B. Braswell, 1994: The lifetime of excess atmospheric carbon dioxide. *Global Biogeochemical Cycles*, **8,** 23-38

Moss, R., J. Edmonds, K. Hibbard, T. Carter, S. Emori, M. Kainuma, T. Kram, M. Manning, J. Meehl, and J. Mitchell, 2010: Representative concentration pathways: a new approach to scenario development for the IPCC Fifth Assessment Report. *Nature*, **463,** 747-756

NRC, 2010a: Adapting to Impacts of Climate Change, Report of the Panel on Adapting to Impacts of Climate Change, NAS/NRC Committee on America's Climate Choices, May 2010

——, 2010b: Limiting the Magnitude of Future Climate Change, Report of the Panel on Limiting the Magnitude of Climate Change, NAS/NRC Committee on America's Climate Choices, May 2010

OMB, 2012: Fiscal Year 2013 Budget of the U.S. Government, 256 pp. [Available online at http://www.whitehouse.gov/omb/factsheet/creating-the-clean-energy-of-tomorrow-and-protecting-the-environment]

Pacala, S., R.A. Birdsey, S.D. Bridgham, R.T. Conant, K. Davis, B. Hales, R.A. Houghton, J.C. Jenkins, M. Johnston, and G. Marland, 2007: The North American carbon budget past and present. *The First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle, Departments of Energy and Commerce and NASA*

Pan, Y., R. Birdsey, J. Hom, and K. McCullough, 2009: Separating effects of changes in atmospheric composition, climate and land-use on carbon sequestration of US Mid-Atlantic temperate forests. *Forest Ecology and Management*, **259,** 151-164

Pan, Y., J. Chen, R. Birdsey, K. McCullough, L. He, and F. Deng, 2011: Age structure and disturbance legacy of North American forests. *Biogeosciences*, **8,** 715–732

Pitt, D.R., 2010: Harnessing community energy: the keys to climate mitigation policy adoption in US municipalities. *Local Environment*, **15,** 717-729

Plattner, G.K., R. Knutti, F. Joos, T. Stocker, W. Von Bloh, V. Brovkin, D. Cameron, E. Driesschaert, S. Dutkiewicz, and M. Eby, 2008: Long-term climate commitments projected with climate-carbon cycle models. *Journal of Climate*, **21,** 2721-2751

Prinn, R.G., 2012: Development and application of earth system models. *Proceedings of the National Academy of Sciences*

Richardson, A.D., T. Andy Black, P. Ciais, N. Delbart, M.A. Friedl, N. Gobron, D.Y. Hollinger, W.L. Kutsch, B. Longdoz, and S. Luyssaert, 2010: Influence of spring and autumn phenological transitions on forest ecosystem productivity. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **365,** 3227-3246

Russell, L.M., P.J. Rasch, G.M. Mace, R.B. Jackson, J. Shepherd, P. Liss, M. Leinen, D. Schimel, N.E. Vaughan, and A.C. Janetos, 2012: Ecosystem Impacts of Geoengineering: A Review for Developing a Science Plan. *AMBIO: A Journal of the Human Environment***,** 1-20

Schimel, D.S., 1995: Terrestrial ecosystems and the carbon cycle. *Global Change Biology*, **1,** 77-91

Shepherd, J., 2009: *Geoengineering the climate: science, governance and uncertainty.* Royal Society.

Shindell, D., J.C.I. Kuylenstierna, E. Vignati, R. van Dingenen, M. Amann, Z. Klimont, S.C. Anenberg, N. Muller, G. Janssens-Maenhout, F. Raes, J. Schwartz, G. Faluvegi, L. Pozzoli, K. Kupiainen, L. Hoglund-Isaksson, L. Emberson, D. Streets, V. Ramanathan, K. Hicks, N.T.K. Oanh, G. Milly, M. Williams, V. Demkine, and D. Fowler, 2012: Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security. *Science*, **335,** 183-189 doi: 10.1126/science.1210026, [Available online at <Go to ISI>://WOS:000299033100044]

Snead, M.C. and A.A. Jones, 2010: Are US states equally prepared for a carbon-constrained world? *Economic Review***,** 67-96

Sue Wing, I., 2008: Explaining the declining energy intensity of the US economy. *Resource and Energy Economics*, **30,** 21-49

Thomson, A.M., K.V. Calvin, L.P. Chini, G. Hurtt, J.A. Edmonds, B. Bond-Lamberty, S. Frolking, M.A. Wise, and A.C. Janetos, 2010: Climate mitigation and the future of tropical landscapes. *Proceedings of the National Academy of Sciences*, **107,** 19633-19638

Thomson, A.M., K.V. Calvin, S.J. Smith, G.P. Kyle, A. Volke, P. Patel, S. Delgado-Arias, B. Bond-Lamberty, M.A. Wise, and L.E. Clarke, 2011: RCP4. 5: a pathway for stabilization of radiative forcing by 2100. *Climatic Change***,** 1-18

U.S. Mayors Climate Protection Agreement: List of Participating Mayors. U.S. Mayors Climate Protection Agreement. [Available online at http://www.usmayors.org/climateprotection/list.asp]

UFNCCC, 2009: Report of the Conference of the Parties on its fifteenth session

UNEP, 2009: *Handbook for the Montreal Protocol on Substances that Deplete the Ozone Layer.* United Nations Environment Programme.

USDA, 2011: U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990-2008. Technical Bulletin No. 1930., O. o. t. C. E. Climate Change Program Office, Ed., U.S. Department of Agriculture, 159 p.

van Vuuren, D., J. Cofala, H. Eerens, R. Oostenrijk, C. Heyes, Z. Klimont, M. Den Elzen, and M. Amann, 2006: Exploring the ancillary benefits of the Kyoto Protocol for air pollution in Europe. *Energy Policy*, **34,** 444-460

van Vuuren, D.P., J. Edmonds, K. Hibbard, G.C. Hurtt, M. Kainuma, T. Kram, V. Krey, J.F. Lamarque, K. Riahi, and A. Thomson, 2011a: The representative concentration pathways: an overview Clim. *Change*, **109,** 5-31

van Vuuren, D.P., S. Deetman, M.G.J. den Elzen, A. Hof, M. Isaac, K. Klein Goldewijk, T. Kram, A. Mendoza Beltran, E. Stehfest, and J. van Vliet, 2011b: RCP2. 6: exploring the possibility to keep global mean temperature increase below 2° C. *Climatic Change*, 1-22

Wang, X. and K.R. Smith, 1999: Secondary Benefits of Greenhouse Gas Control: Health Impacts in China §. *Environmental Science & Technology*, **33,** 3056-3061

Webster, M., A. Sokolov, J. Reilly, C. Forest, S. Paltsev, A. Schlosser, C. Wang, D. Kicklighter, M. Sarofim, J. Melillo, R. Prinn, and H. Jacoby, 2011: Analysis of Policy Targets Under Uncertainty. *Climatic Change*, **112,** 569-583

West, J., A. Fiore, L. Horowitz, and D. Mauzerall, 2006: Mitigating ozone pollution with methane emission controls: global health benefits. *Proceedings of the National Academy of Science*, **103,** 3998-3993

The White House, 2010a: Economic Report of the President, Council of Economic Advisors, The White House 462 pp. [Available online at http://www.whitehouse.gov/sites/default/files/microsites/economic-report-president.pdf]

——, 2010b: *Federal Climate Change Expenditures: Report to Congress.* Office of Management and Budget.

The White House, 2012: A Secure Energy Future: Progress Report, [Available online at http://www.whitehouse.gov/sites/default/files/email-files/the_blueprint_for_a_secure_energy_future_oneyear_progress_report.pdf]

Williams, C.A., G.J. Collatz, J. Masek, and S.N. Goward, 2012: Carbon consequences of forest disturbance and recovery across the conterminous United States. *Global Biogeochemical Cycles*, **26,** GB1005 doi: 10.1029/2010gb003947

World Health Organization and D.L. Davis, 1997: Short-term improvements in public health from global-climate policies on fossil-fuel combustion: an interim report0140-6736, 1341-1349 pp

Zhang, F., J.M. Chen, Y. Pan, R.A. Birdsey, and S. Shen, 2012: Attributing carbon changes in conterminous US forests to disturbance and non-disturbance factors from 1901 to 2010

Zheng, D., L.S. Heath, M.J. Ducey, and J.E. Smith, 2011: Carbon changes in conterminous US forests associated with growth and major disturbances: 1992–2001. *Environmental Research Letters*, **6,** 014012, [Available online at http://stacks.iop.org/1748-9326/6/i=1/a=014012]