Co-benefits of Carbon Standards

Part 1: Air Pollution Changes under Different 111d Options for Existing Power Plants

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Executive Summary

The U.S. Environmental Protection Agency (EPA) is slated to release the nation's first-ever carbon pollution standards for existing power plants on June 2, 2014. Carbon dioxide (CO_2) is one of most abundant greenhouse gases in the atmosphere and a major driver of human-accelerated global climate change. Fossil-fuel-fired power plants are the single largest source of anthropogenic CO_2 emissions in the U.S. They emit approximately 2.2 billion tons of carbon dioxide each year, representing 40 percent of total U.S. CO_2 emissions (USEPA 2014).

Carbon pollution standards that reduce CO_2 emissions from existing power plants can also cut emissions of other power plant pollutants that have negative human and environmental health impacts locally and regionally. These additional power plant pollutants (or, co-pollutants) include sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM) and mercury (Hg). Once emitted, SO_2 contributes to the formation of fine particle pollution ($PM_{2.5}$) and NO_x is a major precursor to ground-level ozone (O_3). For human health, these co-pollutants contribute to increased risk of premature death, heart attacks, increased incidence and severity of asthma, and other health effects (see Table 1). For ecosystems, these co-pollutants contribute to acid rain; the over-fertilization of many types of ecosystems, including grasslands, forests, lakes and coastal waters; ozone damage to trees and crops; and the accumulation of toxic mercury in fish (see Table 1). Therefore, policies intended to address climate change by reducing CO_2 emissions, that also decrease emissions of SO_2, NO_x, and primary PM, can have important human and environmental health co-benefits.

This study, led by Syracuse and Harvard universities, used existing estimates of energy sector emissions for a Reference Case and three alternative policy scenarios to quantify the amount and spatial distribution of resulting changes in emissions, air quality, and atmospheric deposition of sulfur and nitrogen, and to a lesser extent of mercury by the year 2020. Each policy scenario reflects different designs for carbon standards with varying stringency and flexibility. Given that the analysis was conducted prior to the introduction of the EPA standards, none of the three scenarios are likely to represent the exact standard proposed, but they bound a wide range of possible alternatives. From this analysis and ancillary supporting material, we draw the following conclusions (see *Summary of Results* on pages 24-26 for details):

1. Strong carbon pollution standards for existing power plants would decrease emissions of co-pollutants that contribute to local and regional air pollution by more than 750,000 tons per year by 2020 compared to "business-as-usual" shown in the Reference Case.

2. The model results show that by decreasing emissions of co-pollutants, a strong carbon pollution standard would improve air quality and decrease the deposition of harmful pollutants. It is well-documented that the air pollution reductions estimated here have human health and ecosystem benefits.

3. The model results indicate that, with a strong carbon standard, air quality and atmospheric deposition improvements would be widespread with every state receiving some benefit. The greatest improvements are projected for states in and around the Ohio River Valley as well as the Rocky Mountain region.

4. Finally, the analysis suggests that the stronger the standards (in terms of both stringency *and* flexibility), the greater and more widespread are the benefits associated with decreased co-pollutants. It also shows that a weaker standard focused strictly on power plant retrofits could increase emissions and reduce air quality over large areas.

U.S. Power Plant Pollution: Emissions, Transport, and Effects

Power plants are the single largest source of carbon dioxide (CO_2; 40%), sulfur dioxide (SO_2; 73%), and mercury emissions (Hg; 49%) in the U.S. (NEI 2011). They are also the second largest source of nitrogen oxide emissions (NO_x; 24%) (NEI 2011). Carbon pollution standards for existing power plants would not only help confront the challenge of global climate change, they would confer substantial additional local and regional benefits by reducing power plant emissions of these major co-pollutants by up to 27% for SO_2 and Hg and 22% for NO_x in 2020 compared to a Reference Case. Importantly, the benefits reported here are additional benefits associated with the carbon standard beyond the emissions reductions that will occur with existing air quality policies and therefore do not represent double-counting of benefits.

The 1990 Clean Air Act Amendments illustrate how public policy can facilitate cost-effective decreases in emissions of air pollutants. For example the SO_2 allowance trading program resulted in decreased SO_2 emissions from electric power plants of 68 percent between 1990 and 2010, from 15.9 million short tons to 5.1 million short tons (NEI 2011) at approximately 15 percent the original cost estimate (Chan et al. 2012). Despite these cost-effective programs, current emissions and air pollution levels still pose considerable health and environmental challenges. In 2005, fine particulate matter ($PM_{2.5}$), largely from SO_2 and NO_x emissions, were attributed to between 130,000 and 320,000 of premature deaths, 180,000 non-fatal heart attacks, 200,000 hospital and emergency room visits, 2.5 million of asthma exacerbations, and 18 million lost days of work, and other public health effects (Fann et al. 2012). Also in 2005, between 4,700 and 19,000 premature deaths, 77,000 hospital admissions and emergency room visits, and 11 million school absence days were attributed to ground-level ozone (Fann et al. 2012). In 2004, it was reported that over 100 million people in live in areas of the U.S. with ozone concentrations exceeding the 8-hour regulatory standard (USEPA 2004). In light of on-going concerns and mounting scientific research, EPA recently proposed to strengthen the National Ambient Air Quality Standards (NAAQS) for both fine particles and ground-level ozone.

In addition to health effects, elevated ozone can cause crop and forest damage, decades of acidic deposition have eroded the buffering capacity of soils leaving forests and watersheds more sensitive to continued inputs of sulfate and nitrate, and once mercury enters a watershed it persists for thousands of years where it bioaccumulates in food webs and contaminates wildlife and fish that people catch and consume. Moreover, sulfur deposition associated with acid rain can promote the conversion of mercury to methyl mercury, the form that most readily bioaccumulates in the environment. As a growth-limiting nutrient, elevated atmospheric nitrogen deposition can alter the structure and function of terrestrial and aquatic ecosystems.

In order to understand these widespread effects, it is important to characterize and quantify the linkages between power plant emissions, air quality, and the atmospheric deposition of pollutants. Once emitted from fossil-fuel fired power plants, SO_2 and NO_x react in the atmosphere to form sulfuric acid, nitric acid, and several secondary pollutants that have a cascade of health and environmental effects. Similarly mercury, after it is released to the atmosphere, can change chemical form and depending on its form be deposited in rain, snow, gaseous particles within kilometers from the source or circulate globally. The links between emissions, air pollution, and atmospheric deposition are briefly described below and are illustrated in Figure 1.

$PM_{2.5}$ is fine particulate matter (PM) that can occur as primary PM that is emitted directly from a source or is formed in the atmosphere as secondary PM. Secondary PM is by far the largest fraction and is derived from precursor emissions such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOCs), and ammonia (NH_3). Secondary formation occurs through gas-phase photochemical reactions or through liquid phase reactions in clouds and fog droplets in the atmosphere generally downwind of the source. Most $PM_{2.5}$ in rural areas is secondary. It is estimated that approximately half of the $PM_{2.5}$ in the eastern U.S. originates from sulfate associated with SO_2 emissions. Particle pollution forms the major component of haze in cities and in iconic landscapes such as national parks.

Tropospheric ozone is ground level ozone, a major component of what is commonly referred to as "smog". Ground-level ozone is not emitted directly into the air, it is formed in the atmosphere when anthropogenic emissions of NO_x combine with VOCs and react in the presence of sunlight. Peak O_3 concentrations generally occur in summer when higher temperatures and increased sunlight enhance O_3 formation (Knowlton et al. 2004). While elevated ground level O_3 is primarily a concern in urban and suburban areas, ozone and the ozone precursors of NO_x and VOCs can also be transported long distances by wind, causing high ozone levels in rural areas. Tropospheric ozone is also a greenhouse gas pollutant. Consequently, climate change mitigation measures that simultaneously reduce tropospheric ozone may generate additional climate benefits.

Acidic deposition is commonly referred to as "acid rain". Acidic deposition is the transfer (deposition) of strong acids and acid-forming substances from the atmosphere to the surface of the Earth. Acidic deposition includes ions, gases, and particles derived from sulfur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3) emissions, and particulate emissions of acidifying and neutralizing compounds. Acidic deposition can originate from air pollution that crosses state and even national boundaries, and affects large geographic areas (Driscoll et al. 2001b).

Mercury deposition results from mercury emissions to the atmosphere from direct anthropogenic sources, such as power plants; secondary sources that are re-emissions of primary sources; and natural emission sources. Emissions can occur as elemental Hg, gaseous ionic Hg (reactive gaseous mercury), and particulate Hg. These different chemical forms exert significant control over the fate of atmospheric Hg emissions and is the reason that Hg can be a local, regional, or global pollutant, depending on the speciation of the emissions and the associated residence times in the atmosphere. While Hg emission sources are common in more urbanized areas, deposition is also enhanced in forested areas where landscape conditions can lead to high rates of bioaccumulation. Therefore Hg deposition can be harmful in both urban and rural environments (Driscoll et al. 2007).

Nitrogen (N) deposition results from emissions of both inorganic and organic nitrogen. The primary forms of inorganic N emissions are nitrogen oxides (nitric oxide and nitrogen dioxide, referred to collectively as NO_x) and reduced N which includes ammonia (NH_3). Nitrogen oxides result from the partial oxidation of N_2 at high temperatures or from the release of N contained in fossil fuels during combustion. After it is emitted nitrogen can be transported

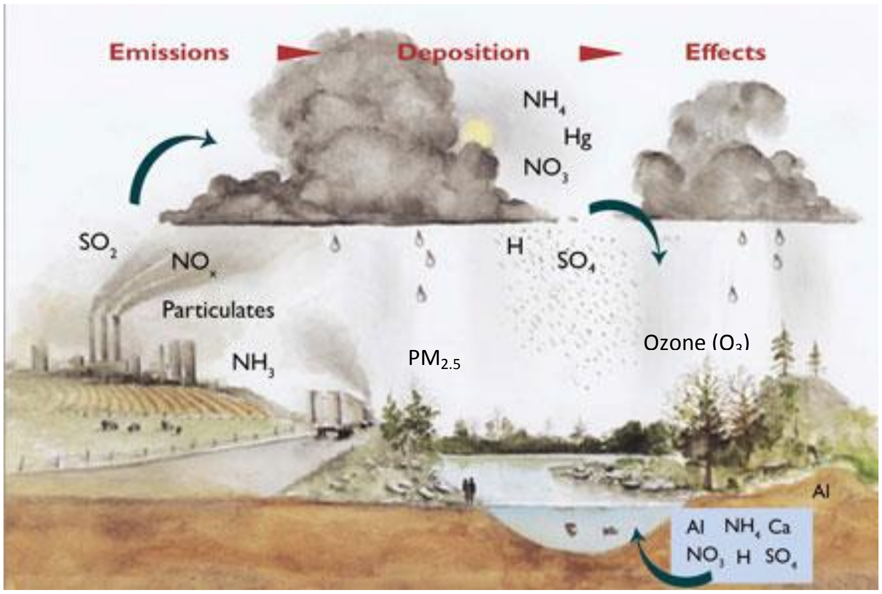


Figure 1: Linking emissions, air quality, deposition, and effects
Adapted from Driscoll et al. 2001a

hundreds of kilometers before it is deposited to Earth in precipitation (wet deposition) and as gases and particles (dry deposition) (Driscoll et al. 2003).

Effects on Human Health and Ecosystems

The co-pollutants emitted by power plants have demonstrated and well-understood health and environmental consequences. These adverse effects have been extensively documented and summarized in the peer-reviewed literature. We summarize the major impacts and supporting scientific evidence in Table 1, below. While changes in air quality can result in nearly immediate improvements in human health, sensitive ecosystems that have been impacted by decades of elevated atmospheric deposition (acid, nitrogen, and mercury) take decades or more to recover and remain a challenge today.

Table 1: Summary of air pollution effects from power plants.

Emissions	Pollutant	Effects	References
SO_2	$PM_{2.5}$	*Human health:* Heart attack, chronic & acute bronchitis, lung cancer, asthma exacerbation, pre-mature death	Pope et al. 1995, Woodruff et al. 1997, Pope et al. 2002, Cohen et al. 2004, Pope et al. 2004, Laden et al. 2006, Krewski et al. 2009, Pope et al. 2009, Cohen et al. 2010, USEPA 2011,
	Sulfur deposition *(sulfate)*	*Ecosystems:* Acidification of soils and surface waters, reduced tree health and productivity in sensitive areas, reduced fish abundance and diversity, increased methyl mercury production, diminished views	Cass 1979, Gorham 1989, Charles 1991, Baker et al. 1996, Likens et al. 1996, DeHayes et al. 1999, Driscoll et al. 2001, Driscoll et al. 2010, Greaver et al. 2012
NO_x	Ground-level ozone (NO_x emissions are ozone precursors)	*Human health:* Difficulty breathing, coughing and sore throat, asthma exacerbation, emphysema, chronic bronchitis, increased infection risk, pre-mature death *Ecosystems:* Reduced tree health and forest productivity, reduced crop productivity, reduced visibility	Gong et al. 1986, Ostro and Rothschild 1989, Schwartz 1994, Schwartz 1995, Chen et al 2000, Burnett et al. 2001, Gilliland et al. 2001, Jaffe et al. 2003, Bell et al. 2004, Gryparis et al. 2004, Karlsson et al. 2004, Huang et al. 2005, Ito et al. 2005, Levy et al. 2005, Peel et al. 2005, Schwartz 2005, Wilson et al. 2005, USEPA 2007, Jerrett et al. 2009, Larsen et al. 2010, Mills et al. 2011
	Nitrogen deposition *(reactive N)*	*Ecosystems:* Over-enrichment of ecosystems, increased production and changes in species	Valiela 1997, Bricker et al. 1999,Valiela et al. 2000, Fenn et al. 2003, Galloway et al. 2003, Pardo et al. 2011
	Nitrogen deposition *(nitrate)*	*Ecosystems:* Acidification of soils and streams, reduced tree health and productivity in sensitive areas, reduced fish abundance/ diversity	Aber et al. 1995, Baker et al. 1996, Magill et al. 1997, Driscoll et al. 2001, Aber et al. 2003
Mercury	Mercury deposition and bioaccum-ulation	*Human health:* Reduced IQ, memory deficits, reduced visual-spatial function, increased risk of heart disease *Fish & wildlife:* decreased reproductive success, increased embryo/chick mortality, altered schooling/ flying/ walking, acute toxicity	Aulerich et al. 1974, Scheuhammer 1988, Salonen et al. 1995, Wiener and Spry 1996, Nocera and Taylor 1998, Guallar et al. 2002, NRC 2002, CDC 2004, Mahaffey et al. 2004, Trasande et al. 2005, Driscoll et al. 2007, Evers et al. 2007, Swain et al. 2007, Roman et al. 2011, USEPA 2011

111d Co-benefits Analysis: Policy Context and Approach

Policy Context

At the direction of a 2013 Presidential memo, the U.S. EPA is using its authority under section 111(d) of the Clean Air Act to issue standards that address carbon pollution from existing power plants. The Presidential memo to EPA states: “I direct you to use your authority under sections 111(b) and 111(d) of the Clean Air Act to issue standards, regulations, or guidelines, as appropriate, to address carbon pollution from modified, reconstructed, and existing power plants….” (White House 2014). Section 111(d) is a state-based program that is based on federal standard, or “emission guideline” (USEPA 2014a). The intent is for EPA to establish a federal standard and for states to design programs that fit the guidelines and achieve the necessary carbon dioxide reductions.

Scope and Approach

A team of scientists is conducting the first integrated, spatially explicit study for the entire lower 48 U.S. states of the benefits to health and ecosystem services associated with different approaches to carbon pollution standards for existing power plants. The study: (1) highlights the fact that power plants emit many harmful and interacting pollutants that degrade air quality; (2) illustrates the linkages between atmospheric pollution, and human and ecosystem health; and (3) shows how a strong carbon pollution standard has local, to regional, to global benefits compared to alternatives. The study has three major parts (Figure 2). Part 1 results are summarized in this report.

The study uses existing estimates of power plant emissions for the Reference Case and three scenarios for the year 2020 to quantify additional changes in air quality (ozone and $PM_{2.5}$) and atmospheric deposition of pollutants (sulfur, nitrogen, and mercury) beyond what would occur under existing air quality policies, using the Community Multiscale Air Quality (CMAQ) Model.

<u>In Part 1</u>, parsed unit-level emissions output from the Integrated Planning Model (IPM) produced by the consulting firm ICF International were used as input to CMAQ. CMAQ was developed by the U.S. EPA and is used by EPA, states and other groups to conduct Regulatory Impact Assessments (RIA) and State Implementation Plans (SIPs), respectively (USEPA 2014b), along with other applications. In this study CMAQ v.4.7.1 (the most currently widely available version) was used, based on EPA’s 2007/2020 modeling platform and year 2007 meteorology from v.3.1 of the Weather Research and Forecast (WRF) model. The CMAQ model produces gridded air quality concentrations and

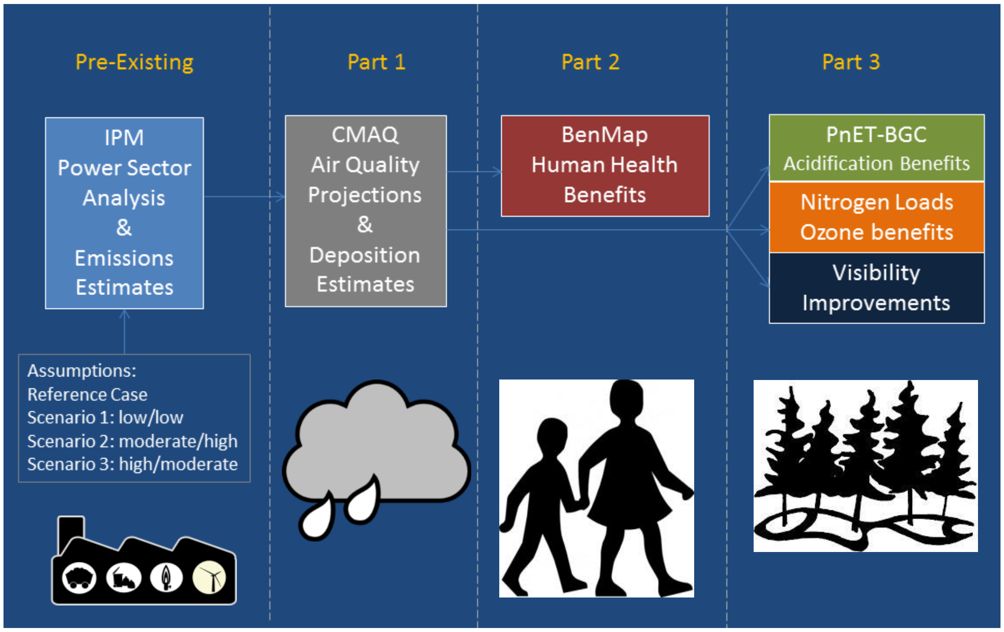


Figure 2: Diagram of co-benefits of carbon standards study.

deposition rates for the entire lower 48 states of the U.S. on a 12-km CONUS domain. Changes in atmospheric concentrations and deposition of air pollutants are projected by simulating emissions, advection, diffusion, chemistry, and deposition for multiple pollutants and pollutant forms.

In Part 2, detailed air quality results will be used to quantify and compare the changes in health impacts across the U.S. from the different policy scenarios using the Benefits Mapping and Analysis Program (BenMAP), published by EPA. *We anticipate these results will be available in late summer 2014.*

In Part 3 air quality and atmospheric deposition results will be used to estimate environmental benefits and changes in ecosystem services using various models. This is likely to include recovery of streams and forests from acid rain, reduced ozone damage to crops and timber, and improved visibility in focal landscapes. *We anticipate these results and a full report on the three parts will be released in September, 2014.*

Carbon Pollution Standards: Reference Case & Policy Scenarios

To estimate changes in air quality, the CMAQ model requires detailed emissions information from power sector models for a future year for a Reference Case and each policy scenario. Output from EPA's Integrated Planning Model (IPM; US EPA 2014c) is often used to run CMAQ. Given the focus of this study is to characterize and quantify changes in co-pollutants and the consequences for human health and ecosystems, IPM results from other studies were used as policy scenarios. IPM results for a Reference Case and three alternatives were acquired from the firm ICF International. The Reference Case is based on the Energy Information Administration's Annual Energy Outlook 2013 and incorporates the implementation of all existing air quality policies. The IPM policy runs include two additional scenarios commissioned by the Bipartisan Policy Center (BPC) and one commissioned by the Natural Resources Defense Council (NRDC), representing a range of policy options.

The three policy scenarios and associated IPM runs were selected from among a suite of alternatives independently developed by either BPC or NRDC. The three scenarios selected represent different stringencies (represented in these scenarios as an emissions rate in tons of CO_2/MWh) and flexibility (represented by options available for compliance and extent to trading or averaging is allowed). The scenarios therefore bound a range of possible options available for controlling CO_2 emissions from power plants and offer insights for understanding and quantifying the consequences for co-pollutants. The scenarios were selected as researchable alternatives and do not represent preferences of the authors of this report. Importantly, none of the options include a strict "mass-based" standard or carbon budget in tons of CO_2/year which has been proposed by other groups (see Phillips 2014). A mass-based alternative would be a useful scenario to analyze in future studies but IPM results for this alternative were not available at the time of this analysis. Moreover, it has been pointed out that EPA or the states can convert emissions rate-based standards to a mass-based standard by using projected generation levels and the performance standard to calculate a corresponding CO_2 emissions budget for each state (Burtraw 2013).

Scenario Descriptions

The assumptions for the Reference Case and three scenarios are described briefly here and are depicted in Figure 3. More information on the Reference Case and Scenario #2 can be found at: http://www.nrdc.org/air/pollution-standards/.

Reference Case was developed jointly by BPC and NRDC. It is benchmarked to the Energy Information Administration's Annual Energy Outlook of 2013, which projects lower electrical demand and, thus, lower CO_2 emissions compared to 2012. It also assumes full implementation of the current clean air policies adopted by EPA (see Figure 3). By comparing changes in air quality under each of the policy scenarios to the Reference Case, added benefits are quantified and double-counting is avoided.

Scenario #1 (Low/Low) is referred to as the "Unit Retrofit" scenario by BPC. Scenario #1 is equivalent to an emissions rate-based standard that uses improvements in heat rates at existing coal-fired power plants to comply with the carbon standard. It could be described as a *low* stringency alternative with *low* flexibility limited to changes that can be made "inside the fenceline" of individual power plants. Heat rate (Btu/kWh) is a measure of power plant efficiency. This scenario is based on the idea that a more efficient power plant will burn less fuel for the electricity it produces and will therefore emit less CO_2 per megawatt of energy. The scenario uses "best-in-class" heat rates for different coal plant categories based on the unit's capacity, fuel type, steam cycle, and boiler type. Coal-fired power plants then have to achieve an emissions rate equivalent to what would be achieved if they closed the gap between its unit-specific heat rate and the best in class heat rate by 40 percent. Under this scenario, the fleet-wide average heat rate would improve 4 percent. This scenario results in a national average emissions rate of 2000 lbs/MWh for coal and 1000 lbs/MWh for gas; only a modest decrease from current emissions rates.

Scenario #2 (Moderate/High) is referred to as the "Moderate Full-Efficiency" scenario in Lashof and Yeh (2014). Scenario #2 is based on a flexible system-wide approach that achieves CO_2 emissions reductions through a state-specific rate-based performance standard for existing power plants. It is a *moderate* stringency scenario with *high* compliance flexibility. For 2020, the national emission rate targets are 1,500 lbs/MWh for coal and 1,000 lbs/MWh for gas. This scenario allows additional renewable energy and energy efficiency to count toward compliance. It also allows emissions averaging across all fossil units in a state and states may opt-in to interstate averaging or credit trading. The scenario assumes energy efficiency is available at a total resource cost of 4.2 to 5.8 cents/kWh (Lashof 2013, Lashof and Yeh 2014). Though details are not specified, this scenario allows states to develop alternative plans, including mass-based standards, provided they achieve equivalent emissions reductions (Lashof 2013). More information on the assumptions for Scenario #2 can be found in the technical appendices at: http://www.nrdc.org/air/pollution-standards/.

Scenario #3 (High/Moderate) is referred to as the "A4" scenario by BPC. It requires supply-side electric sector CO_2 reductions that can implemented up to a cost of $43 per metric ton in 2020. In that way, it is modeled to reflect what might happen if there was a national tax on CO_2 emissions from power plants that is the same as (and increases with) the estimated social cost of carbon (Interagency Working Group 2013). It is a *high* stringency scenario with *moderate* compliance flexibility. In 2020, it results in average national emissions rates of 1200 lbs/MWh for coal-fired power plants and 850 lbs/MWh for gas. The compliance options that are implemented are limited to changes up to the specified cost per ton and include on-site heat rate improvements, co-firing or converting to lower emitting fuel (i.e., natural gas or biomass), or shifting generation dispatch (the order in which power plants are called to operate in response to changing electricity demand) to favor lower carbon emitting electrical generation sources. However, demand-side energy efficiency is not included as a means of reducing emissions for this preliminary modeling scenario (Macedonia 2014).

Figure 3: Reference Case and scenario assumptions.

Reference Case
Policy Assumptions: - All current air quality policies fully implemented - No carbon pollution standards
Included: - EIA 2013 Annual Energy Outlook determines energy demand - Mercury and Air Toxics Standards (MATS) implemented - Clean Air Interstate Rule implemented, including Phase II in 2015 - Regional Greenhouse Gas Initiative (RGGI) model rule for emissions trading included (w/out NJ) - CA Assembly Bill 32 (AB32) included - Regional haze rule included - Wind power production tax credit (PTC) expires - Onshore wind costs: DOE/LBL 2012 Wind Technologies Report - Nuclear units re-licensed, 20-year extension

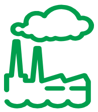
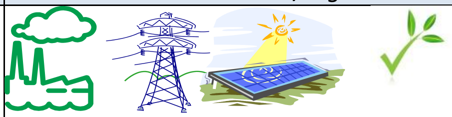
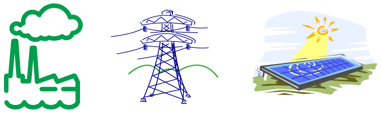
111d Scenarios		
Policy assumptions: - All current air quality policies fully implemented as in the Reference Case - Carbon pollution standards adopted under section 111d for existing power plants		
Scenario 1: *Low/Low*	*Scenario 2:* *Moderate/High*	*Scenario 3:* *High/Moderate*
		
Low stringency, low flexibility and energy efficiency	*Moderate stringency, high flexibility and energy efficiency*	*High stringency, moderate flexibility and energy efficiency*
Stringency estimate: 2000 lbs/MWh coal; 1000 lbs/MWh gas	Stringency benchmark: 1500 lbs/MWh coal; 1000 lbs/MWh gas	Stringency estimate: 1200 lbs/MWh – coal; 850 lbs/MWh
Compliance options: - Limited to on-site carbon emission rate reductions - Power plant efficiency/heat rate upgrades - Modest natural gas & biomass co-firing	Compliance options: - Power plant efficiency/heat rate upgrades - Co-firing with lower-carbon fuels - Dispatch changes to lower-carbon generation sources - State/interstate averaging and trading	Compliance options: - Power plant efficiency/heat rate upgrades - Co-firing with lower-carbon fuels - Dispatch changes to lower-carbon generation sources
Energy efficiency: - Only efficiency measures at the power plant included	Energy efficiency: - Full supply-side and demand-side (end-user) energy efficiency included.	Energy efficiency: - Supply-side efficiency (power plant and transmission lines).

Figure 4a: Power generation by scenario (terawatt/hours).

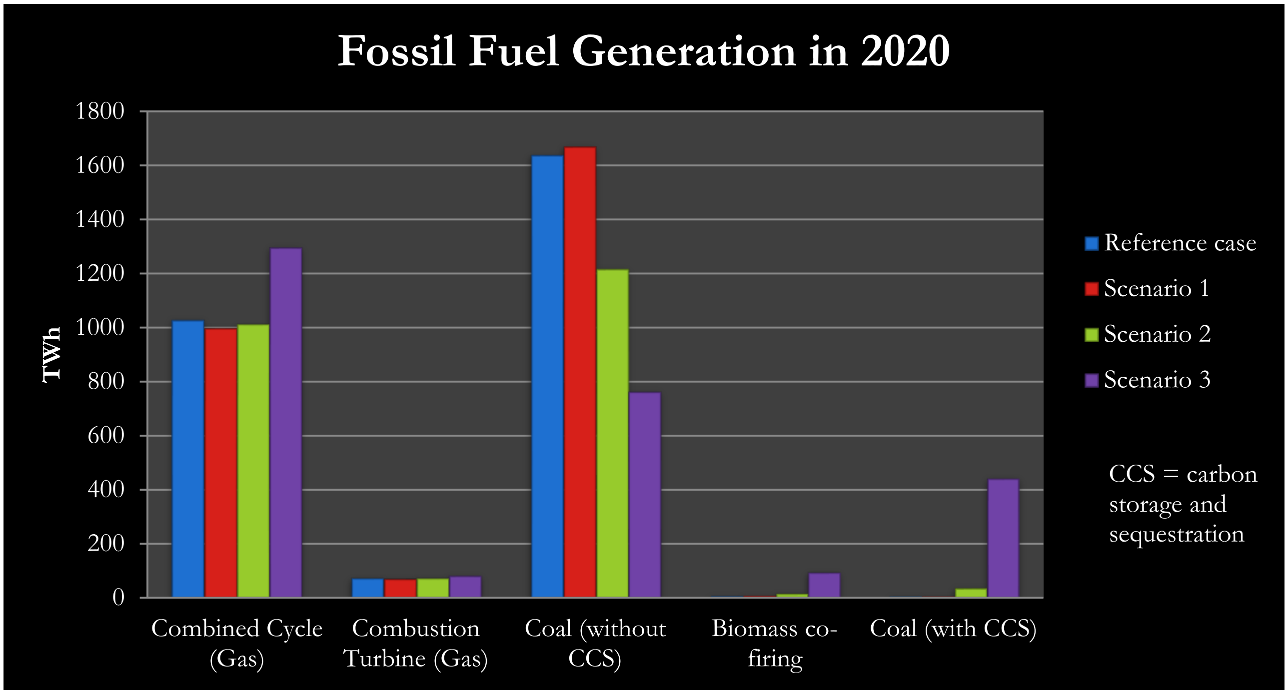
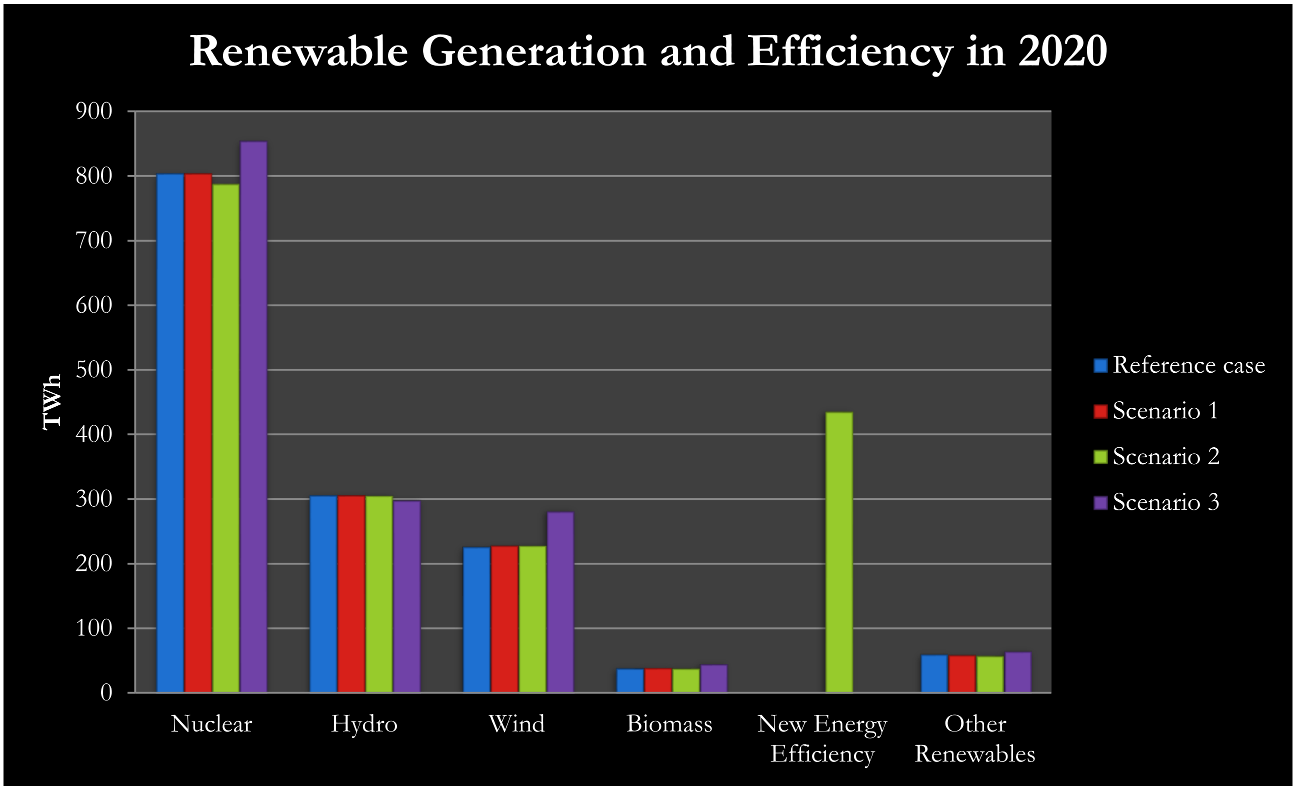


Figure 4b: Power generation by scenario (terawatt hours).



Carbon Standard Scenarios: Simulation of Power Generation and Emissions

For the Reference Case and three scenarios described above, ICF International used the IPM model to simulate changes power generation and to estimate resulting emissions of CO_2, SO_2, NO_x, primary PM, and mercury for 2417 unique power plants in the U.S. (Lashof 2013, Lashof and Yeh 2014, Macedonia 2014). The modeled shift in generation for fossil fuel, renewable, and other sources are shown in Figures 4a and b. Notably, Scenario #1 increases the generation from coal plants without carbon capture and storage (CCS). Scenario #2 is the only scenario that includes increased energy efficiency.

The emissions results in Figures 5a and b show the annual emissions of CO_2 and co-pollutants from the power sector for each scenario. The results for CO_2 emissions are summarized in Table 2. Scenario #1, which results in modest CO_2 reductions by implementing only improvements “inside the fenceline”, results in increased annual SO_2 emissions compared to the Reference Case in 2020. Scenario #2 achieves a 27% decrease in annual emissions of SO_2 and Hg and a 22% cut for NO_x compared to the Reference Case. Similar reductions are achieved by Scenario #3.

Table 2: Change in carbon dioxide emissions from power sector in 2020 by scenario.

Scenario	From 2005 levels	From Reference
Scenario #1 (Low/Low)	-17.4%	-2.2%
Scenario #2 (Moderate/High)	-35.5%	-23.6%
Scenario #3 (High/Moderate)	-49.2%	-39.8%

Three performance measures were then used in this study to compare the three scenario emissions results and to determine the highest-performing scenario among the three with respect to the co-pollutants considered in this study (Table 3). Importantly, this comparison of performance measures does not represent a full economic or cost-benefit analysis for the scenarios. The performance measures show that Scenario #2 resulted in the largest decrease in SO_2 and NO_x emissions per ton of CO_2 reduced, while still achieving lower annual total system costs than the Reference Case. Total system costs are based on fuel costs, operations and maintenance, and capital costs (Lashof and Yeh 2014, BPC 2014). Note that the lowest cost option (Scenario #1) results in increased SO_2 plus NO_x emissions. Scenario #3 achieved lower SO_2 and NO_x reductions per ton of CO_2 reduced and at a much higher cost. Based on these performance measures, Scenario #2 was selected to illustrate the air quality and atmospheric deposition benefits of a strong cost-effective standard that achieves substantial emission decreases for CO_2 and the co-pollutants. Results are available for the other scenarios as well.

Figure 5a & b: Air pollution emissions by scenario (million short tons, thousand short tons, and ponds).

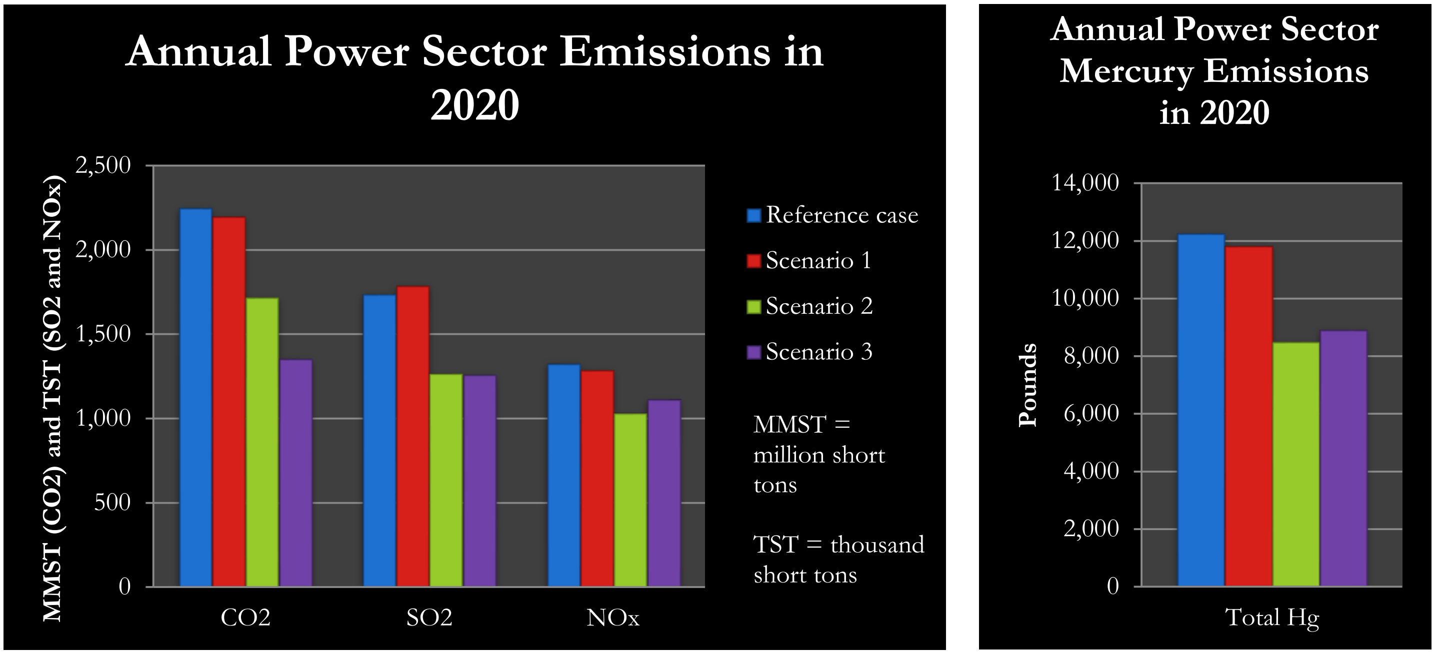


Table 3: Scenario comparison relative to the Reference Case in terms of SO_2 +NO_x emitted per units CO_2 controlled, incremental system costs and incremental costs per mass of CO_2 controlled.

Performance Measures	**SO_2+NO_X reduced/CO_2 reduced** (TST/MMST)[1]	**Incremental Total System Costs** $000,000 (in US 2012$)	**Incremental Total System Cost[2]/MMST CO2 reduced** $000,000 (in US 2012$)
Scenario 1	-0.22	-$1,180	-$23.40
Scenario 2	1.46	-$472	-$0.89
Scenario 3	0.84	$33,541	$37.41

[1] TST= thousand short tons, MMST = million short tons.

[2] Total system costs are based on Lashof and Yeh (2014) for Scenario #2 and on Macedonia (2014) for Scenario #1 and #3. Costs include fuel costs, operations and maintenance, and capital costs.

Air Quality and Atmospheric Deposition Results

The results from the CMAQ model show marked differences in air quality and atmospheric deposition among the three scenarios. With respect to the magnitude and direction of change compared to the Reference Case, the air quality and atmospheric deposition results for the three scenarios parallel the annual emissions results described above. The lowest improvements and some increased impacts occur in Scenario #1 with greater improvements for the various pollutants occur for Scenario 2 and #3. The results underscore the fact that different options for carbon standards can have widely varied consequences for associated air pollution. The details of the carbon standard will exert considerable influence on the health and environmental benefits that accrue to states and local communities.

Scenario #1, the low stringency/low flexibility heat-rate option results in increased SO_2 emissions (+3%) and minimal decreases in NO_x and mercury emissions (-3% for each). As a result, there is increased sulfur deposition (Figure 6a) and higher fine particle pollution ($PM_{2.5}$) (Figure 6b) across large areas compared to the Reference Case with little to no improvement in most of the remaining area. This result is likely due to widespread “emissions rebound” at numerous fossil-fuel-fired power plants in the U.S. fleet. Emissions rebound refers to the increase in emissions that can occur when higher-emitting plants are made more efficient and therefore rise in the dispatch order and run more frequently and for longer periods than in the Reference Case. This emissions rebound effect has been anticipated by others (Phillips 2014) but this is the first time the consequences for air quality at the state level have been quantified and mapped.

The CMAQ results for Scenario #1 show that if a carbon standard has low stringency and compliance limited to strictly “inside the fenceline” options , emissions of co-pollutants could increase, leading to increased pollutant loading and diminished air quality and potential adverse effects on public and environmental health. The CMAQ results of Scenario #2 show that a carbon standard that is stringent and flexible enough to promote a shift toward cleaner sources will reduce emissions of co-pollutants, achieve improved air quality and decreased atmosphere deposition of pollution, and lead to marked health and environmental benefits at the state level. The following maps and tables depict the projected changes in air quality 2020 associated with Scenario #2 (Figures 7 to 11; Table 4-8). Scenario #3 had similar air quality and atmospheric deposition results but at a much higher cost. The number of states with increases, no change, and decreases in average statewide air pollution levels compared to the Reference Case in 2020 are depicted for all three scenarios in Figures 7c, 8c, 9c, and 10c.

Figure 6a: Projected changes in total annual sulfur deposition under Scenario #1 in 2020 (kilograms per hectare-year).

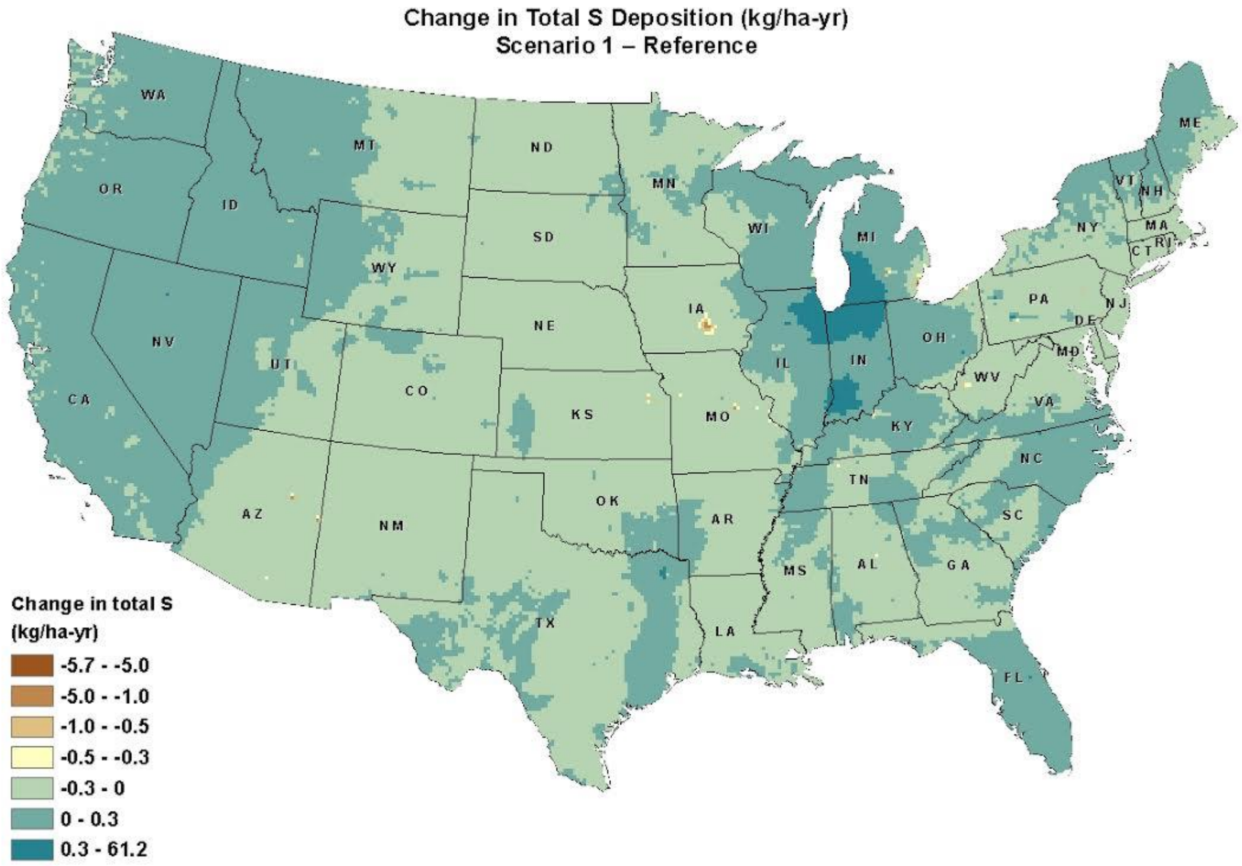


Figure 6b: Projected changes in average annual $PM_{2.5}$ from the Reference Case under Scenario #1 in 2020 (micro-grams per cubic meter).

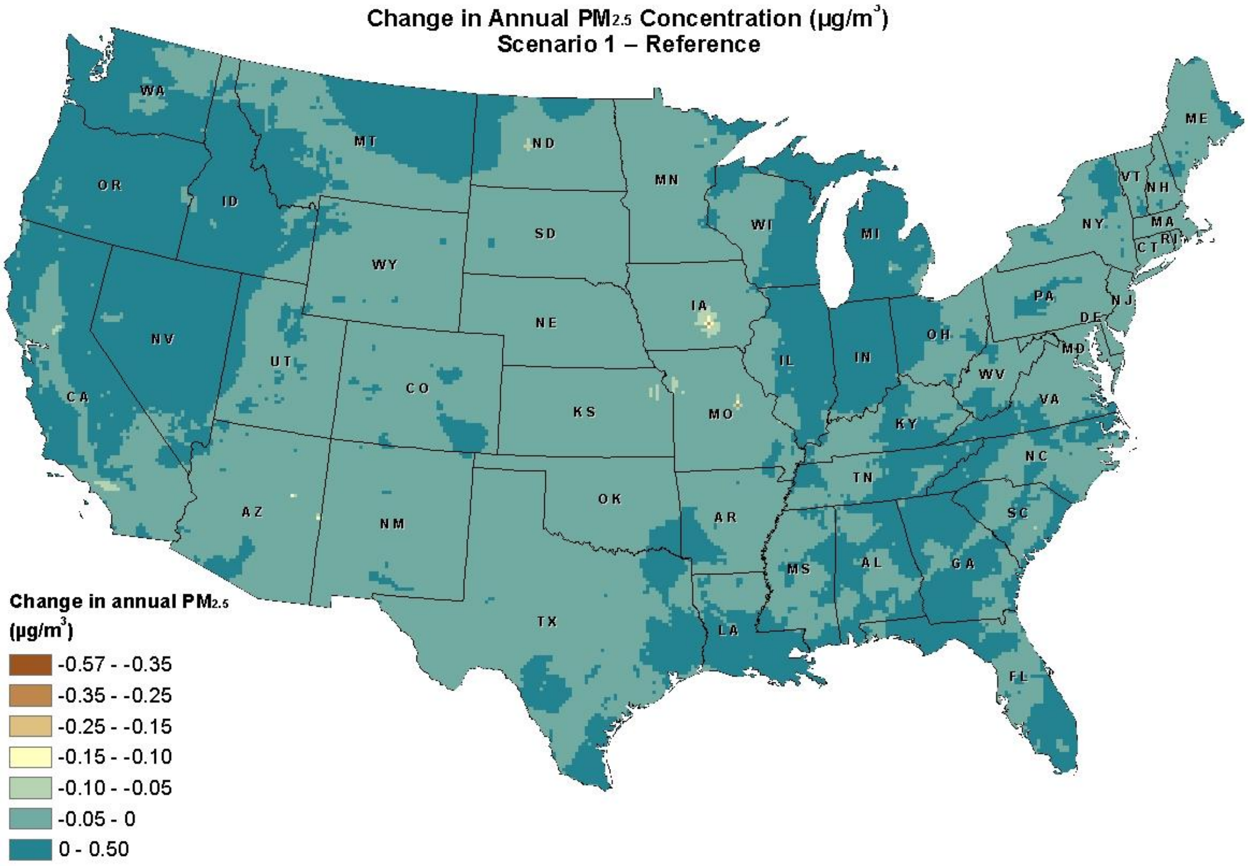


Figure 7a & b: Average annual PM2.5 in 2020 for the Reference Case and change from this condition in Scenario #2 (micro-grams per cubic meter).

Figure 7a

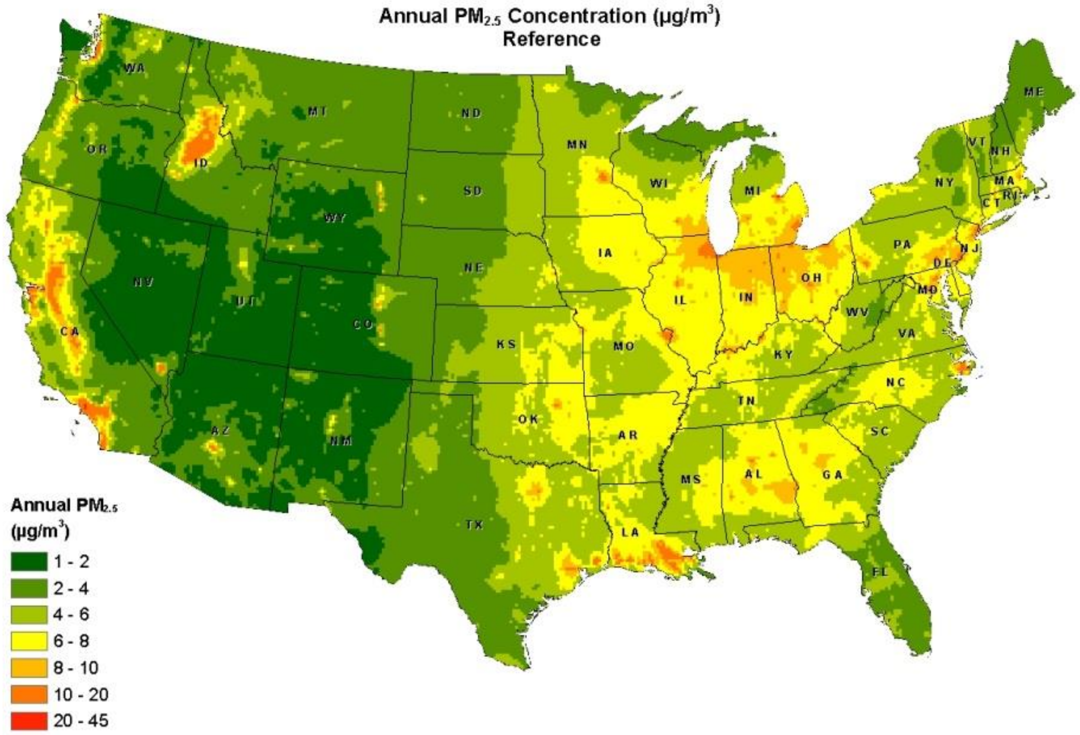


Figure 7b

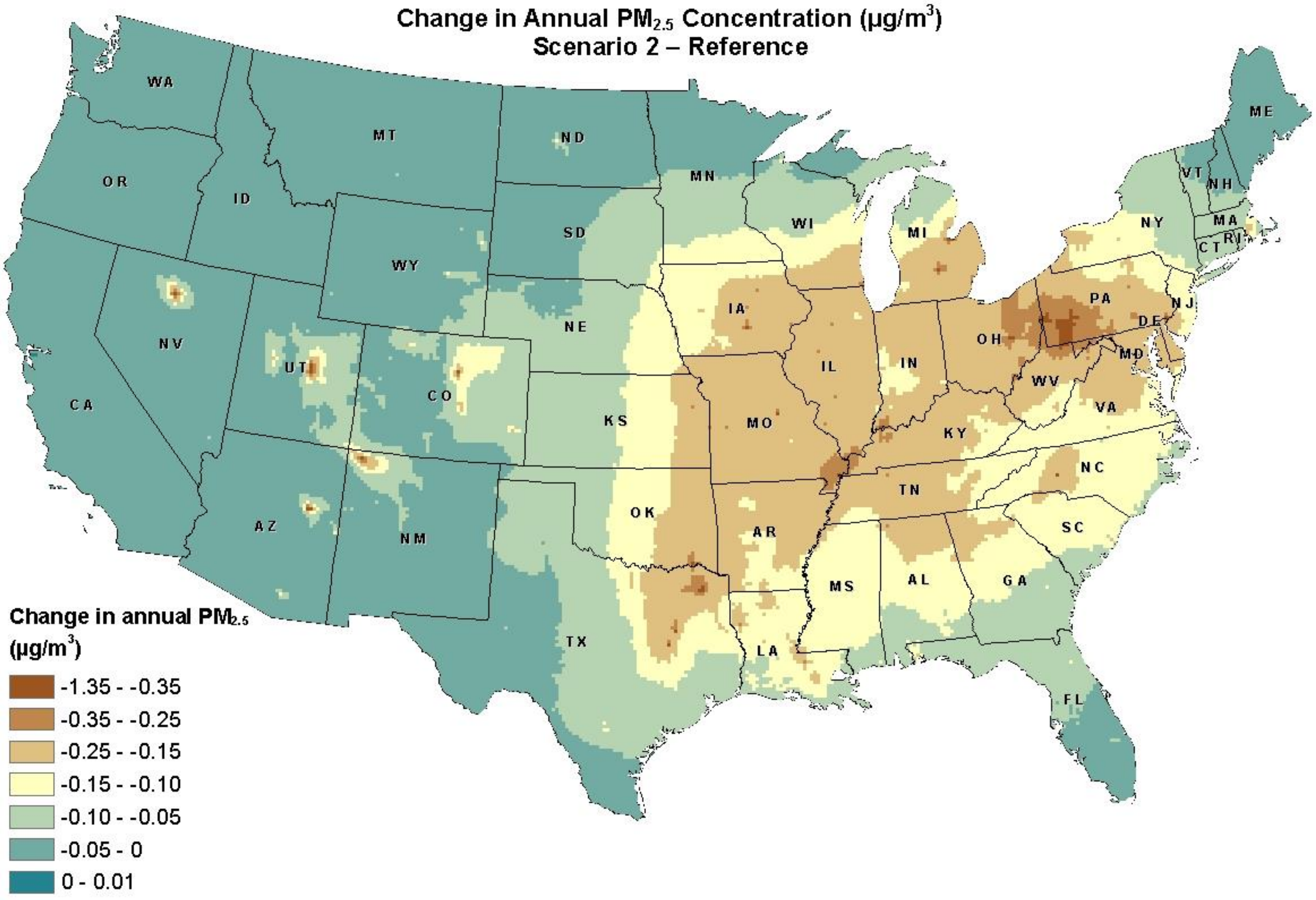


Figure 7c

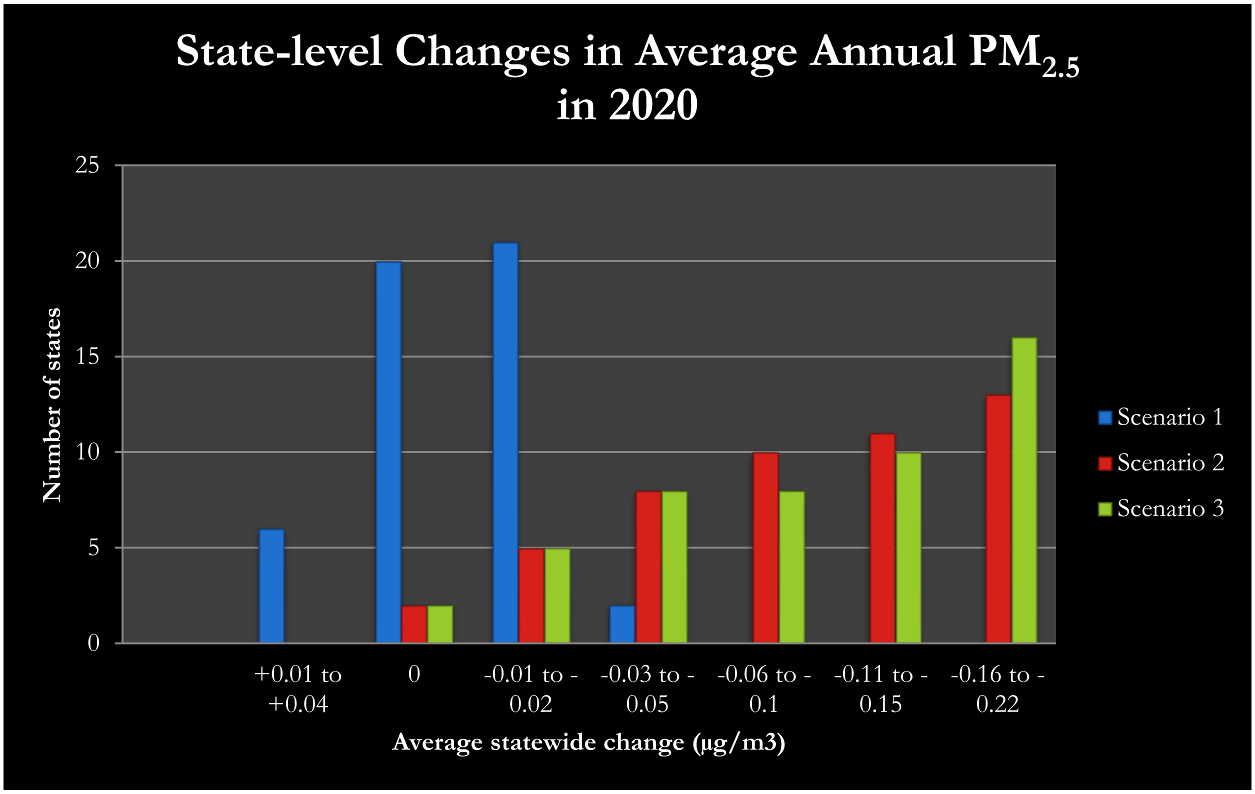


Table 4

Top 15 States with Largest Decreases in Average Annual PM2.5		
State	**Scenario 2 (μg/m^3)**	**Mean Decrease (μg/m^3)**
Ohio	7.66	0.22
Pennsylvania	5.86	0.22
DC	12.68	0.20
Maryland	6.79	0.20
W. Virginia	4.93	0.20
Illinois	7.40	0.19
Missouri	5.93	0.18
Delaware	6.57	0.18
Kentucky	5.97	0.18
Indiana	7.77	0.17
Arkansas	6.15	0.17
Tennessee	5.52	0.16
Iowa	6.22	0.16
Virginia	5.26	0.15
New Jersey	7.13	0.14

Figure 8a & b: Average summer (June 1 – August 31) peak 8-hr ozone for Reference Case and change in this condition for Scenario #2 (parts per billion).

Figure 8a

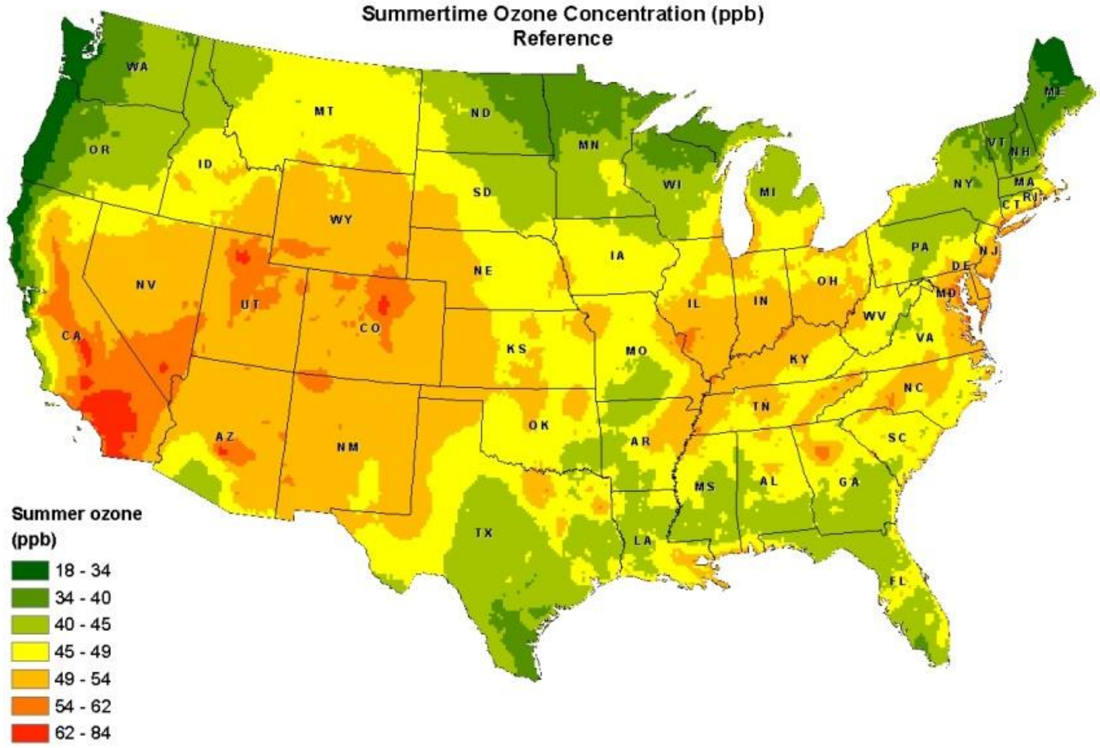


Figure 8b

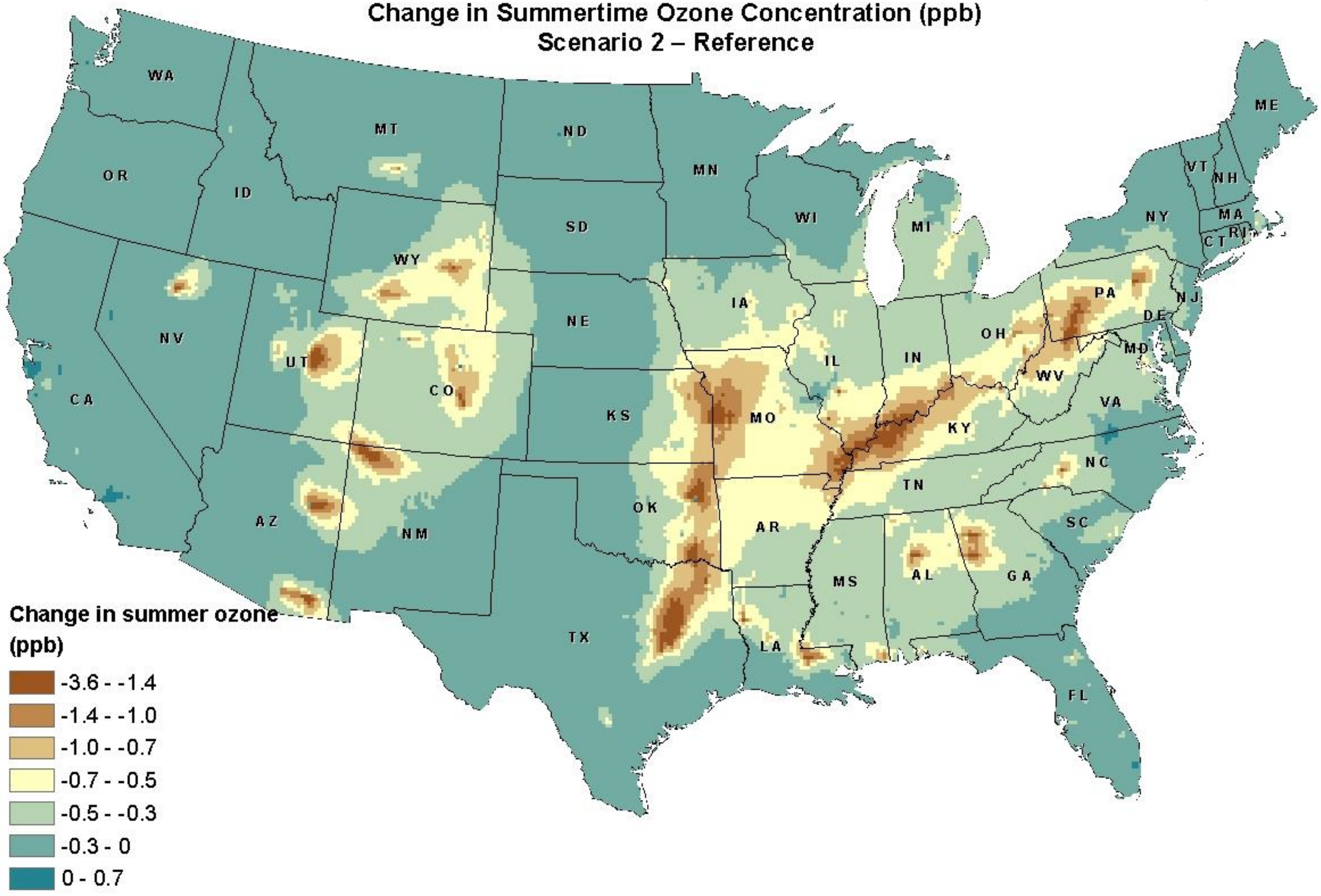


Figure 8c

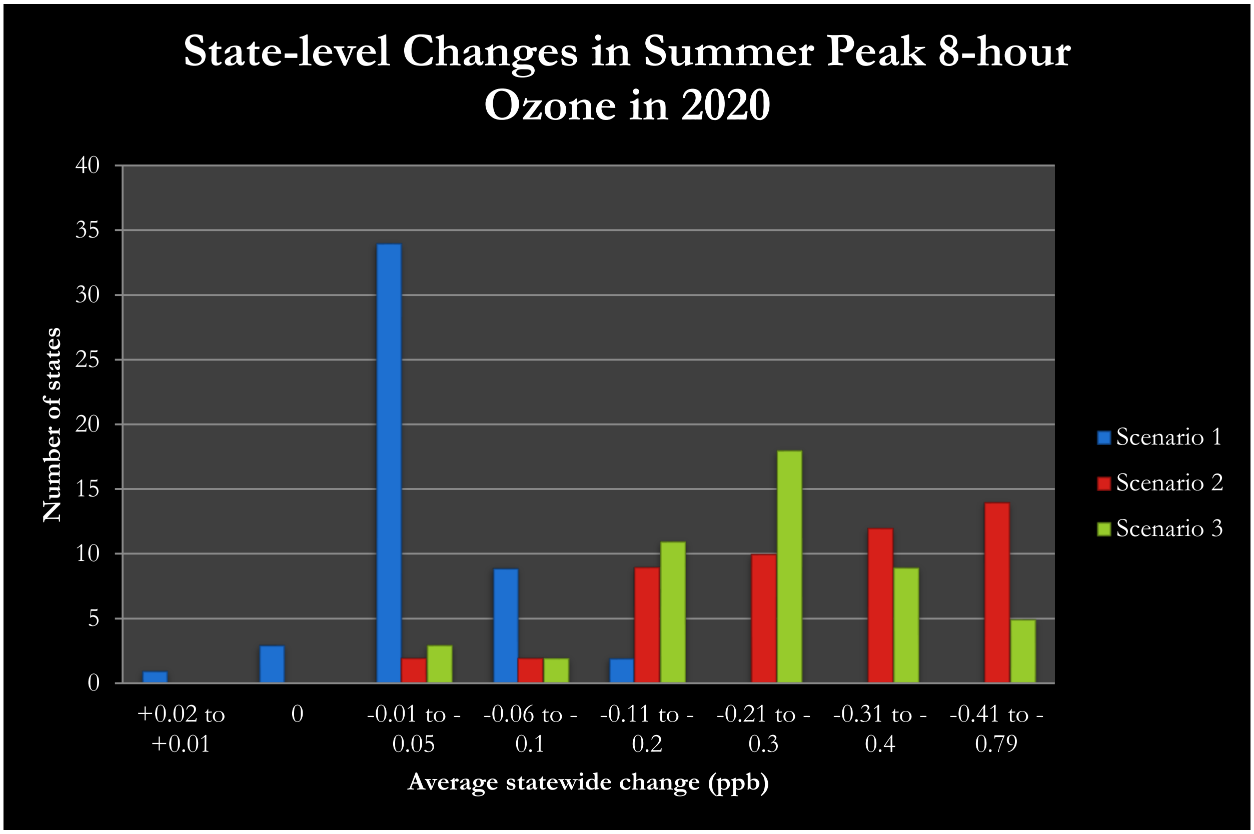


Table 5

Top 15 States with Largest Decreases in Average Summer Peak 8-hour Ozone

State	Scenario #2 (ppb)	Mean decrease (ppb)
Kentucky	49.12	-0.79
Missouri	46.73	-0.75
Pennsylvania	44.75	-0.62
W. Virginia	46.85	-0.59
Indiana	49.67	-0.56
Arkansas	46.03	-0.54
Illinois	49.69	-0.52
Ohio	49.24	-0.51
Oklahoma	47.39	-0.48
Tennessee	49.11	-0.48
Colorado	52.66	-0.45
Alabama	45.13	-0.44
Iowa	46.15	-0.40
Wyoming	51.35	-0.40
Georgia	45.43	-0.39

Figure 9a & b: Average annual peak 8-hr ozone for Reference Case and change in this condition for Scenario #2 (parts per billion).

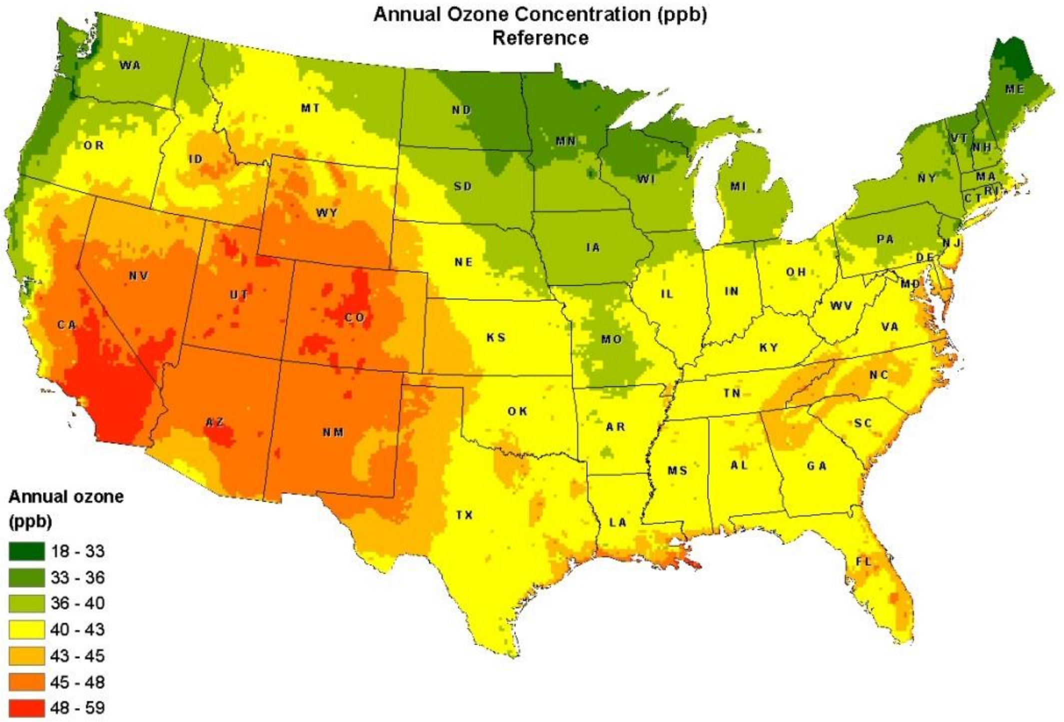


Figure 9a

Figure 9b

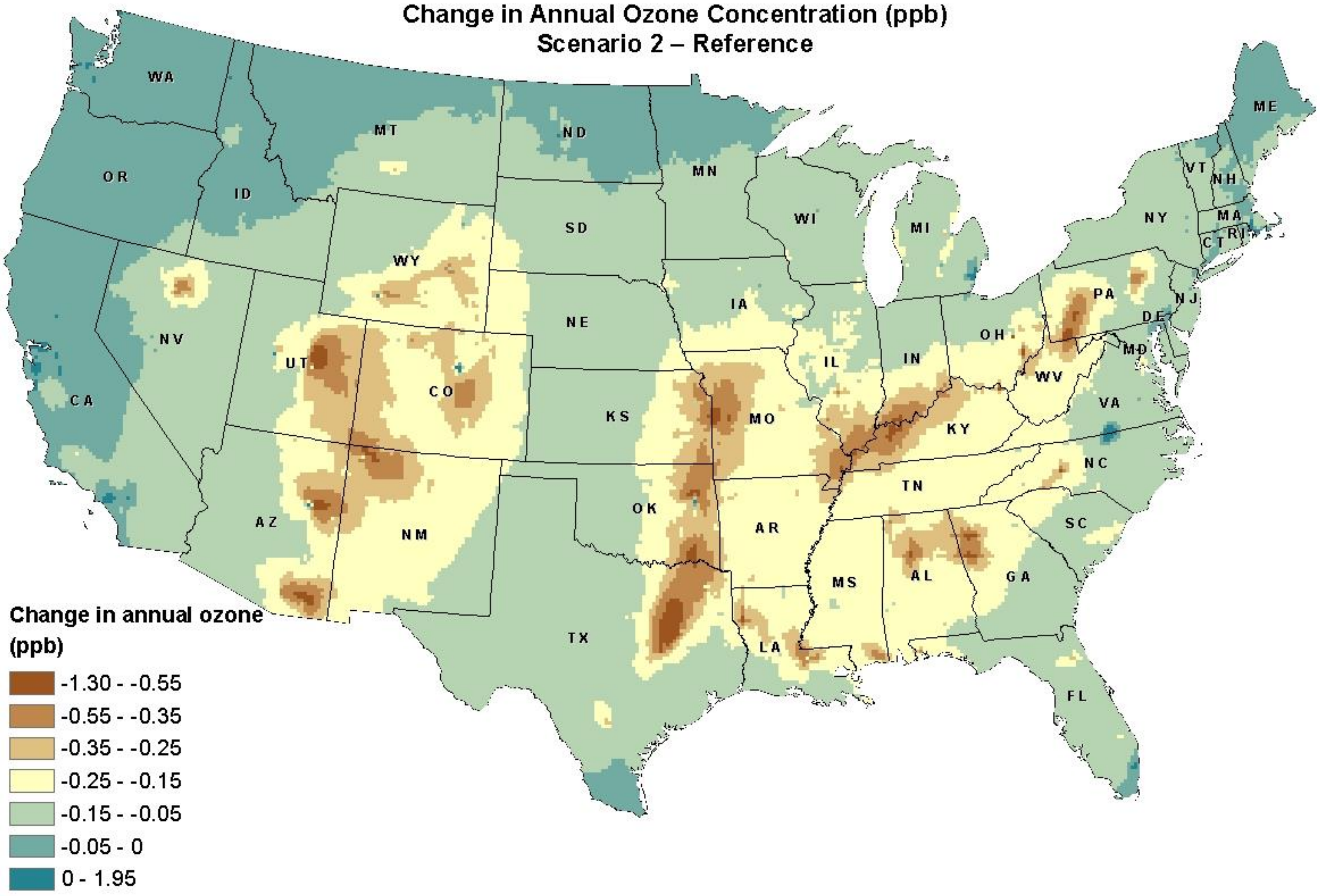


Figure 9c

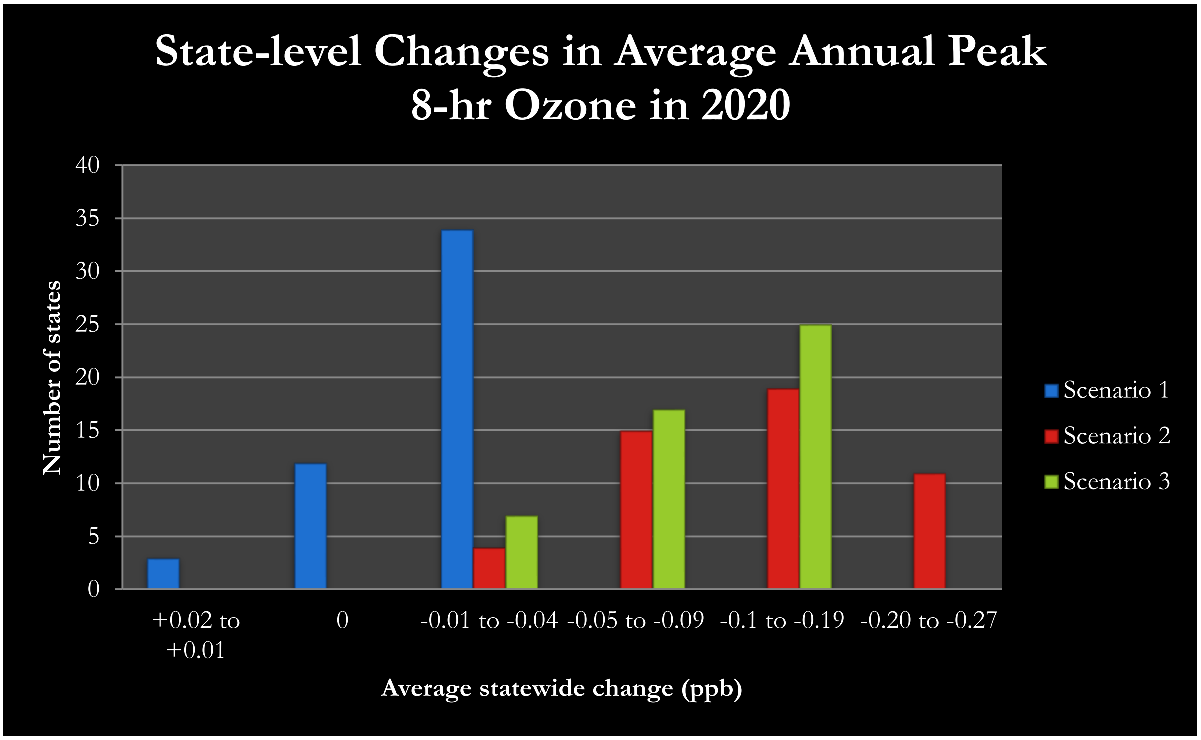


Table 6

Top 15 States with Largest Decreases in Average Annual Peak 8-hr Ozone		
State	Scenario 2 (ppb)	Mean Decrease (ppb)
Kentucky	41.60	0.27
Missouri	39.92	0.27
Colorado	46.22	0.24
Alabama	41.47	0.22
Arkansas	40.86	0.21
W. Virginia	41.42	0.21
Oklahoma	42.10	0.21
New Mexico	46.00	0.21
Tennessee	42.39	0.20
Utah	46.35	0.20
Louisiana	42.43	0.20
Indiana	41.05	0.19
Pennsylvania	39.26	0.19
Illinois	40.72	0.19
Mississippi	41.16	0.18

Figure 10a & b: Total annual sulfur deposition in 2020 for Reference Case and change in this condition for Scenario #2 (kilograms S per hectare-year).

Figure 10a

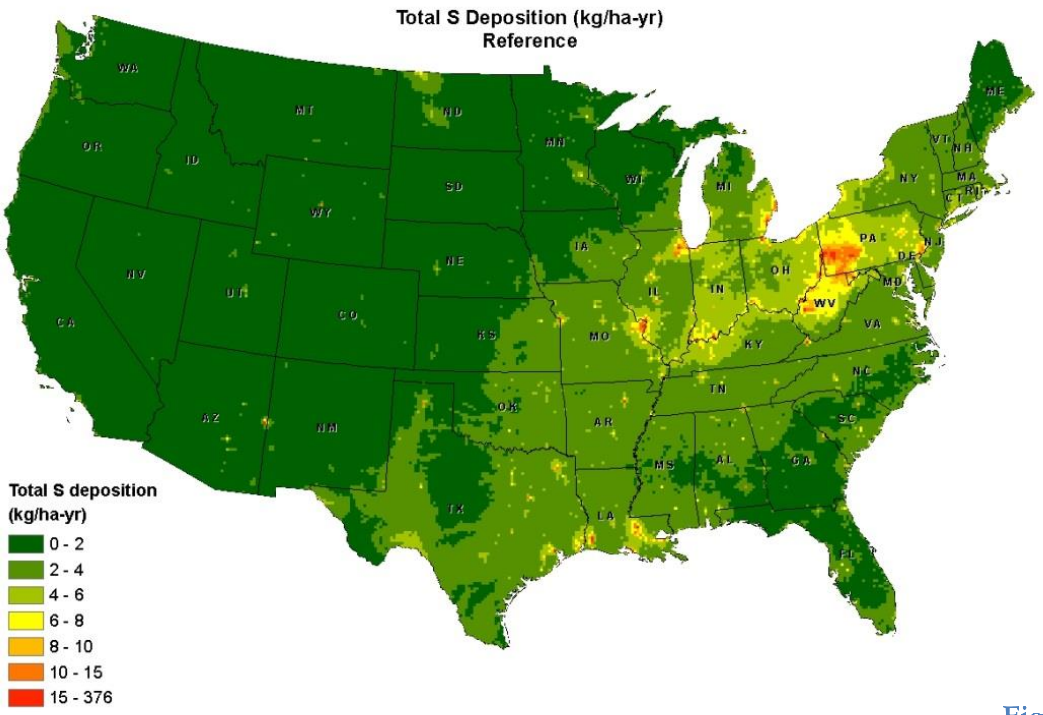


Figure 10b

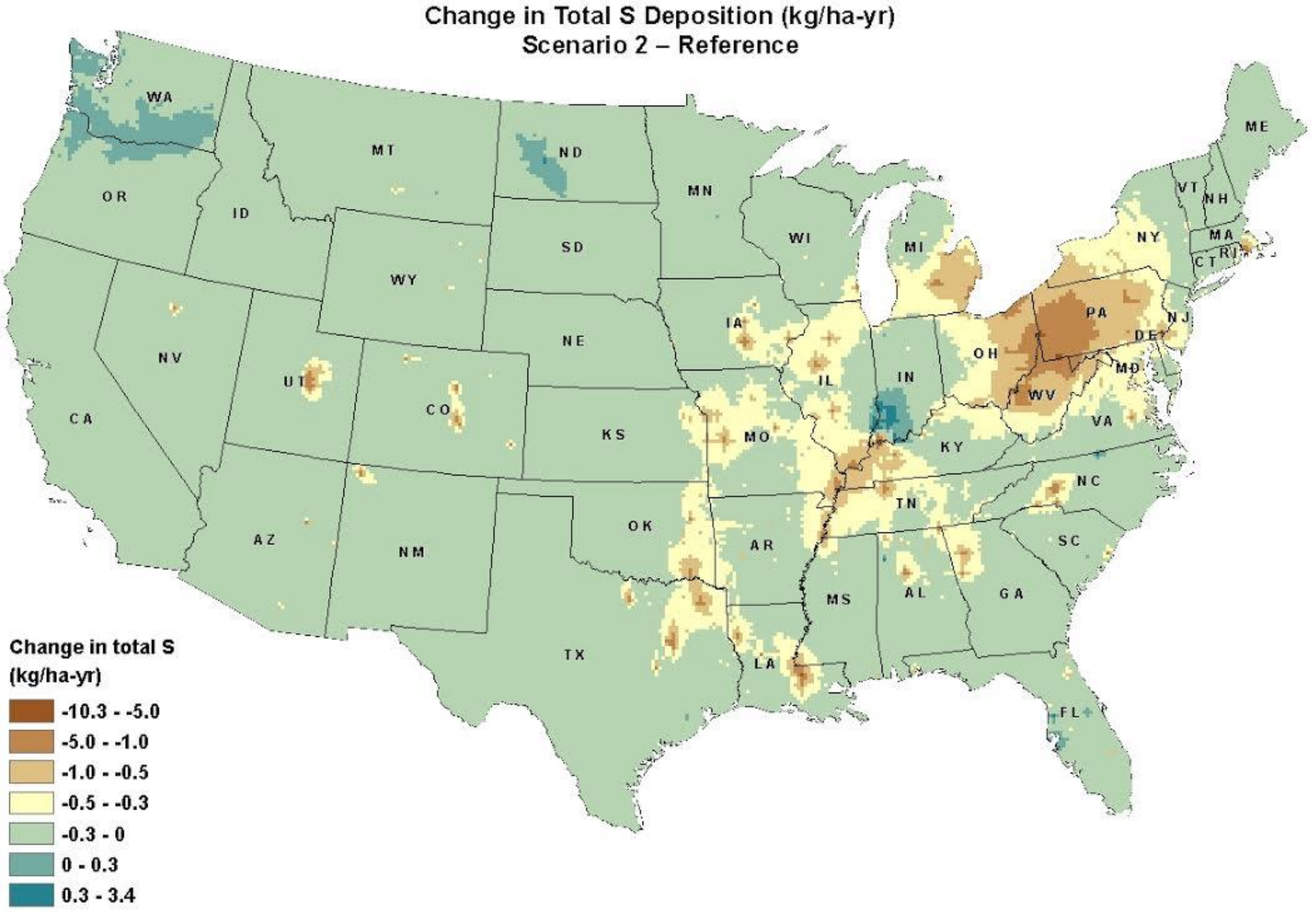


Figure 10c

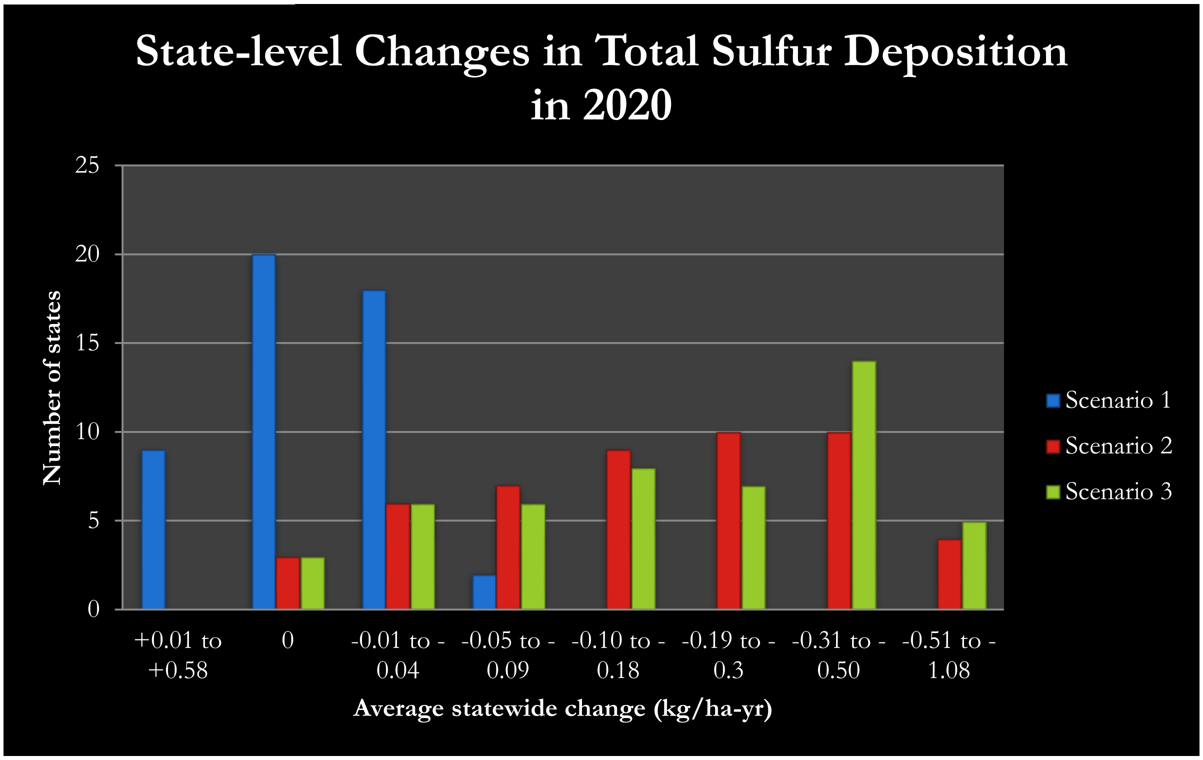


Table 7

Top 15 States with Largest Decrease in Average Annual Total S Deposition

State	Mean Decrease (kg S/ha-yr)	Percent decrease
Pennsylvania	1.08	17.24%
W. Virginia	0.81	13.73%
Ohio	0.60	11.98%
Maryland	0.52	12.97%
Kentucky	0.38	9.20%
Delaware	0.36	10.94%
Illinois	0.36	8.79%
Rhode Island	0.35	8.90%
New Jersey	0.35	9.63%
Tennessee	0.34	11.45%
New York	0.34	9.64%
DC	0.34	6.52%
Missouri	0.34	10.36%
Michigan	0.31	10.14%
Virginia	0.29	9.67%

Figure 11a & b: Total annual nitrogen deposition for Reference Case and change in this condition for Scenario #2 (kilograms N per hectare-year).

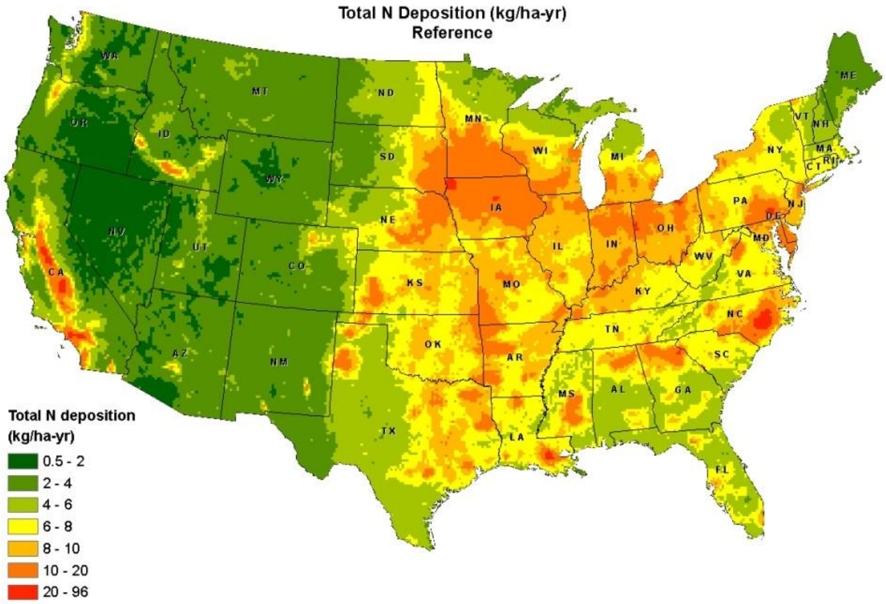
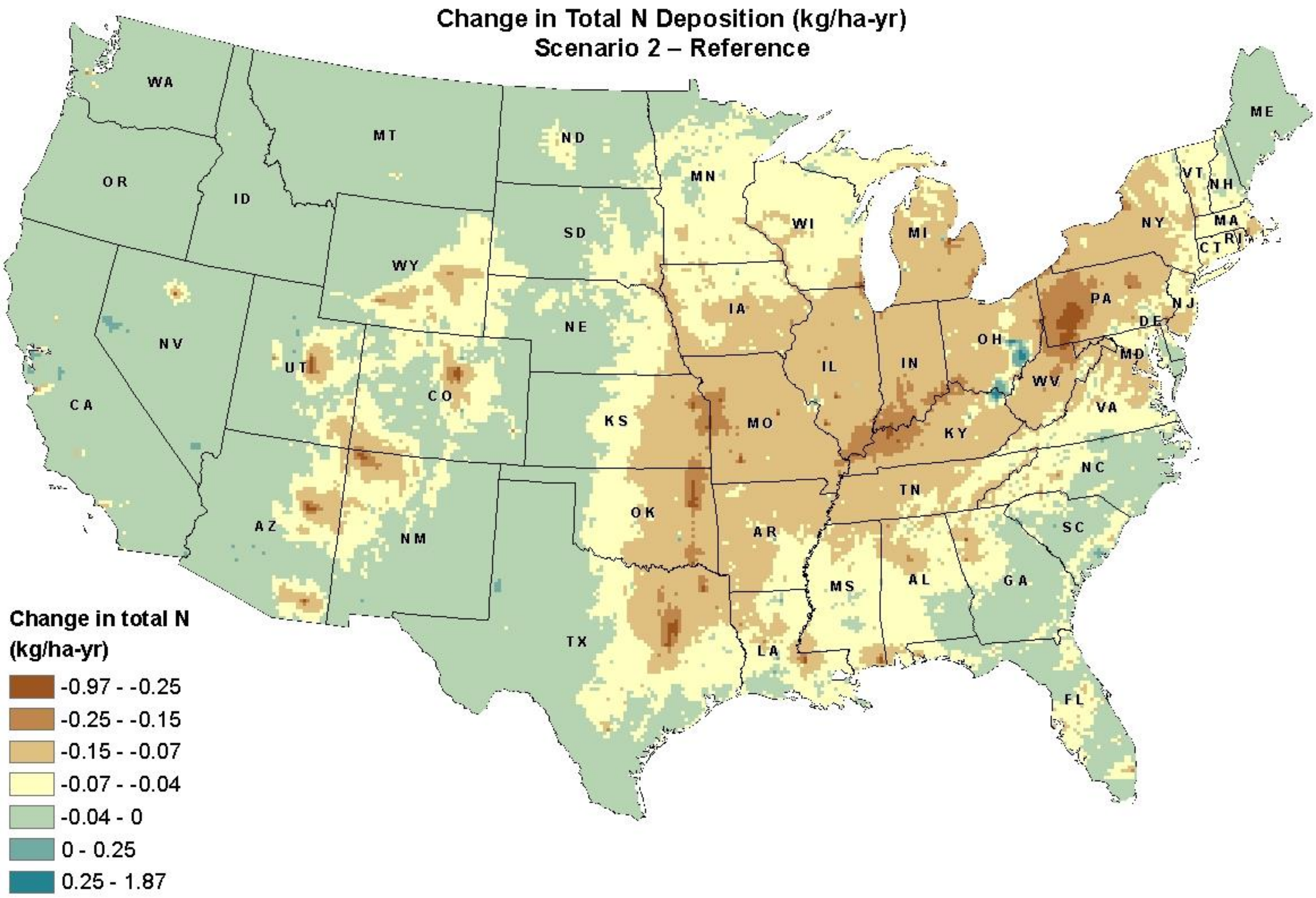


Figure 11a

Table 8

Top 15 States with Largest Decreases in Average Annual Total N Deposition		
State	Mean Decrease (kg N/ha-yr)	Percent decrease
Pennsylvania	0.14	2%
Indiana	0.12	1%
W. Virginia	0.12	2%
Missouri	0.11	1%
Kentucky	0.11	1%
Illinois	0.11	1%

Figure 11b



Summary of Results

This study highlights that, in addition to addressing global climate change, a strong carbon pollution standard for existing power plants will reduce power plant emissions of co-pollutants that contribute to local and regional air pollution.

Details: The top-performing moderate stringency/high flexibility option depicted in Scenario #2 cuts CO_2 emissions from the power sector by 35.5% from 2005 levels by 2020 and by 23.6% from a 2020 Reference Case. Scenario #2 also decreases power plant emissions of co-pollutants by the following amounts in 2020 compared to the Reference Case:

- SO_2 emissions *decrease* by 474,000 short tons/year (-27%)
- NO_x emissions *decrease* by 299,000 short tons/year (-22%)
- Hg emissions *decrease* by 3,334 pounds/year (-27%)

By contrast, the study also highlights how a carbon standard with low stringency and low compliance flexibility limited to actions "inside the fenceline" as depicted in Scenario #1 could result in the following changes in power sector emissions by 2020 compared to the Reference Case:

- SO_2 emissions *increase* by 50,000 short tons/year (+3%)
- NO_x emissions *decrease* by 39,000 short tons/year (-3%)
- Hg emissions *decrease* by 414 pounds/year (-3.3%)

2. The model results show that by reducing the emission of co-pollutants, a strong carbon pollution standard will improve air quality and decrease the deposition of harmful pollutants. It has been well-documented that even modest improvements in air quality can bring important human health and ecosystem benefits.

Details: The CMAQ model runs quantify by how much and where air quality and atmospheric deposition would change under each of the three scenarios. It is clear from the results that the air quality improvements achieved in 2020 under a strong carbon standard would have the added benefit of improving the health of people and ecosystems in states across the U.S. Specifically, for Scenario #2:

- *Average* annual concentrations of fine particulate matter ($PM_{2.5}$) at the state level will decrease by 0.0 to 0.22 $\mu g/m^3$ with the top 15 states experiencing average decreases of 0.14 to 0.22 $\mu g/m^3$.
- Summertime *average* peak 8-hour ozone concentrations at the state level will decrease by 0.01 to 0.79 ppb with the top 15 states experiencing average decreases of 0.39 to 0.79 ppb.

- Annual *average* ozone peak 8-hour ozone concentrations at the state level will decrease by 0.01 to 0.27 ppb with the top 15 states experiencing average decreases of 0.18 to 0.27 ppb.
- Total annual sulfur deposition at the state level will decrease by 0.0 to 1.08 kg/ha-yr with the top 15 states experiencing average decreases of 0.29 to 1.08 kg/ha-yr.

A complete health and ecosystem benefits analysis has not yet been conducted but past studies conducted by EPA for other proposed air pollution standards show that seemingly small improvements in air quality equate to substantial public health benefits. For example, the U.S. EPA's Mercury and Air Toxics Rule, issued in 2011, would reduce annual average $PM_{2.5}$ concentrations by an estimated 0.36 $\mu g/m^3$ and annual average 8-hr ozone concentrations by 0.2 ppb. The U.S. EPA estimated annual health benefits of this rule of 7,600 avoided premature mortality cases (between 4,200 to 11,000), 4,700 avoided non-fatal heart attacks, 130,000 avoided asthma attacks, 5,700 avoided hospital and emergency department visits, 540,000 days of missed work or school, and 3,200,000 restricted activity days. These health benefits were valued between $120 and $280 billion. In Part 2 of this report the health benefits and their economic value will be calculated nationally and for each of the lower 48 states and District of Columbia.

Ecosystems also benefit from decreases in air pollution and atmospheric deposition of sulfur and nitrogen. Reduced ground-level ozone will increase the health and productivity of crops and timber. The projected declines in sulfur deposition will contribute to the recovery of acid-impacted forest watersheds such as the Appalachian Mountain region. Nitrogen deposition is projected to decrease by only 1% to 2%, but there will be modest benefits associated to decreases in ecosystem eutrophication. Note that this analysis is based on total nitrogen deposition which includes both nitrate deposition (driven largely by emission of nitrogen oxides from fossil fuel combustion) and ammonium deposition (driven largely by agricultural emissions). The relative decrease under Scenario #2 would be expected to be approximately two times greater for nitrate deposition alone.

3. The model results show that the air quality and atmospheric deposition improvements associated with decreased emissions co-pollutants under a strong carbon pollution standard are widespread, with every state receiving some benefit. The largest decreases in pollution occur in the eastern US, particularly in states in and around the Ohio River Valley with notable improvements in Rocky Mountain region as well.

Details: The CMAQ results for Scenario #2 provide spatially explicit results that show where the greatest improvements are likely to occur.

- States that are projected to benefit from the largest statewide average decreases in air pollution detrimental to human health ($PM_{2.5}$ and peak annual and summer O_3)

include: OH, PA, MD, WV, IL, KY, MO, IN, AR, CO, AL and WV (based on the top 6 states for each pollutant).

- States that are projected to benefit from the largest statewide average decreases in air pollution detrimental to ecosystems (sulfur and nitrogen) include: PA, WV, OH, MD, KY, DE, IN, IL, and MO (based on the top 6 states for each pollutant).
- Most other states see marked improvements in both air quality and atmospheric deposition of pollutants that vary geographically.

4. Finally, the analysis suggests that the stronger the standards (in terms of both stringency and flexibility), the greater and more widespread the benefits will be from decreased co-pollutants. It also shows that a weaker standard focused strictly on power plant retrofits could increase emissions and reduce air quality over large areas. The resulting improvements in air quality associated with a strong carbon pollution standard would have nearly immediate benefits by reducing illness and premature deaths. Moreover, decreased air pollution will help to continue reversing the damage brought by years of acid, nitrogen deposition, and mercury deposition. In so doing, carbon pollution standards can protect public health and help restore forests, waters, and wildlife, while also mitigating climate change.

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