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Air Pollution Success Stories in the United States: The Value of Long-Term Observation

Timothy J. Sullivan et al.

1. Introduction

Air and water quality have been long-standing concerns in the United States and elsewhere. However, evidence-based policy decisions and management have contributed to large improvements in environmental conditions over the recent past. Socio-economic, environmental, and public health benefits have been substantial. Across the United States, the quality of air and fresh water has vastly improved, mainly in response to the Clean Air and Clean Water Acts enacted nearly a half century ago. We have recently observed decreases in air pollution attributable to policy that have been informed by environmental monitoring and research. Examples illustrated here include decreased lead contamination due to the elimination of tetraethyl lead from gasoline, decreased ground-level (tropospheric) ozone, improved visibility and human health from reduced airborne particulate matter, declines in atmospheric sulfur and nitrogen deposition that acidify the environment, and declines in toxic mercury. None of these environmental stressors have been completely eliminated and further progress is needed, but all have been measurably reduced in the United States and elsewhere by evidence-based policy decisions. As we highlight here using examples across different regions and pollutants, substantial ecological and human health improvements and economic benefits to society have been realized. Many other examples are available, including regional measurements and model simulations that represent responses at dozens or hundreds of locations (cf., U.S. EPA 2013; Fakhraei et al., 2014; Driscoll et al., 2016; Fakhraei et al., 2016; Holmes and Likens, 2016; Sullivan, 2017).

Evaluation of air pollution control policies and thresholds has been guided by advances in process science, monitoring data, and model development and application. Long-term measurements such as are reported here capture the accrued benefits of advances in science and technology that have supported the development of evidence-based regulations and public policy.

2. Fracking Analysis

2.1. Emissions and Atmospheric Deposition of Oxides of Sulfur and Nitrogen

There have been pronounced decreases in emissions and atmospheric deposition of sulfur and nitrogen oxide pollutants since the 1970s, especially throughout the eastern United States (Fig. 1A and B), although legacy damages have been observed. Some pollutants are not readily sequestered, and chemical recovery can take many decades or longer. Sulfur and nitrogen forms of acidifying air pollution are typically lower in the western states, with notable exceptions where nitrogen emissions and associated tropospheric ozone remain high, such as in parts of southern California. Higher air pollution impacts in the eastern United States are driven, in part, by the human population density and use of fossil fuels for energy and transportation in eastern and midwestern states and the dominant west to east direction of prevailing winds across the continent (U.S. EPA, 2009a).

Emissions of sulfur, mainly from coal-burning power plants, and oxidized nitrogen, originating mainly from motor vehicles and power plants, have decreased continuously and substantially across the United States in recent decades (Fig. 1A). While changes in technology and the economy undoubtedly contribute to these trends, reductions in sulfur and nitrogen pollution have been primarily attributed to emissions controlsassociated with the Clean Air Act, its amendments, and other rules and legislation (U.S. EPA, 2009a).

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The National Atmospheric Deposition Program (http://nadp.sws.uiuc.edu/) is an example of high quality environmental monitoring that informs evidence-based decision making. This program, and others, was established in response to enactment and requirements of the Clean Air Act. It includes 270 wet deposition monitoring locations across the United States. Multi-decadal precipitation chemistry trends at an example Adirondack Mountain, NY, lake monitoring site that has been used for research on the effects of acidic deposition have shown marked decreases in sulfur and nitrogen deposition (Fig. 1B) in response to decreases in sulfur dioxideand nitrogen oxide emissions. Dry deposition of air pollutants is more difficult to measure, and is often estimated from models based on monitored air quality and environmental parameters. Estimated total wet plus dry deposition of sulfur and nitrogen have decreased by more than half across much of the eastern United States since monitoring began in the 1970s (Fig. 1B).

2.2. Emissions and Atmospheric Deposition of Mercury

Mercury is emitted into the atmosphere from a variety of sources, particularly coal-fired power plants. Mercury emissions from power plants, incinerators, industry, mining, and biomass burning can travel long distances before being deposited to the surface of the earth. In the United States, mercury emissions and deposition decreased substantially from a peak in the 1980s (Drevnick et al., 2012; Zhang et al., 2016), while in many other countries mercury emissions have continued to increase (Pirrone et al., 2010).

2.3. Acidification

Atmospheric deposition of nitrogen, and especially sulfur, contributes to acidification of soils and surface waters that can harm terrestrial and aquatic life. Nitrogen deposition also contributes to aquatic and terrestrial eutrophication. Key acidification metrics for lakes and streams include the sulfate concentration (largely from atmospheric deposition), the concentration of toxic dissolved inorganic aluminum (dissolved from soil), pH (or hydrogen ion concentration), and acid neutralizing capacity. For example, the acidity of precipitation at

Hubbard Brook Experimental Forest, NH, as reflected by the hydrogen ion concentration, decreased by more than 60 μeq l^{-1} since monitoring began in the 1960s (Fig. 2A). Recent improvements in water quality and acid-base chemistry have been documented for hundreds of montane surface waters such as Big Moose Lake in the Adirondack Park (Fig. 2B; Fakhraei et al., 2014; Driscoll et al., 2016), including decreasing trends in sulfate and inorganic aluminum concentrations, and increasing acid neutralizing capacity. Improvements in water quality in response to decreasing atmospheric sulfur and nitrogen deposition have also been reported for many other surface waters throughout the northeastern United States (Stoddard et al., 1999; Strock et al., 2014), along with the first evidence of improvements in soil chemistry (Lawrence et al., 2015). A critically important characteristic of environmental quality is that recovery processes are complex and vary in time. Improvements in the environment in response to improvements in air quality often unfold over years, decades and longer. Atmospheric sulfur and nitrogen deposition and associated effects data show clear improvements evident now. They represent the beginnings of processes of chemical and biological recovery that will continue to emerge over the next century.

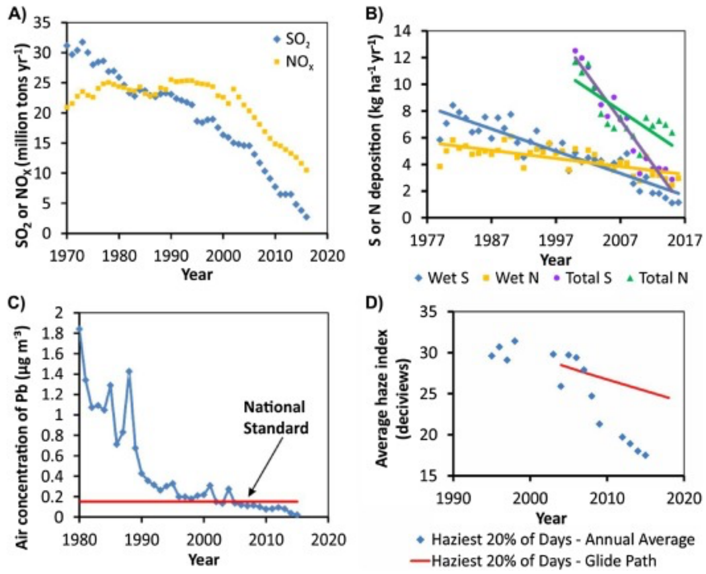

Figure 1. Example time series trends in air pollution levels.

A) National emissions of oxidized nitrogen (NOx) and sulfur dioxide (SO2) throughout the U.S. from U.S. EPA's National Emissions Inventory.

B) Annual wet deposition of sulfur (S) and nitrogen (N) since 1979 as measured by the National Atmospheric Deposition Program at Huntington Forest, NY and total (wet plus dry) deposition estimated by Schwede and Lear (2014) since 2000 at Big Moose Lake, NY.

C) Mean air concentration of lead (Pb) measured at eight United States monitoring sites from 1980 to 2015. Data are annual maximum 3-month averages from U.S. EPA (https://www.epa.gov/air-trends/lead-trends).

D) Annual average haze index on the haziest 20% of days at Shining Rock Wilderness, NC, since 1995, plus the glide path of continuous improvement needed to meet the Regional Haze Rule requirement of zero human-caused haze by the year 2064. Data source: https://webcam.srs.fs.fed.us/graphs/vis/index.php?wilderness=shinin.

2.4. Lead

One of the earliest air pollution abatement successes in the United States was the removal of lead-based fuel additives from gasoline, resulting in a >95% decrease in the concentration of lead in the air (Fig. 1C). Lead causes neurological damage to children and cardiovascular effects in adults, with a strong linear correlation between levels in human blood and air (Thomas et al., 1999). Decreases in environmental lead contamination from atmospheric deposition have been documented in response to lead emissions regulation (Holmes and Likens, 2016), although lead can be strongly held in soil organic matter (Richardson et al., 2015). The redistribution of lead in ecosystems will remain a concern for decades (Kaste et al., 2006).

2.5. Haze

Haze affects how far and how clearly we can see. Visibility can be degraded by light scattering and absorption caused by gasses and particles in the air. Throughout the eastern United States, the most important source of the resulting haze has been ammonium sulfate(http://vista.cira.colostate.edu/Improve/), which derives mainly from human-caused emissions of sulfur dioxide and ammonia. Haze impairs the value of the visitor experience in natural areas (Sullivan, 2017). Federal regulations, as reflected in the Regional Haze Rule, require that states develop plans to reduce haze to natural background by the year 2064 in highly protected national parks and wilderness areas designated as Class I areas. It also requires that states make reasonable progress by following a continuous reduction glide path to natural conditions on the 20% haziest days. Measurements at the Shining Rock Wilderness, NC, indicate that haze levels on the haziest days at this Class I site are decreasing at a rate faster than defined by the Regional Haze Rule (Fig. 1D). Similar observations have been documented at many eastern national parks (Sullivan, 2017), although smoke from forest fires has been an increasingly important component of haze in recent years in many parts of the western United States.

2.6. Ozone

Near ground level in the lowest layer of the atmosphere known as the troposphere, ozone is a gaseous component of smog, formed by atmospheric reactions between nitrogen oxides and volatile organic compounds in the presence of sunlight. Tropospheric ozone is a greenhouse gas and also harms the health of both humans and vegetation (U.S. EPA, 2013). Ozone concentrations are especially high in and downwind of urban areas and at many remote mountainous locations due to atmospheric transport of ozone precursors (Sullivan, 2017). The current National Ambient Air Quality Standard for ozone to protect human and environmental health is equivalent to 70 parts per billion, based on the annual fourth highest daily maximum 8-hour concentration and averaged over a 3-year period. Ozone concentrations at many Class I areas have decreased markedly in recent years (Fig. 2C; U.S. EPA, 2013; Sullivan, 2017).

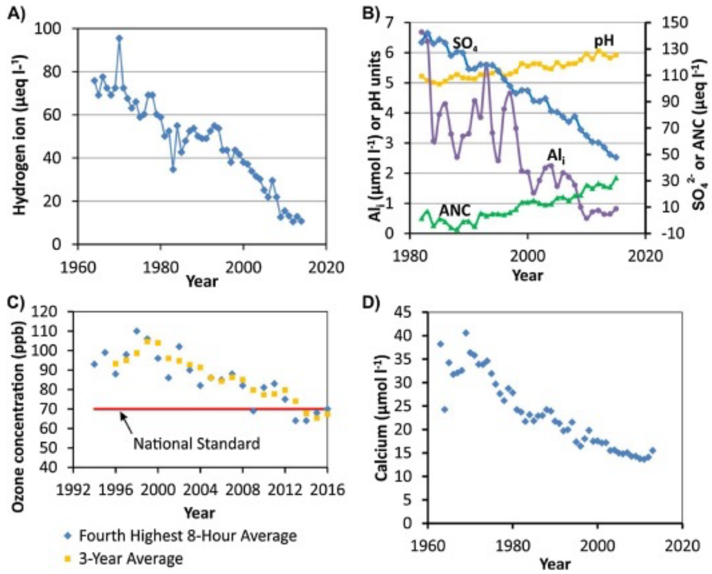

Figure 2.

Example time series trends in air pollution effects.

A) Decreasing concentrations of hydrogen ion in precipitation at Hubbard Brook Experimental Forest, NH over the period of available data. (Data source: Holmes and Likens 2016).

*B) Water chemistry at Big Moose Lake, NY. Adverse impacts on aquatic life are generally associated with inorganic aluminum (Ali) concentrations above 2 μM, pH below about 6.0, and acid neutralizing capacity (ANC) below 50 μeq l−1 (U.S. EPA 2009a). Sulfate (SO42-) is the major driver of effects. (Data source: Adirondack Lakes Survey Corporation [*http://www.adirondacklakessurvey.org/*]).*

C) Atmospheric ozone concentration at Look Rock, Great Smoky Mountains National Park, TN, expressed as the fourth highest 8-hour annual average and three-year average concentration data. Note that ozone is considered as an "effect" because it forms in the atmosphere in response to emissions of its precursors nitrogen oxides and volatile organic compounds. Data source: https://www.epa.gov/outdoor-air-quality-data/monitor-values-report*.*

D) Decreasing concentration of calcium in streamwater at the Hubbard Brook Experimental Forest, NH, reference watershed, in part reflecting delayed recovery of the soil from acidification.

2.7. Mercury Bioaccumulation

Once deposited to soils and water bodies, mercury can be methylated and bioaccumulate in the food web, reaching toxic levels in fish. Game fish, wildlife, and humans who consume contaminated fish can suffer neurological damage from high exposure. Consumption of tuna is the largest source of human mercury exposure in the United States (Sunderland, 2007). However, there is evidence that mercury bioaccumulation is decreasing. For example, concentrations of mercury in Atlantic bluefin tuna (*Thunnus thynnus*) have decreased markedly in recent years due to emission controls (Lee et al., 2016).

2.8. Ongoing Challenges

Despite these successes, we have not eliminated all health and welfare risks from these air pollutants, and others warrant action to evaluate trends in exposure, health, and welfare risk. For example, emissions and deposition of ammonia, which is not regulated in the United States and derives largely from agriculture and motor vehicles, have generally not decreased and in many areas have increased (Parker et al., 2009; Warner et al., 2017).

Some areas that historically received high sulfur and nitrogen deposition reflect a legacy of soil depletion of calcium and other important base cation nutrients, affecting the health and regeneration of calciphylic plants like sugar maple (Sullivan et al., 2013; Holmes and Likens, 2016). Even under much reduced levels, continued sulfur and nitrogen deposition have constrained the recovery of soil base nutrient status and tree growth. For example, at the Hubbard Brook Experimental Forest, soil calcium depletion caused by acidification left a legacy of damage that may take many decades or longer to reverse (Likens, 2013; Fig. 2D), and forest decline attributable partly to acidification was reversed by experimental calcium addition (Battles et al., 2014). Even with the improvements discussed here, additional emissions reductions and/or time may be needed for full recovery, particularly for sensitive components of ecosystems, at this experimental forest and at other locations across the country. Maintaining critical long-term monitoring and associated research will remain fundamental to developing informed evaluations and decisions that define cost-effective policies for the 21st century.

2.9. Effects on Human Well-Being

Globally, it has been estimated that air pollution contributes to the premature deaths of millions of people each year (U.S. EPA, 2009b; West et al., 2016; Landrigan et al., 2017). Air pollution that degrades ecosystem health has reduced the economic and cultural benefits and services that natural ecosystems provide (Beier et al., 2017). Examples include forestry, tourism, fisheries, greenhouse gas mitigation and others. Air quality is fundamental to human and ecosystem health. Outdoor exposure to polluted air contributes to a wide range of human ailments associated with asthma, other respiratory disease, cardiovascular disease, and lung cancer (Brook et al., 2010; Loomis et al., 2013). Improvements via the Clean Air Act over the period 1970 to 1990 provided the United States an estimated $22 trillion in cumulative human health and reduced mortality benefits, with about $0.5 trillion (1990 dollars) in implementation costs. The 1990 Clean Air Act Amendments are estimated to yield additional health and monetary benefits equal to $2 trillion in 2020, with compliance costs of approximately $65 billion in that year (U.S. EPA Office of Air and Radiation, 2011). Projected economic benefits are attributable to preventing about 230,000 cases of premature mortality in 2020; preventing morbidity, including acute myocardial infarctions and chronic bronchitis; and improving the quality of environmental resources, the largest component of which is willingness to pay for improved visibility.

3. Conclusions

Many of the air pollution issues highlighted here have common sources. Thus, cleaning up sources of one pollutant can yield co-benefits with respect to other pollutants. For example, mitigation of water and soil acidification through controls on sulfur emissions from electricity generating units reduces emissions of mercury, particulate matter, and ozone precursors, as well as acidifying compounds.

We increasingly hear public narratives that appear to be grounded in a post-truth world, where empirical evidence and science take a back seat to ideology. Perhaps nowhere is this disregard for facts more evident than in discourse on environmental policy. Environmental scientists are generally effective at analyzing data to assess risk, and communicating those findings through time-tested mechanisms of scientific peer review. We are less skilled at communicating successes and their scientific foundations to the public and policy-makers, despite many clear and cost-effective examples of success from local to global scales. Many of those successes are highlighted with concrete examples here. In a recent editorial, Lubchenco (2017) encouraged scientists to confront the new, and increasingly unsettling, post-truth world by demonstrating the value and relevance of science. We show here important examples of how environmental research and monitoring have informed air quality policy that has reduced adverse effects of pollutants on humans and ecosystems. Pollutant reductions provide environmental, social, and economic benefits. These examples show how we can sustain and enhance these improvements and highlight the urgency to apply these lessons to critical issues such as rising emissions of greenhouse gases. They underscore the importance of data and fact-based decision-making. Continued environmental monitoring and associated research will be even more essential in confronting the accelerating changes that lie ahead in order to track improvements, avoid reversals, and identify emerging threats.

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Emerging Trends in Hydraulic Fracturing

Physicians for Social Responsibility & Concerned Health Professionals of New York

Introduction to Fracking

Since the end of the 20th century, horizontal drilling has been combined with high-volume hydraulic fracturing as novel technologies for extracting dispersed oil and natural gas, primarily from shale bedrock, that would otherwise not flow to the surface. Typically, these unconventional extraction methods (collectively known as "fracking") take place on clustered multi-well pads where individual well bores extend vertically down into the shale formation and then turn horizontally, tunneling through the shale in various directions. These lateral tunnels can extend a mile or more underground.

To liberate the gas (methane) or oil trapped inside the shale, many small explosive charges followed by high volumes of pressurized fluid are sent into the shale layer to expand and extend its many naturally occurring cracks, bedding planes, and faults. Silica sand grains (or sometimes ceramic beads) are carried by the pressurized fluid into these spaces and remain there after the pressure is released, acting to prop open these now-widened fissures in the shale and allowing the methane or oil trapped within to flow up the well.

Fracking fluid consists of fresh water to which is added a sequence of chemicals that include biocides, friction-reducers, gelling agents, anti-scaling, and anti-corrosion agents. Some of the water used to frack wells remains trapped within the fractured zone and, as such, is permanently removed from the hydrologic cycle. The remainder travels back up to the surface. This flowback fluid contains not only the original chemical additives but also naturally occurring substances carried up from the shale zone, which often include brine, heavy metals, and radioactive elements.

Once in production, a fracked well continues to generate liquid throughout its lifetime. This produced water, which contains many of the same toxic substances as flowback fluid, is a second component of fracking waste, and it also requires containment and disposal. In addition, fracking waste includes solid drilling cuttings, which are typically laced with various chemical substances used to aid the drilling process. These cuttings, which can also contain radioactive elements, are typically disposed in landfills.

As fracking operations in the United States have increased in frequency, size, and intensity, and as the transport of extracted materials has expanded, a significant body of evidence has emerged to demonstrate that these activities are dangerous to people and their communities in ways that are difficult—and may prove impossible—to mitigate. Risks include adverse impacts on water, air, agriculture, public health and safety, property values, climate stability, and economic vitality, as well as earthquakes.

Researching these complex, large-scale industrialized activities—and the ancillary infrastructure that supports them—takes time and has been hindered by institutional secrecy. Nonetheless, research is gradually catching up to the last decade's surge in fracking from shale. A growing body of peer-reviewed studies, accident reports, and investigative articles has detailed specific, quantifiable evidence of harm and has revealed fundamental problems with the entire life cycle of operations associated with unconventional drilling, fracking, and fracked-gas infrastructure. Industry studies, as well as independent analyses, indicate inherent engineering problems including uncontrolled and unpredictable fracturing, induced seismicity, extensive methane leakage, and well casing and cement failures that cannot be prevented with currently available materials and technologies.

Fracking-related problems also originate from sources independent of engineering. These include habitat destruction; inadequate solutions for wastewater disposal; the presence of abandoned wells or vertical fault lines that can serve as pathways for fluid migration into aquifers; and standard operational industry norms (venting, flaring, blowdowns) that contribute to methane releases and air pollution.

Earlier scientific predictions and anecdotal evidence are now bolstered by extensive empirical data, confirming that the public health risks from unconventional gas and oil extraction are real, the range of adverse environmental impacts wide, and the negative economic consequences considerable. Our examination of the peer-reviewed medical and public health literature uncovered no evidence that fracking can be practiced in a manner that does not threaten human health.

Despite this emerging body of knowledge, industry secrecy, and government actions and inaction continue to thwart scientific inquiry, leaving many potential problems—especially cumulative, long-term risks—unidentified, unmonitored, and largely unexplored. This problem is compounded by non-disclosure agreements, sealed court records, and legal settlements that prevent families and their doctors from discussing injuries and illness. As a result, no quantitative and comprehensive inventory of human hazards yet exists.

The long-entrenched problem of secrecy shows no sign of resolving. The identity of chemicals used in fracking fluids remains proprietary and lies beyond the reach of federal right-to-know legislation that governs other industries. The nation's largest public database on chemicals used in fracking operations, FracFocus, operates on a voluntary basis, and, while 23 states have adopted it to serve as a de facto chemical disclosure registry, its data has, over time, become increasingly less, rather than more, comprehensive and transparent. As documented in a 2016 study by a Harvard University team, rates of withheld information and claims of trade secrecy have increased since FracFocus was first launched in 2011.[1,2]

The incomplete picture created by lack of transparency not withstanding, the evidence to date indicates that fracking operations pose severe threats to health, both from water contamination and from air pollution. In the United States, more than two billion gallons of water and fracking fluids are injected daily under high pressure into the earth for the purpose of enabling oil and gas extraction via fracking or, after the fracking is finished, to flush the extracted wastewater down any of the 187,570 disposal wells across the country that accept oil and gas waste.[3] All of that two billion daily gallons of fluid is toxic, and it passes through our nation's groundwater aquifers on its way to the deep geological strata below where it demonstrably raises the risk for earthquakes. In the air around drilling and fracking operations and their attendant infrastructure, researchers have measured strikingly high levels of toxic pollutants, including the potent carcinogen benzene and the chemical precursors of ground-level ozone (smog). In some cases, concentrations of fracking-related air pollutants in communities where people live and work exceed federal safety standards. Research shows that air emissions from fracking can drift and pollute the air hundreds of miles downwind.[4,5,6]

About one-third of the natural gas inventory in the United States is used to generate electricity, and, enabled by fracking, natural gas has, as of 2016, exceeded coal as the nation's leading source of electricity.[7] With hydraulically fractured wells now producing more than two-thirds of U.S. natural gas and half of U.S. crude oil, fracking's "unconventional" techniques can no longer be considered atypical nor can the question of their public health risks be considered inconsequential.[8,9]

Drilling and fracking operations and their ancillary infrastructure have profoundly altered Earth's landscape. The flare stacks and artificial lights from major shale plays are visible from space,[10] as is the upward buckling of Earth's surface that is caused by the high-pressure injection of fracking waste water into disposal wells.[11]

The dramatic increase in fracking over the last decade in the United States has pushed oil and gas extraction operations into heavily populated areas. At least six percent of the population—17.6 million Americans—now live within a mile of an active oil or gas well, a number that includes 1.4 million young children and 1.1 million elderly people.[12, 13] About 8.6 million people are served by a drinking water source that is located within a mile from an unconventional well.[14] Understanding the potential for exposure and accompanying adverse impacts is a public health necessity.

Growing Trends

1) Growing evidence shows that regulations are simply not capable of preventing harm.

Studies reveal inherent problems in the natural gas extraction process, such as well integrity failures caused by aging or the pressures of fracking itself, and in the waste disposal process. These issues can lead to water contamination, air pollution with carcinogens and other toxic chemicals, earthquakes, and a range of environmental and other stressors inflicted on communities. Some of fracking's many component parts—which include the subterranean geological landscape itself—are simply not controllable.

Compounding the innate unpredictability of the fracking process: the number of wells and their attendant infrastructure continue to proliferate, creating burgeoning cumulative impacts, and the size of individual wells keep growing. With the horizontal portions of a single well now extending as far as two miles or more underground, fluid injections, once typically three to five million gallons per fracked well, can now easily reach 10 to 20 million gallons per well.

The injection of extreme volumes of fluids creates significant deformations in the shale that are translated upwards, a mile or more, to the surface. Along the way, these "pressure bulbs" can impact, in unpredictable ways, faults and fissures in the overlying rock strata, including strata that intersect fresh water aquifers. Such pressure bulbs may mobilize contaminants left over from previous drilling and mining activities.[15,16] No set of regulations can obviate these potential impacts to groundwater. Similarly, no set of regulations can eliminate earthquake risks.[17]

The state of California determined that fracking can have "significant and unavoidable" impacts on air quality, including driving pollutants above levels that violate air quality standards.[18] Similarly, in northeastern Colorado, ambient levels of atmospheric hydrocarbons continued to increase even with tighter emission standards.[19]

Well sites leak far more methane and toxic vapors than previously understood, and they continue to leak long after they are decommissioned. Abandoned wells are a significant source of methane leakage into the atmosphere, and, based on findings from New York and Pennsylvania, may exceed cumulative total leakage from oil and gas wells currently in production. Plugging abandoned wells does not always reduce methane emissions, and cement plugs themselves deteriorate over time. Further, many abandoned wells are unmapped and their locations unknown. No state or federal agency routinely monitors methane leakage from abandoned wells.[20,21]

Leakage rates among active wells are wildly variable: four percent of wells nationwide are responsible for fully half of all methane emissions from drilling and fracking-related activities. Predicting which wells will become "super-emitters" is not possible, according to a 2016 survey of 8,000 wells using helicopters and infrared cameras. Further, much of this leakage is engineered into the routine operation of fracking extraction, processing and transport infrastructure, as when vapors are vented through release valves in order to regulate pressure.[22,23]

2) Fracking and the disposal of fracking waste threaten drinking water.

Cases of drinking water sources contaminated by drilling and fracking activities, or by associated waste disposal, are now proven. EPA's assessment of fracking's impacts on drinking water resources confirmed specific instances of water contamination caused by drilling and fracking related activities and identified the various pathways by which this contamination has occurred: spills; discharge of fracking waste into rivers and streams; and underground migration of chemicals, including gas, into drinking water wells.

Independently, researchers working in Texas found 19 different fracking-related contaminants— including cancer-causing benzene—in hundreds of drinking water samples collected from the aquifer overlying the heavily drilled Barnett Shale, thereby documenting widespread water contamination. In Pennsylvania, a solvent used in fracking fluid was found in drinking water wells near drilling and fracking operations known to have well casing problems. In California, state regulators admitted that they had mistakenly allowed oil companies to inject drilling wastewater into aquifers containing clean, potable water.[24,25,26] A 2017 study found that fracking wastewater discharged into rivers and streams through treatment plants created dozens of brominated and iodinated disinfection byproducts that are particularly toxic and "raise concerns regarding human health."[27]

As we go to press in early 2018, researchers reported on the discovery of opportunistic, pathogenic bacteria in fracking-impacted water wells in Texas and raised questions about fracking's effects on the microbial ecology of aquifers.[28] The Pennsylvania Department of Environmental Protection determined that fracking wastewater that had leaked from a storage pit contaminated groundwater and rendered a natural spring used for drinking water in Greene County undrinkable.[29] In Arkansas, researchers found that water withdrawals for fracking operations can deplete streams, threaten drinking water supplies, damage aquatic life, and impact recreation.[30, 31]

3) Drilling and fracking contribute to toxic air pollution and smog (ground-level ozone) at levels known to have health impacts.

Volatile organic compounds from drilling and fracking operations, together with nitrogen oxides, are responsible for 17 percent of locally produced ozone in Colorado's heavily drilled Front Range.[32] Colorado has exceeded federal ozone limits for the past decade, a period that corresponds to a boom in oil and gas drilling.[33] Living near drilling and fracking operations significantly increases asthma attacks for residents of Pennsylvania, with those living near active gas wells 1.5-4 times more likely to suffer from asthma attacks than those living farther away, with the closest group having the highest risk.[34,35]

The New York State Department of Environmental Conservation determined that fracking could increase ozone levels in downwind areas of the state, potentially impacting the ability to maintain air quality that meets ozone standards.[36] In California, fracking occurs disproportionately in areas already suffering from serious air quality problems and can drive ozone and other federally regulated air pollutants to levels that violate air quality standards.[18,37] This increased air pollution and smog formation poses a serious risk to all those already suffering from respiratory issues, such as children with asthma. With an average of 203 high-ozone days a year, intensely fracked Kern County, California, is the fifth-most ozonepolluted county in the nation, according to the American Lung Association.

Several studies have documented a sharp uptick in atmospheric ethane, a gas that co-occurs with methane and whose presence is attributable to emissions from oil and gas wells. This trend reverses a previous, decades-long decline; if this rate continues, U.S. ethane levels are expected to hit 1970s levels in about three years. Ethane is a potent precursor to ground-level ozone.[38–41] Emissions from drill site flaring operations also contribute to ozone creation and include several carcinogens, including benzene and formaldehyde. In 2016, the EPA acknowledged that it had dramatically underestimated health-damaging air pollutants from flaring operations.[42,43] A 2017 study of plume samples from gas flares in North Dakota found that incomplete combustion from flaring is responsible for 20 percent of the total emissions of methane and ethane from the Bakken shale fields, which is more than double the expected value.[43]

4) Public health problems associated with drilling and fracking include poor birth outcomes, reproductive and respiratory impacts, cancer risks, and occupational health and safety problems.

Studies of mothers living near oil and gas extraction operations consistently find impairments to infant health, including elevated risks for low birth weight and preterm birth. A 2017 study that examined birth certificates for all 1.1 million infants born in Pennsylvania found poorer indicators of infant health and significantly lower birth weights among babies born to mothers living near fracking sites. A 2015 Pennsylvania study found a 40 percent increase in the risk of preterm birth among infants born to mothers who lived nearby active drilling and fracking sites. A 2014 Colorado study found elevated incidence of neural tube defects and congenital heart defects. New studies in Texas and Colorado likewise found associations with infant deaths, highrisk pregnancies, and low birth weight. A 2017 pilot study in British Columbia found elevated levels of muconic acid—a marker of benzene exposure—in the urine of pregnant women living near fracking sites.[44–47]

An emerging body of evidence, from both human and animal studies, shows harm to fertility and reproductive success from exposure to oil and gas operations, at least some of which may be linked to the dozens of known endocrine-disrupting chemicals used in hydraulic fracturing.[46–50]

A 2017 Colorado study found higher rates of leukemia among children and young adults living in areas dense with oil and gas wells, while a Yale University research team reported that carcinogens involved in fracking operations had the potential to contaminate both air and water in nearby communities in ways that may increase the risk of childhood leukemia. The Yale team identified 55 known or possible carcinogens that may be released into air and water from fracking operations. Of these, 20 are linked to leukemia or lymphoma.[51,52]

Other documented adverse health indicators among residents living near drilling and fracking operations variously include exacerbation of asthma as well as increased rates of hospitalization, ambulance runs, emergency room visits, self-reported respiratory problems and rashes, motor vehicle fatalities, trauma, drug abuse, and gonorrhea. Pennsylvania residents with the highest exposure to active fracked gas wells were nearly twice as likely to experience a combination of migraine headaches, chronic nasal and sinus symptoms, and severe fatigue.[53]

Among workers, risks include both accidents and toxic exposures. On-the-job fatalities from accidents in the oil and gas industry are four to seven times the national average, with contract workers at the highest risk. Occupational safety standards designed to minimize "the consequences of catastrophic releases of toxic, reactive, flammable, or explosive chemicals" in workplaces do not apply to the oil and gas industry due to legal exemptions.[54] Fatality rates among workers in the oil and gas extraction sector in North Dakota were seven times the national fatality rates in this industry, which itself has more deaths from fires and explosions than any other private industry. An increase in workplace deaths has accompanied the fracking boom in West Virginia. On January 22, 2018, a natural gas rig exploded in southeastern Oklahoma, killing five workers. As we go to press in early 2018**,** the U.S. Chemical Safety Board has begun a full investigation into this fatal explosion, in which the well's blowout preventer failed, leading to an uncontrolled release of natural gas during a pause in the drilling process.[55] Between 2011 and 2016, at least 60 workers at oil and gas drilling sites in Oklahoma were killed on the job.

A new study from the University of Tennessee found that workers are exposed to hazardous and carcinogenic air pollutants from multiple sources, with chemical storage tanks presenting the highest cancer risk. Benzene has been detected in the urine of well-pad workers in Colorado and Wyoming. The National Institute for Occupational Safety and Health named oil and gas extraction industry workers among those at risk for silicosis, an incurable lung disease caused by exposure to silica dust, from the silica sand that is used extensively in fracking operations.[56, 57, 58]

5) Natural gas is a threat to the climate.

From a greenhouse gas perspective, natural gas is not a cleaner fuel than coal and may be worse. Methane is a much more potent greenhouse gas than formerly appreciated. The Intergovernmental Panel on Climate Change estimates that, over a 20-year time frame, methane can, pound for pound, trap 86 times more heat than carbon dioxide and is 34 times more potent a greenhouse gas over a 100 year period.[59] Further, real-world methane leakage rates from drilling and fracking operations greatly exceed earlier estimates. In the heavily drilled Barnett Shale of northeastern Texas, methane emissions were shown to be 50 percent higher than the EPA had estimated. Fracking operations and associated infrastructure contribute 71-85 percent of the methane emissions in the region.

Much of the methane emitted from drilling and fracking activities and associated infrastructure originates not from accidental leaks but from losses that are inherent to the design of the machinery or to normal operating use and are, therefore, not possible to mitigate.[60, 61, 62] Inactive, abandoned wells are also significant methane emitters. Methane leakage at the levels now being documented, using multiple approaches in measurement and modeling, negates previously hypothesized benefits from burning methane instead of coal in most existing power plants.

Methane leakage from oil and gas operations makes the urgent task of limiting global warming to below levels called for in the Paris Climate Agreement increasingly difficult. Recent evidence shows that methane emissions from the fossil fuel industry are 20-60 percent higher than previously thought, and that a surge in atmospheric methane levels are now driving climate impacts of rising human-caused greenhouse gases. As we go to press, a major new study led by NASA researchers has confirmed that the sharp uptick in global methane since 2006 is largely attributable to fossil fuel sources.[63] Many climate researchers now call for a renewed emphasis on reducing methane emissions to combat climate change.[64,65]

6) Earthquakes are a proven consequence of drilling and fracking-related activities in many locations.

Several major studies, using different methodologies, have confirmed a causal link between the injection of fracking wastewater in disposal wells and earthquake swarms. Using structural geology analysis, a 2017 study of the Fort Worth basin showed that a recent swarm of small earthquakes in northern Texas was originating in long-inactive, ancient fault lines in deep formations where fracking wastewater is being injected; human activity is the only plausible explanation.[66] Another recent study using satellite-based radar imagery provided proof that the migration of fracking wastewater into faults increased pressures in ways that triggered a 4.8-magnitude earthquake in east Texas in 2012, while a third study documented the rupture of a fault plane that set off a 4.9-magnitude earthquake in Kansas in 2014 immediately following a rapid increase in fracking wastewater injection nearby.[67, 68]

The number of earthquakes of magnitude 3.0 or higher has skyrocketed in Oklahoma since the advent of the fracking boom, with fewer than two per year before 2009 and more than 900 in 2015 alone. The 5.8 earthquake that struck near Pawnee on September 3, 2016 was the strongest in Oklahoma's history. Felt by residents in five states, the Pawnee quake prompted a state of emergency declaration and an order from state regulators to shut down 67 wastewater disposal wells in the area.[69, 70] In October 2016, the EPA recommended a moratorium on the underground injection of fracking wastewater in certain earthquake-prone parts of Oklahoma because regulations had not worked to solve the problem.[71] On November 6, 2013, a magnitude 5.0 earthquake struck Cushing, Oklahoma near the site of the nation's largest oil hub, where 60 million barrels of crude oil were stored. The quake injured one, damaged more than 40 buildings, closed a school, and triggered evacuations. Oil infrastructure was not damaged. Recent evidence shows that the process of fracking itself can trigger small earthquakes, as several confirmed cases demonstrate.

7) Fracking infrastructure poses serious potential exposure risks to those living nearby.

Drilling and fracking activities are relatively short-term operations, but compressor stations are semi-permanent facilities that pollute the air 24 hours a day as long as gas is flowing through pipelines. Day-to-day emissions from compressor stations are subject to highly episodic variations due to pressure changes and maintenance-related deliberate releases and can create periods of potentially extreme exposures. Pipelines themselves can freeze, corrode, break, and leak. Between January 2010 and November 2017, according to data from the federal Pipeline and Hazardous Materials Safety Administration, pipeline incidents killed 100 people, injured 500, prompted the evacuation of thousands, and leaked more than 17 billion cubic feet of methane.[72] Low-pressure flow lines alone are responsible for more than 7,000 spills and leaks since 2009.[73]

In the Upper Midwest, Wisconsin residents living near silica sand mining operations that service the fracking industry reported dust exposure and respiratory problems. Silica dust is a known cause of silicosis and lung cancer.

Fracking infrastructure in the United States also includes 400 underground gas storage facilities in 31 states, with scant federal oversight and aging equipment. The four-month leak at the nation's fifth largest facility, Aliso Canyon in southern California, between October 2015 and February 2016 resulted in exposures of large suburban population to an uncontrollable array of chemicals. With a release of nearly 100,000 metric tons of methane, it became the worst methane leak in U.S. history.[74]

A major pollution source even before the blow-out, Aliso Canyon exposed residents in the region to benzene spikes, high ongoing odorant releases, hydrogen sulfide at levels far above average urban levels, and many other contaminants of concern. More than 8,000 households were evacuated and relocated, with residents reporting multiple symptoms, including headaches, nosebleeds, eye irritation, and nausea. Contaminated house dust became a contentious issue. Measurement of airborne contaminants during the leak was intermittent and contained major gaps. The Aliso Canyon facility reopened on July 31, 2017. Four months later, a gasket failure led to a methane leak, and at least 15 residents noticed foul odors. As of early 2018, more than two years after the original blow-out, the Aliso Canyon facility operates at only 28 percent of its storage capacity, and the community still awaits the initiation of a mandated health study, which, independent researchers say, must include attention to sub-chronic, cumulative exposures.

By the spring of 2018 the California Council of Science and Technology has released a 910-page report analyzing the safety risks of all 14 facilities in the state that store gas in depleted oil fields. Among its findings: gas companies do not disclose the chemicals they are pumping underground; state regulators lack necessary information to assess risks; and many wells servicing the storage fields are 60 to 90 years old with no regulatory limit to the age of the well.[75]

LNG facilities—and the pipelines, coastal terminals, and ships that service them—are a growing component of fracking infrastructure as the shale gas boom has allowed the United States to seek long-term supply contracts for natural gas exports. In July 2017, the United Kingdom received its first delivery of LNG from the Sabine Pass export terminal in Louisiana. The Cove Point LNG export facility in Maryland is, as we go to press, preparing its first shipments of Marcellus Shale gas, destined for Japan and India. Five other U.S. LNG export terminals are in the planning stage.

LNG is purified methane in the form of a bubbling, super-cold liquid. It is created through the capital-intensive, energy-intensive process of cryogenics and relies on evaporative cooling to keep the methane chilled during transport. Explosive and with the ability to flash-freeze human flesh, LNG creates acute security and public safety risks. Its greenhouse gas emissions are 30 percent higher than conventional natural gas due to refrigeration, venting, leaks, and flaring, used to control pressure during regasification. The need to strip volatile impurities such as benzene from the gas prior to chilling it also makes LNG liquefaction plants a source of toxic air pollutants.[76-92]

8) Drilling and fracking activities can bring naturally occurring radioactive materials to the surface.

Exposure to increased radiation levels from fracking materials is a risk for both workers and residents. A study demonstrated that radon levels in Pennsylvania homes rose since the advent of the fracking boom, and buildings in heavily drilled areas had significantly higher radon readings than areas without well pads—a discrepancy that did not exist before 2004. University of Iowa researchers documented a variety of radioactive substances including radium, thorium, and uranium in fracking wastewater and determined that their radioactivity increased over time; they warned that radioactive decay products can potentially contaminate recreational, agricultural, and residential areas.

The New York State Department of Environmental Conservation's "Findings Statement" noted that naturally occurring radioactive materials (NORM) are brought to the surface "in the cuttings, flowback water and production brine. . . . [T]he build-up of NORM in pipes and equipment has the potential to cause a significant adverse impact because it could expose workers handling pipes, for cleaning or maintenance, to increased radiation levels." [36, 93-117]

9) The risks posed by fracking in California are unique.

Hydraulic fracturing in California is practiced differently than in other states, making its risks different, as well. Wells are more likely to be vertical rather than horizontal, and the oil-containing rock layer is shallower. Hence, much less water is used per well for fracking as compared to other states. However, the fracking fluid used is much more chemically concentrated, the fracking zones are located closer to overlying aquifers, and the risk of a fracture reaching groundwater is higher. California is the only state that allows fracking waste to be held in unlined, open pits, which creates risks for both air and groundwater contamination. As of January 2017, 1,000 such pits were operational, with 400 lacking required state permits. The vast majority are located in Kern County.[118] In 2014, the discovery that companies had, for years, been wrongly allowed to inject fracking waste directly into California's freshwater aquifers led to the closing of 175 disposal wells. Impacts on drinking water are unknown.[119, 120]

Most new fracking operations in California take place in areas with a long history of oil extraction. A high density of old and abandoned wells provides potential leakage pathways, should fractures intersect with them. And although fracking requires considerably less water per well in California, it takes place disproportionately in areas of severe water shortages and can compete with municipal and agricultural needs for freshwater.

The combination of ongoing drought and lack of disposal options has resulted in the diversion of fracking wastewater to farmers for irrigation of crops, raising concerns about contaminated water potentially affecting food crops and draining into groundwater. Investigative reports in 2015 revealed that Chevron Corporation piped 21 million gallons of recycled oil and gas wastewater per day to farmers for crop irrigation. Tests showed the presence of several volatile organic compounds, including acetone, which is linked, in lab studies, to kidney, liver, and nerve damage.[121, 122, 123]

These factors project fracking's impacts onto geographically distant populations, especially in cases when wastewater is diverted for use in crop irrigation and livestock watering. Food is a troubling possible exposure route to fracking chemicals, in part because so little is known about these chemicals. According to a hazard assessment of chemicals used in California oil drilling operations that reuse wastewater for livestock watering and other agricultural purposes, more than one-third of the 173 chemicals used are classified as trade secret. Their identities are entirely unknown. Of the remainder, ten are likely carcinogens, 22 are toxic air contaminants, and 14 had no toxicity data available. Estimating risks to consumers of the food produced with wastewater irrigation is thus not possible.[124]

The other area in California where fracking is concentrated, the Los Angeles Basin, is located directly under one of the most populous cities in the world. At least 1.7 million people in Los Angeles live or work within one mile of an active oil or gas well. California does not currently limit how close to residences or schools drilling and fracking activities can be conducted. A new study shows that many of the same chemicals used to stimulate wells during fracking operations are also used in urban oil wells located in densely populated areas of southern California.[125]

10) Fracking in Florida presents many unknowns.

Gas and oil drilling in Florida, now only a minor industry, is currently concentrated in two areas: the western Panhandle near Pensacola and the Everglades area of southwest Florida. So far, fracking has been used at least once—in 2013 at a test well located in the Corkscrew Swamp Sanctuary near Naples in Collier County. The Texas company that fracked this well, using high-pressure acid fracturing techniques to dissolve the bedrock, received a cease and desist order from the Florida Department of Environmental Protection.[126] Renewed interest in oil and gas exploration in Florida has prompted public debate about fracking and whether to promulgate state regulations or prohibit it outright.

Florida has more available groundwater than any other state; it is the drinking water source for 93 percent of Florida's population. Groundwater is also pumped to irrigate crops and provide frost protection to winter crops. Most of this water is held in the Floridan Aquifer, which extends across the entire peninsula and into parts of Georgia, Alabama, and South Carolina. This aquifer provides drinking water to ten million people in both rural and urban communities, including residents of several major cities: Gainesville, Jacksonville, Orlando, Tallahassee, and Tampa. Overlain by smaller, shallower aquifers in southern Florida, it is a highly permeable, highly interconnected subterranean system, with water moving rapidly in multiple directions through massive shelves of limestone, which represent the dissolved shells and fossilized skeletons of prehistoric marine organisms. Honeycombed with pores, fissures, joints, and caves, the underground terrain of the Floridan Aquifer resembles a vast, brittle, sponge partly covered with sand and clay. Springs and sinkholes are common.[127, 128]

It is not known whether fracking in Florida could induce sinkholes to open up or whether alterations in underground pressures could cause springs to go dry. Certainly, Florida's porous geology makes it vulnerable to groundwater contamination. Crumbly, soluble limestone offers pathways for contaminants spilled on the surface to travel deep into the aquifer, where they can be dispersed over great distances by the aquifer's river-like currents. A 2003 experiment with a dye tracer showed the special susceptibility of Florida's groundwater to potential contamination: within a few hours, the red dye traveled through the aquifer a distance (330 feet) that researchers had presumed would take days.[129]

Compounding these risks, Florida's exposure to hurricanes makes it vulnerable to spills of fracking-related chemicals. In August 2017, flooding from Hurricane Harvey shut down fracking sites in Texas and triggered 31 separate spills at wells, storage tanks, and pipelines.[130, 131, 132]

As of early 2018, it is unclear where Florida would send any potential fracking wastewater for treatment and/or for underground injection. Florida currently injects other types of liquid waste into disposal wells that are located above, rather than below, oil- and gas-producing zones. The injection of fracking waste in these same shallower layers may make earthquakes less likely than, for example, in Oklahoma (where it is injected into deep formations), but it would also locate that waste closer to the aquifers, which are poorly mapped. To undertake the necessary study to determine how securely Florida's geological formations could contain wastewater from drilling and fracking operations and protect drinking water would be, in the words of two geophysicists, "a monumental task requiring full-time work…for decades."[133] There are reasons to be concerned. In South Florida in the 1990s, 20 stringently regulated disposal wells failed and leaked sewage waste into the Upper Floridan Aquifer, a potential future source of drinking water for Miami.[134]

11) The economic instabilities of fracking further exacerbate public health risks.

Real-life challenges to the industry's arguments that fracking is good business are increasingly apparent. Independent economic analyses show that the promise of local job creation has been greatly exaggerated, with many jobs going to out-of-area workers. Reports show that oil and gas jobs will increasingly be lost to automation. With the arrival of drilling and fracking operations, communities have experienced steep increases in rates of crime, including sex trafficking, rape, assault, drunk driving, drug abuse, and violent victimization—all of which carry public health consequences, especially for women. Social costs include road damage, failed local businesses, and strains on law enforcement and municipal services. School districts report increased stress. Economic analyses have found that drilling and fracking threaten property values and can diminish tax revenues for local governments. Additionally, drilling and fracking pose an inherent conflict with mortgages and property insurance due to the hazardous materials used and the associated risks.

Throughout its history, the tempo of drilling and fracking operations in the United States has fluctuated markedly. Since 2014, when oil prices dropped precipitously, oil and gas operations have struggled to make a profit. In March 2016, the number of working gas rigs fell to its lowest level since record-keeping began in 1987. Downturns, however, do not necessarily translate into less risk and exposure to harm for those living in frontline communities. In spite of fewer drill rigs, injections of fracking wastewater increased in Ohio by 15 percent in 2015, likely because operators began drilling wells with longer lateral pipelines to access more gas or oil per well, generating more waste even as the pace of drilling slowed.[135] Indeed, according to data provided to investors, the average amount of water used to frack a single well has more than doubled between 2013 and 2016 due to longer laterals and more intensive fracking.

Further, orphaned wells left behind by industry during energy price downturns or after bankruptcy are poorly monitored and, as conduits for gas and fluid leakage, become health and safety threats. Some have exploded.[136]

In 2017, the rate of active shale gas drilling in the United States was, once again, on the upswing.[137] In spite of this uptick, output from two major basins has fallen, likely because easyto-access gas has already been extracted.[138] Because the production of individual wells declines precipitously over the course of a few years, operators must continue drilling new wells at a rapid pace to maintain output.

The unstable economic fundamentals of the industry as a whole have multiple consequences for public health and safety as cumulative impacts mount from wells, both old and new. Weak prices, difficulty generating positive cash flow, short-lived well production, and falling out have led drilling companies to reduce the value of their assets by billions of dollars. Concerns arise that these losses will lead to large-scale firings, cutbacks in safety measures, and landscapes pock-marked by hastily abandoned wells in need of remediation and long-term monitoring.

12) Fracking raises issues of environmental justice.

Inequalities in opportunities to participate in environmental decision-making and uneven impacts of environmental hazards along racial and socioeconomic lines are signature issues of environmental justice. Although not yet fully characterized, emerging evidence reveals that, in several regions where fracking is practiced, well pads and associated infrastructure are disproportionately sited in non-white and low-income communities.

A pattern of racially biased permitting was documented in the heavily fracked Eagle Ford area of southern Texas where a public health research team showed that disposal wells for fracking wastewater were more than twice as common in areas where residents are more than 80 percent people of color than in majority white communities.[139] Since 2007, more than 1,000 waste disposal wells have been permitted in the Eagle Ford Shale region where groundwater is the primary source of drinking water.[140] Another recent study looked at economic disparities in the intensely drilled northern Texas city of Denton and found that those benefiting most from Denton's mineral wealth tended to live elsewhere, while the environmental burdens remained local and fell hardest on those who did not have a voice in mineral-leasing decisions. "Nonmineral owners are essentially excluded from the private decisions, as the mineral owners not only receive the direct monetary benefits, but also hold a great deal of state-sanctioned power to decide if and how [shale gas development] proceeds."[141]

Poor communities of color are disproportionately affected by drilling activities in California. Of Los Angeles residents living within a quarter mile of a well, more than 90 percent are people of color. In November 2015, civic groups led by youth sued the city of Los Angeles for racial discrimination based on allegations of a preferential permitting process and unequal regulatory enforcement for oil wells located in neighborhoods of color. Together, these differential practices have resulted in a higher concentration of wells with fewer environmental protections in black and Latino communities.[142] South Coast Air Quality Management District records show that oildrilling operations in Los Angeles neighborhoods released into the air 21 million pounds of toxic chemicals between June 2013 and February 2017. These emissions included crystalline silica, hydrofluoric acid, and formaldehyde.[143] Across California, gas-fired power plants are disproportionately located in disadvantaged communities, as classified by an environmental justice screening tool developed by the state Office of Environmental Health Hazard Assessment.[144]

Another study found a higher concentration of drilling and fracking operations in impoverished communities throughout the state of Pennsylvania as well as in localized areas of West Virginia, but it did not find differences with respect to race. "The results demonstrate that the environmental injustice occurs in areas with unconventional wells in Pennsylvania with respect to the poor population."[145] These findings are supported by census tract data in western Pennsylvania showing that among nearly 800 gas wells, only two were drilled in communities where home values exceeded $200,000.[146]

13) Health professionals are increasingly calling for bans or moratoria on fracking, based on a range of potential health hazards and as reviews of the data confirm evidence for harm.

In May 2015, the Medical Society of the State of New York passed a resolution recognizing the potential health impacts of natural gas infrastructure and pledging support for a governmental assessment of the health and environmental risks associated with natural gas pipelines.[147] The American Medical Association (AMA) adopted a similar resolution that supports legislation requiring all levels of government to seek a comprehensive Health Impact Assessment regarding the health and environmental risks associated with natural gas pipelines.[148]

In May 2016, Physicians for Social Responsibility called for a ban on fracking.[149] In July 2016, the UK health professional organization Medact released an updated assessment of the potential health impacts of shale fracking in England, concluding that the United Kingdom should abandon its policy to encourage shale gas extraction, and urged an "indefinite moratorium" on fracking.[150] In October 2016, a group of health care professionals in Massachusetts called for an immediate moratorium on major new natural gas infrastructure until the impact of these projects on the health of the communities affected can be adequately determined through a comprehensive Health Impact Assessment.[151] The group noted that the operation of natural gas facilities risks human exposures to toxic, cancer-causing, and radioactive pollution due to the presence of naturally co-occurring contaminants, toxic additives to the hydraulic fracturing process used to produce much of the country's natural gas supply, and through the operation of transmission pipelines.

Also in 2016, in a unanimous vote of the society's 300-member House of Delegates, the Pennsylvania Medical Society called for a moratorium on new shale gas drilling and fracking in Pennsylvania and an initiation of a health registry in communities with pre-existing operations.[152, 153] In February 2017, health officials in Los Angeles called for a comprehensive health study in the aftermath of the massive methane leak in Aliso Canyon.[154]

Concerned Health Professionals of New York, which provided scientific and medical guidance for the successful effort to ban fracking in New York State, has inspired affiliations of likeminded public health scientists and health care providers that have been advocating for moratoria or bans on fracking in various other regions. These include Concerned Health Professionals of Maryland, Concerned Health Professionals of Ireland, and Concerned Health Professionals of Neuquén, Argentina. Other U.S. medical groups calling for bans or moratoria include Chesapeake PSR and the Alliance of Nurses for Healthy Environments.

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Should We Mine the Deep Seafloor?

Stace E. Beaulieu, T. E. Graedel, and Mark D. Hannington

1. Introduction

Resources such as sand, gravel, diamonds, tin, and gold already are extracted from the shallow seabed [Hannington et al., 2017], and the oil and gas industry recently has moved into water depths approaching 3000 m. However, there has been no deep-sea mining thus far. With growing concerns about the scarcity of metals (e.g., European Commission [2014]), due in part to increased demand for a diversity of metals in today's products, declining grades of resources on land [Calvo et al., 2016], and concerns about security of supply [Northey et al., 2014], we are now faced with the question—Should we mine the deep seafloor? A number of different countries and some commercial companies certainly are moving in that direction. The world's first deep-sea mining lease within an Exclusive Economic Zone was granted in 2011 by the government of Papua New Guinea, and as of 2017, 27 exploration contracts for "the Area" beyond national jurisdiction had been issued by the International Seabed Authority (ISA). Draft Exploitation Regulations for the Area were released by the ISA for public comment in November 2016, and in March 2017 the ISA convened an expert group of scientists to discuss the first working draft Environmental Regulations.

Mineral resources on the deep seafloor are poised to contribute to the supply of some metals, if numerous conditions are met: namely, that the resources have been evaluated adequately, that marine ecosystem impacts can be assessed and mitigated, and that adequate legal structures are promulgated to assure clear title and responsible approaches to exploitation. The question—Should we mine the deep seafloor? —is being closely examined by natural and social scientists around the globe. For some people who wish to see an end to land-based mining the answer is "yes"; for others who say that we cannot risk negative impacts on a vast understudied part of our planet, the response is a resounding "no." There are huge uncertainties on all aspects of the debate—including land-based supplies, the scope of future demand, seafloor resource potential, and impacts on ecosystems and their services that contribute to human well-being.

We (the authors of this Commentary) posed this question at a session of the American Association for the Advancement of Science [Graedel et al., 2017]. As natural scientists with expertise in critical metals, seafloor geology, and deep-sea ecosystems, we wanted to explore the best available, objective, scientific evidence to inform the question—Should we mine the deep seafloor? Our goal was to provide a dispassionate review of what is motivating different responses to the question.

2. Uncertainties

The uncertainties have been difficult to address objectively, and the situation analysis for the technical, economic, and environmental feasibility of the proposed industry remains incomplete. Are there enough resources to make a difference? Are they the resources that we need? Do we fully understand the risks to the marine environment? Some consider that the resources are nearly boundless, especially manganese nodules in places such as the Clarion Clipperton Zone (CCZ) in the Pacific (Figure 1). Machines have been built to recover nodules and to mine massive sulfides, although complete mining systems have not yet been fully tested. Challenges of working in the deep sea have been largely overcome by the oil and gas industries. So, what is holding back the emergence of the industry? The return on investment remains a major question. Can the minerals be exploited at a cost that is competitive with land-based mining? Nobody knows, because there are no deep-sea mining operations yet that could serve as economic benchmarks. Also, it remains unclear to what extent a precautionary approach to

Figure 1. Total area of exploration licenses for manganese nodules in the Clarion-Clipperton Zone (CCZ; ~1.1 million km2) compared to the area of Europe. Image credit: GEOMAR Helmholtz Center for Ocean Research Kiel.

the protection of the marine ecosystems would be applied [Mengerink et al., 2014].

Under some scenarios, traditional land-based supplies of resources may be challenged to meet future demand [Ali et al., 2017]. For example, a number of different scenarios for copper demand suggest that by mid-century significant new resources will be needed to enable a better quality of life for people in developing countries [Elshkaki et al., 2016]. The developed world will require mineral resources for widespread implementation of "green" technologies. Estimates of the abundance of manganese nodules in the CCZ suggest that, if recoverable, they could satisfy current demand for manganese, nickel, cobalt, and copper for decades. Seafloor massive sulfide deposits represent a smaller resource but are characterized by much higher grades of metals, including copper, zinc, silver, and gold [Petersen et al., 2016]. It remains unclear, however, whether the sizes and quality of deep-sea deposits would be sufficient to support a new mining industry [Petersen et al., 2016; Hannington et al., 2017].

With a better understanding of the structure and dynamics of deep-sea ecosystems, it is thought that we could design monitoring and protected area networks to reduce impacts [Wedding et al., 2015; Danovaro et al., 2017]. An international survey recently gathered expert opinion to better predict risks from the direct and indirect effects of seabed mining [MIDAS Consortium, 2016]. Concerns remain about sustainable approaches to exploiting the known seabed resources, and whether their development is worth the ecological risk. Environmental impacts in many of the targeted habitats are likely to be long-lasting [MIDAS Consortium, 2016], especially for the ecosystems of relatively quiescent abyssal plains where manganese nodules occur [Jones et al., 2017] and on ferromanganese-encrusted seamounts (some of which are already protected; Figure 2). Catastrophic natural disturbances have been observed at a few hydrothermal vent fields (e.g., Mullineaux et al., [2010]), but the vulnerability and resilience of these ecosystems at active sulfide deposits remain poorly known in a broad range of tectonic and geologic settings. Also, we know very little about ecosystem structure and dynamics at inactive massive sulfide deposits where impacts might be more severe [Van Dover, 2011]. In addition to environmental impacts, there are potential costs to society of lost or degraded ecosystem services. Recent research is identifying the array of services from deep-sea ecosystems [Le et al., 2017], that may have value through direct or indirect use or through conservation (nonuse).

3. Looking Ahead

In only 3 years since scientists called for deep-ocean stewardship [Mengerink et al., 2014], the number of exploration contracts granted by the ISA has more than doubled. Both short- and long-term prospects for deep-sea mining continue to be explored. Yet, the tipping point in terms of economic, scientific, technological, and regulatory advances has not been reached. Although seabed mining off Papua New Guinea is proposed within a couple years [Nautilus Minerals, 2016], there may be time to address some of the uncertainties before any large-scale mining begins. Among the challenges is to establish the resource potential of the deep sea with much greater confidence before the demand for those resources becomes immediate. Even if all of the license areas currently being explored were completely mapped, the cumulative surveys would represent less than 0.5% of

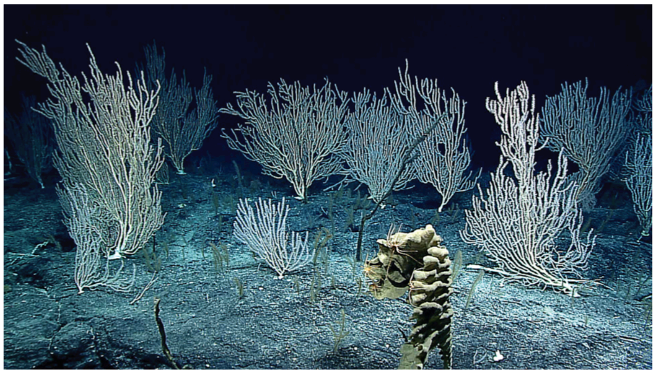

Figure 2. Deep-sea corals at a ferromanganess-encrusted seamount in the Pacific Remote Islands Marine National Monument (PRIMNM). Expanded in 2014, PRIMNM is one of the largest marine protected areas in the world (~1.3 million km^2). Image credit: NOAA Office of Ocean Exploration and Research, Deepwater Wonders of Wake.

the global ocean area. Making informed decisions about how to manage resources in the remaining 99.5% cannot be made without enhanced and continuing exploration of the deep sea.

Whether one answers "yes" or "no" today to mining of the deep seafloor, it is clear that many aspects of resource extraction and environmental regulation are simply inadequately informed to make decisions if doing so becomes a necessity in the future. If we need to acquire new resources, then we need to know where (and when) that exploitation might occur. Pilot tests for mining operations should not be solely for the development of technologies and capacity building, but they also should be designed to better understand responses of ecosystems to disturbances and to inform environmental monitoring and the design of networks of protected areas [Danovaro et al., 2017; Jones et al., 2017]. Environmental regulations are being developed with great uncertainties about resource potential and ecosystem structure, dynamics, and services. Regulations need to be flexible enough to accommodate new knowledge from scientific research that may dramatically change our view of the global ocean resource potential. For example, mineral resources beyond the mid-ocean ridges and on continental margins [Petersen et al., 2016; Hannington et al., 2017], or other potential benefits that humans may receive from the deep ocean such as discoveries that lead to new medicines, may be important considerations for the future. Biological resource potential is being considered in the development of an international legally binding instrument under the United Nations Convention on the Law of the Sea on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction, in particular marine genetic resources [United Nations 2015a]. Natural and social scientists will need to work together to evaluate deep-sea ecosystem services, and this should be part of the cost–benefit analysis for mining projects.

An important related topic is that challenges and opportunities for deep-sea mining straddle several of the United Nations Sustainable Development Goals, including Goal 9 to build infrastructure "with a focus on affordable and equitable access for all;" Goal 10 to reduce inequality; and Goal 14 to conserve and sustainably use the ocean and its resources [United Nations, 2015b]. As noted by Ali et al. [2017], attaining these goals will inevitably "require minerals for infrastructure, but scant attention has been paid to the science and policy needed to meet these targets." A more equitable world appears to require large and continuing supplies of mineral resources (e.g., Elshkaki et al. [2016]), but sustainable development may require a move away from resource-intensive life styles and thus from the high and growing levels of per capita demand. The answer to the question—Should we mine the deep seafloor? —will depend on the interpretation of all of these goals and the steps taken to achieve them.

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Announcements

American Water Resources Association

2018 Spring Specialty Conference: GIS and Water Resources
April 22 - 25, 2018. Orlando, FL
http://www.awra.org/meetings/Orlando2018/index.html

This is the 10th in a series of conferences designed around geospatial solutions to water resources-related problems. Innovative water resources scientists, engineers, modelers, software designers from public/ government agencies, academic and private sectors convene to exchange ideas, compare challenges and identify solutions using process models, geo-referenced field data, remote sensing, or geostatistical models.

Summer Specialty Conference: Managing Transboundary Groundwater
July 9 - 11, 2018. Fort Worth, TX
http://www.awra.org/meetings/FortWorth2018/index.html

Growing populations and economies will increase competition for water resources around the world. Since water resources respect no political boundaries - sometimes not even intra-national or intra-state boundaries - equitable agreements to govern, manage, and protect these resources are essential to the social and economic well-being of all water users. The conference will provide attendees the opportunity to learn about and engage in discussions on innovative approaches for identifying transboundary groundwater resources and the methods to develop sustainable governance and management agreements.

2018 Annual Conference
November 4 - 8, 2018. Baltimore, MD
http://www.awra.org/meetings/Baltimore2018/index.html

This conference will convene water resource professionals and students from throughout the nation and will provide attendees the opportunity to learn about and engage in multi-disciplinary water resource discussions. The program will stimulate conversations on water resource management, research and education. The 2018 conference will also include locally relevant topics such as the Chesapeake Bay, the Delaware River watershed, and eastern water law as well as globally significant issues such as coastal resilience, fire effects on watersheds, communication and outreach strategies and integrated water resources.

American Meteorological Society

2018 Washington Forum
April 24 - 26, 2018. Washington, DC
https://www.ametsoc.org/ams/index.cfm/meetings-events/ams-meetings/2018-ams-washington-forum/

This annual event provides an important platform to examine public policy issues across the weather, water and climate sciences. The Washington Forum broadens and fosters the AMS mission of advancing of atmospheric and related sciences, technologies, applications, and services for the benefit of society.

AMS 33rd Conference on Agricultural and Forest Meteorology/12th Fire and Forest Meteorology Symposium/ Fourth Conference on Biogeosciences.
May 14–17 2018, Boise, ID
https://www.ametsoc.org/ams/index.cfm/meetings-events/ams-meetings/33agforst-12fire-4biogeo/

The theme for the 33rd Conference on Agricultural and Forest Meteorology is "Exploring the Intersection of Landscape Disturbance and Atmosphere/Biosphere Interactions," and will examine different aspects of ecosystem-atmosphere interactions. The theme of 12th Fire and Forest Meteorology Symposium symposium will be research, new techniques and technologies and/or changes in the areas such as the utilization of weather and climate information in relation to wildland fire and operational forecasting (short- to long-term) of fire weather. The theme for the Fourth Conference on Biogeoscience is "Exploring the Intersection of Landscape Disturbance and Atmosphere/Biosphere Interactions," and will examine aspects of surface-atmosphere interactions.

AMS 18th Conference on Mountain Meteorology.
June 25-29, 2018. Santa Fe, New Mexico
https://www.ametsoc.org/ams/index.cfm/meetings-events/ams-meetings/18th-conference-on-mountain-meteorology/

The 18th Conference on Mountain Meteorology, sponsored by the American Meteorological Society (AMS) and organized by the AMS Committee on Mountain Meteorology will examine topics ranging from mountain climate and hydrology and new or emerging topics in mountain meteorology, to mountain waves and terrain induced windstorms.

10th International Conference on Urban Climate/14th Symposium on the Urban Environment
August 6 - 10, 2018. New York, NY
https://www.ametsoc.org/ams/index.cfm/meetings-events/ams-meetings/10th-international-conference-on-urban-climate-14th-symposium-on-the-urban-environment/

This conference comes at a time when accelerated urban development is challenged by the risks and consequences of extreme weather and climate events and global socio-economic disparity. Resiliency and reduced vulnerability to all socio economic sectors have become critical elements to achieve sustainable development. The conference theme is Sustainable and Resilient Urban Environments.

AMS 29th Conference on Severe Local Storms.
October 22-16, 2018. Stowe, VT
https://www.ametsoc.org/ams/index.cfm/meetings-events/ams-meetings/29th-conference-on-severe-local-storms/

This conference will feature experts on topics related to severe local storms and associated hazards of tornadoes, large hail, damaging winds, lightning, and flash floods.

AMS 99th AMS Annual Meeting.
January 6-10, 2019. Phoenix, AZ.
https://annual.ametsoc.org/2019

Join fellow scientists, educators, students, and other professionals from across the weather, water, and climate community in Phoenix, Arizona from 6–10 January, 2019 to share, learn, and collaborate. This year's theme is "Understanding and Building Resilience to Extreme Events by Being Interdisciplinary, International, and Inclusive (III)."

Geological Society of America

GSA Joint Section Meeting: Rocky Mountain and Cordilleran

May 15 -17, 2018. Flagstaff, AZ
https://www.geosociety.org/GSA/Events/Section_Meetings/GSA/Sections/rm/2018mtg/home.aspx

GSA has devised a diverse technical program and field trips that explore the geology of the Southwest and span from modern to ancient processes, and from environmental problems to tectonics, geophysics, paleontology, climate, education, and more. The meeting include sessions on planetary geology and Southwest rivers that build on the strong legacy and current expertise of the local U.S. Geological Survey.

Annual Meeting & Exposition

November 4 - 7, 2018. Indianapolis, IN
http://community.geosociety.org/gsa2018/home

This annual meeting will highlight Indiana area geology as well as the wider world of geoscience research.

American Society of Civil Engineers

World Environmental & Water Congress.

June 3 - 7, 2018. Minneapolis, MN
https://www.ewricongress.org/

The Environmental & Water Resources Institute (EWRI) is the recognized leader within ASCE for the integration of technical expertise and public policy in the planning, design, construction, and operation of environmentally sound and sustainable infrastructure impacting air, land and water resources. Join leading environmental and water resource professionals to discuss the latest topics in water resources.

Society of Environmnetal Toxicology and Chemistry

2018 Asia-Pacific Conference

September 16 - 19, 2018. Daegu, South Korea
http://setac-ap2018.org/

This conference is dedicated to provide highly scientific programs as well as stimulating discussion under the main theme "Data, Science, and Management Promoting Environmental Welfare". In Daegu, experts from different fields of academia, business, and regulatory communities and large student community will take a part of the conference to provide a multidisciplinary and comprehensive overview of the latest researches with advanced solutions to environmental challenges.

North America Annual Conference.

November 4 -8, 2018. Sacramento, CA
https://sacramento.setac.org/

This meeting will explore the link between sustainable economic development and environmental stewardship, with particular focus on ecological and societal considerations. In this context, stewardship represents the practice of transforming sustainable thinking into action. However, we are challenged to decouple the historical connection between economic growth and ecological integrity, and the resultant societal effects. This meeting offers opportunities to feature the connections between desired ecosystem goods and services, stable flourishing societies and sustainable economies.

American Society for Landscape Architects

2018 Annual Meeting
October 19 -22, 2018. Philadelphia, PA
https://www.asla.org/annualmeetingandexpo.aspx

The ASLA annual meeting will feature a diverse spectrum of industry experts providing perspectives on a wide range of subjects, from sustainable design to active living to best practices and new technologies. More than 130 education sessions, field sessions and workshops will be presented during the meeting.

American Geophysical Union

Geoscience and Society Summit
September 23 – 28, 2018. Hamilton, Bermuda
https://connect.agu.org/gss/home

The Summit aims to create a highly interactive forum for effective cooperation between scientists and users of scientific information to tackle global and local challenges around sustainability of natural resources and systems, global health, and resilience.

Fall Meeting
December 10 - 14, 2018 Washington, DC
https://fallmeeting.agu.org/2018/

The AGU 2018 Fall Meeting provides an opportunity to share science with world leaders in Washington, D.C. As the largest Earth and space science gathering in the world, the Fall Meeting places participants in the center of a global community of scientists drawn from myriad fields of study whose work protects the health and welfare of people worldwide, spurs innovation, and informs decisions that are critical to the sustainability of the Earth.

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