Mitigating Climate Change at the Carbon Water Nexus: A Call to Action for the Environmental Engineering Community

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Received: September 6, 2016

Accepted in revised form: September 7, 2016

Abstract

Environmental engineers have played a critical role in improving human and ecosystem health over the past several decades. These contributions have focused on providing clean water and air as well as managing waste streams and remediating polluted sites. As environmental problems have become more global in scale and more deeply entrenched in sociotechnical systems, the discipline of environmental engineering must grow to be ready to respond to the challenges of the coming decades. Here we make the case that environmental engineers should play a leadership role in the development of climate change mitigation technologies at the carbon-water nexus (CWN). Climate change, driven largely by unfettered emissions of fossil carbon into the atmosphere, is a far-reaching and enormously complex environmental risk with the potential to negatively affect food security, human health, infrastructure, and other systems. Solving this problem will require a massive mobilization of existing and innovative new technology. The environmental engineering community is uniquely positioned to do pioneering work at the CWN using a skillset that has been honed, solving related problems. The focus of this special issue, on “The science and innovation of emerging subsurface energy technologies,” provides one example domain within which environmental engineers and related disciplines are beginning to make important contributions at the CWN. In this article, we define the CWN and describe how environmental engineers can bring their considerable expertise to bear in this area. Then we review some of the topics that appear in this special issue, for example, mitigating the impacts of hydraulic fracturing and geologic carbon storage, and we provide perspective on emergent research directions, for example, enhanced geothermal energy, energy storage in sedimentary formations, and others.

Keywords: carbon water nexus; climate mitigation; emerging research directions

Introduction

CLIMATE CHANGE IS UNLIKE ANY PROBLEM that environmental engineers have ever faced (Pachauri and Reisinger, 2007). It will have profound and far-reaching impacts on most of the economic, social, and physical infrastructure on which our societies are built (Weitzman, 2009). Average global temperatures are projected to increase between 2°C and 6°C before 2100, and some of that warming is already being observed as we continue to break heat records (Meehl and Tebaldi, 2004). Most of us alive today will experience some portion of that temperature increase and will observe firsthand

the effects it will have on species loss, hydrologic cycles and weather, agriculture, and the built environment. Perhaps even more apparent will be the ripple effects these changes will have on social patterns such as conflict, migration, and other consequences of natural stressors (Vorosmarty, 2000).

To engineers like us, the technological approaches for managing climate change, for example, deployment of carbon neutral energy and carbon capture and storage, may seem straightforward, but are limited primarily by overarching political and economic constraints (Bellamy, 2015). For this and other reasons, one research direction has been to develop technologies that will help us better *adapt* to this brave new climate. Research and development in the broad area of climate adaptation will be an undoubtedly important area of scholarly and industrial pursuit over the coming decades. Learning to live and successfully operate societies on a planet that is a few degrees warmer will be more complex than we can fully appreciate today (Davis *et al.*, 2010). Of course, conversations about adaptation are predicated on significant and parallel efforts to decarbonize our economy to slow the underlying driver of this temperature increase. Unfortunately, our current pace of decarbonization is insufficient, making

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temperature increase past the end of the 21st century increasingly likely (Moss *et al.*, 2010). At some point, adaptation ceases to be an adequate strategy.

Environmental engineers have an opportunity to be leaders in developing climate mitigation technologies that will help slow the warming and heal the planet. This article presents our view on the ways in which environmental engineers might make critical contributions within what we are calling the carbon-water nexus (CWN). The CWN relates to those natural and engineered physicochemical processes that exist at the interface between greenhouse gas emissions and water cycles. Developing technologies to mitigate the impact of emissions at the CWN will be critical to develop long-term strategies for managing climate change.

While anthropogenic climate change is being driven by changes to the carbon cycle, one of the most immediate ways in which we will observe this impact is on the hydrologic cycle (Barnett *et al.*, 2005). A warmer atmosphere will alter precipitation patterns, reduce freshwater reserves, and drive extreme weather. Efforts to manage our carbon emissions will have important implications on water cycles.

Environmental engineers are especially well positioned to become leaders in research and innovation at the CWN for at least three reasons. First, environmental engineers have extensive experience in the scientific domains needed to design technologies in this space such as water chemistry, environmental microbiology, groundwater and surface water hydrology, and atmospheric chemistry. Second, environmental engineers have a history of understanding large-scale (e.g., field scale) systems, and meaningful efforts to mitigate climate change will need to alter large-scale systems to make a difference. Third, environmental engineers have developed the skills to think about complex environments using the tools of systems engineering and the ways in which proposed technologies will interact with multiple systems (Burnham *et al.*, 2011).

The environmental engineering community could, for example, take a leadership role by advancing efforts to:

1. Use the tools of multiphase flow in porous media and subsurface hydrology to develop large-scale energy storage in sedimentary formations.
2. Use the tools of geochemistry to engineer accelerated weathering processes that would transform carbon into a stable carbonate, while creating valuable materials that could be used in other engineering applications.
3. Use the tools of subsurface hydrology to engineer reservoirs such that enhanced geothermal energy resources can be deployed economically.
4. Use the tools of water treatment to recover resources, such as nutrients and metals, to create new markets and avoid the production of virgin resources.
5. Use the emerging tools of synthetic biology to manipulate carbon cycling in microbial communities, such as abating CH₄ emissions from abandoned coal and natural gas regions, as well as landfills.
6. Use the tools of soil chemistry to develop carbon black or other novel particles that could help improve the carbon balance in soils.
7. Use the tools of membrane separations or ion exchange resins to develop methods to generate power

from salinity gradients or create novel water treatment techniques for produced water from unconventional oil and gas activities.

8. Use the tools of life cycle assessment to explore efficiencies for producing low-carbon liquid fuels from biomass feedstocks without increasing overall water use.
9. Use the tools of atmospheric aerosol chemistry to understand the connections between air quality, the water cycle, changing temperature, and regional climate such that we can better control the role that conventional air pollutants play on regional climates.

This list is intended to be illustrative rather than exhaustive and we envision that there are dozens of other applications in which environmental engineers could make important and high-impact contributions to climate change mitigation. Figure 1 provides a schematic that illustrates a few examples of ways in which engineering of the carbon cycle will impact water in both natural and engineered systems.

Since its inception, the discipline of environmental engineering has had a clear mandate to advance technologies that protect human and environmental health. Environmental engineering has ties to chemical engineering, mechanical engineering, civil engineering, earth sciences, and public health, and its practitioners have historically applied the fundamental principles of chemistry, biology, and engineering to develop solutions to environmental problems. Environmental engineers have worked on a suite of evolving, but related, problems that have grown in scope as our understanding of environmental hazards has grown. These activities were generally tied to major environmental legislation in developed nations. In the United States, for example, the Clean Air Act (CAA), Clean Water Act (CWA), Safe Drinking Water Act (SDWA), Resource Conservation and Recovery Act (RCRA), and Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) all spurred major research and development efforts with far-reaching impacts. Even in the absence of major new environmental legislation, new cross-disciplinary research areas have emerged, including efforts on sustainability science, resilience, and research at the energy-water nexus. We feel that the CWN is related to, but independent of these areas in general and the energy-water nexus in particular. The scientific richness and societal importance of the CWN plays to the strengths of environmental engineering as a discipline. Other related areas of inquiry have been a high priority over the past several years. Interest in energy, water, and food has led to interesting research at the nexuses between the following:

- Water and health, wherein water quantity and quality stresses suggest that water reuse must become the new paradigm in increasingly water-stressed and populated regions.
- Carbon-intensive infrastructure and climate, wherein large-scale infrastructure decisions lock us into long-term greenhouse gas emission profiles at the same time that these infrastructure systems are the most susceptible to extreme weather.
- Agricultural systems and climate stressors, wherein the production of food, fiber, and fuel produces direct and

FIG. 1. Intersection between the carbon cycle and the water cycle with possibilities for research at the carbon-water nexus. Environmental engineers stand to make critical research contributions in a number of ways. In this study, the numbered areas correspond to those in the text and the starred areas are covered in this special issue.

indirect emissions, but changes in temperature profoundly alter our agricultural practices and productivity.

- Energy and water, wherein heightened water scarcity could put the dominant means of producing thermoelectric or hydroelectric power at risk.
- Food and water, wherein intensive agriculture practices are leading to widespread environmental degradation and changes to nutrient cycling, which pit human needs with ecosystem services.

To examine the relative focus of research on these areas, we enumerate the grants recently awarded from the Division of Chemical, Bioengineering, Environmental, and Transport Systems within the Engineering Directorate at the National Science Foundation (NSF). Figure 2 shows the number of grants (active in 2016) that pertain to the nexus of climate and each of the focus areas above. This is not a perfect metric of funding activity within environmental engineering, but many environmental engineers do receive funding from this division, and the Environmental Engineering Program is one of the single largest programs within the division.

FIG. 2. Active National Science Foundation grants from the CBET Division in the Engineering Directorate that include “climate adaptation” plus the keyword in the axis. CBET, Chemical, Bioengineering, Environmental, and Transport.

This graph suggests that the research community is making high-impact discoveries in most areas of climate change adaptation, but there remains a need for an increased focus on climate change mitigation. A big part of this is the nexus of carbon and water and it is where environmental engineers have an opportunity to be research leaders.

The importance of the CWN was reflected in a recent series of workshops funded by the NSF and organized by the Association of Environmental Engineering and Science Professors (AEESP) entitled “Redefining Environmental Engineering and Science.” The workshops were designed to engage the U.S. academic community in rethinking ways the discipline can align its research and teaching agenda with emergent environmental challenges over the coming decades. The workshops were also designed to coincide with the planning for a National Research Council (NRC) initiative focused on defining the “Grand Challenges in Environmental Engineering.” That effort, which will be completed in the coming years, will be analogous to the influential National Academy of Engineering’s report on “Grand Challenges in Engineering,” which helped drive strategic investments in research and development broadly. At the NSF-AEESP workshops, participants were asked to prioritize environmental challenges in terms of the level of effort and funding that should be directed toward research and compare this with current levels devoted to these challenges within their own department. Workshop participants consistently identified research on “climate change impacts and adaptation” as the highest priority for future environmental research, while also indicating that it was clearly not reflective of the current distribution of research activities within their own organizations. This suggests that research related to climate change impacts and adaptation is presently underrepresented in the environmental engineering research landscape, but that this is an area that will be of critical importance in the coming decades.

While clearly pointing to climate change as an important area for environmental engineering, the findings of the

AEESP workshops do not differentiate between climate change adaptation and mitigation. Efforts to respond to the climate change challenge through mitigation can be broadly classified into two types, (1) pollution prevention, in which new technologies are developed to replace carbon-intensive ones or (2) “geoengineering” (aka “climate engineering”), which includes efforts to change greenhouse radiative forcings by taking carbon out of the atmosphere or altering the albedo of the planet. It is worth noting here that “pollution prevention” was a term first developed several decades ago at a time when greenhouse gas emissions were not typically discussed along with more conventional air and water pollutants. However, the spirit of the term is appropriate in this context and indeed the legal definition of pollutant has expanded over the past decade to include Greenhouse Gas Emissions (GHGs). In 2007, the Supreme Court ruled in *Massachusetts versus the U.S. Environmental Protection Agency* (EPA) that greenhouse gases are covered by the CAAs definition of air pollutant, which is an air pollutant that endangers public health and welfare. The next year, Congress passed legislation requiring that the EPA start a program for mandatory reporting of greenhouse gases from all sectors of the U.S. economy. In 2009, the EPA Administrator signed the “Endangerment Finding,” which was that greenhouse gases in the atmosphere threaten the public health and welfare of people. Because of this, the EPA had the legal authority to take actions about greenhouse gases under the CAA.

Pollution Prevention

Efforts to reduce the emissions from the transportation and electric power sectors have been led by the mechanical engineering community as they pursue efforts to harvest wind and tidal energy sources, design more energy-efficient vehicles, and improve on the efficiency of power plants. Electrical engineers and material scientists are making critical advances in batteries and photovoltaics. Civil engineers are developing new materials and methods to advance green building practices. Chemical engineers have made important innovations in biofuels and fuel cell technologies. And computer science and engineering is making dramatic advances in cyber physical systems, sensing, and optimization as it relates to a variety of infrastructure systems. Collectively, these technologies suggest that a smarter and carbon-neutral infrastructure paradigm could be adopted in the coming decades; however, given the long-design life of most infrastructure, this transition will be slow. In the meantime, existing infrastructure investments have locked us into a number of decades of legacy carbon emissions from anthropogenic sources such as power plants, cars, and manufacturing facilities.

Climate Engineering

Climate engineering, or geoengineering as it is often called, refers to any large-scale effort to engineer the climate by changing either the mass or energy balance that is contributing to global warming. Efforts to impact the mass balance might include carbon sequestration technologies, wherein CO₂ is injected into deep geologic formations for permanent storage. Other groups have explored the potential to fertilize large swaths of the ocean to stimulate phototrophic algae growth, which would eventually die and settle at the bottom of the ocean. Other negative emission technologies

could include direct air capture for storage in geologic formations, manipulation of the carbon cycle through soil management, advanced biofuels that do not contribute net fossil carbon in the course of production and combustion, and waste recapture, wherein wastewater, solids, and other materials are captured before they are released into the atmosphere. Efforts to impact the energy balance generally revolve around changing the albedo of the planet. These efforts could be as modest as painting impervious/paved surfaces white to reflect more sunlight back into space, but many also involve large-scale activities like the idea to seed clouds with particles that would reflect sunlight in the upper reaches of the atmosphere. All of these technologies could have unintended consequences, which are difficult to predict because they are impossible to experiment with at small scales. Most of the work in the geoengineering space is being led by environmental scientists, geological engineers, earth scientists, and hydrologists with experience working in the subsurface or climate scientists with the models needed to predict the impact of large-scale interventions in the atmosphere.

The Science and Innovation of Emerging Subsurface Energy Technologies

Many of the technologies discussed above are focused on research within the subsurface and so the theme for this special issue was selected as “The science and innovation of emerging subsurface energy technologies.” This is an important and active area of research as evidenced by a review of publication activity over the past several decades. Figure 3 provides a keyword search in the academic literature involving four of the classes of technology covered here. While some topics represented here, such as geologic disposal of waste from nuclear power activities, have been of great interest for many decades, others have grown in recent years. The article by Haynes *et al.* in this special issue provides new insights on ways to treat legacy impacts associated with uranium mining (Haynes and Clapp, 2016). The other articles in this special issue are largely focused on two broad areas,

FIG. 3. Historical and projected research emphasis as measured by publication record on several subsurface engineering areas. In this study, the number of articles published per year where the “topic” was one of the four listed here (e.g., Groundwater remediation).

hydraulic fracturing of unconventional fossil fuels and geologic storage of CO₂.

Geologic Carbon Sequestration

Investigation of strategies for secure storage of carbon emissions in deep porous formations has been widespread for over two decades (Bachu and Adams, 2003). The idea of injecting CO₂ into the ground instead of releasing it into the atmosphere is fairly well understood and is largely based on technological principles that already exist in established industries such as oil and gas (Bruant *et al.*, 2002). In 2008, a G8 summit set ambitious goals for global commercial readiness by 2020, accelerating the pace of research and injection demonstrations around the world (Meinshausen *et al.*, 2009). In 2014, the Intergovernmental Panel on Climate Change released a report that identified scenarios for stabilizing the earth's temperature (IPCC, 2014). It was concluded unequivocally that carbon capture and sequestration is a key technology without which it is very unlikely that climate stabilization will be achieved successfully.

In the United States, the lack of comprehensive climate legislation has made the economics of widespread deployment unfavorable. Furthermore, there also exist some real questions about the risks to groundwater, seismicity, etc., which must be quantified before investment liabilities are fully understood (Bielicki *et al.*, 2015; Pawar *et al.*, 2016). From a fundamental perspective, questions related to the geochemistry of caprocks (Fitts and Peters, 2013) and the microbiology of the aquifers overlying target repositories are of great interest (Jun *et al.*, 2013). In this special issue, the articles by Mouzakis *et al.* (2016) and Miller *et al.* (2016) make important advances in our understanding of caprocks and their interaction with injected CO₂. Gulliver *et al.* (2016) presents important contributions on how CO₂ injection might impact microbial communities. Unconventional target formations are also of increasing interest and Cui *et al.* presents interesting work on the carbonation of forsterite *in situ* (Hayes *et al.*, 2016).

High-Volume Hydraulic Fracturing

Efforts to produce oil and gas from low permeability formations using hydraulic fracturing and directional drilling have resulted in a major boom in domestic hydrocarbon production (Osborn *et al.*, 2011). These techniques rely on large volumes of fresh water, which have created a host of environmental problems (Barbot *et al.*, 2013), some of which are explored in this study. One major concern associated with hydraulic fracturing is the leakage and seepage of fracturing fluids and methane into overlying formations (Allen *et al.*, 2013). These processes and others will involve the flows of multiple fluids and multiple phases and the work of Zhao *et al.* (2016) begins to quantify the wettability characteristics of these systems. The work by Tao *et al.* (2016) describes a novel method to use carbonation reactions to cement fractures using the favorable reaction kinetics of deep formations. Bi *et al.* (2016) reports on the use of ion-exchange resins to remove radium from produced water. Many of the components included in the fluid formulation are intended to reduce the impact of scaling on fluid flow and so the article by He *et al.* describes the impact of these antiscalants on barite fate in fracturing fluids. Work by Tasker *et al.* (2016) provides

much needed experimental work on the processes influencing metal dissolution into fracturing fluids.

These research areas are leading naturally into at least two other areas, which are not covered in this special issue, but are emerging areas of investment for the coming years.

Enhanced Geothermal

Conventional geothermal energy for utility-scale power requires high thermal gradients that exist largely in the western United States. Geothermal resources in the rest of the country will need to rely on so-called enhanced geothermal processes, wherein a fluid is injected to stimulate the reservoir. These enhanced geothermal processes have a capacity of 13.4 million exajoules (at depths beneath 10 km in the subsurface), which is over six orders of magnitude more energy than the United States currently consumes (Blackwell *et al.*, 2006). Tapping into this massive reserve economically will be a challenge, in large part, because fluid-rock interactions dominate the efficiency of these processes. There is a critical research need to better understand the physicochemical processes and the thermal transfer in target formations to develop technologies for harvesting these vast reserves.

Energy Storage in Sedimentary Formations

One of the critical needs in ramping up renewable energy strategies is the development of large-scale and inexpensive approaches for energy storage. Pumped water storage, wherein water is moved uphill when energy exists in excess and released when energy is needed, has been deployed for decades. Unfortunately, the number of sites that are suitable for this type of energy storage is limited. An analogous approach would be to store compressed air or another compressible fluid in deep sedimentary formations (Buscheck *et al.*, 2014; Hartmann *et al.*, 2012). When the energy is needed, the fluid could be released to run generators. Deep sedimentary formations are more geographically distributed than the sites suitable for pumped water storage, but there are a host of geotechnical and geochemical questions associated with how this technology might be scaled economically and sustainably.

In summary, our hope is that this article and this special issue will form a call to action for research by the environmental engineering community at the CWN and a nucleation point for the ongoing and excellent research taking place to advance strategies to reduce the emissions that are contributing to climate change.

Author Disclosure Statement

No competing financial interests exist.

References

- Allen, D.T., Torres, V.M., Thomas, J., Sullivan, D.W., Harrison, M., Hendler, A., Herndon, S.C., Kolb, C.E., Fraser, M.P., Hill, A.D., *et al.* (2013). Measurements of methane emissions at natural gas production sites in the United States. *Proc. Natl. Acad. Sci. U. S. A.* 110, 17768.
- Bachu, S., and Adams, J.J. (2003). Sequestration of CO₂ in geological media in response to climate change: Capacity of deep saline aquifers to sequester CO₂ in solution. *Energy Convers. Manage.* 44, 3151.

- Barbot, E., Vidic, N.S., Gregory, K.B., and Vidic, R.D. (2013). Spatial and temporal correlation of water quality parameters of produced waters from devonian-age shale following hydraulic fracturing. *Environ. Sci. Technol.* 47, 2562.
- Barnett, T.P., Adam, J.C., and Lettenmaier, D.P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* 438, 303.
- Bellamy, R. (2015). A sociotechnical framework for governing climate engineering. *Sci. Technol. Hum. Values.* 1. <http://sth.sagepub.com/content/early/2015/06/24/0162243915591855.abstract>
- Bi, Y., Zhang, H., Ellis, B.R., and Hayes, K.F. (2016). Removal of radium from synthetic shale gas brines by ion exchange resin. *Environ. Eng. Sci.* 33, 791.
- Bielicki, J.M., Peters, C.A., Fitts, J.P., and Wilson, E.J. (2015). An examination of geologic carbon sequestration policies in the context of leakage potential. *Int. J. Greenh. Gas Control* 37, 61.
- Blackwell, D.D., Negraru, P.T., and Richards, M.C. (2006). Assessment of the enhanced geothermal system resource base of the United States. *Nat. Resour. Res.* 15, 283.
- Bruant, R.G.J., Celia, M.A., Guswa, A.J., and Peters, C.A. (2002). Safe storage of CO₂ in deep saline aquifers. *Environ. Sci. Technol.* 36, 240A.
- Burnham, A., Han, J., Clark, C. E., Wang, M., Dunn, J.B., and Palou-Rivera, I. (2011). Life-cycle greenhouse gas emissions of shale gas, natural gas, coal, and petroleum. *Environ. Sci. Technol.* 46, 619.
- Buscheck, T.A., Bielicki, J.M., Chen, M., Sun, Y., Hao, Y., Edmunds, T.A., Saar, M.O., and Randolph, J.B. (2014). Integrating CO₂ storage with geothermal resources for dispatchable renewable electricity. *Energy Procedia* 63, 7619.
- Cui, J., Sesti, E.L., Moore, J.K., Giammar, D.E., and Hayes, S.E. (2016). Evidence from ²⁹Si solid-state nuclear magnetic resonance of dissolution Reactions of forsterite. *Environ. Eng. Sci.* 33, 799.
- Davis, S.J., Caldeira, K., and Matthews, H.D. (2010). Future CO₂ emissions and climate change from existing energy infrastructure. *Science* 329, 1330.
- Fitts, J.P., and Peters, C.A. (2013). Caprock fracture dissolution and CO₂ leakage. *Rev. Mineral. Geochemistry* 77, 459.
- Gulliver, D. M., Lowry, G.V., and Gregory, K.B. (2016). Comparative study of effects of CO₂ concentration and pH on microbial communities from a saline aquifer, a depleted oil reservoir, and a freshwater aquifer. *Environ. Eng. Sci.* 33, 806.
- Hartmann, N., Vöhringer, O., Kruck, C., and Eltrop, L. (2012). Simulation and analysis of different adiabatic compressed air energy storage plant configurations. *Appl. Energy* 93, 541.
- Haynes IV, L.L., and Clapp, L.W. (2016). In situ bio-reduction/immobilization of uranium at an in situ recovery mining site utilizing membrane infused gaseous hydrogen. *Environ. Eng. Sci.* 33, 817.
- IPCC. (2014). *Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY: Cambridge University Press.
- Jun, Y.S., Giammar, D.E., and Werth, C.J. (2013). Impacts of geochemical reactions on geologic carbon sequestration. *Env. Sci. Technol.* 47, 8.
- Meehl, G.A., and Tebaldi, C. (2004). More intense, more frequent, and longer lasting heat waves in the 21st century. *Science* 305, 994.
- Meinshausen, M., Meinshausen, N., Hare, W., Raper, S.C.B., Frieler, K., Knutti, R., Frame, D.J., and Allen, M.R. (2009). Greenhouse-gas emission targets for limiting global warming to 2 C. *Nature* 458, 1158.
- Miller, Q.R.S., Wang, X., Kaszuba, J.P., Mouzakis, K.M., Navarre-Sitchler, A.K., Alvarado, V., McCray, J.E., Rother, G., Banuelos, J.L., and Heath, J.E. (2016). Experimental study of porosity changes in shale caprocks exposed to carbon dioxide-saturated brine II: Insights from aqueous geochemistry. *Environ. Eng. Sci.* 33, 736.
- Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., Van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., et al. (2010). The next generation of scenarios for climate change research and assessment. *Nature* 463, 747.
- Mouzakis, K.M., Navarre-Sitchler, A.K., Rother, G., Banuelos, J.L., Wang, X., Kaszuba, J.P., Heath, J.E., Miller, Q.R.S., Alvarado, V., and McCray, J.E. (2016). Experimental study of porosity changes in shale caprocks exposed to CO₂-saturated brines I: Evolution of mineralogy, pore connectivity, pore size distribution, and surface area. *Environ. Eng. Sci.* 33, 725.
- Osborn, S.G., Vengosh, A., Warner, N.R., and Jackson, R.B. (2011). Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. *Proc. Natl. Acad. Sci. U. S. A.* 2108, 8172.
- Pachauri, R.K., and Reisinger, A. (2007). *Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland.
- Pawar, R.J., Bromhal, G.S., Chu, S., Dillmore, R.M., Oldenburg, C.M., Stauffer, P.H., Zhang, Y., and Guthrie, G.D. (2016). The national risk assessment partnership's integrated assessment model for carbon storage: A tool to support decision making amidst uncertainty. *Int. J. Greenh. Gas Control* 52, 175.
- Tao, Z., Fitts, J.P., and Clarens, A.F. (2016). Feasibility of carbonation reactions to control permeability in the deep subsurface. *Environ. Eng. Sci.* 33, 778.
- Tasker, T.L., Piotrowski, P.K., Dorman, F.L., and Burgos, W.D. (2016). Metal associations in Marcellus shale and fate of synthetic hydraulic fracturing fluids reacted at high pressure and temperature. *Environ. Eng. Sci.* 33, 753.
- Vorosmarty, C.J. (2000). Global water resources: Vulnerability from climate change and population growth. *Science* 289, 284.
- Weitzman, M.L. (2009). On modeling and interpreting the economics of catastrophic climate change. *Rev. Econ. Stat.* 91, 1.
- Zhou, L., Das, S., and Ellis, B.R. (2016). Effect of surfactant adsorption on the wettability alteration of gas-bearing shales. *Environ. Eng. Sci.* 33, 766.