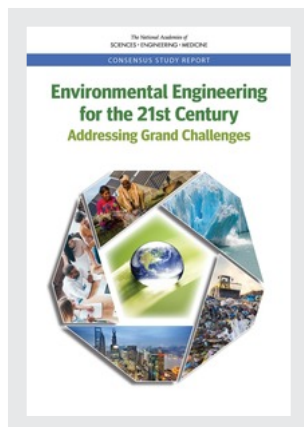


This PDF is available at <http://nap.edu/25121>

SHARE



## Environmental Engineering for the 21st Century: Addressing Grand Challenges (2019)

### DETAILS

124 pages | 7.5 x 11 | PAPERBACK

ISBN 978-0-309-47652-2 | DOI 10.17226/25121

### CONTRIBUTORS

Committee on the Grand Challenges and Opportunities in Environmental Engineering for the Twenty-First Century; Board on Agriculture and Natural Resources; Board on Atmospheric Sciences and Climate; Board on Chemical Sciences and Technology; Board on Energy and Environmental Systems; Board on Earth Sciences and Resources; Board on Environmental Studies and Toxicology; Board on Life Sciences, Engineering, and Medicine; Board on Ocean Studies; Board on Water Science and Technology; Board on Earth and Life Studies; Division on Engineering and Physical Sciences; National Academy of Engineering; National Academies of Sciences, Engineering, and Medicine 2019. *Environmental Engineering for the 21st Century: Addressing Grand Challenges*. Washington, DC: Sciences, Engineering, and Medicine.

### SUGGESTED CITATION

National Academies of Sciences, Engineering, and Medicine 2019. *Environmental Engineering for the 21st Century: Addressing Grand Challenges*. Washington, DC: Sciences, Engineering, and Medicine. <https://doi.org/10.17226/25121>.

GET THIS BOOK

FIND RELATED TITLES

Visit the National Academies Press at [NAP.edu](http://NAP.edu) and login or register to get:

- Access to free PDF downloads of thousands of scientific reports
- 10% off the price of print titles
- Email or social media notifications of new titles related to your interests
- Special offers and discounts



Distribution, posting, or copying of this PDF is strictly prohibited without written permission of the National Academies Press. (Request Permission) Unless otherwise indicated, all materials in this PDF are copyrighted by the National Academy of Sciences.

Copyright © National Academy of Sciences. All rights reserved.

75. National Academies of Sciences, Engineering, and Medicine. 2017. *Safely Transporting Hazardous Liquids and Gases in a Changing U.S. Energy Landscape*. Washington, DC: The National Academies Press.
76. National Research Council. 2007. *Environmental Impacts of Wind-Energy Projects*. Washington, DC: The National Academies Press; National Research Council. 2010. *Electricity from Renewable Resources: Status, Prospects, and Impediments*. Washington, DC: The National Academies Press.
77. National Research Council. 2007. *Environmental Impacts of Wind-Energy Projects*. Washington, DC: The National Academies Press.
78. American Wind Wildlife Institute. 2014. Wind Turbine Interactions with Wildlife and Their Habitats: A Summary of Research Results and Priority Questions. Fact Sheet.
79. National Research Council. 2010. *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use*. Washington, DC: The National Academies Press.
80. Sprecher, B., Y. Xiao, A. Walton, J. Speight, R. Harris, R. Kleijn, G. Visser, and G. J. Kramer. 2014. Life cycle inventory of the production of rare earths and the subsequent production of NdFeB rare earth permanent magnets. *Environmental Science & Technology* 48(7): 3951-3958.
81. Hill, J., E. Nelson, D. Tilman, S. Polasky, and D. Tiffany. 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proceedings of the National Academy of Sciences* 103(30): 11206-11210.
82. Lim, X. 2016. Uphill climb for biogas in Asia. *Chemical & Engineering News* 94:20-22.
83. Levin, T., and V.M. Thomas. 2016. Can developing countries leapfrog the centralized electrification paradigm? *Energy for Sustainable Development* 31: 97-107.
84. Koss, G. 2016. Renewable energy: Necessity drives Alaska's "petri dish" of innovation. *E&E News Greenwire*.
85. National Academies of Sciences, Engineering, and Medicine. 2017. *Enhancing the Resilience of the Nation's Electricity System*. Washington, DC: The National Academies Press.
86. Lawrence Berkeley National Laboratory. 2018. Microgrids at Berkeley Lab: Huatacondo. Available at <https://building-microgrid.lbl.gov/huatacondo>.
87. United Nations Conference on Trade and Development. 2017. *The Least Developed Countries Report 2017: Transformational Energy Access*. Geneva: UNCTAD/LDC/2017.
88. National Research Council. 2010. *The Power of Renewables: Opportunities and Challenges for China and the United States*. Washington, DC: The National Academies Press; National Research Council. 2010. *Electricity from Renewable Resources Status, Prospects, and Impediments*. Washington, DC: The National Academies Press.
89. Chen, H., Q. Ejaz, X. Gao, J. Huang, J. Morris, E. Monier, S. Paltsev, J. Reilly, A. Schlosser, J. Scott, and A. Sokolov. 2016. *Food, Water, Energy, Climate Outlook: Perspectives from 2016*. Massachusetts Institute of Technology Joint Program on the Science and Policy of Global Change.
90. National Academies of Sciences, Engineering, and Medicine. 2017. *Enhancing the Resilience of the Nation's Electricity System*. Washington, DC: The National Academies Press.
91. Penn, I. 2018. The \$3 billion plan to turn Hoover Dam into a giant battery. *New York Times*, July 24.
92. Luo, X., J. Wang, M. Dooner, and J. Clarke. 2015. Overview of current development in electrical energy storage technologies and the application potential in power system operation. *Applied Energy* 137: 511-536.
93. Meadows, D. H. 2008. *Thinking in Systems: A Primer*. White River Junction, VT: Chelsea Green.
94. Mihelcic, J. R., J. B. Zimmerman, and M. T. Auer. 2014. *Environmental Engineering: Fundamentals, Sustainability, Design, Vol. 1*. Hoboken, NJ: Wiley.
95. Sterman, J. D. 1994. Learning in and about complex systems. *System Dynamics Review* 6(2-3): 291-330.
96. Boccard, N. 2010. *Modeling Complex Systems*, 2nd ed. New York: Springer.
97. National Academy of Sciences. 2014. *Climate Change: Evidence and Causes*. Washington, DC: The National Academies Press.
98. U.S. Global Change Research Program. 2017. *Climate Science Special Report: Fourth National Climate Assessment*, Vol. 1. D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock, eds. Washington, DC: USGCRP.
99. U.S. Global Change Research Program. 2017. *Climate Science Special Report: Fourth National Climate Assessment*, Vol. 1. D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock, eds. Washington, DC: USGCRP.
100. National Academies of Sciences, Engineering, and Medicine. 2017. *Attribution of Extreme Weather in the Context of Climate Change*. Washington, DC: The National Academies Press.
101. U.S. Global Change Research Program. 2017. *Climate Science Special Report: Fourth National Climate Assessment*, Vol. 1. D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock, eds. Washington, DC: USGCRP.
102. National Research Council. 2012. *Climate Change: Evidence, Impacts, and Choices*. Washington, DC: The National Academies Press.
103. Intergovernmental Panel on Climate Change. 2015. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the IPCC Fifth Assessment Report*. Cambridge, UK: Cambridge University Press.
104. U.S. Global Change Research Program. 2017. *Climate Science Special Report: Fourth National Climate Assessment*, Vol. 1. D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock, eds. Washington, DC: USGCRP.
105. Knoblauch C., C. Beer, S. Liebner, M. N. Grigoriev, and E. M. Pfeiffer. 2018. Methane production as key to the greenhouse gas budget of thawing permafrost. *Nature Climate Change* 8: 309-312.
106. Intergovernmental Panel on Climate Change. 2014. *Climate Change 2014 Synthesis Report: Summary for Policymakers*.
107. International Panel on Climate Change. 2018. *Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, Y. Chen, S. Connors, M. Gomis, E. Lonnoy, J. B. R. Matthews, W. Moufouma-Okia, C. Péan, R. Pidcock, N. Reay, M. Tignor, T. Waterfield, and X. Zhou (eds.). In Press.
108. U.S. Global Change Research Program. 2017. *Climate Science Special Report: Fourth National Climate Assessment*, Vol. 1. D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock, eds. Washington, DC: USGCRP.
109. World Health Organization. 2018. *Ambient (Outdoor) Air Quality and Health*. Fact Sheet.
110. Williams, J. H., B. Haley, F. Kahl, J. Moore, A. D. Jones, M. S. Torn, and H. McJeon. 2014. *Pathways to Deep Decarbonization in the United States*. [Revision with technical supplement. Nov 16, 2015].
111. Federal Ministry for Economic Affairs and Energy. 2016. *Green Paper on Energy Efficiency*. Berlin, Germany.
112. National Academies of Sciences, Engineering, and Medicine. 2010. *Real Prospects for Energy Efficiency in the United States*. Washington, DC: The National Academies Press.
113. U.S. Energy Information Administration. 2018. *Electricity Explained: Electricity in the United States, Generation, Capacity, and Sales*.

114. National Renewable Energy Laboratory. 2012. *Renewable Electricity Futures Study: Exploration of High-Penetration Renewable Electricity Futures*, Vol. 1. NREL/TP-6A20-52409. Golden, CO: NREL.
115. Cole, T. M., P. Donohoo-Vallett, J. Richards, and P. Das. 2017. *Standard Scenarios Report: A U.S. Electricity Sector Outlook*. NREL/TP-6A20-68548. Golden, CO: National Renewable Energy Laboratory.
116. International Panel on Climate Change. 2018. *Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. V., Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, Y. Chen, S. Connors, M. Gomis, E. Lonnoy, J. B. R. Matthews, W. Moufouma-Okia, C. Péan, R. Pidcock, N. Reay, M. Tignor, T. Waterfield, and X. Zhou (eds.)). In Press.
117. International Energy Agency. 2017. *World Energy Outlook 2017*.
118. Rueter, G., and M. Kuebler. 2017. China leading the way in solar energy expansion as renewables surge. *Deutsche Welle*, July 6.
119. U.S. Department of Energy. Advanced Reactor Technologies <https://www.energy.gov/ne/nuclear-reactor-technologies/advanced-reactor-technologies>.
120. U.S. Energy Information Administration. 2018. *Use of Energy In the United States Explained: Energy Use for Transportation*. Available at [https://www.eia.gov/energyexplained/?page=us\\_energy\\_transportation](https://www.eia.gov/energyexplained/?page=us_energy_transportation).
121. Zev Alliance. 2017. The rise of electric vehicles: The second million. Blog, Jan. 31. Available at <http://www.zevalliance.org/second-million-electric-vehicles>.
122. Lutsey, N., M. Grant, S. Wappelhorst, and H. Zhou. Power Play: How Governments Are Spurring the Electric Vehicle Industry. White Paper. Washington, DC: International Council on Clean Transportation.
123. Mucio, D. 2017. These countries are banning gas-powered vehicles by 2040. *Business Insider*, Oct. 23. Available at <https://www.businessinsider.com/countries-banning-gas-cars-2017-10>.
124. National Research Council. 2011. *Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia*. Washington, DC: The National Academies Press.
125. National Academies of Sciences, Engineering, and Medicine. 2018. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. Washington, DC: The National Academies Press.
126. National Academies of Sciences, Engineering, and Medicine. 2018. *Science Breakthroughs to Advance Food and Agricultural Research by 2030*. Washington, DC: The National Academies Press.
127. National Academies of Sciences, Engineering, and Medicine. 2018. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. Washington, DC: The National Academies Press.
128. Griscom, B. W., J. Adams, P. W. Ellis, R. A. Houghton, G. Lomax, D. A. Miteva, W. H. Schlesinger, D. Shoch, J. V. Siikamäki, P. Smith, P. Woodbury, C. Zganjar, A. Blackman, J. Campari, R. T. Conant, C. Delgado, P. Elias, T. Gopalakrishna, M. R. Hamsik, M. Herrero, J. Kiesecker, E. Landis, L. Laestadius, S. M. Leavitt, S. Minnemeyer, S. Polasky, P. Potapov, F. E. Putz, J. Sanderman, M. Silvius, E. Wollenberg, and J. Fargione. 2017. Natural climate solutions. *Proceedings of the National Academy of Sciences* 114(44): 11645-11650.
129. National Academies of Sciences, Engineering, and Medicine. 2018. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. Washington, DC: The National Academies Press.
130. Hunter, M. C., R. G. Smith, M. E. Schipanski, L. W. Atwood, and D. A. Mortensen. 2017. Agriculture in 2050: Recalibrating targets for sustainable intensification. *Bioscience* 67(4): 386-391.
131. National Research Council. 2015. *Climate Intervention: Reflecting Sunlight to Cool Earth*. Washington, DC: The National Academies Press.
132. U.S. Environmental Protection Agency. 2016. Greenhouse Gas Emissions: Overview of Greenhouse Gases.
133. U.S. Environmental Protection Agency. 2016. Global Methane Initiative: Importance of Methane.
134. National Academies of Sciences, Engineering, and Medicine. 2018. *Improving Characterization of Anthropogenic Methane Emissions in the United States*. Washington, DC: The National Academies Press.
135. Horowitz, J., and J. Gottlieb. 2010. The Role of Agriculture in Reducing Greenhouse Gas Emissions. Economic Brief No. 15. Washington, DC: U.S. Department of Agriculture Economic Research Service.
136. U.S. Global Change Research Program. 2017. *Climate Science Special Report: Fourth National Climate Assessment*, Vol. 1. D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock, eds. Washington, DC: USGCRP.
137. National Research Council. 2012. *Climate Change: Evidence, Impacts, and Choices*. Washington, DC: The National Academies Press.
138. Bates, B., Z. W. Kundzewicz, S. Wu, and J. Palutikof. 2008. Climate Change and Water. IPCC Technical Paper VI. Geneva: Intergovernmental Panel on Climate Change Secretariat.
139. National Academies of Sciences, Engineering, and Medicine. 2016. *Attribution of Extreme Weather Events in the Context of Climate Change*. Washington, DC: The National Academies Press.
140. Geophysical Fluid Dynamics Laboratory. 2018. Global Warming and Hurricanes: An Overview of Current Research Results. Princeton University Forrestal Campus.
141. Baltes, N. J., J. Gil-Humanes, and D. F. Voytas. 2017. Chapter One-Genome Engineering and Agriculture: Opportunities and Challenges. *Progress in Molecular Biology and Translational Science* 149: 1-26.
142. Phelan, P. E., K. Kaloush, M. Miner, J. Golden, B. Phelan, H. Silva II, and R. A. Taylor. 2015. Urban heat island: Mechanisms, implications, and possible remedies. *Annual Review of Environment and Resources* 40: 285-307.
143. Lempert, R. J., D. G., Groves, S. W., Popper, and S. C. Bankes. 2006. A General, Analytic Method for Generating Robust Strategies and Narrative Scenarios. *Management Science* 52(4): 514-528; Haasnoot, M., J. H. Kwakkel, W. E. Walker, and J. ter Maat. 2013. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change* 23(2): 485-498.
144. Westerling, A. L., B. P. Bryant, H. K. Preisler, T. P. Holmes, H. G. Hidalgo, T. Das, and S. R. Shrestha. 2011. Climate change and growth scenarios for California wildfire. *Climatic Change* 109(Supp. 1): 445-463; Barbero, R., J. T. Abatzoglou, N. K. Larkin, C. A. Kolden, and B. Stocks. 2015. Climate change presents increased potential for very large fires in the contiguous United States. *International Journal of Wildland Fire* 24(7): 892-899.
145. Smith, A., C. A. Kolden, T. B. Paveglio, M. A. Cochrane, D. M. Bowman, M. A. Moritz, A. D. Kliskey, L. Alessa, A. T. Hudak, C. M. Hoffman, J. A. Lutz, L. P. Queen, S. J. Goetz, P. E. Higuera, L. Boschetti, M. Flannigan, K. M. Yedinak, A. C. Watts, E. K. Strand, J. W. Van Wagtenonk, J. W. Anderson, B. J. Stocks, and J. T. Abatzoglou. 2016. The science of firescapes: Achieving fire-resilient communities. *BioScience* 66(2): 130-146.
146. National Research Council. 2012. *Disaster Resilience: A National Imperative*. Washington, DC: The National Academies Press.
147. Field, C. B., V. R. Barros, K. J. Mach, M. D. Mastrandrea, M. van Aalst, W. N. Adger, D. J. Arent, J. Barnett, R. Betts, T. E. Bilir, J. Birkmann, J. Carmin, D. D. Chadee, A. J. Challinor,

- M. Chatterjee, W. Cramer, D. J. Davidson, Y. O. Estrada, J.-P. Gattuso, Y. Hijikata, O. Hoegh-Guldberg, H. Q. Huang, G. E. Insarov, R. N. Jones, R. S. Kovats, P. Romero-Lankao, J. N. Larsen, I. J. Losada, J. A. Marengo, R. F. McLean, L. O. Mearns, R. Mechler, J. F. Morton, I. Niang, T. Oki, J. M. Olwoch, M. Opondo, E. S. Poloczanska, H.-O. Pörtner, M. H. Redsteer, A. Reisinger, A. Revi, D. N. Schmidt, M. R. Shaw, W. Solecki, D. A. Stone, J. M. R. Stone, K. M. Strzepek, A. G. Suarez, P. Tschakert, R. Valentini, S. Vicuña, A. Villamizar, K. E. Vincent, R. Warren, L. L. White, T. J. Wilbanks, P. P. Wong, and G. W. Yohe. 2014. Technical summary. Pp. 35-94 in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the IPCC Fifth Assessment Report*. C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, and L. L. White, eds. Cambridge, UK, and New York: Cambridge University Press.
148. Shiferaw, B., M. Smale, H. Braun, E. Duveiller, M. Reynolds, and G. Muricho. 2013. Crops that feed the world 10. Past successes and future challenges to the role played by wheat in global food security. *Food Security* 5(3): 291-317.
149. Howden, S. M., J. F. Soussana, F. N. Tubiello, N. Chhetri, M. Dunlop, and H. Meinke. 2007. Adapting agriculture to climate change. *Proceedings of the National Academy of Sciences* 104(50): 19691-19696; Smit, B., and M. W. Skinner. 2002. Adaptation options in agriculture to climate change: A typology. *Mitigation and Adaptation Strategies for Global Change* 7:85-114.
150. Field, C.B., V.R. Barros, K.J. Mach, M.D. Mastrandrea, M. van Aalst, W.N. Adger, D.J. Arent, J. Barnett, R. Betts, T.E. Bilir, J. Birkmann, J. Carmin, D.D. Chadee, A.J. Challinor, M. Chatterjee, W. Cramer, D.J. Davidson, Y.O. Estrada, J.-P. Gattuso, Y. Hijikata, O. Hoegh-Guldberg, H.-Q. Huang, G.E. Insarov, R.N. Jones, R.S. Kovats, P. Romero Lankao, J.N. Larsen, I.J. Losada, J.A. Marengo, R.F. McLean, L.O. Mearns, R. Mechler, J.F. Morton, I. Niang, T. Oki, J.M. Olwoch, M. Opondo, E.S. Poloczanska, H.-O. Pörtner, M.H. Redsteer, A. Reisinger, A. Revi, D.N. Schmidt, M.R. Shaw, W. Solecki, D.A. Stone, J.M.R. Stone, K.M. Strzepek, A.G. Suarez, P.Tschakert, R.Valentini, S.Vicuña, A.Villamizar, K.E.Vincent, R. Warren, L.L.White, T.J.Wilbanks, P.P.Wong, and G.W.Yohe. 2014. Technical Summary. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 35-94.
151. U.S. Global Change Research Program. 2017. *Climate Science Special Report: Fourth National Climate Assessment*, Vol. 1. D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock, eds. Washington, DC: USGCRP. doi: 10.7930/J0J964J6.
152. Milman, O. 2017. Atlantic City and Miami Beach: Two takes on tackling the rising waters. *The Guardian*, Mar. 20.
153. Katz, C. 2013. To Control Floods, The Dutch Turn to Nature for Inspiration. *Yale Environment* 360.
154. Coastal Protection and Restoration Authority of Louisiana. 2017. Louisiana's Comprehensive Master Plan for a Sustainable Coast. Coastal Protection and Restoration Authority of Louisiana. Baton Rouge, LA.
155. Watts, N., M. Amann, S. Ayeb-Karlsson, K. Belesova, T. Bouley, M. Boykoff, P. Byass, W. Cai, D. Campbell-Lendrum, J. Chambers, and P. M. Cox. 2017. The Lancet countdown on health and climate change: From 25 years of inaction to a global transformation for public health. *The Lancet* 391(10120): 581-630.
156. Haines, A. 2008. Climate change, extreme events, and human health. Pp. 57-74 in *Global Climate Change and Extreme Weather Events: Understanding the Contributions to Infectious Disease Emergence*. Washington, DC: The National Academies Press.
157. Zorrilla, C. D. 2017. The view from Puerto Rico—Hurricane Maria and its aftermath. *New England Journal of Medicine* 377(19): 1801-1803.
158. National Research Council. 2009. *Informing Decisions in a Changing Climate*. Washington, DC: The National Academies Press; Ditttrich, R., A. Wreford, and D. Moran. 2016. A survey of decision-making approaches for climate change adaptation: Are robust methods the way forward? *Ecological Economics* 122: 79-89; Walker, W. E., M. Haasnoot, and J. H. Kwakkel. 2013. Adapt or perish: A review of planning approaches for adaptation under deep uncertainty. *Sustainability* 5(3): 955-979.
159. Matthews, E., C. Amann, S. Bringezu, W. Hüttler, C. Ottke, E. Rodenburg, D. Rogich, H. Schandl, E. Van, D. Voet, and H. Weisz. 2000. *The Weight of Nations: Material Outflows from Industrial Economies*. Washington, DC: World Resources Institute.
160. U.S. Environmental Protection Agency. 2018. National Overview: Facts and Figures on Materials, Wastes and Recycling. Trends—1960 to Today.
161. Ellen MacArthur Foundation. 2013. *Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition*, Vol. 1.
162. Hoornweg, D., and P. Bhada-Tata. 2012. *What a Waste: A Global Review of Solid Waste Management*. Washington, DC: World Bank.
163. Hoornweg, D., P. Bhada-Tata, and C. Kennedy. 2013. Environment: Waste production must peak this century. *Nature* 503: 615.
164. Kharas, H. 2017. The Unprecedented Expansion of the Global Middle Class: An Update. Global Economy and Development at Brookings. Working Paper 100. Brookings Institution.
165. National Research Council. 2005. *Contaminants in the Subsurface: Source Zone Assessment and Remediation*. Washington, DC: The National Academies Press.
166. National Research Council. 2005. *Contaminants in the Subsurface: Source Zone Assessment and Remediation*. Washington, DC: The National Academies Press.
167. National Research Council. 2013. *Alternatives for Managing the Nation's Complex Contaminated Groundwater Sites*. Washington, DC: The National Academies Press.
168. Health Effects Institute. 2015. The Advanced Collaborate Emissions Study (ACES). Executive Summary. Boston: HEI; Khalek, I. A., T. L. Bougher, P. M. Merritt, and B. Zielinska. 2011. Regulated and unregulated emissions from highway heavy-duty diesel engines complying with U.S. Environmental Protection Agency 2007 emissions standards. *Journal of the Air and Waste Management Association* 61(4): 427-442.
169. World Water Assessment Programme. 2009. *The United Nations World Water Development Report 3: Water in a Changing World*. Paris: UNESCO, and London: Earthscan, Table 8.1, p. 137.
170. International Food Policy Research Institute and VEOLIA. 2015. The Murky Future of Global Water Quality: New Global Study Projects Rapid Deterioration in Water Quality. White Paper. Washington, DC: IFPRI and Chicago: VEOLIA Water North America; World Health Organization. 2016. Air Pollution Levels Rising in Many of the World's Poorest Cities. News Release.
171. Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, J. Willis, D. Anderson, S. Doney, R. Feely, P. Hennon, V. Kharin, T. Knutson, F. Landerer, T. Lenton, J. Kennedy, and R. Somerville,



- 2014: Our changing climate. Pp. 19-67 in *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, T. C. Richmond, and G. W. Yohe, eds., U.S. Global Change Research Program. doi:10.7930/J0KW5CXT.
172. Lindstrom, A. B., M. J. Strynar, and E. L. Libelo. 2011. Polyfluorinated compounds: Past, present, and future. *Environmental Science & Technology* 45(19): 7954-7961.
173. Roser, M. 2018. Life Expectancy. Our World in Data. Available at <https://ourworldindata.org/life-expectancy>.
174. GBD 2016 Risk Factors Collaborators. 2017. Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or cluster of risks, 1990-2016: A systematic analysis for the Global Burden of Disease Study 2016. *The Lancet* 390(10100): 1345-1422.
175. GBD 2016 Risk Factors Collaborators. 2017. Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or cluster of risks, 1990-2016: A systematic analysis for the Global Burden of Disease Study 2016. *The Lancet* 390(10100): 1345-1422.
176. Health Effects Institute. 2018. State of Global Air. Available at: [www.stateofglobalair.org](http://www.stateofglobalair.org).
177. Landrigan, P. J., R. Fuller, N. J. Acosta, O. Adeyi, R. Arnold, A. B. Baldé, R. Bertollini, S. Bose-O'Reilly, J. I. Boufford, P. N. Breysse, T. Chiles, C. Mahidol, A. M. Coll-Seck, M. L. Cropper, J. Fobil, V. Fuster, M. Greenstone, and M. Zhong. 2017. *The Lancet Commission on pollution and health. The Lancet* 391(10119): 462-512.
178. Cunningham, V. L., M. Buzby, T. Hutchinson, F. Mastrocco, N. Parke, and N. Roden. 2006. Effects of human pharmaceuticals on aquatic life: Next steps. *Environmental Science & Technology* 40(11):3456-3462; Iwanowicz, L. R., V. S. Blazer, A. E. Pinkney, C. P. Guy, A. M. Major, K. Munney, S. Mierzykowski, S. Lingenfelter, A. Secord, K. Patnode, T. J. Kubiak, C. Stern, C. M. Hahn, D. D. Iwanowicz, H. L. Walsh, and A. Sperry. 2016. Evidence of estrogenic endocrine disruption in smallmouth and largemouth bass inhabiting Northeast U.S. national wildlife refuge waters: A reconnaissance study. *Ecotoxicology and Environmental Safety* 124: 50-59.
179. Jambeck, J. R., R. Geyer, C. Wilcox, T. R. Siegler, M. Perryman, A. Andray, R. Narayan, and K. L. Law. 2015. Plastic waste inputs from land into the ocean. *Science* 347(6223): 768-771.
180. Tosetto, L., C. Brown, and J. E. Williamson. 2016. Microplastics on beaches: Ingestion and behavioural consequences for beachhoppers. *Marine Biology* 163(10): 199; Nelms, S. E., T. S., Galloway, B. J. Godley, D. S. Jarvis, and P. K. Lindeque. 2018. Investigating microplastic trophic transfer in marine top predators. *Environmental Pollution* 238: 999-1007; World Economic Forum. 2016. *The New Plastics Economy: Rethinking the Future of Plastics*. Geneva, Switzerland.
181. Anderson, D. M., P. M. Glibert, and J. M. Burkholder. 2002. Harmful algal blooms and eutrophication: Nutrient sources, composition, and consequences. *Estuaries* 25(4): 704-726.
182. Michalak, A. M. 2016. Study role of climate change in extreme threats to water quality. *Nature* 535(7612): 349-352.
183. Mueller, R., and V. Yingling. 2017. History and Use of Per- and Polyfluoroalkyl Substances (PFAS). Fact Sheet. Interstate Technology Regulatory Council. November.
184. Mueller, R., and V. Yingling. 2018. Environmental Fate and Transport for Per- and Polyfluoroalkyl Substances. Fact Sheet. Interstate Technology Regulatory Council. March.
185. National Ground Water Association. 2018. PFAS: Top 10 Facts. Available at [https://www.ngwa.org/docs/default-source/default-document-library/pfas/pfastop-10.pdf?sfvrsn=8c8ef98b\\_2](https://www.ngwa.org/docs/default-source/default-document-library/pfas/pfastop-10.pdf?sfvrsn=8c8ef98b_2).
186. Agency for Toxic Substances and Disease Registry. 2018. Toxicological Profile for Perfluoroalkyls: Draft for Public Comment, June. Available at <https://www.atsdr.cdc.gov/toxprofiles/tp200.pdf>.
187. China Council for International Cooperation on Environment and Development. 2014. Special Policy Study on Soil Pollution Management. Available at <http://environmental-partnership.org/wp-content/uploads/2016/01/SPS-on-Soil-Pollution-Management.pdf>.
188. Hu, Y., X. Liu, J. Bai, K. Shih, E. Y. Zeng, and H. Cheng. 2013. Assessing heavy metal pollution in the surface soils of a region that had undergone three decades of intense industrialization and urbanization. *Environmental Science and Pollution Research* 20(9): 6150-6159.
189. Hu, Y., H. Cheng, and S. Tao. 2016. The challenges and solutions for cadmium-contaminated rice in China: A critical review. *Environment International* 92-93: 515-532.
190. Coulon, F. K. Jones, H. Li, Q. Hu, J. Gao, F. Li, M. Chen, Y.-G. Zhu, R. Liu, M. Liu, K. Canning, N. Harries, P. Bardos, P. Nathanail, R. Sweeney, D. Middleton, M. Charnley, J. Randall, M. Richell, T. Howard, I. Martin, S. Spooner, J. Weeks, M. Cave, F. Yu, F. Zhang, Y. Jiang, P. Longhurst, G. Prpich, R. Bewley, J. Abra, and S. Pollard. 2016. China's soil and groundwater management challenges: Lessons from the UK's experience and opportunities for China. *Environment International*, 91: 196-200.
191. Song, Y., D. Hou, J. Zhang, D. O'Connor, G. Li, Q. Gu, S. Li, and P. Liu. 2018. Environmental and socio-economic sustainability appraisal of contaminated land remediation strategies: A case study at a mega-site in China. *Science of The Total Environment* 610-611: 391-401.
192. U.S. Environmental Protection Agency. 2000. Tetrachloroethylene (Perchloroethylene). Available at: <https://www.epa.gov/sites/production/files/2016-09/documents/tetrachloroethylene.pdf>.
193. <http://zwia.org/>.
194. U.S. Environmental Protection Agency. 1999. *Achieving Clean Air and Clean Water: Report of the Blue Ribbon Panel on Oxygenates in Gasoline*. EPA420-R-99-021.
195. Landrigan, P. J., R. Fuller, N. J. Acosta, O. Adeyi, R. Arnold, N. Basu, A. B. Baldé, R. Bertollini, S. Bose-O'Reilly, J. I. Boufford, P. N. Breysse, T. Chiles, C. Mahidol, A. M. Coll-Seck, M. L. Cropper, J. Fobil, V. Fuster, M. Greenstone, A. Haines, D. Hanrahan, D. Hunter, M. Khare, A. Krupnick, B. Lanphear, B. Lohani, K. Martin, K. V. Mathiasen, M. A. McTeer, C. J. L. Murray, J. D. Ndahimananjara, F. Perera, J. Potočnik, A. S. Preker, J. Ramesh, J. Rockström, C. Salinas, L. D. Samson, K. Sandilya, P. D. Sly, K. R. Smith, A. Steiner, R. B. Stewart, W. A. Suk, O. C. P. van Schayck, G. N. Yadama, K. Yumkella, and M. Zhong. 2018. *The Lancet Commission on Pollution and Health. The Lancet* 391(10119): 462-512.
196. Zeng, X., J. A. Mathews, and J. Li. 2018. Urban mining of e-waste is becoming more cost-effective than virgin mining. *Environmental Science & Technology* 52(8): 4835-4841; Nguyen, R. T., L. A. Diaz, D. D. Imholte, and T. E. Lister. 2017. Economic assessment for recycling critical metals from hard disk drives using a comprehensive recovery process. *JOM* 69(9): 1546-1552.
197. National Academies of Sciences, Engineering, and Medicine. 2018. *Gaseous Carbon Waste Streams Utilization: Status and Research Needs*. Washington, DC: The National Academies Press.
198. Deublein, D., and A. Steinhauser, eds. 2011. *Biogas from Waste and Renewable Resources: An Introduction*. Weinheim, Germany: Wiley VCH Verlag.
199. McCarty, P. L., J. Bae, and J. Kim. 2011. Domestic wastewater treatment as a net energy producer—Can this be achieved? *Environmental Science & Technology* 45(17): 7100-7106.
200. Water Environment Research Foundation. 2012. *Barriers to Biogas Use for Renewable Energy*. Report OWSO 11C10. Alexandria, VA: WERF.

201. Smith, A. L., L. B. Stadler, L. Cao, N. G. Love, L. Raskin, and S. J. Skerlos. 2014. Navigating wastewater energy recovery strategies: A life cycle comparison of anaerobic membrane bioreactor and conventional treatment systems with anaerobic digestion. *Environmental Science & Technology* 48(10): 5972-5981.
202. Steffen, W., K. Richardson, J. Rockström, S. E. Cornell, I. Fetzer, E. M. Bennett, R. Biggs, S. R. Carpenter, W. De Vries, C. A. De Wit, C. Folke, D. Gerten, J. Heinke, G. M. Mace, L. M. Persson, V. Ramanathan, B. Reyers, and S. Sörlin. 2015. Planetary boundaries: Guiding human development on a changing planet. *Science* 347(6223): 1259855.
203. Jasinski, S. M. 2017. Phosphate rock. Mineral Commodity Summaries. U.S. Geological Survey.
204. Mihelcic, J. R., L. M. Fry, and R. Shaw. 2011. Global potential of phosphorus recovery from human urine and feces. *Chemosphere* 84(6): 832-839.
205. Larsen, T. A., A. C. Alder, R. I. L. Eggen, M. Maurer, and J. Lienert. 2009. Source separation: Will we see a paradigm shift in wastewater handling? *Environmental Science & Technology* 43(16): 6121-6125.
206. International Fertilizer Industry Association. 2009. *Energy Efficiency and CO<sub>2</sub> Emissions in Ammonia Production: 2008-2009 Summary Report*. Paris: IFA.
207. National Academy of Engineering. 1997. *The Industrial Green Game: Implications for Environmental Design and Management*. Washington, DC: The National Academy Press.
208. U.S. Environmental Protection Agency. 2016. *Advancing Sustainable Materials Management: 2014. Fact Sheet*.
209. Organisation for Economic Co-operation and Development. 2015. *Environment at a Glance 2015: OECD Indicators*. Paris: OECD Publishing.
210. Baldé, C. P., V. Forti, V. Gray, R. Kuehr, and P. Stegmann. 2017. *The Global E-waste Monitor 2017: Quantities, Flows, and Resources*. Bonn, Geneva, and Vienna. United Nations University, International Telecommunication Union, and International Solid Waste Association.
211. U.S. Environmental Protection Agency. 2004. Evaluation Report: Multiple Actions Taken to Address Electronic Waste, but EPA Needs to Provide Clear National Direction. Office of the Inspector General, Report No. 2004-P-00028.
212. Hansen, T. L., J. la Cour Jansen, Å. Davidsson, and T. H. Christensen. 2007. Effects of pre-treatment technologies on quantity and quality of source-sorted municipal organic waste for biogas recovery. *Waste Management* 27(3): 398-405.
213. Lewis, J. J., and S. K. Pattanayak. 2012. Who adopts improved fuels and cookstoves? A systematic review. *Environmental Health Perspectives* 120(5): 637-645.
214. World Bank Group. 2017. Populations Estimates and Projections. Available at <https://data.worldbank.org/data-catalog/population-projection-tables>.
215. UN Habitat. 2016. *Urbanization and Development: Emerging Futures*. World Cities Report 2016. Nairobi, Kenya: United Nations Human Settlements Programme.
216. UN Habitat. 2016. *Urbanization and Development: Emerging Futures*. World Cities Report 2016. Nairobi, Kenya: United Nations Human Settlements Programme.
217. United Nations Environment Programme. 2012. Global Initiative for Resource Efficient Cities: Engine to Sustainability; UN Habitat. 2016. *Urbanization and Development: Emerging Futures*. World Cities Report 2016. Nairobi, Kenya: United Nations Human Settlements Programme.
218. Editorial. 2016. A missed opportunity for urban health. *The Lancet* 388(10056): 2057. doi:10.1016/S0140-6736(16)32056-6; Editorial. 2017. Health in slums: Understanding the unseen. *The Lancet* 389(10068): 478-479. doi:10.1016/S0140-6736(17)30266-0.
219. Ezeh, A., O. Oyeade, D. Satterthwaite, Y. F. Chen, R. Ndugwa, J. Sartori, B. Mberu, G. J. Melendez-Torres, T. Haregu, S. I. Watson, and W. Caiaffa. 2017. The history, geography, and sociology of slums and the health problems of people who live in slums. *The Lancet* 389(10068): 547-558; Landrigan, P. J., R. Fuller, N. J. Acosta, O. Adeyi, R. Arnold, A. B. Baldé, R. Bertollini, S. Bose-O'Reilly, J. I. Boufford, P. N. Breyes, and T. Chiles, C. Mahidol, A. M. Coll-Seck, M. L. Cropper, J. Fobil, V. Fuster, M. Greenstone, A. Haines, D. Hanrahan, D. Hunter, M. Khare, A. Krupnick, B. Lanphear, B. Lohani, K. Martin, K. V. Mathiasen, M. A. McTeer, C. J. L. Murray, J. D. Ndahimananjara, F. Perera, J. Potočnik, A. S. Preker, J. Ramesh, J. Rockström, C. Salinas, L. D. Samson, K. Sandilya, P. D. Sly, K. R. Smith, A. Steiner, R. B. Stewart, W. A. Suk, O. C. P. van Schayck, G. N. Yadama, K. Yumkella, and M. Zhong. 2018. The Lancet Commission on Pollution and Health. *The Lancet* 391(10119): 462-512.
220. Morse, S. S., J. A. K. Mazet, M. Woolhouse, C. R. Parrish, D. Carroll, W. B. Karesh, C. Zimbrana-Torrel, W. I. Lipkin, and P. Daszak. 2012. Prediction and prevention of the next zoonosis. *The Lancet* 380(9857):1956-1965.
221. Revi, A., D. E. Satterthwaite, F. Aragón-Durand, J. Corfee-Morlot, R. B. R. Kiunsi, M. Pelling, D. C. Roberts, and W. Soleck. 2014. Urban areas. Pp. 535-612 in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the IPCC Fifth Assessment Report*. C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, and L. L. White, eds. Cambridge, UK, and New York: Cambridge University Press.
222. American Society of Civil Engineers; Engineers. 2017. *2017 Infrastructure Report Card: A Comprehensive Assessment of America's Infrastructure*.
223. Organisation for Economic Co-operation and Development. 2007. *Infrastructure to 2030, Vol.2: Mapping Policy for Electricity, Water and Transport*. Paris: OECD Publishing.
224. National Academies of Sciences, Engineering, and Medicine. 2016. *Pathways to Urban Sustainability: Challenges and Opportunities for the United States*. Washington, DC: The National Academies Press; Ramaswami, A., A. Russell, P. Culligan, K. Sharma, and E. Kumar. 2016. Meta-principles for developing smart, sustainable, and healthy cities. *Science* 352(6288): 940-943.
225. Jeong, H., O. A. Broesicke, B. Drew, D. Li, and J. C. Crittenden. 2016. Life cycle assessment of low impact development technologies combined with conventional centralized water systems for the City of Atlanta, Georgia. *Environmental Science and Engineering* 10(6): 1-13.
226. New York State Department of Environmental Conservation. New York City Water Supply. Available at: [www.dec.ny.gov/lands/25599.html](http://www.dec.ny.gov/lands/25599.html).
227. Zanella, A., N. Bui, A. Castellani, L. Vangelista, and M. Zorzi. 2014. Internet of Things for smart cities. *IEEE Internet of Things Journal* 1(1): 22-32.
228. Debnath, A. K., H. C. Chin, M. M. Haque, and B. Yuen. 2014. A methodological framework for benchmarking smart transport cities. *Cities* 37: 47-56.
229. Ramaprasad, A., A. Sánchez-Ortiz, and T. Syn. 2017. A unified definition of a smart city. Pp. 13-24 in *Electronic Government*. M. Janssen, K. Axelsson, O. Glassey, B. Klievink, R. Krimmer, I. Lindgren, P. Parycek, H. J. Scholl, and D. Trutnev, eds. Springer, Cham.
230. World Economic Forum. 2018. *Harnessing Artificial Intelligence for the Earth*.
231. Palca, J. 2018. Betting on artificial intelligence to guide earthquake response. NPR, April 20. Available at: <https://www.npr.org/>

- 2018/04/20/595564470/betting-on-artificial-intelligence-to-guide-earthquake-response.
232. Laursen, L. 2014. Barcelona's smart city ecosystem. *MIT Technology Review*, Nov. 18.
  233. Amsterdam Smart City. Smartphone app for citizens to manage street lighting. Available at: <https://amsterdamsmartcity.com/products/amsterdam-offers-smartphone-app-for-cityzens-to-manage-street-lighting>.
  234. Korkali, M., J. G. Veneman, B. F. Tivnan, J. P. Bagrow, and P. D. Hines. 2017. Reducing cascading failure risk by increasing infrastructure network interdependence. *Scientific Reports* 7(44499).
  235. Examples are Ecube Lab' (<https://www.ecubelabs.com/solution/>); Bigbelly (<http://bigbelly.com/>); and IBM. 2015. IBM Intelligent Waste Management Platform. White Paper. Available at: <https://www-01.ibm.com/common/ssi/cgi-bin/ssialias?htmlfid=GWW03059USEN>.
  236. World Bank. 2015. How an open traffic platform is helping Asian cities mitigate congestion, pollution. News.
  237. CrimeRadar. Frequently Asked Questions. Available at: <https://rio.crimetradar.org/faq>.
  238. Sidewalk Labs. 2017. Vision Sections of RFP Submission. RFP No. 2017-13.
  239. Woyke, E. 2018. A smarter smart city. *MIT Technology Review*, Feb. 21.
  240. Sidewalk Labs. 2017. Vision Sections of RFP Submission. RFP No. 2017-13.
  241. World Economic Forum. 2018. *Harnessing Artificial Intelligence for the Earth*.
  242. National Academies of Sciences, Engineering, and Medicine. 2016. *Building Smart Communities for the Future: Proceedings of a Workshop—in Brief*. Washington, DC: The National Academies Press.
  243. Klepeis, N. E., W. C. Nelson, W. R. Ott, J. P. Robinson, A. M. Tsang, P. Switzer, J. V. Behar, S. C. Hern, and W. H. Engelmann. 2001. The National Human Activity Pattern Survey (NHAPS): A resource for assessing exposure to environmental pollutants. *Journal of Exposure Science and Environmental Epidemiology* 11(3): 231-252.
  244. Dai, D., A. J. Prussian II, L. C. Marr, P. J. Vikesland, M. A. Edwards, and A. Pruden. 2017. Factors shaping the human exposome in the built environment: Opportunities for engineering control. *Environmental Science & Technology* 51(14): 7759-7774.
  245. Jones, K. E., N. G. Patel, M. A. Levy, A. Storeygard, D. Balk, J. L. Gittleman, and P. Daszak. 2008. Global trends in emerging infectious diseases. *Nature* 451(7181): 990-993.
  246. Lerner, H., and C. Berg. 2017. A comparison of three holistic approaches to health: One Health, EcoHealth, and Planetary Health. *Frontiers in Veterinary Science* 4(163); Centers for Disease Control and Prevention. 2018. One Health Basics. Available at: <https://www.cdc.gov/onehealth/basics>.
  247. Vikesland, P. J., A. Pruden, P. J. J. Alvarez, D. Aga, H. Burgmann, X. Li, C. M. Manaia, I. Nambi, K. Wigginton, T. Zhang, and Y. Zhu. 2017. Toward a comprehensive strategy to mitigate dissemination of environmental sources of antibiotic resistance. *Environmental Science & Technology* 51(22): 13061-13069.
  248. Omira, A. 2016. Kibagare Haki Zetu Bio-Centre: A Transformation Story. Umande Trust, Aug. 8. Available at: <http://umande.org/kibagare-haki-zetu-bio-centre-a-transformation-story>.
  249. P.L. 109-58; P.L. 111-364.
  250. U.S. Environmental Protection Agency. 2017. Environmental Justice FY2017 Progress Report. 240-R1-8001.
  251. Maintenance and Management Oversight Committee. Muddy River Restoration Project: Flood Control Improvement. Available at: <http://www.muddyrivermmoc.org/flood-control>.
  252. C40 Cities. 2015. Cities100: Copenhagen—Creating a Climate Resilient Neighborhood. Available at: [http://www.c40.org/case\\_studies/cities100-copenhagen-creating-a-climate-resilient-neighborhood](http://www.c40.org/case_studies/cities100-copenhagen-creating-a-climate-resilient-neighborhood).
  253. Zhang, W., S. Guhathakurta, J. Fang, and G. Zhang. 2015. Exploring the impact of shared autonomous vehicles on urban parking demand: An agent-based simulation approach. *Sustainable Cities and Society* 19: 34-45.
  254. UN Habitat. 2016. *Urbanization and Development: Emerging Futures*. World Cities Report 2016. Nairobi, Kenya: United Nations Human Settlements Programme.
  255. Jeong, H., O. A. Broesicke, B. Drew, and J. C. Crittenden. 2018. Life cycle assessment of small-scale greywater reclamation systems combined with conventional centralized water systems for the City of Atlanta, Georgia. *Journal of Cleaner Production* 174: 333-342.
  256. U.S. Environmental Protection Agency. 2015. Catalog of CHP Technologies. Available at: <https://www.epa.gov/chp/catalog-chp-technologies>.
  257. James, J.-A., V. M. Thomas, A. Pandit, D. Li, and J. C. Crittenden. 2016. Water, air emissions, and cost impacts of air-cooled microturbines for combined cooling, heating, and power systems: A case study in the Atlanta region. *Engineering* 2(4):470-480; James, J.-A., S. Sung, H. Jeong, O. A. Broesicke, S. P. French, D. Li, and J. C. Crittenden. 2017. Impacts of combined cooling, heating, and power systems and rainwater harvesting on water demand, carbon dioxide and NOx emissions for Atlanta. *Environmental Science & Technology* 52:3-10.
  258. MacKerron, G., and S. Mourato. 2013. Happiness is greater in natural environments. *Global Environmental Change* 23(5): 992-1000.
  259. Guerry, A., S. Polasky, J. Lubchenco, R. Chaplin-Kramer, G. C. Daily, R. Griffin, M. H. Ruckelshaus, I. J. Bateman, A. Duraipappah, T. Elmqvist, M. W. Feldman, C. Folke, J. Hoekstra, P. Kareiva, B. Keeler, S. Li, E. McKenzie, Z. Ouyang, B. Reyers, T. Ricketts, J. Roelström, H. Tallis, and B. Vira. 2015. Natural capital informing decisions: From promise to practice. *Proceedings of the National Academy of Sciences* 112: 7348-7355.
  260. Lemos, M. C., C. J. Kirchhoff, and V. Ramprasad. 2012. Narrowing the climate information usability gap. *Nature Climate Change* 2(11): 789-794.
  261. Rizwan, A. M., D. Y. C. Leung, and C. Liu. 2008. A review on the generation, determination and mitigation of urban heat island. *Journal of Environmental Sciences* 20: 120-128; Phelan, P. E., K. Kaloush, M. Miner, J. Golden, B. Phelan, H. Silva III, and R. A. Taylor. 2015. Urban heat island: Mechanisms, implications, and possible remedies. *Annual Review of Environment and Resources* 40: 285-307.
  262. Carpenter, S. R., N. F. Caraco, D. L. Correll, R. W. Howarth, A. N. Sharpley, and V. H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications* 8(3): 559-568.
  263. Hill, J., S. Polasky, E. Nelson, D. Tilman, H. Huo, L. Ludwig, J. Neumann, H. Zheng, and D. Bonta. 2009. Climate change and health costs of air emissions from biofuels and gasoline. *Proceedings of the National Academy of Sciences* 106(6): 2077-2082.
  264. National Research Council. 2005. *Valuing Ecosystem Services: Toward Better Environmental Decision-Making*. Washington, DC: The National Academies Press; Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-Being: Synthesis*. Washington, DC: Island Press; Díaz, S., U. Pascual, M. Stenseke, B. Martín-López, R. T. Watson, Z. Molnár, R. Hill, K. M. A. Chan, I. A. Baste, K. A. Brauman, S. Polasky, A. Church, M. Lonsdale, A. Larigauderie, P. W. Leadley, A. P. E.

- van Oudenhoven, F. van der Plaat, M. Schröter, S. Lavorel, Y. Aumeeruddy-Thomas, E. Bukvareva, K. Davies, S. Demissew, G. Erpul, P. Failler, C. A. Guerra, C. L. Hewitt, H. Keune, S. Lindley, and Y. Shirayama. 2018. An inclusive approach to assess nature's contributions to people. *Science* 359: 270-272.
265. Scheffer, M., S. R. Carpenter, J. A. Foley, C. Folke, and B. Walker. 2001. Catastrophic shifts in ecosystems. *Nature* 413: 591-596; Lenton, T., H. Held, E. Kriegler, J. W. Hall, W. Lucht, S. Rahmstorf, and H. J. Schellnhuber. 2008. Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences* 105: 1786-1793.
266. Natural Capital Project. Available at: <https://www.naturalcapitalproject.org>.
267. Goldstein, J. G. Caldarone, T. K. Duarte, D. Ennaanay, N. Hannahs, G. Mendoza, S. Polasky, S. Wolny, and G. C. Daily. 2012. Integrating ecosystem service tradeoffs into land-use decisions. *Proceedings of the National Academy of Sciences* 109(19): 7565-7570.
268. Schenk, R., and P. White, eds. 2014. *Environmental Life Cycle Assessment: Measuring the Environmental Performance of Products*. Vashon Island, WA: American Center for Life Cycle Assessment.
269. Freeman, A. M. III, J. Herriges, and C. L. Kling. 2014. *The Measurement of Environmental and Resource Values: Theory and Methods*, 3rd Ed. New York: Resources for the Future Press.
270. Johnston, R. J., J. Rolfe, R. S. Rosenberger, and R. Brouwer, eds. 2015. *Benefit Transfer of Environmental and Resource Values: A Guide for Researchers and Practitioners*. Dordrecht, The Netherlands: Springer.
271. Elkington, J. 1997. *Cannibals with Forks: The Triple Bottom Line of 21st Century Business*. Oxford, UK: Capstone.
272. U.S. Environmental Protection Agency. 2017. Safer Choice: Design for the Environment: Programs, Initiatives, and Projects.
273. National Research Council. 2014. *Sustainability Concepts in Decision-Making: Tools and Approaches for the U.S. Environmental Protection Agency*. Washington, DC: The National Academies Press.
274. Dilling, L., and M. C. Lemos. 2011. Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy. *Global Environmental Change* 21(2): 680-689.
275. Bucchi, M., and B. Trench. 2008. *Handbook of Public Communication of Science and Technology*. Routledge. Available at: [https://moodle.ufsc.br/pluginfile.php/1485212/mod\\_resource/content/1/Handbook-of-Public-Communication-of-Science-and-Technology.pdf](https://moodle.ufsc.br/pluginfile.php/1485212/mod_resource/content/1/Handbook-of-Public-Communication-of-Science-and-Technology.pdf) [accessed April 2, 2018].
276. Nisbet, M. C., and D. A. Scheufele. 2009. What's next for science communication? Promising directions and lingering distractions. *American Journal of Botany* 96(10): 1767-1778. Available at: <http://www.amjbot.org/content/96/10/1767.full>.
277. U.S. Census Bureau. 2015. American Community Survey Public Use Microdata Sample; Blaney, L., J. Perlinger, S. Bartelt-Hunt, R. Kandiah, and J. Ducoste. 2017. Another grand challenge: Diversity in environmental engineering. *Environmental Engineering Science* 35(6):568-572.
278. Herring, C. 2009. Does diversity pay?: Race, gender, and the business case for diversity. *American Sociological Review* 74(2): 208-224; Hunt, V., D. Layton, and S. Prince. 2014. *Diversity Matters*. London: McKinsey & Co.
279. Baumol, W. J., and W. E. Oates. 1988. *The Theory of Environmental Policy*, 2nd Ed. Cambridge, UK and New York: Cambridge University Press; Sterner, T. 2003. *Policy Instruments for Environmental and Natural Resource Management*. Washington, DC: Resources for the Future.
280. Weiss, J. A., and M. Tschirhart. 1994. Public information campaigns as policy instruments. *Journal of Policy Analysis and Management* 13(1): 82-119.
281. Allcott, H. 2011. Social norms and energy conservation. *Journal of Public Economics* 95: 1082-1095; Schultz, P. W., J. M. Nolan, R. B. Cialdini, N. J. Goldstein, and V. Griskevicius. 2007. The constructive, destructive, and reconstructive power of social norms. *Psychological Science* 18: 429-434.
282. Larrick, R. P., and J. B. Soll. 2008. Economics. The MPG illusion. *Science* 320: 1593-1594.
283. Thaler, R. H., and C. R. Sunstein. 2008. *Nudge: Improving Decisions about Health, Wealth and Happiness*. New Haven, CT: Yale University Press.
284. Vandenbergh, M. P., P. C. Stern, G. T. Gardner, T. Dietz, and J. M. Gilligan. 2010. Implementing the behavioral wedge: Designing and adopting effective carbon emissions reduction programs. *Environmental Law Reporter* 40: 10547-10554.
285. Johnson E. J., and D. Goldstein. 2003. Do defaults save lives? *Science* 302(5649): 1338-1339.
286. Beshears, J., J. J. Choi, D. Laibson, and B. C. Madrian. 2009. The importance of default options for retirement saving outcomes: Evidence from the United States. Pp. 167-195 in *Social Security Policy in a Changing Environment*. Chicago: University of Chicago Press; Halpern, S. D., P. A. Ubel, and D. A. Asch. 2007. Harnessing the Power Of Default Options To Improve Health Care. *New England Journal of Medicine* 357: 1340-1344; Ebeling, F., and S. Lotz. 2015. Domestic uptake of green energy promoted by opt-out tariffs. *Nature Climate Change* 5(9): 868.
287. Thaler, R. H., and C. R. Sunstein. 2008. *Nudge: Improving Decisions about Health, Wealth and Happiness*. New Haven, CT: Yale University Press.
288. Waissbein, O., Y. Glemarec, H. Bayraktar, and T. S. Schmidt. 2013. *Derisking Renewable Energy Investment. A Framework to Support Policymakers in Selecting Public Instruments to Promote Renewable Energy Investment In Developing Countries*. New York: United Nations Development Programme.
289. Smith, J. 2014-2015. Sunshine: India's new cash crop. International Water Management Institute.
290. Litke, D. W. 1999. *Review of Phosphorus Control Measures in the United States and Their Effects on Water Quality*. Water-Resources Investigations Report 99-4007. Denver, CO: U.S. Geological Survey.
291. ABET Engineering Accreditation Commission. 2017. Criteria for Accrediting Engineering Programs. Available at: <http://www.abet.org/wp-content/uploads/2018/02/E001-18-19-EAC-Criteria-11-29-17.pdf>.
292. Department for Professional Engineers. 2014. Professionals in the Workplace: Engineers. Available at: <http://dpeaflcio.org/programs-publications/professionals-in-the-workplace/scientists-and-engineers>.
293. Examples include Olin College, Dartmouth College, Texas A&M University, the University of Michigan, and Smith College.
294. National Academy of Engineering. 2004. *The Engineer of 2020: Visions of Engineering in the New Century*. Washington, DC: The National Academies Press.
295. Grand Scholars Program. National Academies of Engineering. Available at: <http://www.engineeringchallenges.org/GrandChallengeScholarsProgram.aspx>.
296. Duderstadt, J. 2009. Engineering for a Changing World, Pp. 17-26 in *Holistic Engineering Education: Beyond Technology*. D. Grasso and M. Burkins, eds. New York: Springer.
297. National Research Council. 2012. *Research Universities and the Future of America: Ten Breakthrough Actions Vital to Our Nation's Prosperity and Security*. Washington, DC: The National Academies Press; President's Council of Advisors on Science and Technology. 2012. *Transformation and Opportunity: The Future of the U.S. Research Enterprise*. Executive Office of the President.



298. National Academy of Sciences, National Academy of Engineering, and Institute of Medicine. 2005. *Facilitating Interdisciplinary Research*. Washington, DC: The National Academies Press; American Academy of Arts & Sciences. 2013. *ARISE 2: Unleashing America's Research & Innovation Enterprise*. Cambridge, MA.
299. National Academy of Sciences, National Academy of Engineering, and Institute of Medicine. 2005. *Facilitating Interdisciplinary Research*. Washington, DC: The National Academies Press.
300. National Research Council. 2014. *Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond*. Washington, DC: The National Academies Press; National Research Council. 2015. *Enhancing the Effectiveness of Team Science*. Washington, DC: The National Academies Press.
301. Pollack, M., and M. Snir. 2008. Best Practices Memo: Promotion and Tenure of Interdisciplinary Faculty. Computing Research Association; University of Southern California. 2011. Guidelines for Assigning Authorship and for Attributing Contributions to Research Products and Creative Works.
302. Pittman, J., H. Tiessen, and E. Montaña. 2016. The evolution of interdisciplinarity over 20 years of global change research by the IAI. *Current Opinion in Environmental Sustainability* 19: 87-93.
303. National Academies of Sciences, Engineering, and Medicine. 2017. *A New Vision for Center-Based Engineering Research*. Washington, DC: The National Academies Press.
304. Palmer, M. A., J. G. Kramer, J. Boyd, and D. Hawthorne. 2016. Practices for facilitating interdisciplinary synthetic research: The National Socio-Environmental Synthesis Center (SESYNC). *Current Opinion in Environmental Sustainability* 19: 111-122.

## FIGURE SOURCES

### GRAND CHALLENGE 1

- FIGURE 1-1** FAO Aquastat database, [http://www.fao.org/nr/water/aquastat/tables/WorldData-Withdrawal\\_eng.pdf](http://www.fao.org/nr/water/aquastat/tables/WorldData-Withdrawal_eng.pdf).
- FIGURE 1-2** Priya Shyamsundar. The Nature Conservancy.
- FIGURE 1-3** AeroFarms LLC.
- FIGURE 1-4** Adapted from High Level Panel of Experts. 2014. Food Losses and Waste in the Context of Sustainable Food Systems. A Report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. Rome: FAO.
- FIGURE 1-5** Adapted from Organisation for Economic Co-operation and Development. 2012. *OECD Environmental Outlook to 2050: The Consequences of Inaction*.
- FIGURE 1-6** Gassert, F., M. Luck, M. Landis, P. Reig, and T. Shiao. 2015. Aqueduct Global Maps 2.1: Constructing Decision-Relevant Global Water Risk Indicators. Working Paper. Washington, DC: World Resources Institute.
- FIGURE 1-7** Courtesy of Liang Dong, Iowa State University.
- SIDEBOX FIGURE** Pamela Burroff-Murr, Purdue University in Genççer, E., C. Miskin, X. Sun, M. R. Khan, P. Bermel, M. A. Alam, and R. Agrawal. 2017. Directing solar photons to sustainably meet food, energy, and water needs. *Scientific Reports* 7: 3133.
- FIGURE 1-8** National Research Council. 2010. *Electricity from Renewable Resources: Status, Prospects, and Impediments*. Washington, DC: The National Academies Press.

### GRAND CHALLENGE 2

- FIGURE 2-1** Berkeley Earth. 2018. Global Temperature Report for 2017. Available at: <http://berkeleyearth.org/global-temperatures-2017>.
- FIGURE 2-2** U.S. Environmental Protection Agency. 2018. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016*. Available at <https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2016>.
- FIGURE 2-3** U.S. Global Change Research Program. 2017. Climate Science Special Report: Fourth National Climate Assessment, Vol. 1. D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock, eds. Washington, DC: USGCRP.

- FIGURE 2-4** Gasparri, A., Y. Guo, F. Sera, A. M. Vicedo-Cabrera, V. Huber, S. Tong, M. de Sousa Zanotti Stagliorio Coelho, P. H. Nascimento Saldiva, E. Lavigne, P. Matus Correa, N. Valdes Ortega, H. Kan, S. Osorio, J. Kyselý, A. Urban, J. J. K. Jaakkola, N. R. I. Ryt, M. Pascal, P. G. Goodman, A. Zeka, P. Michelozzi, M. Scortichini, M. Hashizume, Y. Honda, M. Hurtado-Diaz, J. C. Cruz, X. Seposo, H. Kim, A. Tobias, C. Iñiguez, B. Forsberg, D. O. Åström, M. S. Ragetli, Y. L. Guo, C.-F. Wu, A. Zanobetti, J. Schwartz, M. L. Bell, T. N. Dang, D. D. Van, C. Heaviside, S. Vardoulakis, S. Hajat, A. Haines, and B. Armstrong. 2017. Projections of temperature-related excess mortality under climate change scenarios, *The Lancet Planetary Health* 1(9).

### GRAND CHALLENGE 3

- BOX 3-1** Hoornweg, D., and P. Bhada-Tata. 2012. *What a Waste: A Global Review of Solid Waste Management*. Washington, DC: World Bank.
- FIGURE 3-2** Data from GBD 2016 Risk Factors Collaborators. 2017. Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or cluster of risks, 1990-2016: A systematic analysis for the Global Burden of Disease Study 2016. *The Lancet* 390(10100): 1345-1422.
- FIGURE 3-3** Adapted from Procurement Opportunities in the Circular Economy. Anthesis News + Insights [blog]. Available at: <https://blog.anthesisgroup.com/procurement-in-circular-economy>.

### GRAND CHALLENGE 4

- FIGURE 4-1** ©Nic Lehoux for the Bullitt Center.
- BOX 4-2** Sidewalk Labs.

### GRAND CHALLENGE 5

- BOX 5-1** Goldstein, J., G. Caldarone, T. K. Duarte, D. Ennaanay, N. Hannahs, G. Mendoza, S. Polasky, S. Wolny, and G. C. Daily. 2012. Integrating ecosystem service tradeoffs into land-use decisions. *Proceedings of the National Academy of Sciences* 109(19): 7565-7570.
- FIGURE 5-1** Adapted from Moss, R., P. L. Scarlett, M. A. Kenney, H. Kunreuther, R. Lempert, J. Manning, B. K. Williams, J. W. Boyd, E. T. Cloyd, L. Kaatz, and L. Patton. 2014. Decision support: Connecting science, risk perception, and decisions. Pp 620-647 in *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, T. C. Richmond, and G. W. Yohe, eds. U.S. Global Change Research Program. Available at: <https://nca2014.globalchange.gov/report/response-strategies/decision-support>.
- FIGURE 5-2** Wikimedia Commons.
- BOX (ON INCENTIVIZING WATER CONSERVATION WITH SMART SOLAR PUMPS):** Prashanth Vishwanathan/IMWI.

## APPENDIX A

---

### STATEMENT OF TASK

An ad hoc committee of the Water Science and Technology Board of the National Academies of Sciences, Engineering, and Medicine will undertake a study to identify high-priority challenges and opportunities for the broad field of environmental engineering for the next several decades. Given the current and emerging environmental challenges of the 21st century, a study that describes how the field of environmental engineering and its aligned sciences might evolve to better address these needs could serve as a guide to the community and help frame research priorities. These should be significant societal challenges that will require the expertise of environmental engineering and its aligned sciences to resolve or manage. For each challenge, the committee will:

- Discuss the relevance of the challenge, its magnitude, and implications;
- Identify the key questions or issues related to the challenge that require the expertise of environmental engineering to address;
- Discuss the state of knowledge and practice in environmental engineering and aligned sciences relevant to these questions and issues; and
- Identify areas where knowledge and practice need to advance to address these challenges.