AGU PUBLICATIONS

Water Resources Research

COMMENTARY

10.1002/2017WR020889

Special Section:
Earth and Space Science Is Essential for Society

The food-energy-water nexus: Transforming science for society

Bridget R. Scanlon[1], **Ben L. Ruddell**[2], **Patrick M. Reed**[3], **Ruth I. Hook**[1], **Chunmiao Zheng**[4], **Vince C. Tidwell**[5], and **Stefan Siebert**[6]

[1]Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, Austin, Texas, USA, [2]School of Informatics, Computing, and Cyber Systems, Arizona State University, Northern Arizona University, Flagstaff, Arizona, USA, [3]School of Civil and Environmental Engineering, Cornell University, Ithaca, New York, USA, [4]School of Environment Science and Engineering, South University of Science and Technology of China, Shenzhen, Guangdong, China, [5]Sandia National Laboratories, Albuquerque, New Mexico, USA, [6]Institute of Crop Science and Resource Conservation (INRES), University of Bonn, Bonn, Germany

Key Points:
- Food consumes 90% of global freshwater but 25–30% is lost or wasted; therefore, saving food saves embodied water and energy
- Resource scarcity can be managed by reducing demands, increasing supplies, storage, or transport
- Advances in remote sensing and modeling provide tools to develop adaptive strategies to manage the FEW nexus

Correspondence to:
B. R. Scanlon,
bridget.scanlon@beg.utexas.edu

Citation:
Scanlon, B. R., B. L. Ruddell, P. M. Reed, R. I. Hook, C. Zheng, V. C. Tidwell, and S. Siebert (2017), The food-energy-water nexus: Transforming science for society, *Water Resour. Res.*, *53*, 3550–3556, doi:10.1002/2017WR020889.

Received 4 APR 2017
Accepted 14 APR 2017
Accepted article online 20 APR 2017
Published online 4 MAY 2017

Abstract Emerging interdisciplinary science efforts are providing new understanding of the interdependence of food, energy, and water (FEW) systems. These science advances, in turn, provide critical information for coordinated management to improve the affordability, reliability, and environmental sustainability of FEW systems. Here we describe the current state of the FEW nexus and approaches to managing resource conflicts through reducing demand and increasing supplies, storage, and transport. Despite significant advances within the past decade, there are still many challenges for the scientific community. Key challenges are the need for interdisciplinary science related to the FEW nexus; ground-based monitoring and modeling at local-to-regional scales; incorporating human and institutional behavior in models; partnerships among universities, industry, and government to develop policy relevant data; and systems modeling to evaluate trade-offs associated with FEW decisions.

1. The Food, Energy, and Water Challenge

A substantial percentage of the global population lacks adequate access to FEW resources. Although efforts to meet the Millennium Development Goals of the United Nations have increased access to FEW resources within the past 15 years, ~800 million people are still considered food insecure, ~800 million lack access to safe drinking water, and ~1.2 billion lack access to electricity [*Food and Agriculture Organization* (*FAO*), 2015; *IEA*, 2016; *United Nations*, 2016]. The increase in global population from 7.4 billion (2016) to 9.7 billion in 2050 [*United Nations*, 2015], the increase in per capita gross domestic product (GDP) by 1–5% in different countries [*PWC*, 2015], and changes in dietary preferences to increased meat protein are projected to substantially increase pressures on available FEW resources (Figure 1). The FEW nexus is reflected in terms such as "feeding ourselves thirsty" [*Roberts and Barton*, 2015] and "thirsty energy" [*Rodriguez et al.*, 2013].

Pressure on FEW resources will be further exacerbated by their complex interdependencies. At the global scale, food production is extremely water intensive, accounting for ~70% of global freshwater withdrawal and 90% of freshwater consumption [*Siebert et al.*, 2010]. The energy intensity of food production is lower, representing ~30% of global energy consumption [*FAO*, 2011]. However, ~25–30% of global food produced is estimated to be lost at postharvest or processing stages, or wasted at retail and consumer stages, representing substantial losses in the embodied water and energy [*Gustavsson et al.*, 2011; *Kummu et al.*, 2012]. While food itself represents a form of energy, use of food crops for biofuels has brought considerable attention to the high water intensity of crop production, as indicated by phrases such as "blue impacts of green energy" or "cars versus carnivores" [*de Fraiture et al.*, 2008; *Gerbens-Leenes et al.*, 2009].

Energy production is much less water intensive than food production, accounting for ~15% of global water withdrawal, with only 11% of this water being consumed [*IEA*, 2012]. Water is used for oil and gas extraction and electricity generation (a secondary form of energy), the latter dominated by hydroelectricity and thermoelectric cooling of fossil fuel and nuclear power plants [*Healy et al.*, 2015]. There is much discussion about the high water intensity of oil and gas extraction from unconventional low-permeability reservoirs in the United States using hydraulic fracturing and horizontal drilling. However, studies indicate that these

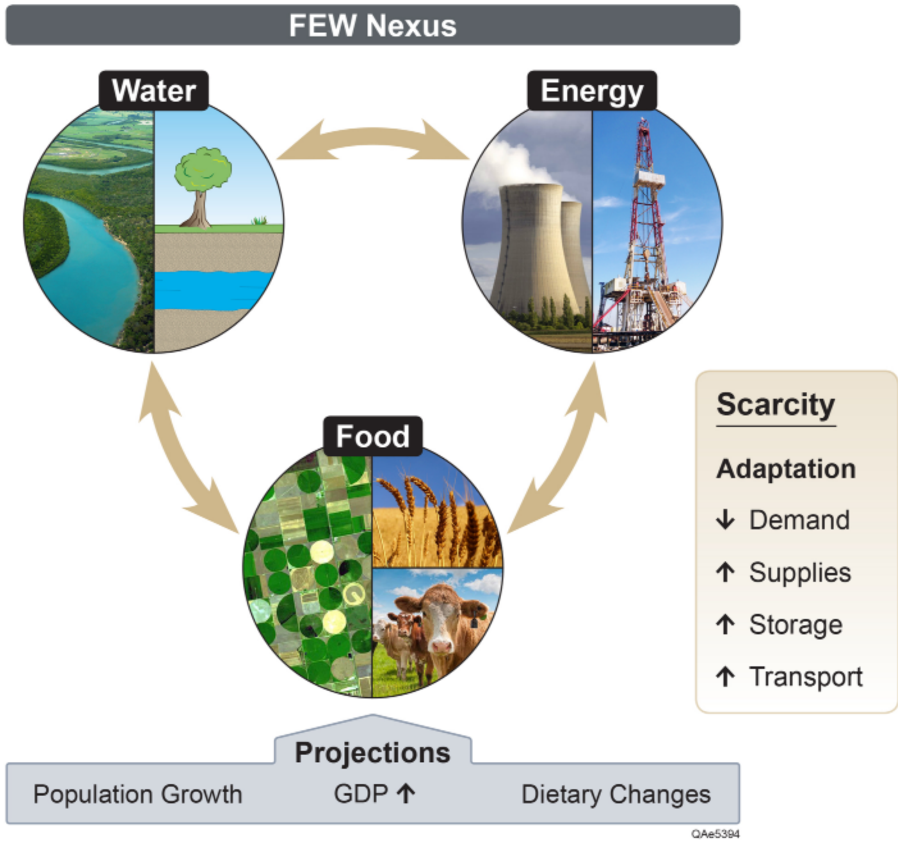

Figure 1. The Food-Energy-Water nexus showing the interconnection among the components and adaptation strategies for scarcity.

processes represent less than 1% of total freshwater withdrawal at the national level, although the percentage locally can be much higher [*Nicot and Scanlon*, 2012; *Scanlon et al.*, 2014; *Kondash and Vengosh*, 2015].

More collisions among FEW resources are likely, considering increasing climate extremes with longer-term droughts and more-intense floods. The 2003 European heat wave provides an example of a catastrophic collision between water and energy, with an estimated 70,000 fatalities caused in part by nuclear power-plant shutdowns because of low river levels and elevated water temperatures limited cooling requirements [*EEA*, 2010]. Reduced access to FEW resources can result in social strife and impact international security [*Willis et al.*, 2016].

Research on the nexus of FEW resources and their impact on the Earth system is critical if we want to provide affordable and reliable resources in an environmentally sustainable way. A variety of new science programs are designed to address these nexus issues within the context of climate and the Earth system. Examples include the Belmont Forum's Sustainable Urban Global Initiative. The U.S. National Science Foundation initiated the Innovations at the Nexus of Food, Energy and Water Systems (INFEWS) program, which is designed to support research to understand current and projected coupled processes related to society and the environment. The program addresses physical processes (e.g., technologies for more-efficient resource use), natural processes (e.g., hydrologic), and biological processes (e.g., agroecosystem productivity). Emphasis on social/behavioral processes related to decision making and governance is becoming more and more important. Monitoring, networking, computational approaches, and visualization are essential for assessment and decision making. The U.S. Department of Energy also has a strong program focusing on the water and energy nexus [*DOE*, 2014].

The objective of this commentary is to show the power of the scientific community to develop approaches in FEW systems to adapt to resource scarcity. We highlight the potential value of future partnerships among universities, industry, and government to develop policy-relevant data at local-to-global scales for input to interdisciplinary systems models that address trade-offs related to FEW system management.

2. Addressing the Food-Energy-Water Nexus

2.1. Characterizing and Monitoring the Nexus

You cannot manage what you do not measure. Several advances have been made toward quantifying various components of the FEW nexus. The water footprint (WF), which quantifies human consumption and/or pollution of fresh water, includes green water (rainfall/soil moisture), blue water (surface/groundwater), and gray water (freshwater volume required to assimilate contaminants to meet regulatory guidelines) [*Hoekstra and Mekonnen*, 2012]. The global WF is estimated to be 9100 km^3/yr (74% green, 11% blue, 15% gray). Per capita WFs are much higher in the United States (2850 m^3/yr) than in China (1070 m^3/yr) or India (980 m^3/yr). Global average WFs of different food products vary widely, with the average per calorie WF of beef exceeding that of cereals by a factor of ~20 [*Mekonnen and Hoekstra*, 2012].

While many previous studies indicate that vegetarian diets would result in large blue-water savings (e.g., up to 23% in Europe) [*Vanham et al*., 2013], a recent analysis of 2010 USDA dietary guidelines indicates that changes in the projected food mix to include increased fruit and vegetables would result in up to a 16% increase in the blue-water footprint [*Tom et al*., 2015]. This study indicates that low-calorie fruits and vegetables have higher blue-water WFs than grains and meats, considering food waste at retail and consumer levels. In other words, promoting healthy diets may not be healthy for the planet. However, *Tom et al*. [2015] cite as a major limitation of the study its meta-analysis approach and reliance on literature data. *Wang and Zimmerman* [2016] question the reliability of WF accounting because of confusion over water withdrawals versus consumption; total WF versus green, blue, or gray footprints, or lack of specification, and conflicting international data sets, underscoring the need for much more detailed evaluation of data. While WFs allow us to rank foods based on their water consumption, they do not provide any indication of the water scarcity or excess at locations where the food is produced [*Hoekstra*, 2016].

2.2. Global Analysis of Food-Energy-Water Scarcity

Many analyses of FEW systems are concerned with resource scarcity or excess based on comparison of demand relative to supply. Global water-scarcity maps have been developed using models based on a variety of different metrics [*Smakhtin et al*., 2004; *Alcamo et al*., 2007; *Wada et al*., 2011; *Reig et al*., 2013; *Brauman et al*., 2016]. Global models indicate that unsustainable groundwater depletion supplies irrigation in many hotspots globally [*Wada et al*., 2012]. Maps of global food-demand projections have also been developed using different models within the Agricultural Model Intercomparison Project (AgMIP) [*Valin et al*., 2014]. On the energy side, oil production has been exceeding demands, resulting in a sharp drop in oil prices from ~$100 in 2014 to $52 in 2015 [*BP*, 2016]. Because electricity cannot readily be stored, supplies need to meet instantaneous demands. Electricity supplies can be highly vulnerable during droughts because elevated temperatures generally maximize electricity demand when water supplies are at a minimum [*Averyt et al*., 2011].

2.3. Managing Scarce Resources: Conservation

Scarcity in FEW resources can be partially managed by reducing demands (conservation). The large proportion of food that is lost or wasted provides an excellent opportunity to reduce water and energy demand by reducing food waste. Global analysis indicates that ~25% of food production, cropland area, and fertilizer applications are lost through food loss and waste [*Kummu et al*., 2012]. Therefore, reducing food loss to the lowest level found in each region evaluated would provide sufficient food to feed an additional billion people. There is much interest in reducing irrigation-water demands by changing technologies from flood to drip systems, with the common mantra of "more crop per drop" [*Falkenmark and Rockstrom*, 2006; *Molden*, 2007]. However, integrated basin-scale studies in the North China Plain and U.S. Rio Grande Basin indicate that more water-efficient irrigation technologies may have the perverse result of depleting water resources because they reduce irrigation return flows and aquifer recharge and can result in expansion of irrigated areas [*Kendy et al*., 2003; *Perry*, 2007; *Ward and Pulido-Velazquez*, 2008]. These studies suggest that policies should focus on reducing water depletions rather than on increasing irrigation efficiencies.

Global modeling and regional analysis show opportunities for making irrigation more sustainable by combining inefficient surface-water irrigation to recharge groundwater during wet periods with efficient groundwater irrigation during droughts, with applications in northwest India and the U.S. California Central Valley [*Faunt*, 2009; *Döll et al*., 2012; *Scanlon et al*., 2016]. Water for energy can be conserved by decoupling thermoelectric power generation from freshwater use. Analysis of U.S. data indicates that switching to brackish groundwater or dry cooling would result in substantial water savings in water-scarce basins, increasing power-plant generation expenses by less than 10% and increasing parasitic energy load by ~5% [*Tidwell et al*., 2014a]. Increasing renewables based on wind and solar sources also reduces water demand for electricity generation. Water conservation for oil and gas extraction is achieved through reuse of produced water. The oil industry produces ~10 L of water per liter of oil; this water has been reused for enhanced oil recovery over many decades [*Veil*, 2015].

2.4. Managing Scarce Resources: Increasing Supplies

FEW system management also addresses opportunities to increase supplies, which is often associated with increased interdependence among components of FEW systems. While food production greatly increased in the past as a result of the Green Revolution, recent genetically modified (GM) crops have the potential to further enhance food production through advances in genome sequencing for development of pest-resistant varieties and drought tolerance [*Godfray et al*., 2010]. However, public acceptance of GM foods is an important issue. Increasing water supplies generally involves development of alternative sources such as desalinating brackish groundwater or seawater, treating municipal wastewater, or capturing storm water. These nontraditional water sources, however, require more energy and are more expensive. Analysis for power generation in the semiarid western United States indicates that water supplies from these alternative sources were sufficient to meet projected increases in water demand but that water costs would increase because of treatment requirements [*Tidwell et al*., 2014b]. Energy supplies (oil and gas) have been increasing in the United States through advances in technology (hydraulic fracturing and horizontal drilling), resulting in the shale oil and gas revolution with large increases in water requirements.

2.5. Managing Scarce Resources: Storage and Transport

The spatial and temporal disconnects between demand and supply can be partially resolved through storage and transport of resources. Food storage is very valuable for managing supply/demand imbalances related to droughts or economic drivers. Results of global analysis indicate that food stocks have remained fairly stable over the past 50 years, representing ~500 kcal/cap and an ability to feed the global population for about half a year [*Laio et al*., 2016]. Natural water storage occurs in lakes and aquifers, with manmade storage focusing on surface water reservoirs. However, adverse environmental impacts of reservoirs and large evaporative losses have shifted the focus in some regions to storing water in the subsurface in aquifers using managed aquifer recharge [*Dillon et al*., 2009; *Scanlon et al*., 2016]. While primary energy sources can be stored, e.g., oil reserves and coal reserves, storage of electricity is not generally feasible, resulting in instantaneous supplies having to meet peak demands, usually during the hottest hours of the year in many regions. The lack of storage results in additional reserve capacity of up to a factor of ~3 times for some regions in the United States to provide a buffer during peak times [*Shear*, 2014].

Resources are transported to different extents to manage supply/demand imbalances. Although water is transported naturally in rivers and aquifers, transport via canals and aqueducts is energy intensive because water is heavy. The south-north water-transfer project in China is being designed to transport ~28 km^3/yr of water from the Yangtze River in the south to semiarid regions in the north where water demand is high [*Shifflett et al*., 2015]. The energy intensity of this system is very high, both to transport and treat the water, with an estimated 900 sewage-treatment plants required. California developed an integrated aqueduct system to transport water from the humid north to the semiarid south, where it is used for irrigation and municipal purposes [*Faunt*, 2009].

Oil and gas commodities are traded globally. However, the United States has been moving toward increased energy security, with crude-oil production almost doubling since 2008 because of the shale oil and gas revolution, greatly reducing dependence on foreign oil. Electricity can also be readily transported through grid networks. However, transmission grids are expensive; for example, Texas spent ~ $8 billion to connect renewable wind generation in rural areas to demand centers [*Scanlon et al*., 2014]. Food trade provides another opportunity to transport both food and the embedded water and energy in the food, or virtual water and energy. Because the weight of food is much less than the weight of water embodied in the food, food trade can be considered an approach to transporting water. A recent study indicates that global food trade accounts for 23% of food production, with a doubling of food calories traded between 1986 and

2009 [*d'Odorico et al*., 2014]. Global analysis indicates that food trade generally mitigates water stress in ~80% of the countries studied, [*Wang and Zimmerman*, 2016].

Some negative implications of food trade include trade dependency and associated loss of resilience to shocks in the production and trade systems. During the recent food crisis of 2008, exporting countries issued export bans, causing some trade-dependent countries to become (virtually) water/food insecure [*Tamea et al*., 2016]. A shift in China's national food-security policy in 2000 resulted in substantial increases in soy imports from Brazil, with a savings in global water [*Dalin et al*., 2012]. Similarly, Saudi Arabia has passed water-sustainability legislation banning use of fresh groundwater for irrigation of feed for animals after decades of depleting their water resources. Saudi dairy companies now own slices of the desert in Arizona and California for the explicit purpose of turning southwestern United States sunshine and groundwater into hay destined for Saudi cattle [*Graham*, 2016].

3. Science Needs for Coordinated Food-Energy-Water Management

Data needs based on monitoring networks and modeling analyses are essential to advancing understanding in the FEW nexus. The past couple of decades have seen a shift from local to regional data and modeling efforts to global scales, with significant advances in remote sensing and global modeling. Satellites critical to FEW management allow monitoring of global water storage (GRACE) and vegetation (MODIS). Global hydrologic and land-surface models also provide important information on water availability for FEW systems [*Bierkens*, 2015]; however, model intercomparisons reveal large uncertainties in these models [*Haddeland et al*., 2014; *Schewe et al*., 2014]. New insights are emerging by coupling trade data for global food transport with embedded water and energy to understand the stocks and flows of our economic use of resources [*Dang et al*., 2016]. However, a spatial disconnect exists between global data and the scales at which FEW systems are managed. There is a need to balance the current emphasis on global analyses with more local-to-regional analyses to provide data at more policy-relevant scales. However, ground-based monitoring networks have been on the decline within the past decades in the United States and regional-scale modeling efforts are more limited. A bottom-up approach to data collection would link households, farmers, and industries to FEW systems, providing more-robust data that could be used to develop regional-to-national-level insights.

Interdisciplinary research is essential for effective management of FEW systems. While the various science disciplines have long histories of working independently in components of the FEW nexus, future research should integrate physical, agroecological, and social sciences with economics. Global case studies of coupled human and natural systems reflect integration of social-ecological systems with human-environmental systems that provide valuable insights into heterogeneity, thresholds, and resilience [*Liu et al*., 2007]. FEW management would benefit greatly from partnerships among universities, industry, and government to address the complexity of FEW systems. With large-scale agricultural and energy industries controlling FEW systems in many regions, collaboration between academia and industry will be essential to effect change. Working with governments will provide an opportunity to develop policies more likely to improve FEW management. For example, the Coalition for Environmentally Responsible Economies (CERES) works with agribusinesses to develop socially responsible behavior to reduce adverse environmental impacts of food production [*Roberts and Barton*, 2015].

Nexus science and recent advances in our modeling and analysis frameworks allow humans to be an integral part of the science [*AghaKouchak et al*., 2015; *Konar et al*., 2016]. In the context of dependencies, recent descriptive-modeling frameworks [*Dalin et al*., 2012; *Ruddell et al*., 2014; *Zhang et al*., 2017] are providing a more detailed understanding of the connected and evolving consequences of the regional-to-global dynamics within our FEW systems. Big data and big computing [*Lohr*, 2015] allow quantitative analyses to capture the qualitative aspects of FEW systems (e.g., preferences, consumer behavior, and decision making). In the move from descriptive studies to those seeking to provide prescriptive recommendations, many recent breakthroughs have occurred related to adaptation pathways for coevolving human demands, innovative management policies, and adaptive infrastructure investment [*Haasnoot et al*., 2013; *Dittrich et al*., 2016; *Kingsborough et al*., 2016; *Zeff et al*., 2016; *Hermans et al*., 2017]. Integrating multiple disciplines in science and academia, industry, and government holds great promise for transforming FEW science for societal benefit.

Acknowledgment
Bridget Scanlon would like to acknowledge support from the Mitchell Foundation and the Sloan Foundation for support.

References

AghaKouchak, A., D. Feldman, M. Hoerling, T. Huxman, and J. Lund (2015), Recognize anthropogenic drought, *Nature*, *524*(7566), 409–411.
Alcamo, J., M. Florke, and M. Marker (2007), Future long-term changes in global water resources driven by socio-economic and climatic changes, *Hydrol. Sci. J.*, *52*(2), 247–275.
Averyt, K. B., J. B. Fisher, A. T. Huber-Lee, A. Lewis, J. Macknick, N. T. Madden, J. Rogers, and S. Tellinghuisen (2011), Freshwater use by U.S. Power Plants: Electricity's thirst for a precious resource: A report of the energy and water in a warming world initiative, *NREL Rep.*, *TP-6A20-5327*, 62 p., Union of Concerned Scientists, Cambridge, Mass.
Bierkens, M. F. P. (2015), Global hydrology 2015: State, trends, and directions, *Water Resour. Res.*, *51*, 4923–4947, doi:10.1002/2015WR017173.
BP (2016), *BP Statistical Review of World Energy, June 2016*, 45 p., London.
Brauman, K. A., B. D. Richter, S. Postel., M. Malsy, and M. Florke (2016), Water depletion: An improved metric for incorporating seasonal and dry-year water scarcity into water risk assessments, *Elementa*, *4*, 83, doi:10.12952/journal.elementa.000083.
Dalin, C., M. Konar, N. Hanasaki, A. Rinaldo, and I. Rodriguez-Iturbe (2012), Evolution of the global virtual water trade network, *Proc. Natl. Acad. Sci. U. S. A.*, *109*(16), 5989–5994.
Dang, Q., M. Konar, J. J. Reimer, G. Di Baldassarre, X. W. Lin, and R. J. Zeng (2016), A theoretical model of water and trade, *Adv. Water Resour.*, *89*, 32–41.
de Fraiture, C., M. Giordano, and Y. S. Liao (2008), Biofuels and implications for agricultural water use: Blue impacts of green energy, *Water Policy*, *10*, 67–81.
Dillon, P. J., P. Pavelic, D. Page, H. Beringen, and J. Ward (2009), Managed aquifer recharge, An introduction, *Waterlines Rep. Ser. 13*, 86 p., Natl. Water Comm., Canberra, Australia.
Dittrich, R., A. Wreford, and D. Moran (2016), A survey of decision-making approaches for climate change adaptation: Are robust methods the way forward?, *Ecol. Econ.*, *122*, 79–89.
D'Odorico, P., J. A. Carr, F. Laio, L. Ridolfi, and S. Vandoni (2014), Feeding humanity through global food trade, *Earths Future*, *2*(9), 458–469.
DOE (2014), The Water-Energy Nexus: Challenges and Opportunities, 238 p., U.S. Dep. of Energy, Copenhagen, Denmark.
Döll, P., H. Hoffmann-Dobrev, F. T. Portmann, S. Siebert, A. Eicker, M. Rodell, G. Strassberg, and B. R. Scanlon (2012), Impact of water withdrawals from groundwater and surface water on continental water storage variations, *J. Geodyn.*, *59–60*, 143–156, doi:10.1016/j.jog.2011.05.001.
EEA (2010), Mapping the impacts of natural hazards and technological accidents in Europe: An overview of the last decade, *Tech. Rep. 13/2010*, 144 p., Copenhagen, Denmark.
Falkenmark, M., and J. Rockstrom (2006), The new blue and green water paradigm: Breaking new ground for water resources planning and management, *J. Water Resour. Plann. Manage.*, *132*(3), 129–132.
Faunt, C. C. (Ed.) (2009), Groundwater availability of the Central Valley Aquifer, California, *U.S. Geol. Surv. Prof. Pap. 1766*, 173 p.
Food and Agriculture Organization (FAO) (2011), Energy Smart Food for People and Agriculture, issue paper, 25 p., Rome, Italy.
Food and Agriculture Organization (FAO) (2015), The State of Food Insecurity in the World 2015, 57 p., Intl. Food for Agric. Dev. World Food Program, Rome, Italy.
Gerbens-Leenes, W., A. Y. Hoekstra, and T. H. van der Meer (2009), The water footprint of bioenergy, *Proc. Natl. Acad. Sci. U. S. A.*, *106*(25), 10,219–10,223.
Godfray, H. C. J., J. R. Beddington, I. R. Crute, L. Haddad, D. Lawrence, J. F. Muir, J. Pretty, S. Robinson, S. M. Thomas, and C. Toulmin (2010), Food security: The challenge of feeding 9 billion people, *Science*, *327*(5967), 812–818.
Graham, K. (2016), *Saudi Arabia Buying up Farmland in Southwestern U.S.* [Available at http://www.digitaljournal.com/business/business/saudi-arabia-buying-up-farmland-in-southwestern-usa/article/455152.]
Gustavsson, J., C. Cederberg, U. Sonesson, R. van Otterdijk, and M. A. (2011), Global food losses and food waste: Extent, causes and prevention, *Food Agric. Organ.*, 29.
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 Environ. Change*, *23*(2), 485–498.
Haddeland, I., et al. (2014), Global water resources affected by human interventions and climate change, *Proc. Natl. Acad. Sci. U. S. A.*, *111*(9), 3251–3256.
Healy, R. W., W. A. Alley, M. A. Engle, P. B. McMahon, and J. D. Bales (2015), The water-energy nexus: An earth science perspective, *U.S. Geol. Surv. Circular 1407*, 107 p.
Hermans, L. M., M. Haasnoot, J. ter Maat, and J. H. Kwakkel (2017), Designing monitoring arrangements for collaborative learning about adaptation pathways, *Environ. Sci. Policy*, *69*, 29–38.
Hoekstra, A. Y. (2016), A critique on the water-scarcity weighted water footprint in LCA, *Ecol. Indic.*, *66*, 564–573.
Hoekstra, A. Y., and M. M. Mekonnen (2012), The water footprint of humanity, *Proc. Natl. Acad. Sci. U. S. A.*, *109*(9), 3232–3237.
IEA (2012), Water for Energy: Is energy becoming a thirstier resource?, in *World Energy Outlook 2012*, chap. 17, 31 p., Cedex, France.
IEA (2016), *World Energy Outlook 2016 Energy Access Database*, Cedex, France. [Available at http://www.worldenergyoutlook.org/resources/energydevelopment/energyaccessdatabase/.]
Kendy, E., D. J. Molden, T. S. Steenhuis, and C. Liu (2003), Policies drain the North China Plain: Agricultural Policy and Groundwater Depletion in Luancheng County, 1949-2000, *Int. Water Manage. Inst. Res. Rep. 71*, 44.
Kingsborough, A., E. Borgomeo, and J. W. Hall (2016), Adaptation pathways in practice: Mapping options and trade-offs for London's water resources, *Sustain. Cit. Soc.*, *27*, 386–397.
Konar, M., T. P. Evans, M. Levy, C. A. Scott, T. J. Troy, C. J. Vorosmarty, and M. Sivapalan (2016), Water resources sustainability in a globalizing world: Who uses the water?, *Hydrol. Processes*, *30*(18), 3330–3336.
Kondash, A., and A. Vengosh (2015), Water footprint of hydraulic fracturing, *Environ. Sci. Technol. Lett.*, *2*(10), 276–280.
Kummu, M., H. de Moel, M. Porkka, S. Siebert, O. Varis, and P. J. Ward (2012), Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use, *Sci. Total Environ.*, *438*, 477–489.
Laio, F., L. Ridolfi, and P. D'Odorico (2016), The past and future of food stocks, *Environ. Res. Lett.*, *11*(3).
Liu, J. G., et al. (2007), Complexity of coupled human and natural systems, *Science*, *317*(5844), 1513–1516.
Lohr, S. (2015), Data-ism: The Revolution Transforming Decision-Making, Consumer Behavior, and Almost Everything Else, HarperCollins Publ., New York.
Mekonnen, M. M., and A. Y. Hoekstra (2012), A global assessment of the water footprint of farm animal products, *Ecosystems*, *15*(3), 401–415.
Molden, D. (Ed.) (2007), *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*, 665 pp., Earthscan and IWMI, Sri Lanka.

Nicot, J. P., and B. R. Scanlon (2012), Water use for shale-gas production in Texas, US, *Environ. Sci. Technol.*, *46*(6), 3580–3586.
Perry, C. (2007), Efficient irrigation; Inefficient communication; Flawed recommendations, *Irrig. Drain.*, *56*(4), 367–378.
PWC (2015), *The World in 2050: Will the Shift in Global Economic Power Continue*?, 43 p., Arlington, Va.
Reig, P., T. Shiao, and F. Gassert (2013), *Aqueduct Water Risk Framework*, WRI working paper, 16 p., Water Resour. Inst., Washington, D. C. [Available at http://www.wri.org/publication/aqueduct-waterrisk-framework.]
Roberts, E., and B. Barton (2015), *Feeding Ourselves Thirsty: How the Food Sector is Managing Global Water Risks*, CERES report, 71 p.
Rodriguez, D., A. Delgado, P. DeLaquil, and A. Sohns (2013), Thirsty energy, water papers, World Bank, Washington, D. C. [Available at http://documents.worldbank.org/curated/en/835051468168842442/Thirsty-energy.]
Ruddell, B. L., E. A. Adams, R. Rushforth, and V. C. Tidwell (2014), Embedded resource accounting for coupled natural-human systems: An application to water resource impacts of the western US electrical energy trade, *Water Resour. Res.*, *50*, 7957–7972, doi:10.1002/2013WR014531.
Scanlon, B. R., R. C. Reedy, and J. P. Nicot (2014), Will water scarcity in semiarid regions limit hydraulic fracturing of shale plays?, *Environ. Res. Lett.*, *9*(12), doi:10.1088/1748-9326/9/12/124011.
Scanlon, B. R., R. C. Reedy, C. C. Faunt, D. Pool, and K. Uhlman (2016), Enhancing drought resilience with conjunctive use and managed aquifer recharge in California and Arizona, *Environ. Res. Lett.*, *11*(3).
Schewe, J., et al. (2014), Multimodel assessment of water scarcity under climate change, *Proc. Natl. Acad. Sci. U. S. A.*, *111*(9), 3245–3250.
Shear, T. (2014), NERC's Summer Reliability Assessment highlights regional electricity capacity margins, in *Energy Information Administration, Today in Energy, June 20, 2014*, Energy Inf. Admin., Washington, D. C. [Available at http://www.eia.gov/todayinenergy/detail.cfm?id=6510.]
Shifflett, S. C., J. L. Turner, L. Dong, I. Mazzocco, and B. Yunwen (2015), *China's Water-Energy-Food Roadmap: A Global Choke Point Report*, 55 p., Greenovation Hub and Wilson Cent., Washington, D. C.
Siebert, S., J. Burke, J. M. Faures, K. Frenken, J. Hoogeveen, P. Döll, and F. T. Portmann (2010), Groundwater use for irrigation: A global inventory, *Hydrol. Earth Syst. Sci.*, *7*, 3977–4021.
Smakhtin, V., C. Revenga, and P. Döll (2004), A pilot global assessment of environmental water requirements and scarcity, *Water Int.*, *29*(3), 307–317.
Tamea, S., F. Laio, and L. Ridolfi (2016), Global effects of local food-production crises: A virtual water perspective, *Sci. Rep*, *6*.
Tidwell, V. C., J. Macknick, K. Zemlick, J. Sanchez, and T. Woldeyesus (2014a), Transitioning to zero freshwater withdrawal in the U.S. for thermoelectric generation, *Appl. Energy*, *131*, 508–516, doi:10.1016/j.apenergy.2013.11.028.
Tidwell, V. C., et al. (2014b), Mapping water availability, projected use and cost in the western United States, *Environ. Res. Lett.*, *9*(6).
Tom, M. S., P. S. Fishbeck, and C. T. Hendrickson (2015), Energy use, blue water footprint, and greenhouse gas emissions for current food consumption patterns and dietary recommendations in the US, *Environ. Syst. Decis.*, *35*(4), 92.
United Nations (2015), World Population Prospects: The 2015 Revision, Key Findings and Advance Tables, *Working Pap. ESA/P/WP.241*, 59 p., United Nations Dept. of Econ. and Soc. Affairs (UNDESA), Popul. Div., New York. [Available at https://esa.un.org/unpd/wpp/Publications/Files/Key_Findings_WPP_2015.pdf.]
United Nations (2016), *The Millennium Development Goals Report 2015*, 72 p., New York.
Valin, H., et al. (2014), The future of food demand: Understanding differences in global economic models, *Agric. Econ.*, *45*(1), 51–67.
Vanham, D., M. M. Mekonnen, and A. Y. Hoekstra (2013), The water footprint of the EU for different diets, *Ecol. Indic.*, *32*, 1–8.
Veil, J. (2015), U.*S. Produced Water Volumes and Management Practices in 2012*, report, Groundwater Prot. Counc.
Wada, Y., L. P. H. van Beek, D. Viviroli, H. H. Durr, R. Weingartner, and M. F. P. Bierkens (2011), Global monthly water stress: 2. Water demand and severity of water stress, *Water Resour. Res.*, *47*, W07518, doi:10.1029/2010WR009792.
Wada, Y., L. P. H. van Beek, and M. F. P. Bierkens (2012), Nonsustainable groundwater sustaining irrigation: A global assessment, *Water Resour. Res.*, *48*, W00L06, doi:10.1029/2011WR010562.
Wang, R. R., and J. Zimmerman (2016), Hybrid analysis of blue water consumption and water scarcity implications at the global, national, and basin levels in an increasingly globalized world, *Environ. Sci. Technol.*, *50*(10), 5143–5153.
Ward, F. A., and M. Pulido-Velazquez (2008), Water conservation in irrigation can increase water use, *Proc. Natl. Acad. Sci. U. S. A.*, *105*(47), 18,215–18,220.
Willis, H. H., D. G. Groves, J. S. Ringel, Z. Mao, S. Efron, and M. Abbott (2016), *Developing the Pardee Rand Food-Energy-Water Security Index*, 59 p., Rand Corp., Santa Monica, Calif.
Zeff, H. B., J. D. Herman, P. M. Reed, and G. W. Characklis (2016), Cooperative drought adaptation: Integrating infrastructure development, conservation, and water transfers into adaptive policy pathways, *Water Resour. Res.*, *52*, 7327–7346, doi:10.1002/2016WR018771.
Zhang, L., H. Dobslaw, T. Stacke, A. Güntner, R. Dill, and M. Thomas (2017), Validation of terrestrial water storage variations as simulated by different global numerical models with GRACE satellite observations, *Hydrol. Earth Syst. Sci.*, *21*(2), 821–837.