Embedded resources and connected networks: Ideas for research and implementation of water, energy, and food SDGs.

Caitlin Grady, Assistant Professor, Penn State University (corresponding author)
cagrady@psu.edu
+1 (814) 865 – 9434
212 Sackett Building
University Park, PA 16802
Paniz Mohammadpour, Doctoral Candidate, Penn State University
Tasnuva Mahjabin, Post Doctoral Researcher, Penn State University

Abstract:

While relationships within individual water, energy, and food (WEF) systems have been well characterized in a variety of locations in several research contexts, we lack a systematic understanding of how governance, geophysical, climatic, and socio-economic contextual factors contribute to WEF Sustainable Development Goal (SDG) achievements across time and space. This gap is due in part to the fact that WEF data sources are disparate and disconnected causing research to occur at differing spatial and temporal scales. Additionally, there are numerous governance challenges to addressing overlapping WEF SDG progress. In this paper, we will highlight several research strategies in network science and embedded resource accounting for addressing WEF connections. Then, these strategies will be discussed and critiqued in the context of accelerating SDG progress at multiple scales. The goal of this paper is to highlight potential innovative socio-technical solutions while also presenting discourse around implementation challenges faced when tackling multiple SDGs simultaneously.

Introduction:

The Water, Energy, and Food (WEF) nexus research framework is no longer in its infancy. Research themes that sought to understand the interlinkages between water, food, and energy systems date back to as least the 1970s though the Bonn 2011 Nexus conference if often hailed as the turning point in accelerating and expanding the WEF nexus as we consider it today.[1] Over the last decade, modeling approaches used to understand WEF interlinkages have become increasingly complex and numerous.[2] No unified framework or modeling methodology has emerged as a single best practice for quantifying and displaying WEF interdependencies. Critiques hail the WEF nexus framing as unhelpful in part because it can represent both everything and nothing at the same time.[3] Building upon both critiques and challenges, there is a need to critically review and analyze WEF nexus approaches to promote a discourse around useful strategies for the next generation of research across interlinked global sustainable resources.

The following conference paper seeks to serve as a starting point for critically reviewing several WEF research approaches. First, we utilize this introduction to include a short

[1] Hoff, "Understanding the Nexus. Background Paper for the Bonn 2011 Conference."
[2] Bazilian et al., "Considering the Energy, Water and Food Nexus"; Dargin, Daher, and Mohtar, "Complexity versus Simplicity in Water Energy Food Nexus (WEF) Assessment Tools"; Chang et al., "Quantifying the Water-Energy-Food Nexus."
[3] Wichelns, "The Water-Energy-Food Nexus."

literature review summarizing several key issues in the WEF nexus research space. In the second section, we explain and highlight several major WEF quantification modeling approaches as well as weaknesses associated with such approaches. After outlining these approaches, we discuss ways in which these strategies can help or hinder accelerating progress towards achieving the Sustainable Development Goals. We conclude with several recommendations for the WEF nexus research community to guide our discussion on the future of this field.

The WEF nexus provides a compelling framework for SDG development pursuit for a number of reasons. First, all three areas, water, food, and energy, have billions of people without access to appropriate quality or quantity (or both) of one or more of these resources.[4] Additionally, all three resources have rapidly growing global demand and real resource constraints. These three areas are also spatially varied in regional availability and are all global goods that involve international trade. The emergence of WEF nexus framing across the last decade showcases a shift towards integrative thinking and systems concepts across multiple global challenges.[5] Relating to achieving the SDGs however, framing the WEF nexus crosses three entire SDG goals each with multiple targets and criteria while also relating in part to numerous other goals. This can certainly create tradeoffs that are not always positive among SDGs.[6] It is important therefore to recognize and navigate these tradeoffs to ensure SDG achievement in one area does not degrade achievements in another.

To further both research and practice across the WEF nexus, tools are necessary across multiple scales and levels of policy support in order to bring the nexus integration vision to fruition through action.[7] Several of the tools that have been developed in part for this vision vary in complexity and simplicity and thus vary in suitability across different assessment requirements.[8] For this conference paper, we highlight three research strategies for nexus integration: embedded resource accounting, network analysis, and the development of WEF indices or indicators. The following section highlights strengths and weaknesses of these approaches before continuing onto describing their application in light of achieving the SDGs. We conclude this paper by suggesting concrete steps both researchers and practitioners can take to accelerate SDG progress at multiple scales.

Research strategies & research critiques:

While there are numerous research strategies across the WEF nexus, we will highlight three that have been used to cross disciplines, scales, and geographic boundaries in pursuit of WEF nexus understandings.

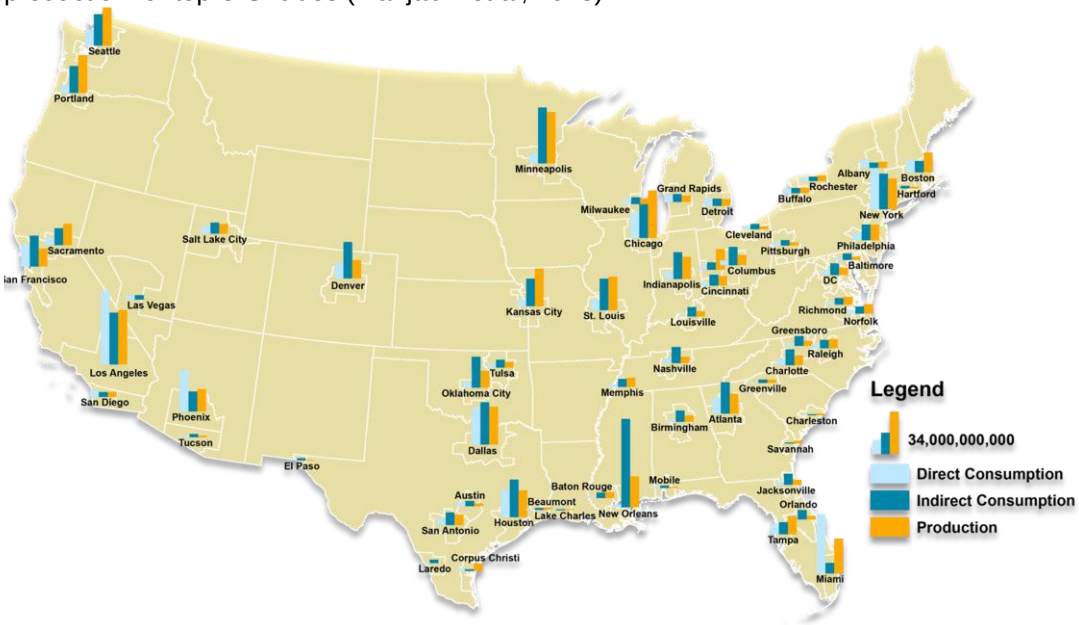
---

[4] United Nations, “The Sustainable Development Goals Report 2020.”
[5] Al-Saidi and Elagib, “Towards Understanding the Integrative Approach of the Water, Energy and Food Nexus”; Hoff, “Understanding the Nexus. Background Paper for the Bonn 2011 Conference”; Bazilian et al., “Considering the Energy, Water and Food Nexus.”
[6] Fader et al., “Toward an Understanding of Synergies and Trade-Offs Between Water, Energy, and Food SDG Targets”; Pradhan et al., “A Systematic Study of Sustainable Development Goal (SDG) Interactions.”
[7] Al-Saidi and Elagib, “Towards Understanding the Integrative Approach of the Water, Energy and Food Nexus”; Dargin, Daher, and Mohtar, “Complexity versus Simplicity in Water Energy Food Nexus (WEF) Assessment Tools.”
[8] Dargin, Daher, and Mohtar, “Complexity versus Simplicity in Water Energy Food Nexus (WEF) Assessment Tools.”

Embedded resource accounting:

Embedded resource accounting is a generic name for a variety of approaches that seek to transform systems into a unified unit of measurement (the embedded resource) to make it easier to compare and analyze multiple systems simultaneously. These tools utilize different approaches but all seek to provide quantitative information about stocks and flows of natural resources.[9] Examples of this include carbon footprints, land footprints, ecological footprints, and water footprints.[10] In further summary, this research approach may, for example, take a look at all of the agricultural commodities being grown within a particular study site and use simple calculations to assign each commodity an amount of water, or water footprint, necessary for that crop to be produced. Then, all of the commodities can be compared to each other through their water intensities. The strengths of these tools stem from their ability to balance both complexity and simplicity by unifying disparate data sources into one unit of measurement. They can also be applied across scales easily and in cases that vary in spatial, temporal, and geographic boundaries. Figure 1 showcases an example of embedded resource accounting study that utilized water footprints to showcase the consumption and production of various commodities in cities across the United States.[11] This type of study, for example, could be used by a particular city interested in reducing its overall water demand by changing food choices or finding different, more sustainable, sources for providing these resources.

Figure 1: Spatial distribution of the blue and green water footprint of consumption and production for top U.S. cities (Mahjabin et al, 2018)



[9] McGrane et al., "Scaling the Nexus."
[10] Vanham et al., "Environmental Footprint Family to Address Local to Planetary Sustainability and Deliver on the SDGs."
[11] Mahjabin et al., "Large Cities Get More for Less."

Several limitations exist when using embedded resource accounting techniques. Embedded resource accounting often requires the grouping of goods, products, commodities, or services into large homogeneous groups leading to low resolution of specific consumer driven relationships (for example, detailed food choice between a small range of products or people). Additionally, many assumptions are made using national or international averages to equate products to particular resources without considering the spatial heterogeneity of the actual resource use. These studies are also sometimes critiqued for being black-boxes with limited societal use due to the myriad of assumptions necessary to create unified units of measurement across diverse goods and services. Finally, embedded resource accounting is often representing "virtual trade" without consideration of influences like transportation or other critical infrastructure that can serve as vital to the provisioning of services or sustainability of resources. Research communities investing in embedded resource accounting should find ways to tackle these concerns to strengthen the usefulness and usability of such outputs for SDG achievements.

Network Analyses:

Built upon mathematical graph theory, network modeling is a research methodology approach that has been utilized in countless domains including everything from ecology to economics to WEF nexus interactions. This approach allows you to tie items (nodes) together through connections or strengths (links). In examining network properties using graph theory you can then understand how behaviors between systems are structured and simulate changes to the structures to understand risk, vulnerability, and resilience. An extremely common application of network analyses in the WEF nexus has been to utilize networks to quantify trade and transfers of WEF goods between cities, regions, or countries (for example[12]). Network tools have also been utilized to showcase social relationships between stakeholders in the WEF nexus.[13] In international development, such social networks can be utilized as a tool for project selection or collaboration.[14] Strengths of these approaches include that networks can be built on a variety of scales and can be used to represent many different types of relationships. Analyzing networks is also considered relatively easy since there are several open source tools and software packages that can allow for analysis with minimal investment.

As with embedded resource accounting, network tools also hold several limitations, particularly with regard to SDG advancement. First, a network construction is only as good as the data or relationships defining the connections. As previously noted, negative and positive feedbacks between various WEF SDGs are both important and difficult to quantify. Additionally, theorized relationships across networks are able to tell us statistically about the network but fail to provide the nuance of governance, resource access, or behavior. Like with embedded resource accounting, it would be critical to

[12] Mahjabin et al., "Integrating Embedded Resources and Network Analysis to Understand Food-Energy-Water Nexus in the US."
[13] Ghafoori Kharanagh, Banihabib, and Javadi, "An MCDM-Based Social Network Analysis of Water Governance to Determine Actors' Power in Water-Food-Energy Nexus"; Daher et al., "Toward Creating an Environment of Cooperation between Water, Energy, and Food Stakeholders in San Antonio."
[14] Grady, He, and Peeta, "Integrating Social Network Analysis with Analytic Network Process for International Development Project Selection."

develop methodologies in partnership with stakeholders interested in using research outcomes in order to derive results that are useful and usable outside of research settings.

WEF indicator development:

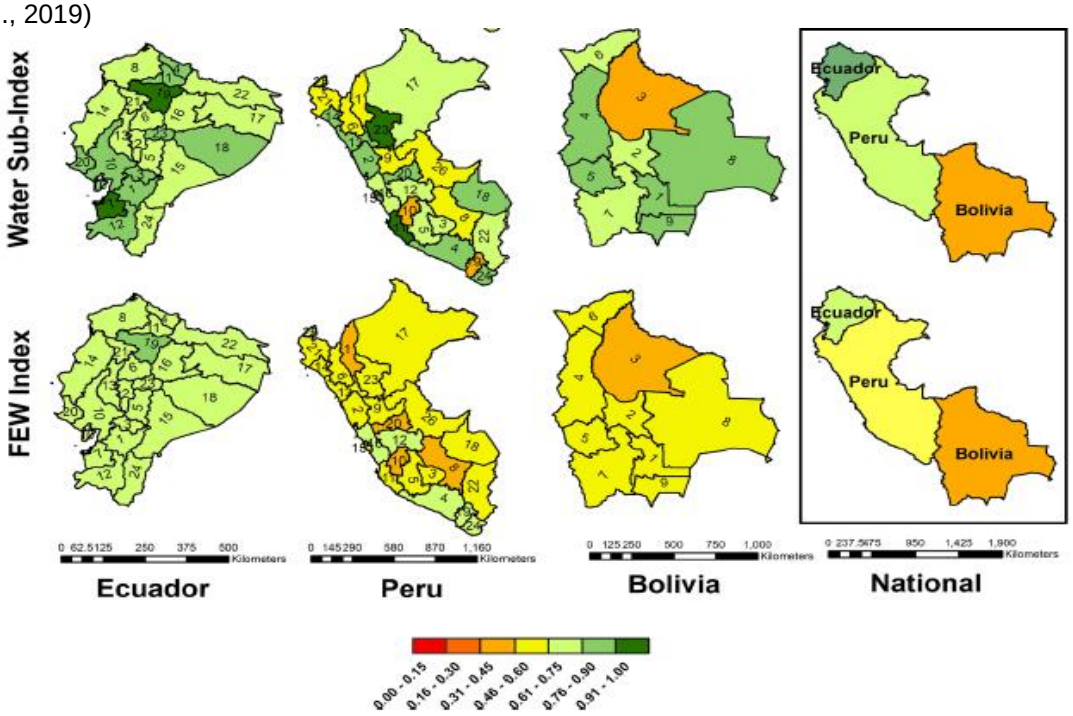
The third series of methods we chose to highlight in this paper includes development of WEF indicators. Indicators are widely used across research and practitioner communities worldwide because they often provide information about the status of resources or issues in a way that is transparent, easily understood, and usable for the development of guidelines for governance and decision making. Numerous studies have developed or presented indicators for use across the WEF nexus.[15] These indicators can range from very complicated to simplistic and span a variety of data collection and interpretation techniques. One such example is the RAND Corporation's development of a global index for evaluating Food-Energy-Water Security, the FEW Index, to help prepare critical cross-sectoral information for development agencies and research communities alike.[16] Although this work presented helpful linkages between some components of SDGs and measurements or models of WEF systems, it failed to examine the spatial and regional dimensions of security within the nexus and provide an easy replicable methodology for widespread use. One extension of this work further showcased a technique to quantify food, energy, and water security to provide a new and practical approach for the enhancement of global development based on using data collected by countries in fulfillment of various United Nations goals.[17] In particular, this approach proposed a more holistic view to implement the SDGs in partnership with more than one development goal at a time (Figure 2). This work was not only published in the scientific literature to support research efforts but was also translated into Spanish and published in a special issue of the magazine Económica so that it would be more broadly available to communities outside of traditional WEF research scholars.[18]

Indicators and indices also fail to fully realize the potential synergies between research and practitioner uses. One limitation of developing new indicators is that such efforts often require deploying new data collection or data management. When developing indicators that are using data already collected for WEF development, limitations still exist as they often fail to capture the nuance of influences such as institutional structure and governance.[19] For example, while showcasing ways to prioritize development among water, food, and energy may be useful theoretically, it does not describe how there may be two, or three, or more different government agencies or ministries involved in the provisioning of WEF resources thus sidelining one ministry to prioritize another is difficult to advocate for in practice. Finally, indicators are only as good as the data they seek to represent and, similar to all three of these research areas, data availability can challenge the usefulness of research outcomes. Multiple scholars have articulated the

[15] Yuan and Lo, "Developing Indicators for the Monitoring of the Sustainability of Food, Energy, and Water."
[16] Willis et al., *Developing the Pardee RAND Food-Energy-Water Security Index*.
[17] Mohammadpour et al., "From National Indices to Regional Action—An Analysis of Food, Energy, Water Security in Ecuador, Bolivia, and Peru."
[18] Mohammadpour et al., "Desde indices nacionales hasta la accion regional: Un analisis sobre la seguridad de la comida, agua y energía en Ecuador, Bolivia y Perú."
[19] Newell, Goldstein, and Foster, "A 40-Year Review of Food–Energy–Water Nexus Literature and Its Application to the Urban Scale."

need to utilize case-study based recommendations and customized tools instead of pursuit of one ultimate model that can accurately represent the WEF nexus.[20] Additionally, it is critical to find techniques, methods, and frameworks that are able to integrate stakeholder groups across researchers, decision makers, policy actors, and communities.[21]

Figure 2 Example of the water security index and the FEW security index (Mohammadpour et al., 2019)



Accelerating SDG progress at multiple scales:

This conference paper highlighted a variety of WEF nexus approaches research and implementation of water, energy, and food SDGs as well as the limitations of these approaches. This highlights several needs for researchers and practitioners alike in moving forward to fulfil Agenda 2030 of the United Nations. In summarizing several limitations of the WEF research methodologies highlighted here, it is important to be critical of data availability and data sources used for any WEF research pursuit. The quality and usability of data certainly influences the usefulness of research outputs for practitioner communities. Additionally, there is a need for research to pursue methods that balance complexity and simplicity, can be used across scale, space, and time, and are developed in partnership with the stakeholders most related to the efforts.

[20] Al-Saidi and Elagib, "Towards Understanding the Integrative Approach of the Water, Energy and Food Nexus"; Dargin, Daher, and Mohtar, "Complexity versus Simplicity in Water Energy Food Nexus (WEF) Assessment Tools."
[21] Newell, Goldstein, and Foster, "A 40-Year Review of Food–Energy–Water Nexus Literature and Its Application to the Urban Scale"; Mohammadpour et al., "From National Indices to Regional Action—An Analysis of Food, Energy, Water Security in Ecuador, Bolivia, and Peru."

For the research community, it is critical to incorporate issues of institutional structure, governance, access, human behavior, and equity into our WEF nexus pursuits. Static, ill-defined case studies fail to elicit meaningful policy or governance recommendations that are directly usable for managers and development practitioners. Moreover, it is critical to find new outlets for communication beyond peer-reviewed journal articles including translating works into languages of relevance, engaging in purposeful and planned dissemination, and working with stakeholders throughout the process to ensure the research outcomes are both useful and usable. It is also important for researchers to view WEF nexus research with an increasingly critical lens so that work moves beyond the status quo and incorporates diverse viewpoints and perspectives to build convergent science approaches.

Beyond an individual research scholar, academic institutions as a whole must find ways to value transdisciplinary efforts that require co-creation and integration between academic and non-academic stakeholders. These efforts often require substantial time and care and are not often viewed as valuable as traditional academic outputs such as journal and conference presentations - at least by a wide majority of institutions. Institutions however should see these efforts as critical to global international development, particularly in the field of sustainability. The National Academies has highlighted the importance of convergent transdisciplinary work and calls upon institutions to alter incentives and success metrics to include such important efforts.[22] Not only can these efforts contribute to advancing Agenda 2030 but they can also provide research scholars practical understandings of change happening across local, regional, and global scales from people who work across communities daily.

Acknowledgements:
The efforts for this work were partially supported by funding from the National Science Foundation Award number #1941657.

References:

Al-Saidi, Mohammad, and Nadir Ahmed Elagib. “Towards Understanding the Integrative Approach of the Water, Energy and Food Nexus.” *Science of The Total Environment* 574 (January 2017): 1131–39. https://doi.org/10.1016/j.scitotenv.2016.09.046.

Bazilian, Morgan, Holger Rogner, Mark Howells, Sebastian Hermann, Douglas Arent, Dolf Gielen, Pasquale Steduto, et al. “Considering the Energy, Water and Food Nexus: Towards an Integrated Modelling Approach.” *Energy Policy* 39, no. 12 (December 2011): 7896–7906. https://doi.org/10.1016/j.enpol.2011.09.039.

Chang, Yuan, Guijun Li, Yuan Yao, Lixiao Zhang, and Chang Yu. “Quantifying the Water-Energy-Food Nexus: Current Status and Trends.” *Energies* 9, no. 2 (January 22, 2016): 65. https://doi.org/10.3390/en9020065.

Daher, Bassel, Bryce Hannibal, Kent E. Portney, and Rabi H. Mohtar. “Toward Creating an Environment of Cooperation between Water, Energy, and Food Stakeholders in San Antonio.” *Science of The Total Environment* 651 (February 2019): 2913–26. https://doi.org/10.1016/j.scitotenv.2018.09.395.

Dargin, Jennifer, Bassel Daher, and Rabi H. Mohtar. “Complexity versus Simplicity in Water Energy Food Nexus (WEF) Assessment Tools.” *Science of The Total Environment* 650 (February 2019): 1566–75. https://doi.org/10.1016/j.scitotenv.2018.09.080.

[22] National Academies of Sciences, Engineering, & Medicine, *Convergence*.

Fader, Marianela, Colleen Cranmer, Richard Lawford, and Jill Engel-Cox. “Toward an Understanding of Synergies and Trade-Offs Between Water, Energy, and Food SDG Targets.” *Frontiers in Environmental Science* 6 (November 12, 2018): 112. https://doi.org/10.3389/fenvs.2018.00112.

Ghafoori Kharanagh, Samaneh, Mohammad Ebrahim Banihabib, and Saman Javadi. “An MCDM-Based Social Network Analysis of Water Governance to Determine Actors’ Power in Water-Food-Energy Nexus.” *Journal of Hydrology* 581 (February 2020): 124382. https://doi.org/10.1016/j.jhydrol.2019.124382.

Grady, Caitlin A., Xiaozheng He, and Srinivas Peeta. “Integrating Social Network Analysis with Analytic Network Process for International Development Project Selection.” *Expert Systems with Applications* 42, no. 12 (July 2015): 5128–38. https://doi.org/10.1016/j.eswa.2015.02.039.

Hoff, H. “Understanding the Nexus. Background Paper for the Bonn 2011 Conference.” Stockholm Environment Institute, 2011. https://mediamanager.sei.org/documents/Publications/SEI-Paper-Hoff-UnderstandingTheNexus-2011.pdf.

Mahjabin, Tasnuva, Susana Garcia, Caitlin Grady, and Alfonso Mejia. “Large Cities Get More for Less: Water Footprint Efficiency across the US.” Edited by Felix Creutzig. *PLOS ONE* 13, no. 8 (August 20, 2018): e0202301. https://doi.org/10.1371/journal.pone.0202301.

Mahjabin, Tasnuva, Alfonso Mejia, Seth Blumsack, and Caitlin Grady. “Integrating Embedded Resources and Network Analysis to Understand Food-Energy-Water Nexus in the US.” *Science of The Total Environment* 709 (March 2020): 136153. https://doi.org/10.1016/j.scitotenv.2019.136153.

McGrane, Scott J., Michele Acuto, Francesca Artioli, Po-Yu Chen, Robert Comber, Julian Cottee, Geremy Farr-Wharton, et al. “Scaling the Nexus: Towards Integrated Frameworks for Analysing Water, Energy and Food.” *The Geographical Journal*, May 30, 2018. https://doi.org/10.1111/geoj.12256.

Mohammadpour, Paniz, Tasnuva Mahjabin, Jose Fernandez, and Caitlin Grady. “From National Indices to Regional Action—An Analysis of Food, Energy, Water Security in Ecuador, Bolivia, and Peru.” *Environmental Science & Policy* 101 (November 2019): 291–301. https://doi.org/10.1016/j.envsci.2019.08.014.

Mohammadpour, Paniz, Tasnuva Mahjabin, Jose Fernandez, and Caitlin A. Grady. “Desde indices nacionales hasta la accion regional: Un analisis sobre la seguridad de la comida, agua y energía en Ecuador, Bolivia y Perú.” *Revista Económica*, June 2020.

National Academies of Sciences, Engineering, & Medicine. *Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond*. Washington, D.C.: National Academies Press, 2014. https://doi.org/10.17226/18722.

Newell, Joshua P, Benjamin Goldstein, and Alec Foster. “A 40-Year Review of Food–Energy–Water Nexus Literature and Its Application to the Urban Scale.” *Environmental Research Letters* 14, no. 7 (July 9, 2019): 073003. https://doi.org/10.1088/1748-9326/ab0767.

Pradhan, Prajal, Luís Costa, Diego Rybski, Wolfgang Lucht, and Jürgen P. Kropp. “A Systematic Study of Sustainable Development Goal (SDG) Interactions: A SYSTEMATIC STUDY OF SDG INTERACTIONS.” *Earth’s Future* 5, no. 11 (November 2017): 1169–79. https://doi.org/10.1002/2017EF000632.

United Nations. “The Sustainable Development Goals Report 2020.” United Nations Publications, 2020. https://unstats.un.org/sdgs/report/2020/The-Sustainable-Development-Goals-Report-2020.pdf.

Vanham, Davy, Adrian Leip, Alessandro Galli, Thomas Kastner, Martin Bruckner, Aimable Uwizeye, Kimo van Dijk, et al. “Environmental Footprint Family to Address Local to Planetary Sustainability and Deliver on the SDGs.” *Science of The Total Environment* 693 (November 2019): 133642. https://doi.org/10.1016/j.scitotenv.2019.133642.

Wichelns, Dennis. “The Water-Energy-Food Nexus: Is the Increasing Attention Warranted, from Either a Research or Policy Perspective?” *Environmental Science & Policy* 69 (March 2017): 113–23. https://doi.org/10.1016/j.envsci.2016.12.018.

Willis, Henry, David Groves, Jeanne Ringel, Zhimin Mao, Shira Efron, and Michele Abbott. *Developing the Pardee RAND Food-Energy-Water Security Index: Toward a Global Standardized, Quantitative, and Transparent Resource Assessment*. RAND Corporation, 2016. https://doi.org/10.7249/TL165.

Yuan, Mei-Hua, and Shang-Lien Lo. “Developing Indicators for the Monitoring of the Sustainability of Food, Energy, and Water.” *Renewable and Sustainable Energy Reviews* 119 (March 2020): 109565. https://doi.org/10.1016/j.rser.2019.109565.