

## Emerging Themes and Future Directions of Multi-Sector Nexus Research and Implementation

Khan, Zarrar; Abraham, Edo; Aggarwal, Srijan; Ahmad Khan, Manal; Arguello, Ricardo; Bereslawski, Julia Lacal; Bielicki, Jeffrey M.; Jewitt, Graham P. W.; Pande, Saket; More Authors

**DOI**

[10.3389/fenvs.2022.918085](https://doi.org/10.3389/fenvs.2022.918085)

**Publication date**

2022

**Document Version**

Final published version

**Published in**

Frontiers in Environmental Science

**Citation (APA)**

Khan, Z., Abraham, E., Aggarwal, S., Ahmad Khan, M., Arguello, R., Bereslawski, J. L., Bielicki, J. M., Jewitt, G. P. W., Pande, S., & More Authors (2022). Emerging Themes and Future Directions of Multi-Sector Nexus Research and Implementation. *Frontiers in Environmental Science*, 10, 1-11. Article 918085. <https://doi.org/10.3389/fenvs.2022.918085>

**Important note**

To cite this publication, please use the final published version (if applicable). Please check the document version above.

**Copyright**

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

**Takedown policy**

Please contact us and provide details if you believe this document breaches copyrights. We will remove access to the work immediately and investigate your claim.



## OPEN ACCESS

## Edited by:

Samuel Asumadu Sarkodie,  
Nord University, Norway

## Reviewed by:

Andrea L. Pierce,  
University of Delaware, United States  
Anik Bhaduri,  
Australian Rivers Institute, Griffith  
University, Australia

## \*Correspondence:

Zarrar Khan  
zarrar.khan@pnnl.gov

## †ORCID:

Zarrar Khan  
orcid.org/0000-0002-8147-8553

Edo Abraham  
orcid.org/0000-0003-0989-5456

Srijan Aggarwal  
orcid.org/0000-0002-9141-9936

Ricardo Arguello  
orcid.org/0000-0002-6251-722X

Meghna Babbar-Sebens  
orcid.org/0000-0001-8140-563X

Jeffrey M. Bielicki  
orcid.org/0000-0001-8449-9328

Pamela Collins  
orcid.org/0000-0002-0914-8832

Bassel Daher  
orcid.org/0000-0002-0096-6783

Fabio A. Diuana  
orcid.org/0000-0003-1981-4824

Amin A. Elshorbagy  
orcid.org/0000-0002-5740-8029

Solomon H. Gebrechorkos  
orcid.org/0000-0001-7498-0695

Tailin Huang  
orcid.org/0000-0001-7767-3930

Maria João Ferreira dos Santos  
orcid.org/0000-0002-6558-7477

J. Leah Jones  
orcid.org/0000-0002-8529-6503

Elke Kellner  
orcid.org/0000-0003-2474-0938

Jonathan Lamontagne  
orcid.org/0000-0003-3976-1678

Angélique Lansu  
orcid.org/0000-0001-6905-8751

Ruopu Li  
orcid.org/0000-0003-3500-0273

Pedro Linares  
orcid.org/0000-0002-0572-1937

Diego Marazza  
orcid.org/0000-0001-9870-5559

Ryan A. McManamay  
orcid.org/0000-0002-5551-3140

Fernando Miralles-Wilhelm  
orcid.org/0000-0001-5812-1014

Raphaël Payet-Burin  
orcid.org/0000-0001-6403-3985

Jon Sampedro  
orcid.org/0000-0002-2277-1530

Kelly T. Sanders  
orcid.org/0000-0003-4466-0054

Jennifer Schmidt  
orcid.org/0000-0002-0945-3204

# Emerging Themes and Future Directions of Multi-Sector Nexus Research and Implementation

Zarrar Khan<sup>1\*†</sup>, Edo Abraham<sup>2†</sup>, Srijan Aggarwal<sup>3†</sup>, Manal Ahmad Khan<sup>4</sup>, Ricardo Arguello<sup>5†</sup>, Meghna Babbar-Sebens<sup>6†</sup>, Julia Lacal Bereslawski<sup>7</sup>, Jeffrey M. Bielicki<sup>8,9†</sup>, Pietro Elia Campana<sup>10</sup>, Maria Eugenia Silva Carrazzone<sup>11</sup>, Homero Castanier<sup>12</sup>, Fi-John Chang<sup>13</sup>, Pamela Collins<sup>14†</sup>, Adela Conchado<sup>15,16</sup>, Koteswara Rao Dagani<sup>17</sup>, Bassel Daher<sup>18†</sup>, Stefan C. Dekker<sup>19</sup>, Ricardo Delgado<sup>20</sup>, Fabio A. Diuana<sup>21†</sup>, Jonathan Doelman<sup>22,23</sup>, Amin A. Elshorbagy<sup>24†</sup>, Chihhao Fan<sup>13</sup>, Rossana Gaudioso<sup>25</sup>, Solomon H. Gebrechorkos<sup>26†</sup>, Hatim M. E. Geli<sup>27</sup>, Emily Grubert<sup>28</sup>, Daisy Huang<sup>4</sup>, Tailin Huang<sup>29†</sup>, Ansir Ilyas<sup>30</sup>, Aleksandr Ivakhnenko<sup>31</sup>, Graham P. W. Jewitt<sup>32,33,34</sup>, Maria João Ferreira dos Santos<sup>35†</sup>, J. Leah Jones<sup>36†</sup>, Elke Kellner<sup>37,38†</sup>, Elisabeth H. Krueger<sup>39</sup>, Ipsita Kumar<sup>40</sup>, Jonathan Lamontagne<sup>41†</sup>, Angélique Lansu<sup>42†</sup>, Sanghyun Lee<sup>43</sup>, Ruopu Li<sup>44†</sup>, Pedro Linares<sup>45†</sup>, Diego Marazza<sup>46†</sup>, Maria Pía Mascari<sup>47</sup>, Ryan A. McManamay<sup>48†</sup>, Measrainsey Meng<sup>49</sup>, Simone Mereu<sup>50,51</sup>, Fernando Miralles-Wilhelm<sup>52,53†</sup>, Rabi Mohtar<sup>54,55</sup>, Abubakr Muhammad<sup>30</sup>, Adenike Kafayat Opejin<sup>36</sup>, Saket Pande<sup>56</sup>, Simon Parkinson<sup>57</sup>, Raphaël Payet-Burin<sup>58†</sup>, Meenu Ramdas<sup>59</sup>, Eunice Pereira Ramos<sup>60</sup>, Sudatta Ray<sup>61</sup>, Paula Roberts<sup>62</sup>, Jon Sampedro<sup>1†</sup>, Kelly T. Sanders<sup>49†</sup>, Marzieh Hassanzadeh Saray<sup>63</sup>, Jennifer Schmidt<sup>64†</sup>, Margaret Shanfield<sup>65†</sup>, Sauleh Siddiqui<sup>66</sup>, Micaela Suriano<sup>67</sup>, Makoto Taniguchi<sup>68†</sup>, Antonio Trabucco<sup>69†</sup>, Marta Tuninetti<sup>70†</sup>, Adriano Vinca<sup>62†</sup>, Björn Weeser<sup>71†</sup>, Dave D. White<sup>32</sup>, Thomas B. Wild<sup>1†</sup>, Kamini Yadav<sup>72</sup>, Nithiyandam Yogeswaran<sup>73†</sup>, Tokuta Yokohata<sup>74</sup> and Qin Yue<sup>75†</sup>

<sup>1</sup>Joint Global Change Research Institute (JGCR), Pacific Northwest National Laboratory (PNNL), College Park, MD, United States, <sup>2</sup>Department of Water Resources Management, Delft University of Technology, Delft, Netherlands, <sup>3</sup>College of Engineering and Mines, University of Alaska Fairbanks, Fairbanks, AK, United States, <sup>4</sup>National Geographic Partners, Washington, DC, United States, <sup>5</sup>Unidad de Planificación Rural Agropecuaria (UPRA), Bogotá, Colombia, <sup>6</sup>School of Civil and Construction Engineering, College of Engineering, Oregon State University, Corvallis, OR, United States, <sup>7</sup>Consultant, Banco Interamericano de Desarrollo, Buenos Aires, Argentina, <sup>8</sup>Department of Civil, Environmental, and Geodetic Engineering, The Ohio State University, Columbus, OH, United States, <sup>9</sup>John Glenn College of Public Affairs, The Ohio State University, Columbus, OH, United States, <sup>10</sup>Department of Sustainable Energy Systems, Mälardalen University, Västerås, Sweden, <sup>11</sup>Consultora Bioeconomía Sostenible en FAO, Roma, Italy, <sup>12</sup>Empresa Pública Metropolitana de Agua Potable y Saneamiento de Quito, Quito, Ecuador, <sup>13</sup>Department of Bioenvironmental Systems Engineering and Hydrotech Research Institute, National Taiwan University, Taipei, Taiwan, <sup>14</sup>Conservation International, Arlington, VA, United States, <sup>15</sup>Environmental Missions, The Overview Effect, Madrid, Spain, <sup>16</sup>Sustainability and Circular Economy, Universidad Pontificia Comillas, Madrid, Spain, <sup>17</sup>Indian Institute of Technology Hyderabad, Kandi, India, <sup>18</sup>Texas A&M Energy Institute, Texas A&M University, College Station, TX, United States, <sup>19</sup>Copernicus Institute of Sustainable Development, Utrecht, Netherlands, <sup>20</sup>Universidad de los Andes, Bogotá, Colombia, <sup>21</sup>Universidade Federal do Rio de Janeiro, Janeiro, Brazil, <sup>22</sup>Department of Climate, Air and Energy, PBL Netherlands Environmental Assessment Agency, The Hague, Netherlands, Canada, <sup>23</sup>Copernicus Institute for Sustainable Development, Utrecht University, Utrecht, Netherlands, <sup>24</sup>Department of Civil, Geological and Environmental Engineering, College of Engineering, University of Saskatchewan, Saskatoon, SK, Canada, <sup>25</sup>Secretaría Nacional de Ambiente, Agua y Cambio Climático, Montevideo, Uruguay, <sup>26</sup>University of Southampton, Southampton, United Kingdom, <sup>27</sup>Department of Animal and Range Sciences and New Mexico Water Resources Research Institute, New Mexico State University, Las Cruces, NM, United States, <sup>28</sup>Georgia Institute of Technology, Atlanta, GA, United States, <sup>29</sup>NCKU School for Sustainability, National Cheng Kung University, Tainan City, Taiwan, <sup>30</sup>Centre for Water Informatics and Technology, Lahore University of Management and Sciences (LUMS), Lahore, Pakistan, <sup>31</sup>Department of Petroleum Engineering, Kazakh-British Technical University, Almaty, Kazakhstan, <sup>32</sup>Centre for Water Resources Research, University of KwaZulu-Natal, Durban, South Africa, <sup>33</sup>IHE Delft Institute for Water Education, Delft, Netherlands, <sup>34</sup>Faculty of Civil Engineering and Geosciences, Technical University Delft, Delft, Netherlands, <sup>35</sup>Department of Geography, University of Zurich, Zurich, Switzerland, <sup>36</sup>Global Institute of Sustainability and Innovation, Arizona State University, Tempe, Switzerland, <sup>37</sup>Wyss Academy for Nature, University of Bern, Bern, Switzerland, <sup>38</sup>School of Sustainability, Arizona State University, Tempe, AZ, United States, <sup>39</sup>Institute for Biodiversity and Ecosystem Dynamics, Department of Ecosystem and Landscape Dynamics (IBED-ELD), University of Amsterdam (UvA), Amsterdam, Netherlands,

Margaret Shanfield  
 orcid.org/0000-0003-1710-1548  
 Makoto Taniguchi  
 orcid.org/0000-0001-7416-0275  
 Antonio Trabucco  
 orcid.org/0000-0002-0743-3680  
 Marta Tuninetti  
 orcid.org/0000-0003-2619-8783  
 Adriano Vinca  
 orcid.org/0000-0002-3051-178X  
 Björn Weeser  
 orcid.org/0000-0001-7400-319X  
 Thomas B. Wild  
 orcid.org/0000-0002-6045-7729  
 Nithyanandam Yogeswaran  
 orcid.org/0000-0002-4089-9247  
 Qin Yue  
 orcid.org/0000-0003-1664-4516

### Specialty section:

This article was submitted to  
 Environmental Systems Engineering,  
 a section of the journal  
 Frontiers in Environmental Science

**Received:** 12 April 2022

**Accepted:** 15 June 2022

**Published:** 11 August 2022

### Citation:

Khan Z, Abraham E, Aggarwal S,  
 Ahmad Khan M, Arguello R,  
 Babbar-Sebens M, Bereslawski JL,  
 Bielicki JM, Campana PE,  
 Silva Carrazzone ME, Castanier H,  
 Chang F-J, Collins P, Conchado A,  
 Dagani KR, Daher B, Dekker SC,  
 Delgado R, Diuana FA, Doelman J,  
 Elshorbagy AA, Fan C, Gaudioso R,  
 Gebrechorkos SH, Geli HME,  
 Grubert E, Huang D, Huang T, Ilyas A,  
 Ivakhnenko A, Jewitt GPW,  
 Ferreira dos Santos MJ, Jones J,  
 Kellner E, Krueger EH, Kumar I,  
 Lamontagne J, Lansu A, Lee S, Li R,  
 Linares P, Marazza D, Mascari MP,  
 McManamay RA, Meng M, Mereu S,  
 Miralles-Wilhelm F, Mohtar R,  
 Muhammad A, Opejin AK, Pande S,  
 Parkinson S, Payet-Burin R,  
 Ramdas M, Ramos EP, Ray S,  
 Roberts P, Sampedro J, Sanders KT,  
 Saray MH, Schmidt J, Shanfield M,  
 Siddiqui S, Suriano M, Taniguchi M,  
 Trabucco A, Tuninetti M, Vinca A,  
 Weeser B, White DD, Wild TB,  
 Yadav K, Yogeswaran N, Yokohata T  
 and Yue Q (2022) Emerging Themes  
 and Future Directions of Multi-Sector  
 Nexus Research and Implementation.  
*Front. Environ. Sci.* 10:918085.  
 doi: 10.3389/fenvs.2022.918085

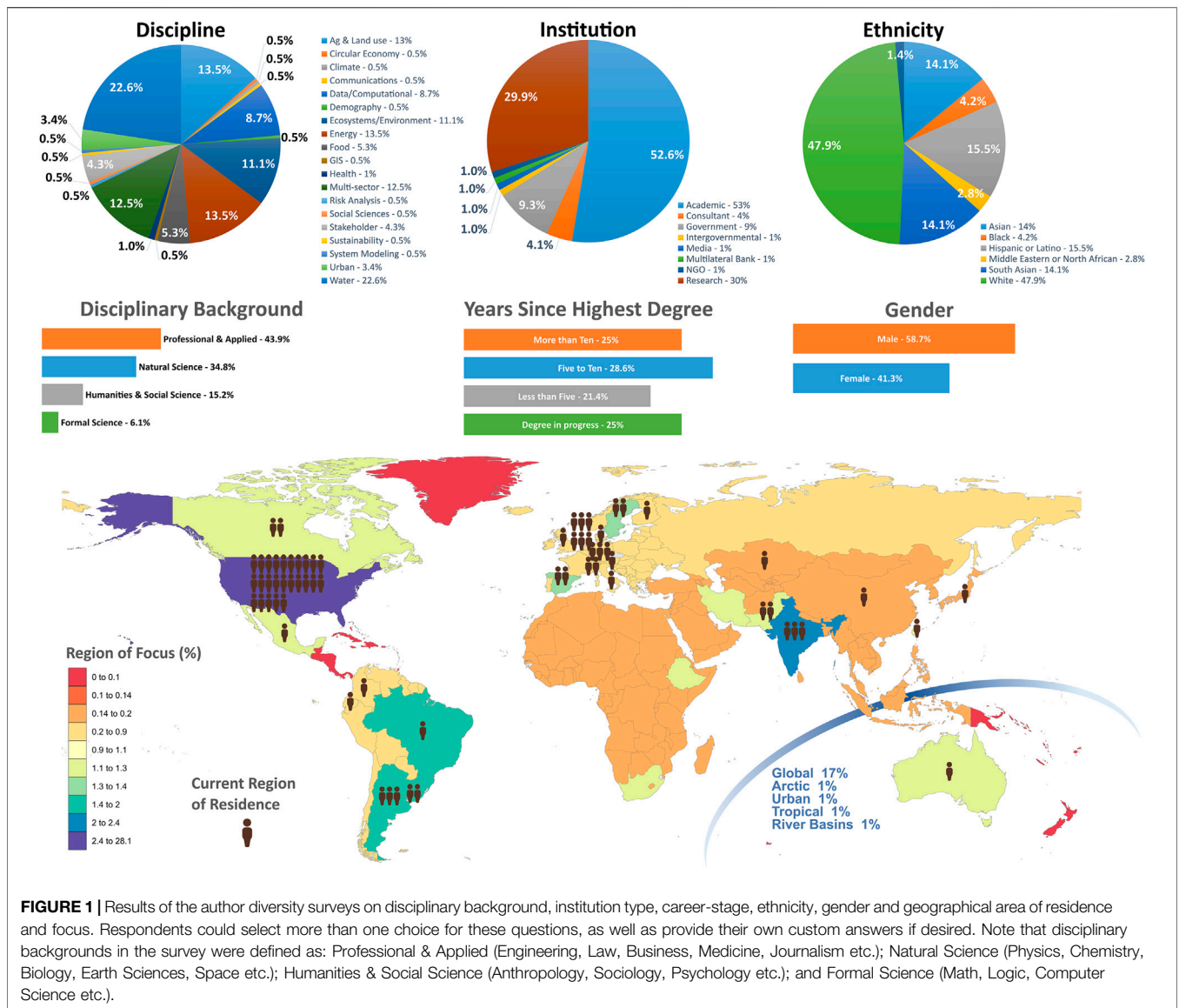
<sup>40</sup>Department of Geographical Sciences, University of Maryland, College Park, MD, United States, <sup>41</sup>Department of Civil and Environmental Engineering, Tufts University, Medford, MA, United States, <sup>42</sup>Open University of Netherlands, Open University, Heerlen, Netherlands, <sup>43</sup>Department of Agricultural and Rural Engineering, Chungbuk National University, Cheongju, South Korea, <sup>44</sup>School of Earth Systems and Sustainability, Southern Illinois University, Carbondale, IL, United States, <sup>45</sup>Universidad Pontificia Comillas, Instituto de Investigación Tecnológica (IIT), Madrid, Spain, <sup>46</sup>Università di Bologna, Bologna, Italy, <sup>47</sup>Oficina de Planeamiento y Presupuesto (OPP) - Presidencia de la República Oriental del Uruguay, Montevideo, Uruguay, <sup>48</sup>Department of Environmental Science, Baylor University, Waco, TX, United States, <sup>49</sup>Faculty of Agricultural and Food Sciences, American University of Beirut, Beirut, Lebanon, <sup>50</sup>Consiglio Nazionale delle Ricerche, Istituto per la Bioeconomia, CNR-IBE, Sassari, Italy, <sup>51</sup>CMCC - Centro Euro-Mediterraneo sui Cambiamenti Climatici, IAFES Division, Sassari, Italy, <sup>52</sup>College of Science, George Mason University, Fairfax, VA, United States, <sup>53</sup>The Nature Conservancy, Arlington, VA, United States, <sup>54</sup>Biological and Agricultural Engineering and Zachry Department of Civil Engineering, Water Energy Food Research Group, Texas A&M University, College Station, TX, United States, <sup>55</sup>Faculty of Agricultural and Food Sciences, American University of Beirut, Beirut, Lebanon, <sup>56</sup>Department of Hydrology, Delft University of Technology, Delft, Netherlands, <sup>57</sup>International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, <sup>58</sup>Department of Environmental Engineering, Technical University of Denmark, Lyngby, Denmark, <sup>59</sup>Indian Institute of Technology Bhubaneswar, Indian Institute of Technology Bhubaneswar, Khordha, India, <sup>60</sup>Division of Energy Systems, KTH - Royal Institute of Technology, Stockholm, Sweden, <sup>61</sup>Emmett Interdisciplinary Program in Environment & Resources (EIPER), Stanford University, Stanford, CA, United States, <sup>62</sup>Organismo Regulador de la Seguridad de Presas (ORSEP), Buenos Aires, Argentina, <sup>63</sup>Department of Process and Environmental Engineering, University of Oulu, Oulu, Finland, <sup>64</sup>University of Alaska Anchorage, Anchorage, AK, United States, <sup>65</sup>College of Science and Engineering, Flinders University, Bedford Park, SA, Australia, <sup>66</sup>Department of Environmental Science, American University, Washington, DC, United States, <sup>67</sup>Instituto Nacional del Agua (INA), Buenos Aires, Argentina, <sup>68</sup>Research Institute for Humanity and Nature (RIHN), Kyoto, Japan, <sup>69</sup>Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Lecce, Italy, <sup>70</sup>Department of Environment, Land, and Infrastructure Engineering, Politecnico di Torino, Turin, Italy, <sup>71</sup>Center for International Development and Environmental Research (ZEU), Justus Liebig University, Giessen, Germany, <sup>72</sup>ORISE Fellow, USDA Forest Service, Riverside, CA, United States, <sup>73</sup>National Forensic Sciences University, Ministry of Home Affairs, Government of India, Delhi, India, <sup>74</sup>National Institute for Environmental Studies, Center for Global Environmental Research, Tsukuba, Japan, <sup>75</sup>College of Environmental Science and Engineering, Peking University, Beijing, China

Water, energy, and food are all essential components of human societies. Collectively, their respective resource systems are interconnected in what is called the “nexus”. There is growing consensus that a holistic understanding of the interdependencies and trade-offs between these sectors and other related systems is critical to solving many of the global challenges they present. While nexus research has grown exponentially since 2011, there is no unified, overarching approach, and the implementation of concepts remains hampered by the lack of clear case studies. Here, we present the results of a collaborative thought exercise involving 75 scientists and summarize them into 10 key recommendations covering: the most critical nexus issues of today, emerging themes, and where future efforts should be directed. We conclude that a nexus community of practice to promote open communication among researchers, to maintain and share standardized datasets, and to develop applied case studies will facilitate transparent comparisons of models and encourage the adoption of nexus approaches in practice.

**Keywords:** nexus, water, energy, food, multi-sector

## INTRODUCTION

International literature clearly shows the benefits of integrated management of resources across sectors to capitalize on synergies and avoid conflicts (Lazaro et al., 2021; van den Heuvel et al., 2020; Imasiku and Ntagwirumugara, 2020; Elagib and Al-Saidi, 2020; Bakhshianlamouki et al., 2020; Sušnik, 2018; Karabulut et al., 2018; de Strasser et al., 2016; Payet-Burin et al., 2021). This concept of the interconnected nature of the water, energy, food, and other related systems is categorized in the literature as “nexus” research. The nexus discourse was highlighted at the World Economic Forum in 2011 (Hoff, 2011; Leck et al., 2015) in response to the recognition of the need for better global policy coordination to manage the relationships between multi-sector commodity prices and resource scarcity. The event was followed by an exponential increase in research associated with defining, scoping, and modeling nexus interactions which have important implications across human and earth systems at variable scales ranging from the globe to cities and from centuries to hours. Decisions to meet one goal in one sector can have serious implications for the attainment of other goals in other sectors. Examples include how choices between different power generation mixes to lower



emissions can affect water withdrawals and consumption (Parkinson et al., 2016; Liu et al., 2017a; Larsen et al., 2019; Liu et al., 2019); how expansion of biofuels and BECCS (Bio-Energy with Carbon Capture and Storage) competes with food production and other land uses (Rulli et al., 2016; Stoy et al., 2018); how the choice between rainfed or irrigated crops impacts both water and energy needs (FAO, 2014; El-Gafy, 2017; Khan et al., 2021); and how the choice between pumping groundwater, using streamflow, or transferring water from other regions affects both energy needs and agricultural productivity (Bakhshianlamouki et al., 2020; Payet-Burin et al., 2021; Wu et al., 2021). While the theoretical benefits of the nexus have been demonstrated in several modeling exercises and example case-studies, there remain several challenges and hurdles in implementation of these ideas in real policy and governance mechanisms which require securing strategic and financial support from leadership to modify long-established single-sector institutional and administrative structures. These

challenges partially arise from a lack of clear and measurable evidence of the benefits of actual nexus integration efforts.

The fundamental concept of the “nexus” calls for a holistic collaborative approach if we are to understand complex co-dependent systems that have inherently different characteristics and that are traditionally managed at different spatial, temporal, and jurisdictional boundaries. Despite this need for a fuller perspective, however, most nexus studies are conducted by individual institutions or research groups that, regardless of their intention, explore the nexus through the lens of their particular expertise and professional experience. While several literature reviews bring together recommendations from these various studies, they remain as compilations of ideas from individual perspectives (Fernandes Torres et al., 2019; Johnson et al., 2019; Newell et al., 2019; Simpson and Jewitt, 2019; Tashtoush et al., 2019; Abdi et al., 2020; Endo et al., 2020; Stylianopoulou et al., 2020; Purwanto et al., 2021). Thus, there

remains the need to incorporate the central essence of the “nexus” and collaboratively reflect on the lessons learned in order to inform future directions by collecting and listening to opinions from members of the diverse range of sectors involved (Howarth and Monasterolo, 2017; Liu et al., 2018; Staddon et al., 2021). This study addresses this need by bringing together 75 co-authors from a wide range of disciplines, demographics, and career stages to converge on what the most critical water–energy–food nexus issues today are and how they should be tackled in the future.

## METHODOLOGY

This article was developed over a period of 2 years where the thematic structure and organizational layout were an organic process, emergent from interactions across a series of sequential surveys with members of the energy-water nexus community. The paper uses the principles of the Delphi Method (Okoli and Pawlowski, 2004) (i.e., arriving at a group opinion based on multiple iterations of surveys) to arrive at the final arguments presented. The initial idea for the paper was the result of discussions between several presenters and conveners of multisector nexus sessions at the American Geophysical Union (AGU) conference in December 2019. This group then solicited expressions of interest from other researchers actively working on multi-sector nexus research based on their participation in relevant nexus sessions at major conferences such as the European Geophysical Union (EGU) and American Geophysical Union (AGU) as well as by reaching out to authors of recent relevant publications. Over the course of 2 years each participant was asked to reach out to their own networks to solicit additional interest. All co-authors of the paper served as a panel of experts for nexus studies and together designed and answered a series of survey questionnaires. The answers to the survey questions were all anonymous and public, with respondents being able to submit multiple opinions, view the responses of all other participants, as well as update their own responses as desired. The earlier questionnaires investigated authors’ diversity, as well as how this paper should be structured including the format, outline, and layout of the paper.

Given the core concept of “nexus” studies and the corresponding implications across socio-economic and geographic boundaries, the need for a diverse authorship is all the more compelling. A key feature of this study has been the attempt at documenting the diversity of the many co-authors. Both intellectual diversity (diversity of cognitive approach and disciplinary background) as well as demographic diversity (diversity of gender, race, geography) have been clearly shown to improve problem-solving, creativity, and scientific outcomes (Hackett and Rhoten, 2009; Herring, 2009; Joshi and Roh, 2009; Kalev, 2009; Woolley et al., 2010; Mauser et al., 2013; Freeman and Huang, 2014; Smith-Doerr et al., 2017). In spite of the proven value of diversity, progress on diversity in the sciences has been slow (Bernard and Cooperdock, 2018). A summary of the diversity statistics determined via an anonymous survey sent

out to all co-authors is provided in **Figure 1**. While the results show an imbalance in the representation across disciplines, institution types, ethnicity, and regions of focus, they provide insights into where efforts should be made to further diversify future studies such as these.

An initial list of 82 questions was collected and then combined into the four themes that form the subsequent sections of this paper: Scope and Definition, Nexus Methodologies, Applying the Nexus in Practice, and Challenges and Future Directions. Raw, unedited responses to all surveys are provided as part of the **Supplementary Material**. These responses were collated and then synthesized into the sections that follow.

## Scope and Definition

The number of studies on the nexus has grown exponentially since 2011 (Bazilian et al., 2011; Cairns and Krzywoszynska, 2016; Wichelns, 2017; Newell et al., 2019; Opejin et al., 2020) with various definitions of the nexus, covering different sectors, stakeholders and spatio-temporal scales (Siddiqi and Anadon, 2011; Karlberg et al., 2015; Keskinen et al., 2015; King and Jaafar, 2015; Sušnik, 2018; Roggema and Yan, 2019; Wada et al., 2019; Bakhshianlamouki et al., 2020; Imasiku and Ntagwirumugara, 2020; Khan et al., 2020; Benites-Lazaro et al., 2021; Elagib et al., 2021; Lazaro et al., 2021; Wild et al., 2021). The resulting ambiguity of the definition and scope of the nexus has been identified as a key barrier to operationalizing nexus methods in practice (Endo et al., 2017; Weitz et al., 2017; Wichelns, 2017; Albrecht et al., 2018; Urbinatti et al., 2020a; Urbinatti et al., 2020a; Hogeboom et al., 2021). While delimiting the scope of the nexus with formal definitions may help in its adoption by decision makers, it could also hamper the field of studies by putting boundaries around a concept that should not have intrinsic boundaries. While there is no way to truly map all of the interactions between physical, ecological, biological, economic, social, and other systems, the essence of nexus studies is to try and capture the relevant trade-offs and feedbacks that may influence their outcomes. Several nexus review papers (Endo et al., 2017; Dai et al., 2018; Newell et al., 2019; Tashtoush et al., 2019; Abdi et al., 2020; Stylianopoulou et al., 2020; Purwanto et al., 2021; Vinca et al., 2021) show that existing nexus methodologies are unable to equally or appropriately weigh the different systems considered, because there is a lack of data, a lack of knowledge, or a lack of interest. Caution should be taken not to draw system boundaries arbitrarily or out of convenience simply to address methodological or data-availability constraints. There is also ambiguity in the status of “nexus research” as its own discipline and what sets it apart from similar fields of study such as systems dynamics and integrated resource management. While still unclear, together with the evolution of its scope, nexus research as a discipline is adopting its own characteristics by combining methodologies from these other fields of studies with a focus on inform multi-sector policy and governance.

Pressures on limited natural resource systems are currently increasing, and these are coupled with climate change, more frequent extreme events, migration, urbanization, demographic growth, and ecosystem tipping points, amongst other dynamic and intersectoral changes (Canyon et al., 2015; Siri et al., 2016;

Allen et al., 2019; Hameed et al., 2019; Mabhaudhi et al., 2019; Olawuyi, 2020; Zarei, 2020). These changes are presenting themselves with an urgency that calls for nexus concepts to be put into practice. To achieve this goal, pathways for transforming existing, siloed systems must be developed to overcome institutional and legal barriers and to enable the transfer of nexus approaches into decision making, policy, and infrastructure development. To move in this direction—and keeping in mind the restrictions posed by an absolute, fixed definition that we discussed above—we support the establishment of a nexus community of practice (Snyder and Wenger, 2010; Reed, 2014; Mohtar and Lawford, 2016; Smith et al., 2017) to maintain a fluid, working, and evolving definition, scope, and framework of the nexus that can be mapped to a range of situations and scales. The idea here is to give some structure to a flexible concept. Any major paradigm calls for a group of experts to lay the foundation upon which research is built. For example, the term “ecosystem” has evolved over the past 150 years as researchers define and revise it to fit our changing scientific understanding (Naeem, 2002; Chaudhary et al., 2015). Such a framework would encourage different communities to get in touch and work on developing common conventions, standards, and benchmarks (Snyder et al., 2004; Snyder and Wenger, 2010; Reed, 2014; Smith et al., 2017; IChemE, 2021; SIWI, 2021). As discussed in the following sections, this nexus community of practice would provide a central open-source and accessible platform to host, curate and manage nexus-related data, definitions, metrics, case studies, standards, and policy instruments, amongst other items. The nexus community of practice can be a new effort or build upon existing efforts such as the Multisector Dynamics (MSD) community (<https://multisectordynamics.org/>) or the United Nations Development Programme’s Sustainable Development Goals Integration project (<https://sdgintegration.undp.org/>). Care should be taken to ensure that the community of practice maintains a diverse membership from different regions, backgrounds, and disciplines to capture the voices of a broad spectrum of stakeholders.

## Nexus Methodologies

While several literature reviews compare nexus models and methods (Endo et al., 2017; Kaddoura and El Khatib, 2017; Albrecht et al., 2018; Dai et al., 2018; Liu et al., 2018; Zhang et al., 2018; Abdi et al., 2020; Endo et al., 2020; Stylianopoulou et al., 2020; Purwanto et al., 2021; Vinca et al., 2021) and while new models and methodologies are necessary to advance any discipline, we found that there is a lack of and a strong need for quantitative comparison, validation, and assessment of the suitability of the large number of existing and upcoming nexus models. A good summary from Vinca et al. (2021) shows the range of methodologies across several nexus models. The methodological approaches differ in a range of ways, including types of linkages between sectors (hard linked vs. soft linked), optimization vs. simulations, number of sectors included, as well as both temporal and spatial scales (local, state/province, river basin, national, continental to global). It is recommended

that the nexus community of practice hosts an ongoing multi-model comparison exercise and platform in which suitable nexus models can participate in a series of controlled case studies. Results, strengths, weaknesses, and relevance to different situations can then be compared. The case studies should be transparent, reproducible, and open to the public to increase trust and understanding of the different participating models. The multi-model intercomparisons can follow the format of existing efforts such as the Agricultural Model Intercomparison Project (AGMIP) (Rosenzweig et al., 2013; Rosenzweig et al., 2018) and the Coupled Model Intercomparison Project (CMIP) series (Eyring et al., 2016).

In addition to the lack of any mechanism to empirically compare existing and new nexus methodologies, another key issue faced in the nexus discipline has been the availability and compatibility of data across scales and sectors (Liu et al., 2017b; Larsen et al., 2019; Abdi et al., 2020). The hurdles to accessing data include incomplete and missing data, access restrictions imposed by governments and data hosting organizations, inconsistent formats and resolutions across sectors, inconsistent units, and the lack of a central database to host the data. We recommend that an open-source central database repository should be maintained with standardized units, formatting, and metadata requirements. While collection, maintenance and re-structuring of datasets may require a level of effort and resources not easily achievable, a first step in this direction could be a collection of relevant meta-data that provides links to original resources and that catalogues availability, formats, units, resolution, and scales. Such a collection could be hosted on existing open-source platforms such as Zenodo communities (<https://zenodo.org/communities/>). The collection should be accompanied by a data map summarizing the existing datasets in the database and which sectors, areas and scales continue to be sparsely represented. The data map can be used to identify areas where more efforts are needed to improve data collection and to establish justification for future research in those areas.

Finally, to increase awareness and acceptability of nexus approaches, both input data and inter-model comparison results should be made easily accessible to allow the community and decision makers to assess these across scales and sectors for their specific needs. The visualization of results and communication to the public are key to increasing the success of the implementation of the nexus, as also highlighted in other studies (Bucchi and Trench, 2014; Brownell et al., 2013; McNutt, 2013). Several existing platforms and dashboards (e.g., WRI’s Aqueduct Water Risk Atlas (WRI, 2021), IIASA’s Global Hotspots Explorer (IIASA, 2021), Nexus Tool 2.0 (Daher and Mohtar, 2015)) can be used as examples to communicate results to the broader community including researchers, policy makers, industry practitioners and other non-governmental organizations (Moallemi, 2021).

## Applying the Nexus in Practice

While several studies continue to show the benefits of integrated planning (Mirzabaev et al., 2015; Pittock et al., 2015; Rasul and

Sharma, 2016; Dhaubanjari et al., 2017; Kurian, 2017; Stoy et al., 2018; Munoz Castillo et al., 2019; Payet-Burin et al., 2021; Wu et al., 2021), explicit implementation of nexus considerations at a decision-making level—and particularly across multiple scales—has been limited (Cremades et al., 2019; Johnson et al., 2019; Simpson and Jewitt, 2019; van Gevelt, 2020). The few examples of operational nexus implementation seem to be a response to shared resource conflicts rather than a result of long-term nexus foresight (Abbott et al., 2017; de Amorim et al., 2018; Kalair et al., 2019; Olawuyi, 2020; Weinthal and Sowers, 2020). Similarly, water needs for power plant cooling have prompted several energy ministries to take the water–energy nexus into serious consideration at an operational level.

We note that the Sustainable Development Goals (SDGs) (UNDESA, 2021) are and will be an essential framework for the adoption of nexus methodologies into practice. The SDG framework, with its metrics for multiple individual sectors, has already pushed decision makers in several countries towards considering long-term integrated goals (Griggs et al., 2013; Le Blanc, 2015; Costanza et al., 2016; Yillia, 2016; Fleming et al., 2017; Liu et al., 2018; Saladini et al., 2018; Stephan et al., 2018; Mabhaudhi et al., 2019). A nexus approach can be used to map out interdependencies and identify plausible pathways for achieving different SDG targets (Hülsmann et al., 2018; Mitra et al., 2020). Given the existence of trade-offs between sectors and actors, we recommend an overarching “nexus” planning body to review any region’s long-term cross-sectoral plans as a whole, to communicate and justify trade-offs, to promote joint decision making, and to help managers and policy makers consider the situation beyond their individual sectoral boundaries (Boas et al., 2016; Hagemann and Kirschke, 2017; Weitz et al., 2017; Liu et al., 2018; Pahl-Wostl et al., 2021). For example, increasing hydropower production can support SDG7 as a clean energy source but can also impact downstream food production (SDG 2) as well as the hydrological cycle (SDG6) (Fader et al., 2018). In some countries, such a framework could be integrated into existing overarching planning bodies, but perhaps with a more specific focus on resource management. Such an overarching body would be responsible for monitoring individual SDG sector metrics combined with new cross-sectoral nexus metrics that quantify the strength and magnitude of interconnectivity and inter-dependencies between sectors and actors. This overarching body would also assess how the cross-sectoral inter-relations affect the need for co-planning and integrated decision making (Willis, 2016; El-Gafy, 2017; Byers et al., 2018; Arthur et al., 2019; Venghaus and Dieken, 2019; Khan et al., 2021; Voelker et al., 2022).

Additionally, we recommend that the nexus community of practice develop and maintain a set of nexus metrics that can be used to complement the SDGs and keep track of the interconnections across sectors. These metrics can build upon existing frameworks (Arthur et al., 2019; Voelker et al., 2022) such as the Willis et al., 2016 Pardee RAND Food–Energy–Water Security Index (Willis, 2016), the El-Gafy 2017 Water–Food–Energy Index (El-Gafy, 2017), the Byers et al., 2018 global multisector exposure and

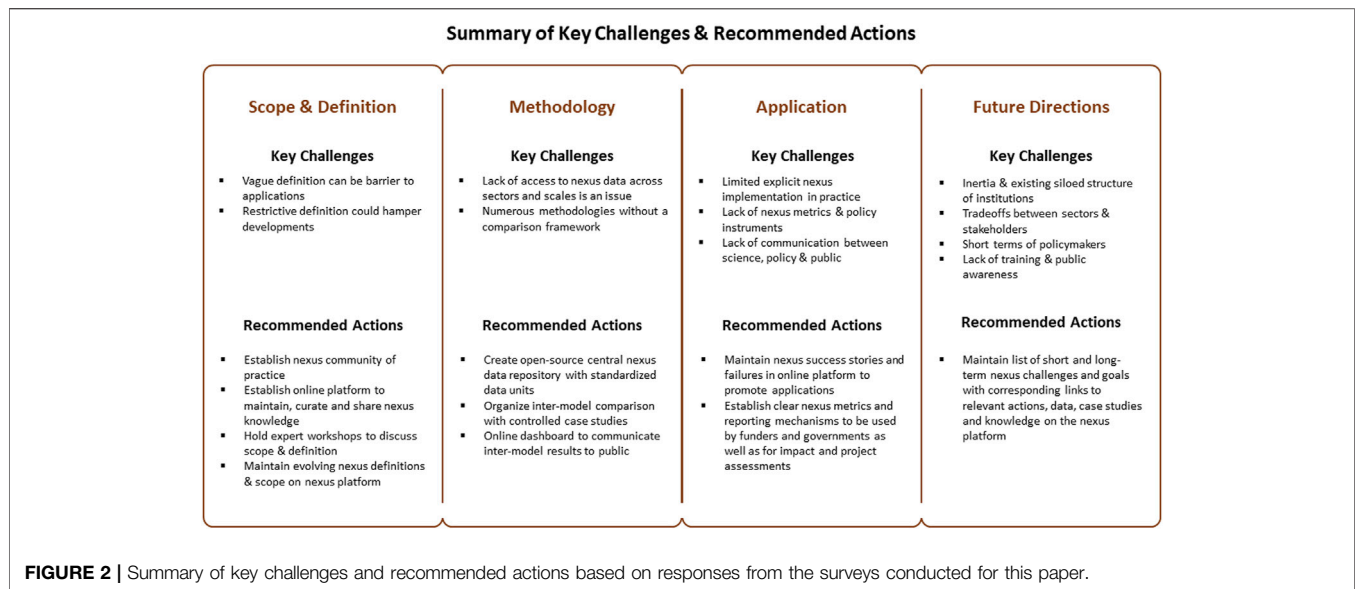
vulnerability hotspot index (Byers et al., 2018), the Venghaus and Dieken 2019 FEW Security Index (Venghaus and Dieken, 2019), and the Khan et al., 2021 Interconnectivity Magnitude and Spread Indices (Khan et al., 2021). The metrics can also be accompanied by templates and reporting mechanisms to assist adoption across governance bodies such as developed in: Weitz et al., 2017 - Integrative governance applied to the Water–Energy–Food nexus (Weitz et al., 2017); Rasul and Neupane 2021 - Framework for water, energy and food policy coordination (Rasul and Neupane, 2021); and White et al., 2017 - Stakeholder analysis for nexus governance (White et al., 2017). Additional metrics using Environmental, Social and Governance (ESG) criteria can also be used to identify stakeholder and policy-maker perspectives (Uen et al., 2018; Huang and Chang, 2021). Once established, we envision the nexus data reporting and metrics mechanisms becoming best practice across sectors as well as in the evaluation and appraisal of new large-scale projects. These can then supplement and become part of other evaluation frameworks such as the environmental and sustainable impact assessments used by governments, funding agencies, and multi-lateral banks (Singh et al., 2009; Bond et al., 2012; Morgan, 2012).

Finally, in addition to the metrics and reporting mechanisms, a library of policy successes, wins, failures, and examples is needed (Venkatesh et al., 2014; Liu, 2016; Wicaksono and Kang, 2019) and can be built based on existing efforts such as the Arizona State University’s Social-Ecological Systems (SES) case study library (ASU, 2021) or the SIM4Nexus library of case studies (SIM4Nexus, 2021). These should include clear cross-sectoral benefits and trade-offs from economic, SDG, and ecosystem perspectives. This library of real-world case studies will provide others with motivation and examples for adopting similar practices in other regions and under other planning frameworks. Organized, transparent and accessible results will also help inform societal viewpoints which in turn are important in shaping those of elected officials and for guiding future funding of research.

## Challenges and Future Directions

One of the main challenges to the implementation of nexus concepts continues to be the inertia in the continued segregation of individual sector institutions and decision-making bodies (Shannak et al., 2018; Cremades et al., 2019; Kurian, 2019; Simpson and Jewitt, 2019; Payet-Burin et al., 2021). This segregation is further strengthened by the lack of mutual benefits across sectors, stakeholders, and geographical entities competing for limited shared resources (Abbott et al., 2017; de Amorim et al., 2018; Kalair et al., 2019; Urbinatti et al., 2020b; Olawuyi, 2020; Weinthal and Sowers, 2020). Additionally, insular, sector-specific training and expertise results in ignorance about the broader picture and can result in apathy towards system-wide losses in favor of individual sector gains.

Another challenge is that a nexus approach requires long-term foresight because the maximum potential gains are often realized



only several years or decades after implementation. These sorts of long-term plans may not be especially compelling to policy makers, whose shorter-term appointments increase the appeal of immediate, visible achievements. However, this short-versus-long-term distinction is a false dichotomy. Given the increasing pressures emerging from globalization, land degradation, and climate change and the resulting increase in frequency and magnitude of extreme events, as well as the worsening scarcity of resources, actions that address long-term sustainability issues will be investments in improving short-term security and resilience issues at the same time.

There is concern that nexus studies as a discipline may create a generation of generalists without sectoral expertise. Similar to the need for an overarching nexus body to connect individual sectoral institutions, it is clear that such generalists are needed to help connect the dots between the different sectors or to provide a holistic view of the broader system. Like systems thinking, the nexus approach is an important discipline in its own right and is necessary in order to complement advancements in individual sectors.

The final part of the survey focused on identifying critical research questions and directions in both the near and the long term. In the near term (next decade), the following three areas were identified as being the most critical:

- 1) Consolidate existing nexus models and efforts and carry out quantitative inter-model comparisons and validation exercises to identify research gaps, strengths, weaknesses and suitability of models for different situations, scales, and stakeholders.
- 2) Organize and curate data from across the various sectors and make these accessible to facilitate transparent model intercomparisons, as well as more robust and accessible analyses.
- 3) Focus on transfer of scientific concepts into real-world implementation, decision making and stakeholder practice.

For the longer term (next 5 decades), the following key lines of research were identified:

- 1) Understanding and leveraging analysis across multiple spatial, temporal, and sectoral resolutions
- 2) Including major societal issues such as migration, pollution, health, disease, biodiversity, poverty, inequality, and violence
- 3) More robust inclusion of shocks, disasters, and extremes into the system
- 4) More robust uncertainty analysis
- 5) Adoption of artificial intelligence (AI) and Internet-of-Things (IoT) into data reporting and analysis
- 6) Consideration of moving from metrics and reporting to nexus regulation if seen as beneficial.

## DISCUSSION

The large and growing body of nexus literature shows that integrated and holistic management of interconnected global systems is becoming critical as the pressures on our limited and shared resources increase (Canyon et al., 2015; Siri et al., 2016; Allen et al., 2019; Hameed et al., 2019; Mabhaudhi et al., 2019; Olawuyi, 2020; Zarei, 2020). Past reviews of nexus literature (Cremades et al., 2019; Johnson et al., 2019; Simpson and Jewitt, 2019; Opejin et al., 2020; van Gevelt, 2020; Vinca et al., 2021) raised some of the same points highlighted in this study, such as the need for applied case studies, the curation of standardized data, the categorization of appropriate models for different use-cases, a shift from analysis to implementation through policy and governance mechanisms, and integration with existing multi-sector frameworks such as the SDGs. The conclusions from this paper reiterate several of these past recommendations but, in addition, highlight a concern that the scope of the nexus discipline is increasing in complexity and ambiguity as the number of new methodologies and studies grows. Several other past studies have compared nexus methodologies (Endo et al., 2017; Kaddoura and El Khatib, 2017; Albrecht et al., 2018; Dai et al., 2018; Liu et al., 2018; Zhang et al., 2018; Johnson et al., 2019; Endo et al., 2020; Stylianopoulou et al., 2020; Purwanto et al., 2021; Vinca et al., 2021), but to date these have been



qualitative due to the lack of any organized mechanism for quantitative comparisons. This perspective article highlights the need for quantitative inter-model comparisons to allow for a better understanding of the applicability of existing and new methodologies to different scopes, sectors, and applications. The overarching conclusion of the paper is that there is a need to push towards organizing the discipline into a nexus community of practice responsible for curating and maintaining nexus data, methods, models, and case studies to improve the understanding, accessibility, and transparency of nexus research for real-world applications. To achieve this end, the recommendations made in this paper have been summarized into the list of 10 recommended action items as shown in **Figure 2**.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

## REFERENCES

- Abbott, M., Bazilian, M., Egel, D., and Willis, H. H. (2017). Examining the Food-Energy-Water and Conflict Nexus. *Curr. Opin. Chem. Eng.* 18, 55–60. doi:10.1016/j.coche.2017.10.002
- Abdi, H., Shahbazitabar, M., and Mohammadi-Ivatloo, B. (2020). Food, Energy and Water Nexus: A Brief Review of Definitions, Research, and Challenges. *Inventions* 5, 56. doi:10.3390/inventions5040056
- Albrecht, T. R., Crotoof, A., and Scott, C. A. (2018). The Water-Energy-Food Nexus: A Systematic Review of Methods for Nexus Assessment. *Environ. Res. Lett.* 13, 043002. doi:10.1088/1748-9326/aaa9c6
- Allen, M., et al. (2019). “Technical Summary: 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*. Available at: [https://www.ipcc.ch/site/assets/uploads/sites/2/2018/12/SR15\\_TS\\_High\\_Res.pdf](https://www.ipcc.ch/site/assets/uploads/sites/2/2018/12/SR15_TS_High_Res.pdf).
- Arthur, M., Liu, G., Hao, Y., Zhang, L., Liang, S., Asamoah, E. F., et al. (2019). Urban food-energy-water nexus indicators: A review. *Resour. Conserv. Recycl.* 151, 104481. doi:10.1016/j.resconrec.2019.104481
- ASU (2021). Case Studies of Social-Ecological Systems | SES Library. Tempe, AZ: Arizona State University - School of Human Evolution and Social Change. Available at: <https://seslibrary.asu.edu/case>.
- Bakhshianlamouki, E., Masia, S., Karimi, P., van der Zaag, P., and Sušnik, J. (2020). A system dynamics model to quantify the impacts of restoration measures on the water-energy-food nexus in the Urmia lake Basin, Iran. *Sci. Total Environ.* 708, 134874. doi:10.1016/j.scitotenv.2019.134874
- Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., et al. (2011). Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy Policy* 39, 7896–7906. doi:10.1016/j.enpol.2011.09.039
- Benites-Lazaro, L. L., Nascimento, N., Urbinatti, A., Amaral, M., and Giatti, L. L. (2021). “The Social Network Analysis to Study Discourse on Water-Energy-Food Nexus,” in *The Water-Energy-Food Nexus: Concept and Assessments*. Editor S. S. Muthu (Springer), 127–144. doi:10.1007/978-981-16-0239-9\_5
- Bernard, R. E., and Cooperdock, E. H. G. (2018). No progress on diversity in 40 years. *Nat. Geosci.* 11, 292–295. doi:10.1038/s41561-018-0116-6
- Boas, I., Biermann, F., and Kanie, N. (2016). Cross-sectoral strategies in global sustainability governance: towards a nexus approach. *Int. Environ. Agreements* 16, 449–464. doi:10.1007/s10784-016-9321-1

## AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

## FUNDING

This research was partially funded with a grant from the National Science Foundation # 1739835 and # IIA-1301346 to Hatim M. E. Geli and his collaborators. Partial support was also provided to Hatim M. E. Geli and his collaborators by New Mexico State University.

## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2022.918085/full#supplementary-material>

- Bond, A., Morrison-Saunders, A., and Pope, J. (2012). Sustainability assessment: the state of the art. *Impact Assess. Proj. Apprais.* 30, 53–62. doi:10.1080/14615517.2012.661974
- Brownell, S. E., Price, J. V., and Steinman, L. (2013). Science Communication to the General Public: Why We Need to Teach Undergraduate and Graduate Students This Skill as Part of Their Formal Scientific Training. *J. Undergrad. Neurosci. Educ.* 12, E6.
- Bucchi, M., and Trench, B. (2014). “Science communication research: themes and challenges,” in *Routledge Handbook of Public Communication of Science and Technology* England, UK, (Routledge).
- Byers, E., Gidden, M., Leclère, D., Balkovic, J., Burek, P., Ebi, K., et al. (2018). Global exposure and vulnerability to multi-sector development and climate change hotspots. *Environ. Res. Lett.* 13, 055012. doi:10.1088/1748-9326/aabf45
- Cairns, R., and Krzywoszynska, A. (2016). Anatomy of a buzzword: The emergence of ‘the water-energy-food nexus’ in UK natural resource debates. *Environ. Sci. Policy* 64, 164–170. doi:10.1016/j.envsci.2016.07.007
- Canyon, D. V., Burkle, F. M., and Speare, R. (2015). Managing Community Resilience to Climate Extremes, Rapid Unsustainable Urbanization, Emergencies of Scarcity, and Biodiversity Crises by Use of a Disaster Risk Reduction Bank. *Disaster Med. public health Prep.* 9, 619–624. doi:10.1017/dmp.2015.124
- Chaudhary, S., McGregor, A., Houston, D., and Chettri, N. (2015). The evolution of ecosystem services: A time series and discourse-centered analysis. *Environ. Sci. Policy* 54, 25–34. doi:10.1016/j.envsci.2015.04.025
- Costanza, R., Daly, L., Fioramonti, L., Giovannini, E., Kubiszewski, I., Mortensen, L. F., et al. (2016). Modelling and measuring sustainable wellbeing in connection with the UN Sustainable Development Goals. *Ecol. Econ.* 130, 350–355. doi:10.1016/j.ecolecon.2016.07.009
- Cremades, R., Mitter, H., Tudose, N. C., Sanchez-Plaza, A., Graves, A., Broekman, A., et al. (2019). Ten principles to integrate the water-energy-land nexus with climate services for co-producing local and regional integrated assessments. *Sci. Total Environ.* 693, 133662. doi:10.1016/j.scitotenv.2019.133662
- Daher, B. T., and Mohtar, R. H. (2015). Water-energy-food (WEF) Nexus Tool 2.0: guiding integrative resource planning and decision-making. *Water Int.* 40, 748–771. doi:10.1080/02508060.2015.1074148
- Dai, J., Wu, S., Han, G., Weinberg, J., Xie, X., Wu, X., et al. (2018). Water-energy nexus: A review of methods and tools for macro-assessment. *Appl. Energy* 210, 393–408. doi:10.1016/j.apenergy.2017.08.243
- de Amorim, W. S., Valduga, I. B., Ribeiro, J. M. P., Williamson, V. G., Krauser, G. E., Magtoto, M. K., et al. (2018). The nexus between water, energy, and food in the context of the global risks: An analysis of the interactions between food, water, and energy security. *Environ. Impact Assess. Rev.* 72, 1–11. doi:10.1016/j.eiar.2018.05.002

- de Strasser, L., Lipponen, A., Howells, M., Stec, S., and Bréthaut, C. (2016). A Methodology to Assess the Water Energy Food Ecosystems Nexus in Transboundary River Basins. *Water* 8, 59. doi:10.3390/w8020059
- Dhaubanjari, S., Davidsen, C., and Bauer-Gottwein, P. (2017). Multi-Objective Optimization for Analysis of Changing Trade-Offs in the Nepalese Water-Energy-Food Nexus with Hydropower Development. *Water* 9, 162. doi:10.3390/w9030162
- El-Gafy, I. (2017). Water-food-energy nexus index: analysis of water-energy-food nexus of crop's production system applying the indicators approach. *Appl. Water Sci.* 7, 2857–2868. doi:10.1007/s13201-017-0551-3
- Elagib, N. A., and Al-Saidi, M. (2020). Balancing the benefits from the water-energy-land-food nexus through agroforestry in the Sahel. *Sci. Total Environ.* 742, 140509. doi:10.1016/j.scitotenv.2020.140509
- Elagib, N. A., Gayoum Saad, S. A., Basheer, M., Rahma, A. E., and Gore, E. D. L. (2021). Exploring the urban water-energy-food nexus under environmental hazards within the Nile. *Stoch. Environ. Res. Risk Assess.* 35, 21–41. doi:10.1007/s00477-019-01706-x
- Endo, A., Tsurita, I., Burnett, K., and Orenco, P. M. (2017). A review of the current state of research on the water, energy, and food nexus. *J. Hydrology Regional Stud.* 11, 20–30. doi:10.1016/j.ejrh.2015.11.010
- Endo, A., Yamada, M., Miyashita, Y., Sugimoto, R., Ishii, A., Nishijima, J., et al. (2020). Dynamics of water-energy-food nexus methodology, methods, and tools. *Curr. Opin. Environ. Sci. Health* 13, 46–60. doi:10.1016/j.coesh.2019.10.004
- Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., et al. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.* 9, 1937–1958. doi:10.5194/gmd-9-1937-2016
- Fader, M., Cranmer, C., Lawford, R., and Engel-Cox, J. (2018). Toward an Understanding of Synergies and Trade-Offs Between Water, Energy, and Food SDG Targets. *Front. Environ. Sci.* 6, 112. doi:10.3389/fenvs.2018.00112
- FAO (2014). *The Water-Energy-Food Nexus: A New Approach in Support of Food Security and Sustainable Agriculture*. Rome, Italy, Food and Agriculture Organization FAO.
- Fernandes Torres, C. J., Peixoto de Lima, C. H., Suzart de Almeida Goodwin, B., Rebelo de Aguiar Junior, T., Sousa Fontes, A., Veras Ribeiro, D., et al. (2019). A Literature Review to Propose a Systematic Procedure to Develop "Nexus Thinking" Considering the Water-Energy-Food Nexus. *Sustainability* 11, 7205. doi:10.3390/su11247205
- Fleming, A., Wise, R. M., Hansen, H., and Sams, L. (2017). The sustainable development goals: A case study. *Mar. Policy* 86, 94–103. doi:10.1016/j.marpol.2017.09.019
- Freeman, R. B., and Huang, W. (2014). Collaboration: Strength in diversity. *Nature* 513, 305. doi:10.1038/513305a
- Griggs, D., Stafford-Smith, M., Gaffney, O., Rockström, J., Öhman, M. C., Shyamsundar, P., et al. (2013). Sustainable development goals for people and planet. *Nature* 495, 305–307. doi:10.1038/495305a
- Hackett, E. J., and Rhoten, D. R. (2009). The Snowbird Charrette: Integrative interdisciplinary collaboration in environmental research design. *Minerva* 47, 407–440. doi:10.1007/s11024-009-9136-0
- Hagemann, N., and Kirschke, S. (2017). Key Issues of Interdisciplinary NEXUS Governance Analyses: Lessons Learned from Research on Integrated Water Resources Management. *Resources* 6, 9. doi:10.3390/resources610009
- Hameed, M., Moradkhani, H., Ahmadalipour, A., Moftakhari, H., Abbaszadeh, P., and Alipour, A. (2019). A Review of the 21st Century Challenges in the Food-Energy-Water Security in the Middle East. *Water* 11, 682. doi:10.3390/w11040682
- Herring, C. (2009). Does diversity pay? Race, gender, and the business case for diversity. *Am. Sociol. Rev.* 74, 208–224. doi:10.1177/000312240907400203
- Hoff, H. (2011). *Understanding the Nexus: Background Paper for the Bonn2011 Nexus Conference*, Stockholm, SEI.
- Hogeboom, R. J., Bas W, Borsje, Mekdelawit M, Deribe, Freek D, van der M., Mehvar, S., Markus, A. M., et al. (2021). Resilience Meets the Water-Energy-Food Nexus: Mapping the Research Landscape. *Front. Environ. Sci.* 9, 630395. doi:10.3389/fenvs.2021.630395
- Howarth, C., and Monasterolo, I. (2017). Opportunities for knowledge co-production across the energy-food-water nexus: Making interdisciplinary approaches work for better climate decision making. *Environ. Sci. Policy* 75, 103–110. doi:10.1016/j.envsci.2017.05.019
- Huang, A., and Chang, F.-J. (2021). Prospects for rooftop farming system dynamics: An action to stimulate water-energy-food nexus synergies toward green cities of tomorrow. *Sustainability* 13, 9042. doi:10.3390/su13169042
- Hülsmann, S., and Ardakanian, R. (2018). "The Nexus Approach as Tool for Achieving SDGs: Trends and Needs," in *Managing Water, Soil and Waste Resources to Achieve Sustainable Development Goals: Monitoring and Implementation of Integrated Resources Management*. Editors S. Hülsmann and R. Ardakanian New York, (Springer International Publishing), 1–9. doi:10.1007/978-3-319-75163-4\_1
- IIASA (2021). Global Hotspots explorer. Available at: <https://hotspots-explorer.org/>.
- ICHEME, IChemE. Energy Community of Practice. Available at: [https://www.icheme.org/membership/communities/communities-of-practice/energy-community-of-practice/\(2021\)](https://www.icheme.org/membership/communities/communities-of-practice/energy-community-of-practice/(2021)).
- Imasiku, K., and Ntagwirumugara, E. (2020). An impact analysis of population growth on energy-water-food-land nexus for ecological sustainable development in Rwanda. *Food Energy Secur.* 9, e185. doi:10.1002/fes3.185
- Johnson, N., Burek, P., Byers, E., Falchetta, G., Flörke, M., Fujimori, S., et al. (2019). Integrated Solutions for the Water-Energy-Land Nexus: Are Global Models Rising to the Challenge? *Water* 11, 2223. doi:10.3390/w11112223
- Joshi, A., and Roh, H. (2009). The role of context in work team diversity research: A meta-analytic review. *Amj* 52, 599–627. doi:10.5465/amj.2009.41331491
- Kaddoura, S., and El Khatib, S. (2017). Review of water-energy-food Nexus tools to improve the Nexus modelling approach for integrated policy making. *Environ. Sci. Policy* 77, 114–121. doi:10.1016/j.envsci.2017.07.007
- Kalair, A. R., Abas, N., Ul Hasan, Q., Kalair, E., Kalair, A., and Khan, N. (2019). Water, energy and food nexus of Indus Water Treaty: Water governance. *Water-Energy Nexus* 2, 10–24. doi:10.1016/j.wen.2019.04.001
- Kalev, A. (2009). Cracking the glass cages? Restructuring and ascriptive inequality at work. *Am. J. Sociol.* 114, 1591–1643. doi:10.1086/597175
- Karabulut, A. A., Crenna, E., Sala, S., and Udias, A. (2018). A proposal for integration of the ecosystem-water-food-land-energy (EWFLE) nexus concept into life cycle assessment: A synthesis matrix system for food security. *J. Clean. Prod.* 172, 3874–3889. doi:10.1016/j.jclepro.2017.05.092
- Karlberg, L., Hoff, T., Amsalu, K., Andersson, T., Binnington, F., Flores, A., et al. Tackling Complexity: Understanding the Food-Energy-Environment Nexus in Ethiopia's Lake Tana Sub-basin. *Water Altern.*, 8, 25 (2015).
- Keskinen, M., Someth, P., Salmivaara, A., and Kumm, M. (2015). Water-Energy-Food Nexus in a Transboundary River Basin: The Case of Tonle Sap Lake, Mekong River Basin. *Water* 7, 5416–5436. doi:10.3390/w7105416
- Khan, Z., Wild, T. B., Iyer, G., Hejazi, M., and Vernon, C. R. (2021). The future evolution of energy-water-agriculture interconnectivity across the US. *Environ. Res. Lett.* 16, 065010. doi:10.1088/1748-9326/ac046c
- Khan, Z., Wild, T. B., Silva Carrazzone, M. E., Gaudioso, R., Mascari, M. P., Bianchi, F., et al. (2020). Integrated energy-water-land nexus planning to guide national policy: an example from Uruguay. *Environ. Res. Lett.* 15, 094014. doi:10.1088/1748-9326/ab9389
- King, C., and Jaafar, H. (2015). Rapid assessment of the water-energy-food-climate nexus in six selected basins of North Africa and West Asia undergoing transitions and scarcity threats. *Int. J. Water Resour. Dev.* 31, 343–359. doi:10.1080/07900627.2015.1026436
- Kurian, M. (2019). One Swallow Does Not Make a Summer: Siloes, Trade-Offs and Synergies in the Water-Energy-Food Nexus. *Front. Environ. Sci.* 7, 32. doi:10.3389/fenvs.2019.00032
- Kurian, M. (2017). The water-energy-food nexus. *Environ. Sci. Policy* 68, 97–106. doi:10.1016/j.envsci.2016.11.006
- Larsen, M. A. D., Petrovic, S., Engström, R. E., Drews, M., Liersch, S., Karlsson, K. B., et al. (2019). Challenges of data availability: Analysing the water-energy nexus in electricity generation. *Energy Strategy Rev.* 26, 100426. doi:10.1016/j.esr.2019.100426
- Lazaro, L. L. B., Giatti, L. L., Bermann, C., Giarolla, A., and Ometto, J. (2021). Policy and governance dynamics in the water-energy-food-land nexus of biofuels: Proposing a qualitative analysis model. *Renew. Sustain. Energy Rev.* 149, 111384. doi:10.1016/j.rser.2021.111384
- Le Blanc, D. (2015). Towards Integration at Last? The Sustainable Development Goals as a Network of Targets. *Sust. Dev.* 23, 176–187. doi:10.1002/sd.1582
- Leck, H., Conway, D., Bradshaw, M., and Rees, J. (2015). Tracing the Water-Energy-Food Nexus: Description, Theory and Practice. *Geogr. Compass* 9, 445–460. doi:10.1111/gec3.12222
- Liu, J., Hull, V., Godfray, H. C. J., Tilman, D., Gleick, P., Hoff, H., et al. (2018). Nexus approaches to global sustainable development. *Nat. Sustain* 1, 466–476. doi:10.1038/s41893-018-0135-8

- Liu, J., Yang, H., Cudennec, C., Gain, A. K., Hoff, H., Lawford, R., et al. (2017). Challenges in operationalizing the water-energy-food nexus. *Hydrological Sci. J.* 62, 1714–1720. doi:10.1080/02626667.2017.1353695
- Liu, L., Hejazi, M., Iyer, G., and Forman, B. A. (2019). Implications of water constraints on electricity capacity expansion in the United States. *Nat. Sustain.* 2, 206–213. doi:10.1038/s41893-019-0235-0
- Liu, L., Hejazi, M., Li, H., Forman, B., and Zhang, X. (2017). Vulnerability of US thermoelectric power generation to climate change when incorporating state-level environmental regulations. *Nat. Energy* 2, 17109. doi:10.1038/energy.2017.109
- Liu, Q. (2016). Interlinking climate change with water-energy-food nexus and related ecosystem processes in California case studies. *Ecol. Process* 5, 14. doi:10.1186/s13717-016-0058-0
- Mabhaudhi, T., Nhamo, L., Mpendeli, S., Nhemachena, C., Senzanje, A., Sobratee, N., et al. (2019). The Water-Energy-Food Nexus as a Tool to Transform Rural Livelihoods and Well-Being in Southern Africa. *Ijerp* 16, 2970. doi:10.3390/ijerp16162970
- Mausser, W., Klepper, G., Rice, M., Schmalzbauer, B. S., Hackmann, H., Leemans, R., et al. (2013). Transdisciplinary global change research: the co-creation of knowledge for sustainability. *Curr. Opin. Environ. Sustain.* 5, 420–431. doi:10.1016/j.cosust.2013.07.001
- McNutt, M. (2013). Improving Scientific Communication. *Science* 342, 13. doi:10.1126/science.1246449
- Mirzabaev, A., Guta, D., Goedecke, J., Gaur, V., Börner, J., Virchow, D., et al. (2015). Bioenergy, food security and poverty reduction: trade-offs and synergies along the water-energy-food security nexus. *Water Int.* 40, 772–790. doi:10.1080/02508060.2015.1048924
- Mitra, B. K., Sharma, D., Kuyama, T., Pham, B. N., Islam, G. M. T., and Thao, P. T. M. (2020). Water-energy-food nexus perspective: Pathway for Sustainable Development Goals (SDGs) to country action in India. *Apn Sci. Bull.* 10, 34–40. doi:10.30852/sb.2020.1067
- Moallemi, E. A., (2021). Evaluating Participatory Modeling Methods for Co-creating Pathways to Sustainability. *Earth's Future* 9, e2020EF001843. doi:10.1029/2020ef001843
- Mohtar, R. H., and Lawford, R. (2016). Present and future of the water-energy-food nexus and the role of the community of practice. *J. Environ. Stud. Sci.* 6, 192–199. doi:10.1007/s13412-016-0378-5
- Morgan, R. K. (2012). Environmental impact assessment: the state of the art. *Impact Assess. Proj. Apprais.* 30, 5–14. doi:10.1080/14615517.2012.661557
- Munoz Castillo, R., Feng, K., Sun, L., Guilhoto, J., Pfister, S., Miralles-Wilhelm, F., et al. (2019). The land-water nexus of biofuel production in Brazil: Analysis of synergies and trade-offs using a multiregional input-output model. *J. Clean. Prod.* 214, 52–61. doi:10.1016/j.jclepro.2018.12.264
- Naeem, S. (2002). Ecosystem Consequences of Biodiversity Loss: The Evolution of a Paradigm. *Ecology* 83, 1537–1552. doi:10.1890/0012-9658(2002)083[1537:ecobl]2.0.co;2
- Newell, J. P., Goldstein, B., and Foster, A. (2019). A 40-year review of food-energy-water nexus literature and its application to the urban scale. *Environ. Res. Lett.* 14, 073003. doi:10.1088/1748-9326/ab0767
- Okoli, C., and Pawlowski, S. D. (2004). The Delphi method as a research tool: an example, design considerations and applications. *Inf. Manag.* 42, 15–29. doi:10.1016/j.im.2003.11.002
- Olawuyi, D. (2020). Sustainable development and the water-energy-food nexus: Legal challenges and emerging solutions. *Environ. Sci. Policy* 103, 1–9. doi:10.1016/j.envsci.2019.10.009
- Opejin, A. K., Aggarwal, R. M., White, D. D., Jones, J. L., Maciejewski, R., Mascaro, G., et al. (2020). A Bibliometric Analysis of Food-Energy-Water Nexus Literature. *Sustainability* 12, 1112. doi:10.3390/su12031112
- Pahl-Wostl, C., Gorris, P., Jäger, N., Koch, L., Lebel, L., Stein, C., et al. (2021). Scale-related governance challenges in the water-energy-food nexus: toward a diagnostic approach. *Sustain. Sci.* 16, 615–629. doi:10.1007/s11625-020-00888-6
- Parkinson, S. C., Djalali, N., Krey, V., Fricko, O., Johnson, N., Khan, Z., et al. (2016). Impacts of Groundwater Constraints on Saudi Arabia's Low-Carbon Electricity Supply Strategy. *Environ. Sci. Technol.* 50, 1653–1662. doi:10.1021/acs.est.5b05852
- Payet-Burin, R., Kromann, M., Pereira-Cardenal, S., Strzpek, K. M., and Bauer-Gottwein, P. (2021). Nexus vs. Silo Investment Planning Under Uncertainty. *Front. Water* 0. doi:10.3389/frwa.2021.672382
- Pittock, J., Orr, S., Stevens, L., Aheeyar, M., and Smith, M. (2015). Tackling Trade-offs in the Nexus of Water, Energy and Food. *Aquat. Procedia* 5, 58–68. doi:10.1016/j.aqpro.2015.10.008
- Purwanto, A., Sušnik, J., Suryadi, F. X., and de Fraiture, C. (2021). Water-energy-food nexus: Critical review, practical applications, and prospects for future research. *Sustainability* 13, 1919. doi:10.3390/su13041919
- Rasul, G., and Neupane, N. (2021). Improving Policy Coordination Across the Water, Energy, and Food, Sectors in South Asia: A Framework. *Front. Sustain. Food Syst.* 5, 602475. doi:10.3389/fsufs.2021.602475
- Rasul, G., and Sharma, B. (2016). The nexus approach to water-energy-food security: an option for adaptation to climate change. *Clim. Policy* 16, 682–702. doi:10.1080/14693062.2015.1029865
- Reed, J. (2014). Communities of Practice A Tool for Creating Institutional Change in Support of the Mission of the Federal Energy Management Program. Available at: [https://www.energy.gov/sites/prod/files/2015/04/f21/communities\\_of\\_practice.pdf](https://www.energy.gov/sites/prod/files/2015/04/f21/communities_of_practice.pdf). (Accessed April 16, 2015).
- Roggema, R., and Yan, W. (2019). Developing a design-led approach for the food-energy-water nexus in cities. *Urban Plan.* 4, 123–138. doi:10.17645/up.v4i1.1739
- Rosenzweig, C., Jones, J. W., Hatfield, J. L., Ruane, A. C., Boote, K. J., Thorburn, P., et al. (2013). The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. *Agric. For. Meteorology* 170, 166–182. doi:10.1016/j.agrformet.2012.09.011
- Rosenzweig, C., Ruane, A. C., Antle, J., Elliott, J., Ashfaq, M., Chatta, A. A., et al. (2018). Coordinating AgMIP data and models across global and regional scales for 1.5°C and 2.0°C assessments. *Phil. Trans. R. Soc. A* 376, 20160455. doi:10.1098/rsta.2016.0455
- Rulli, M. C., Bellomi, D., Cazzoli, A., De Carolis, G., and D'Odorico, P. (2016). The water-land-food nexus of first-generation biofuels. *Sci. Rep.* 6, 22521. doi:10.1038/srep22521
- Saladini, F., Betti, G., Ferragina, E., Bouraoui, F., Cupertino, S., Canitano, G., et al. (2018). Linking the water-energy-food nexus and sustainable development indicators for the Mediterranean region. *Ecol. Indic.* 91, 689–697. doi:10.1016/j.ecolind.2018.04.035
- Shannak, S. d., Mabrey, D., and Vittorio, M. (2018). Moving from theory to practice in the water-energy-food nexus: An evaluation of existing models and frameworks. *Water-Energy Nexus* 1, 17–25. doi:10.1016/j.wen.2018.04.001
- Siddiqi, A., and Anadon, L. D. (2011). The water-energy nexus in Middle East and North Africa. *Energy Policy* 39, 4529–4540. doi:10.1016/j.enpol.2011.04.023
- SIM4Nexus (2021). SIM4NEXUS Case Studies. Available at: <https://www.sim4nexus.eu/index.php?wert=Home>.
- Simpson, G. B., and Jewitt, G. P. W. (2019). The Development of the Water-Energy-Food Nexus as a Framework for Achieving Resource Security: A Review. *Front. Environ. Sci.* 7. doi:10.3389/fenvs.2019.00008
- Singh, R. K., Murty, H. R., Gupta, S. K., and Dikshit, A. K. (2009). An overview of sustainability assessment methodologies. *Ecol. Indic.* 9, 189–212. doi:10.1016/j.ecolind.2008.05.011
- Siri, J. G., Newell, B., Proust, K., and Capon, A. (2016). Urbanization, Extreme Events, and Health. *Asia Pac. J. Public Health* 28, 15S–27S. doi:10.1177/1010539515595694
- SIWI (2021). A community of Practice on Water and Open Government. Available at: <https://www.siw.org/what-we-do/a-community-of-practice-on-water-and-open-government/>.
- Smith, D. W., Welch, M., Bennett, K. E., Padgham, J., and Mohtar, R. (2017). Building a WEF Nexus Community of Practice (NCoP). *Curr. Sustain. Renew. Energy Rep.* 4, 168–172. doi:10.1007/s40518-017-0080-6
- Smith-Doerr, L., Alegria, S. N., and Sacco, T. (2017). How Diversity Matters in the US Science and Engineering Workforce: A Critical Review Considering Integration in Teams, Fields, and Organizational Contexts. *Engag. STS* 3, 139–153. doi:10.17351/ests2017.142
- Snyder, W. M., and Wenger, E. (2010). "Our world as a learning system: A communities-of-practice approach," in *Social Learning Systems and Communities of Practice 107–124* New York, (Springer). doi:10.1007/978-1-84996-133-2\_7
- Snyder, W., Wenger, E., and de Sousa Briggs, X. (2004). Communities of practice in government: Leveraging knowledge for performance. *PUBLIC Manag.* 32, 17–22.
- Staddon, S., Byg, A., Chapman, M., Fish, R., Hague, A., and Horgan, K. (2021). The value of listening and listening for values in conservation. *People Nat.* doi:10.1002/pan3.10232
- Stephan, R. M., Mohtar, R. H., Daher, B., Embid Irujo, A., Hillers, A., Ganter, J. C., et al. (2018). Water-energy-food nexus: a platform for implementing the Sustainable Development Goals. *Water Int.* 43, 472–479. doi:10.1080/02508060.2018.1446581

- Stoy, P. C., Ahmed, S., Jarchow, M., Rashford, B., Swanson, D., Albeke, S., et al. (2018). Opportunities and Trade-offs among BECCS and the Food, Water, Energy, Biodiversity, and Social Systems Nexus at Regional Scales. *BioScience* 68, 100–111. doi:10.1093/biosci/bix145
- Stylianopoulou, K. G., Papapostolou, C. M., and Kondili, E. M. (2020). “Water–energy–food Nexus: a focused review on integrated methods,” in *Environmental Sciences Proceedings* Switzerland, (Multidisciplinary Digital Publishing Institute), 2–46.
- Sušnik, J. (2018). Multi-Stakeholder Development of a Serious Game to Explore the Water-Energy-Food-Land-Climate Nexus: The SIM4NEXUS Approach. *Water* 10, 139. doi:10.3390/w10020139
- Tashtoush, F. M., Al-Zubari, W. K., and Shah, A. (2019). A review of the water-energy-food nexus measurement and management approach. *Int. J. Energy Water Res.* 3, 361–374. doi:10.1007/s42108-019-00042-8
- Uen, T.-S., Chang, F.-J., Zhou, Y., and Tsai, W.-P. (2018). Exploring synergistic benefits of Water-Food-Energy Nexus through multi-objective reservoir optimization schemes. *Sci. Total Environ.* 633, 341–351. doi:10.1016/j.scitotenv.2018.03.172
- UNDESA (2021). Sustainable Development. The 17 Goals. Available at: <https://sdgs.un.org/goals>.
- Urbinaati, A. M., Benites-Lazaro, L. L., Carvalho, C. M. d., and Giatti, L. L. (2020). The conceptual basis of water-energy-food nexus governance: systematic literature review using network and discourse analysis. *J. Integr. Environ. Sci.* 17, 21–43. doi:10.1080/1943815x.2020.1749086
- Urbinaati, A. M., Dalla Fontana, M., Stirling, A., and Giatti, L. L. (2020). ‘Opening up’ the governance of water-energy-food nexus: Towards a science-policy-society interface based on hybridity and humility. *Sci. Total Environ.* 744, 140945. doi:10.1016/j.scitotenv.2020.140945
- van den Heuvel, L., Blicharska, M., Masia, S., Sušnik, J., and Teutschbein, C. (2020). Ecosystem services in the Swedish water-energy-food-land-climate nexus: Anthropogenic pressures and physical interactions. *Ecosyst. Serv.* 44, 101141. doi:10.1016/j.ecoser.2020.101141
- van Gevelt, T. (2020). The water-energy-food nexus: bridging the science-policy divide. *Curr. Opin. Environ. Sci. Health* 13, 6–10. doi:10.1016/j.coesh.2019.09.008
- Venghaus, S., and Dieken, S. (2019). From a few security indices to the FEW Security Index: Consistency in global food, energy and water security assessment. *Sustain. Prod. Consum.* 20, 342–355. doi:10.1016/j.spc.2019.08.002
- Venkatesh, G., Chan, A., and Brattebø, H. (2014). Understanding the water-energy-carbon nexus in urban water utilities: Comparison of four city case studies and the relevant influencing factors. *Energy* 75, 153–166. doi:10.1016/j.energy.2014.06.111
- Vinca, A., Riahi, K., Rowe, A., and Djilali, N. (2021). Climate-Land-Energy-Water Nexus Models Across Scales: Progress, Gaps and Best Accessibility Practices. *Front. Environ. Sci.* 9, 252. doi:10.3389/fenvs.2021.691523
- Voelker, T., Blackstock, K., Kovacic, Z., Sindt, J., Strand, R., and Waylen, K. (2022). The role of metrics in the governance of the water-energy-food nexus within the European Commission. *J. Rural Stud.* 92, 473–481. doi:10.1016/j.jrurstud.2019.08.001
- Wada, Y., Vinca, A., Parkinson, S., Willaarts, B. A., Magnuszewski, P., Mochizuki, J., et al. (2019). Co-designing Indus Water-Energy-Land Futures. *One Earth* 1, 185–194. doi:10.1016/j.oneear.2019.10.006
- Weinthal, E., and Sowers, J. (2020). The water-energy nexus in the Middle East: Infrastructure, development, and conflict. *WIREs Water* 7, e1437. doi:10.1002/wat2.1437
- Weitz, N., Strambo, C., Kemp-Benedict, E., and Nilsson, M. (2017). Closing the governance gaps in the water-energy-food nexus: Insights from integrative governance. *Glob. Environ. Change* 45, 165–173. doi:10.1016/j.gloenvcha.2017.06.006
- White, D., Jones, J., Maciejewski, R., Aggarwal, R., and Mascaro, G. (2017). Stakeholder Analysis for the Food-Energy-Water Nexus in Phoenix, Arizona: Implications for Nexus Governance. *Sustainability* 9, 2204. doi:10.3390/su9122204
- Wicaksono, A., and Kang, D. (2019). Nationwide simulation of water, energy, and food nexus: Case study in South Korea and Indonesia. *J. Hydro-environment Res.* 22, 70–87. doi:10.1016/j.jher.2018.10.003
- Wichelns, D. (2017). The water-energy-food nexus: Is the increasing attention warranted, from Either a research or policy perspective? *Environ. Sci. Policy* 69, 113–123. doi:10.1016/j.envsci.2016.12.018
- Wild, T., Khan, Z., Clarke, L., Hejazi, M., Bereslawski, J. L., Suriano, M., et al. (2021). Integrated Energy-Water-Land Nexus Planning in the Colorado River Basin (Argentina) (in revision). *Reg. Environ. Change* 21, 62. doi:10.1007/s10113-021-01775-1
- Willis, H. H., (2016). *Developing the Pardee RAND Food-Energy-Water Security Index: Toward a Global Standardized, Quantitative, and Transparent Resource Assessment*, Santa Monica, Calif, RAND,
- Woolley, A. W., Chabris, C. F., Pentland, A., Hashmi, N., and Malone, T. W. (2010). Evidence for a collective intelligence factor in the performance of human groups. *science* 330, 686–688. doi:10.1126/science.1193147
- WRI, Aqueduct Water Risk Atlas. Available at: [https://www.wri.org/applications/aqueduct/water-risk-atlas/\(2021\)](https://www.wri.org/applications/aqueduct/water-risk-atlas/(2021)).
- Wu, L., Elshorbagy, A., Pande, S., and Zhuo, L. (2021). Trade-offs and synergies in the water-energy-food nexus: The case of Saskatchewan, Canada. *Resour. Conservation Recycl.* 164, 105192. doi:10.1016/j.resconrec.2020.105192
- Yillia, P. T. (2016). Water-Energy-Food nexus: framing the opportunities, challenges and synergies for implementing the SDGs. *Österr Wasser-Abfallw* 68, 86–98. doi:10.1007/s00506-016-0297-4
- Zarei, M. (2020). The water-energy-food nexus: A holistic approach for resource security in Iran, Iraq, and Turkey. *Water-Energy Nexus* 3, 81–94. doi:10.1016/j.wen.2020.05.004
- Zhang, C., Chen, X., Li, Y., Ding, W., and Fu, G. (2018). Water-energy-food nexus: Concepts, questions and methodologies. *J. Clean. Prod.* 195, 625–639. doi:10.1016/j.jclepro.2018.05.194

**Author Disclaimer:** Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation or of National Geographic Partners.

**Conflict of Interest:** MA was employed by National Geographic Partners at the time of the writing of this article.

The author HG received funding from National Science Foundation. The funder was not involved in the study design, collection, analysis, interpretation of data, the writing of this article or the decision to submit it for publication.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

**Publisher’s Note:** All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Copyright © 2022 Khan, Abraham, Aggarwal, Ahmad Khan, Arguello, Babbar-Sebens, Bereslawski, Bielicki, Campana, Silva Carrazzone, Castanier, Chang, Collins, Conchado, Dagani, Daher, Dekker, Delgado, Diuana, Doelman, Elshorbagy, Fan, Gaudioso, Gebrechorkos, Geli, Grubert, Huang, Huang, Ilyas, Ivakhnenko, Jewitt, Ferreira dos Santos, Jones, Kellner, Krueger, Kumar, Lamontagne, Lansu, Lee, Li, Linares, Marazza, Mascari, McManamay, Meng, Mereu, Miralles-Wilhelm, Mohtar, Muhammad, Opejin, Pande, Parkinson, Payet-Burin, Ramdas, Ramos, Ray, Roberts, Sampedro, Sanders, Saray, Schmidt, Shanafield, Siddiqui, Suriano, Taniguchi, Trabucco, Tuninetti, Vinca, Weeser, White, Wild, Yadav, Yogeswaran, Yokohata and Yue. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.