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

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

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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

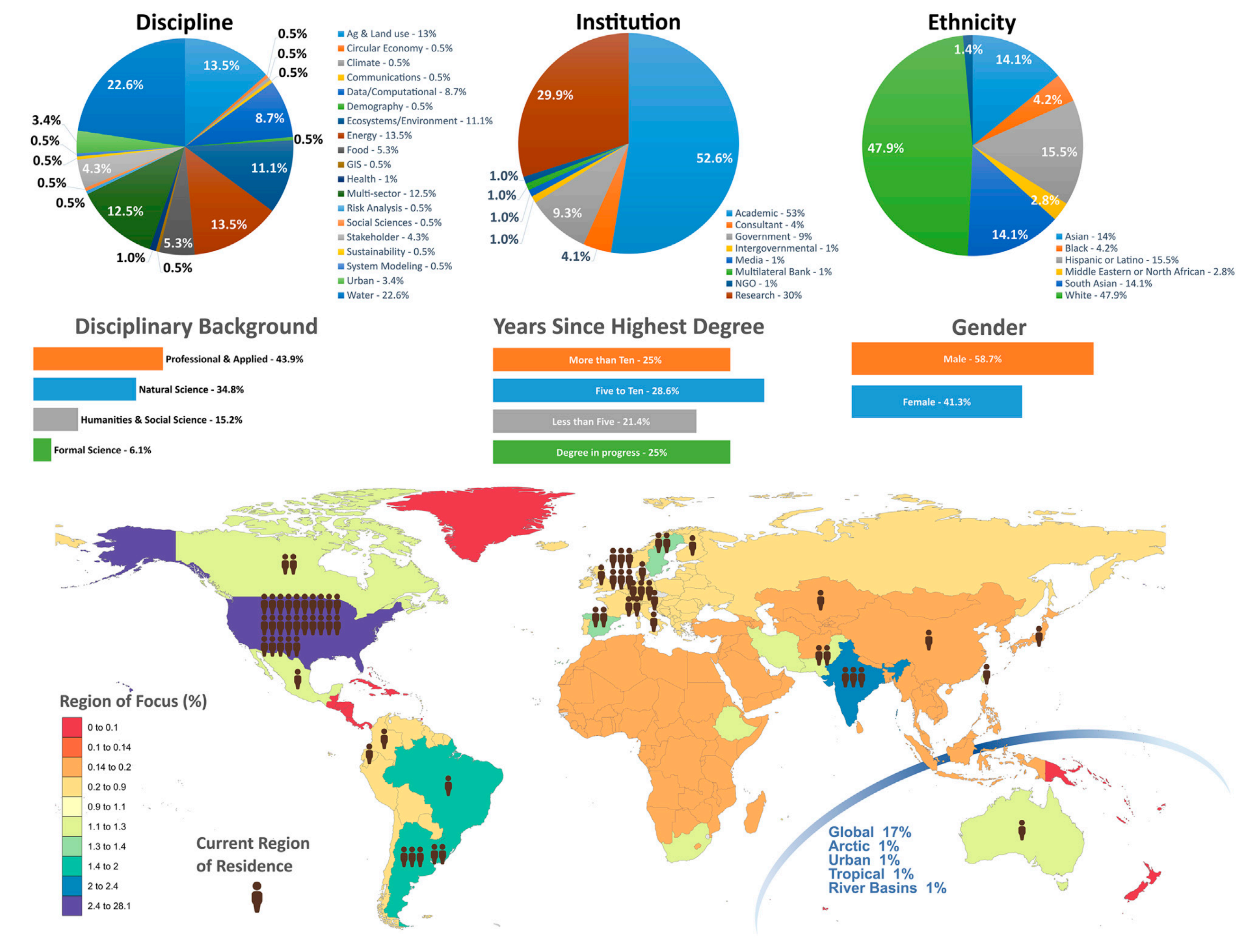

FIGURE 1 | Results of the author diversity surveys on disciplinary background, institution type, career-stage, ethnicity, gender and geographical area of residence and focus. Respondents could select more than one choice for these questions, as well as provide their own custom answers if desired. Note that disciplinary backgrounds in the survey were defined as: Professional & Applied (Engineering, Law, Business, Medicine, Journalism etc.); Natural Science (Physics, Chemistry, Biology, Earth Sciences, Space etc.); Humanities & Social Science (Anthropology, Sociology, Psychology etc.); and Formal Science (Math, Logic, Computer Science etc.).

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; Dhaubanjar 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

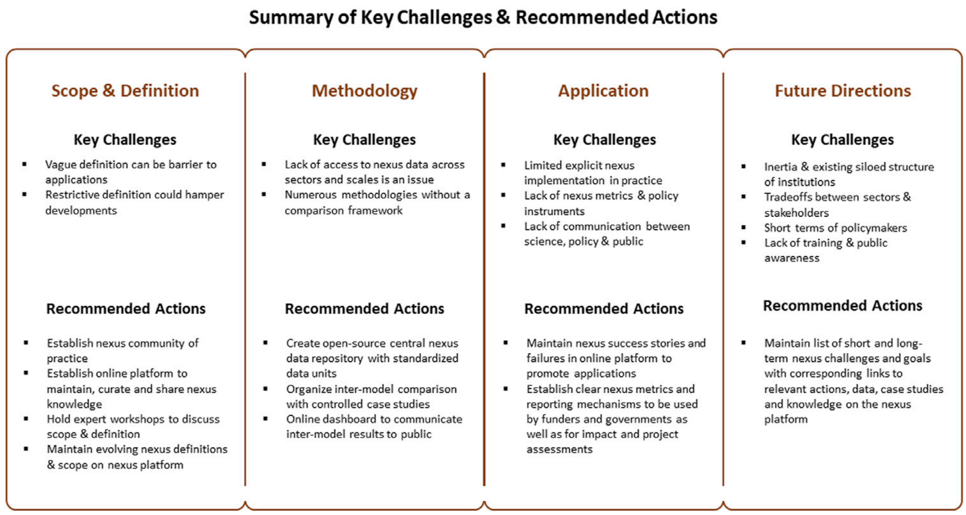

FIGURE 2 | Summary of key challenges and recommended actions based on responses from the surveys conducted for this paper.

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.

AUTHOR CONTRIBUTIONS

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

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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

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