A Comprehensive Review of the Nexus of Food, Energy, and Water Systems: What the Models Tell Us

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Abstract: The world faces mounting challenges related to food, energy, and water security. Modeling approaches have emerged in the last decade to address this problem with mixed outcomes across a range of boundaries, including local, regional, national, and by research agendas. This paper delves into a comprehensive meta-analysis of the literature to identify the prevalence and strengths of these emergent approaches on the agendas they were applied to, the boundary levels, nexus dimensions, and the perspectives of the social and political dynamics. The research highlights the critical gaps that remain in the intersection of the different nexus agendas. A crucial observation was the scarcity of food, energy, and water models that incorporate technology adoption and economic implementation of nexus projects. On the core dimensions of the nexus, there is an important opportunity to include ecosystems, soil health, human health, and waste as key nexus dimensions. Although it is difficult to include social and political dynamics in nexus studies, this research identified proxies including (1) stakeholder interactions; (2) the intersection of access, security, and education; and (3) trade patterns and measures of prosperity. **DOI: 10.1061/(ASCE)WR.1943-5452.0001564.**

Introduction

We live in an interconnected world where human and environmental systems are intrinsically linked. The physical systems influencing and impacted by human activities are food, energy, and water (FEW), and these systems are fused into a nexus concept. The concept emerged to address the interrelated challenges confronting these systems in the age of climate change, unprecedented ecological degradation, and impacts of population growth. These systems are intrinsically interrelated, with strong synergies and trade-offs in resource consumption leading to challenging environmental and socioeconomic consequences (Kurian et al. 2019; Xu et al. 2019; Mabhaudhi et al. 2018). The year 2011 set the global stage for nexus research and prioritization of a range of challenges, such as productivity improvement, economic development, enhanced governance, poverty alleviation, and green growth (Hoff 2011).

Untangling the nexus challenges is paramount for the future success of sustainability and climate change efforts to avert environmental degradation and promote human flourishing. The nexus crosses multiple spatial and temporal boundaries, from the household to the planet, from one-seasonal impact to decades-long changes. This multidimensional nature brings to the forefront the question of setting and implementing FEW-related projects. From the highest level, countries determine national goals. However, accomplishing these goals requires local and regional implementations. This downscaling of national goals to local and regional projects can be a point of conflict. Mismanaging and stressing the interconnected systems of food, energy, and water further exacerbates socioeconomic inequality (Givens et al. 2018; Pittock et al. 2016; Mirzabaev et al. 2015; Romero-Lankao and Gnatz 2019; Grindle et al. 2015).

The ideal example of the tension may be seen with hydropower impact considerations, in which energy decisions have substantial impacts on ecosystems, agriculture, economic development, and migratory fish populations (Smajgl and Ward 2013; Basheer and Elagib 2018; Pittock et al. 2016; Momblanch et al. 2019; Amjath-Babu et al. 2019). These complexities have driven studies to explore appropriate modeling techniques, highlight trade-offs and synergies, and identify important problems to tackle.

This paper's methodology focused on searching academic databases for "food-energy-water nexus" configurations, for a narrowed selection of 314 studies. To achieve a better understanding of nexus literature, the selected studies were evaluated by agenda, modeling approach, boundary levels, nexus dimensions, data sources, and geographic distribution. The research questions for this review included the following:

- What agendas and boundary levels are currently pursed in the nexus literature, and what gaps persist?
- How are different methodologies applied and to what end?
- Which alternative nexus dimensions should be promoted?
- How can social and political dynamics be better incorporated into models?
- What is the geographic distribution of nexus studies?

We found that implementation is still a persisting challenge, but that opportunities to enhance efforts are rising in awareness and guidelines. Nonetheless, additional research needs to integrate financial and sociopolitical concerns into plans and designs. We identified complementary modeling techniques by agenda and boundary levels, and opportunities for multimodel approaches. For nexus dimensions, the significant nontraditional dimensions were ecosystems, soil, health, and waste. Although these are found in the literature, they are often tangential, and therefore require a modeling reorientation of emphasis. On the social and political

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dynamics, we identified proxies that could bridge the modeling perspectives to address these challenging aspects, including stakeholder interactions, access, security and education, trade patterns, and measures of prosperity.

The contribution of this paper to the literature is fourfold. First, it provides a comprehensive and current overview of agendas throughout the nexus. This offers guidance on agendas that are underrepresented and highlights the directions that have been covered, including a geographic distribution of agendas. Second, the methodology used for each agenda and boundary level was mapped, aiding scholars and decision makers to identify which models and boundary levels to consider for their research goals with confidence in the benefits of their choice. Third, an analysis of alternative nexus dimension shed light on the prevalence and models that are applied for each dimension. Fourth, it made an identification of the proxies to assist researchers in identifying ways to include social and political dynamic dimensions.

The paper begins with a concise introduction to the background of the nexus literature aimed to uncover existing gaps. This is followed by the research design and the categories that became apparent in the analysis. The inductive-deductive approach elicited findings with commentaries on the summaries of the extant literature, research gaps, and the potentials for future work in the conclusion. Fig. S1 shows a content layout of the comprehensive review.

Background

The extant literature has examined the nexus with emphasis on agenda frameworks appropriate for nexus work (Endo et al. 2015). Prior work on the water-energy (EW) nexus categorized existing research into technological, environmental, economic, political, and social agendas (Hamiche et al. 2016). A different approach grouped studies according to their nexus indicators such as flux, efficiency, and environmental impacts (Arthur et al. 2019). Other examples include the emerging research agenda of environmental livelihood security that analyzed the nexus to understand potential linkages and limitations to livelihood perspectives (Biggs et al. 2015), as well as climate change (Bazilian et al. 2011; Hellegers et al. 2008; Pittock et al. 2013; Khan and Hanjra 2009; Ravindranath et al. 2011), sustainable development (Gregory et al. 2005; Zhang et al. 2018b; DeNicola et al. 2015; Duić et al. 2013; Rasul 2016; D'Odorico et al. 2018), urbanization (Guan et al. 2020; Shah et al. 2021; Raub et al. 2021; Arthur et al. 2019), sector linkages (Mahjabin et al. 2020; Kondash et al. 2021; Opejin et al. 2020), governance, scale, and implementation (Bach et al. 2012; Campbell 2008; Ringler et al. 2013; Jones and White 2021; Huntington et al. 2021; Opejin et al. 2020), and power dynamics (Bréthaut et al. 2019; Dombrowsky and Hensengerth 2018; Covarrubias et al. 2019; Givens et al. 2018).

However, modeling and incorporating politics and social dynamics in nexus research is not common, and additional work is needed in this domain (Albrecht et al. 2018). Two recent interesting research directions are to explore the impacts of the COVID-19 pandemic on resource insecurity (Calder et al. 2021), as well as evaluating the role of psychology to better understand the impact of human behavior on the nexus activities (Dreyer et al. 2020). The main criticism amounts to which complex subsystem to include, the trade-off boundaries, lack of geopolitical influences (Guillaume et al. 2015; Leese and Meisch 2015; Allouche et al. 2015), and questions of novelty specification (Benson et al. 2015; Wichelns 2017; Cairns and Krzywoszynska 2016). Leading efforts are to include ecological, social, and political dimensions in additional studies (De Grenade et al. 2016; Allouche et al. 2015; Wichelns 2017; Caputo et al. 2021; Itayi et al. 2021; Niet et al. 2021).

Reviews of nexus tools have been conducted, elaborating the applications of existing tools and frameworks (Mohtar and Lawford 2016; Kaddoura and El Khatib 2017; Albrecht et al. 2018; Dai et al. 2018). We learned from Albrecht et al. (2018) that specific and reproducible approaches are scarce and are unable to capture the interactions they pursue. Yet, although there is a dominance of quantitative approaches, social science perspectives are limited, and the methods exist in silos. These combine to demand for mixed-methods approaches. The view of natural sciences' dominance over social perspectives is shared by Wiegleb and Bruns' (2018) request that both are equally engaged to overcome the perceptions that social science is less legitimate than natural sciences, economics, and engineering. Further, because multiple boundary analysis frames are found in the literature, mixed boundaries raise the question of which modeling techniques can be applied appropriately.

Review Methodology

The comprehensive meta-analysis method adopted is consistent with the methods in standard literature review papers. The overview of this meta-analysis methodology is provided in Fig. 1, which

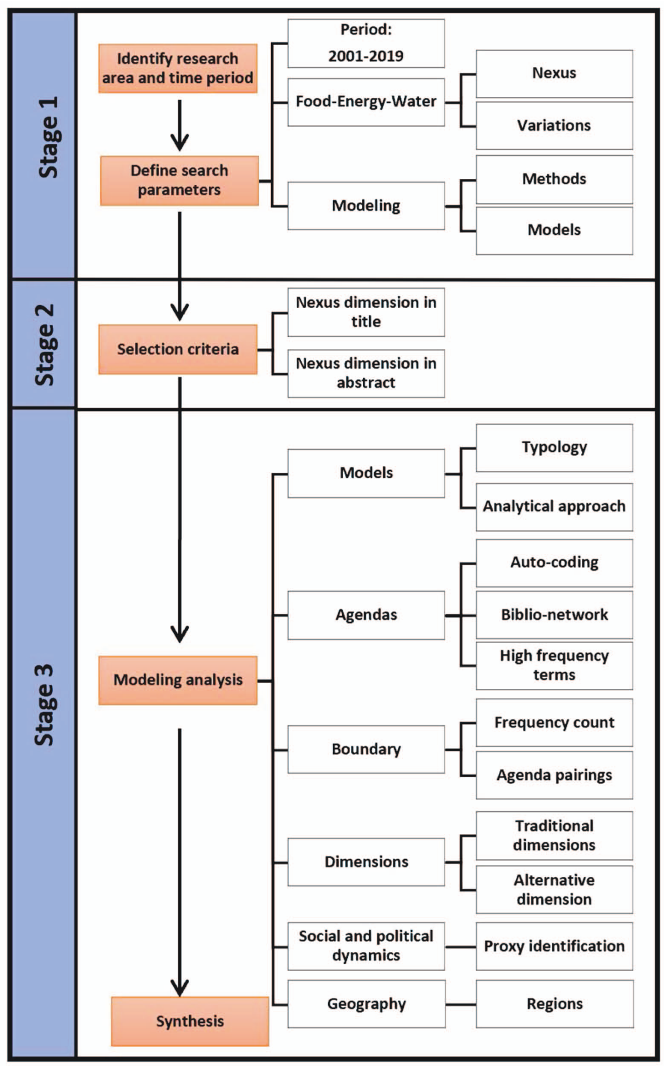

Fig. 1. (Color) Methodology.

highlights the process in three phases: defining the search criteria, the selection process, and, lastly, the analysis. First, the aggregation of research publications was initiated by searching for "food-energy-water nexus modeling" as search words and their combinations in peer-reviewed academic journals on two indexes: Web of Science and Google Scholar. Both titles and abstracts were reviewed for presence of a nexus dimension. Other combinations included different ordering of "food energy water," "models," and "modeling of." Second, the selection phase resulted in 314 studies between 2002 and 2019, and a diverse range of traditional (FEW) and alternative dimensions. Following the selection criteria, exclusions were based on single-dimension articles; that is, articles pertaining only to either water or food or energy were excluded.

In the third phase, article analysis, nine parameters were examined: (1) modeling approach, i.e., the type of model implemented, (2) data source in the models, (3) key nexus dimensions, (4) the contribution of the study, (5) agenda of the topic, (6) approach, i.e., empirical, theoretical, or semitheoretical, (7) analysis level, i.e., farmer/household, city, basin, or country, (8) frame of analysis, i.e., local, regional, national, global, and specific multilevel, and (9) geographical distribution of the study. Table 1 summarizes the modeling, nexus dimensions, focus, and agendas.

To examine the nexus agendas, three qualitative steps were taken: autocoding (NVIVO version 12) (QSR 2018), linkage analysis (VOSViewer version 1.6.18), and word frequency (NVIVO). Synthesizing the autocoded themes, linkages and high-frequency terms resulted in nine research agendas: (1) economic decisions and environmental livelihood security with respect to FEW security and the behavior of local and regional nexus stakeholders, (2) governance, particularly on the impacts of policies on resource use, (3) infrastructure and supply chains, with specific attention to consumption, critical infrastructure improvements, and resource trade-offs, (4) sustainable development, with emphasis on climate change, sustainable development goals, and growth, (5) urbanization pertaining to sustainable cities, (6) technology adaptation evaluating the impacts of technologies in industries, (7) implementation process of nexus projects, (8) model utilization for specific problems, and (9) nexus definitions. Visualizations of the thematic clusters from the linkage analysis and word frequency cloud are given Figs. S2 and S3.

The modeling typology was determined by the count of studies applying a specific approach with a minimum of eight to be included as a standalone category. In total, eight modeling approaches were identified: agent-based modeling (ABM), which simulates decisions and interactions of agents; complex adaptive systems (CAS) for dynamic networks of interacting subsystems; system dynamics (SD) for stock-and-flow models and causal loop analyses; material flow analysis (MFA), which quantifies stocks and flows of biological and physical systems, e.g., life cycle

Table 1. Overview of key article items

Key item	Framework	References
Modeling	1. The contributions of the modeling approaches are summarized in Table 3. 2. An overview of agenda/boundaries is presented in Table 4. 3. Aside from standalone approaches, a variety of complementary multimodel approaches are observed: • OPT + ABM/SD • ABM + CAS/SD/OPT • SD + MFA • REG + ABM/GIS 4. Data sources are varied in the literature, with dominance of government data, literature review, and international organizations, in addition to less-often utilization of research center output, surveys, interviews, and utility authority data	Tian et al. (2018), Martinez-Hernandez et al. (2017), de Fraiture (2007), Mulligan et al. (2014), Wang et al. (2019b), Kurian (2017), and Bieber et al. (2018)
Nexus dimensions	1. In addition to the main nexus dimensions of food, energy, and water, more attention is given to climate, economics, ecosystems, and land. 2. Special emphasis on ecosystems, health, soil, and waste will enhance nexus studies.	Venghaus and Hake (2018), Maass (2017), Hatfield et al. (2017), Roidt and Avellán (2019), Islas-Espinoza and de las Heras (2015), Karabulut et al. (2018), Miller-Robbie et al. (2017), and Sahle et al. (2019)
Focus	1. Infrastructure expansion and efficiency are prevalent topics. 2. River basin dynamics focus on synergies and trade-offs around water and energy planning with agriculture production. 3. Sustainable agriculture explores improved cultivation, biofuels, and efficiency upgrades. 4. Analysis of urban networks and urbanization impacts is an increasing topic of interest in the literature. 5. Economic decisions continue to dominate.	Gandiglio et al. (2017), Jalilov et al. (2016), Allam and Eltahir (2019), Vlotman and Ballard (2014), Salmoral and Yan (2018), Heard et al. (2017), Foran (2013), Hermann et al. (2012), Hanes et al. (2018), Wang et al. (2018), and Liang et al. (2018)
Agendas	1. Prevalent agendas: • Governance and policy evaluation • Infrastructure and supply chains 2. Agendas with increasing research attention: • Urbanization • Sustainable development 3. Agendas with relatively low research attention: • Implementation • Technology adoption	Weitz et al. (2017b), Bieber et al. (2018), Yung et al. (2019), de Amorim et al. (2018), Haltas et al. (2017), Bijl et al. (2018), Leck et al. (2015), Basheer et al. (2018), Bizikova et al. (2013), Hoff et al. (2019), Al-Saidi and Lahham (2019), Davies and Garrett (2018), and Rasul (2016)

analysis and social accounting matrices (SAM); and governance (GOV), a semiquantitative collection of methods for policy making and decisions in resource management including integrative environmental management (Visseren-Hamakers 2015; Galaz et al. 2012; Weitz et al. 2017b; Märker et al. 2018), comparative policy analysis between agencies or nations (Sharmina et al. 2016; Villamayor-Tomas et al. 2015; Stein et al. 2018), and political economy in nature (Matthews and Motta 2015). The last three approaches are optimization (OPT), regression (REG), and a variety of analytical approaches (AA) that groups all infrequent methodological instances such as geographical information systems (GIS) (Gondhalekar and Ramsauer 2017; Wang et al. 2019b), Delphi method for expert judgment (Smajgl et al. 2016; Smajgl and Ward 2013), index systems (Schlör et al. 2018; Hake et al. 2016; Wang et al. 2018), and other quantitative tools (Neto et al. 2018; Huckleberry and Potts 2019).

Results

This section presents the results categorized in our contributions, including agenda distribution, boundary analysis, alternative nexus dimensions, proxies for social and power dynamics, geographic distribution of nexus studies, and modeling pathways for improved decision making.

Nexus Agendas

Nexus agendas are not distributed equally throughout the literature, visualized in Fig. 2. The largest share of agendas is governance and policy evaluation, with 93 studies (29%), followed by infrastructure and supply chains with 60 studies (19%). The middle range of studies cover economic decisions and environmental livelihood security [41 (13%)], sustainable development [36 (12%)], and urbanization [31 (10%)]. The lowest frequency of agendas were model applications [18 (6%)], implementation [15 (5%)], technology adoption [10 (3%)], and nexus definitions [10 (3%)]. Fig. S4 presents a visualization of the agenda distribution. Further observed in Fig. 2 is the rising attention given to environmental security, sustainable development, and urbanization in recent years. A list of example agenda publications is given in Table S1.

The gap in the literature is the minimal attention given to technology adoption and implementation studies. The technology adoption studies provided meaningful guidelines on approaches to adopt nexus technologies or policies. First, clear institutionalized government and business sector support is needed to address knowledge, training, technical capacity, and stakeholder interest (Al-Saidi and Lahham 2019; Davies and Garrett 2018). Second, long-term consideration of life cycle analysis and economic implementation strategies are needed for successful adoption practices (Picart-Palmade et al. 2019; Cai et al. 2018). Third, the success of adoption is related to local technology and ecosystem considerations of impacted shared-governance stakeholders (Martinez-Hernandez et al. 2017; Halbe et al. 2015). These three guidelines influence the broad range of technologies explored, including distributed energy solutions, water and wastewater improvements, and urban agriculture technologies. This underrepresented agenda suggests additional work is necessary to test in the field and include in the widespread research components that complement governance-, implementation-, and material-resource-focused studies.

Two interrelated trends emerged from reviewing implementation studies, including governance structure and framing and collaboration. The former relates to appropriate governance structures and relationships with the private sector as essential for successful project implementation. This includes aligning institutional dynamics to promote cross-disciplinary collaboration and reduce administrative complexity when nexus links are quantified (Huckleberry and Potts 2019; Weitz et al. 2017a). An important topic often overlooked in the literature was project financing. Addressing cost recovery and uncertainty as part of nexus designs will further promote implementation processes, especially when the private sector and multiple stakeholders are included (Kurian 2017; Visseren-Hamakers 2015; Yung et al. 2019). The final perspective of governance structure centers on understanding political power dynamics. Political influence can be excreted by both private investors and political figures and processes (Dombrowsky and Hensengerth 2018; Weitz et al. 2017b). Thus, to reach the point of implementing nexus research, understanding the power dynamics can aid in mitigating financial and political pressures.

Power dynamics are related to framing and collaboration. Implementation-focused research has advocated for broad stakeholder collaboration on decision making and framing the problem from social, cultural, and local technoeconomic perspectives (Howarth and Monasterolo 2016; Hoff et al. 2019). The notions are straightforward: identify direct and indirect stakeholders to envision, invest, and transform nexus thinking and projects (Bizikova et al. 2013; Bielicki et al. 2019; Ringler et al. 2013). The challenge

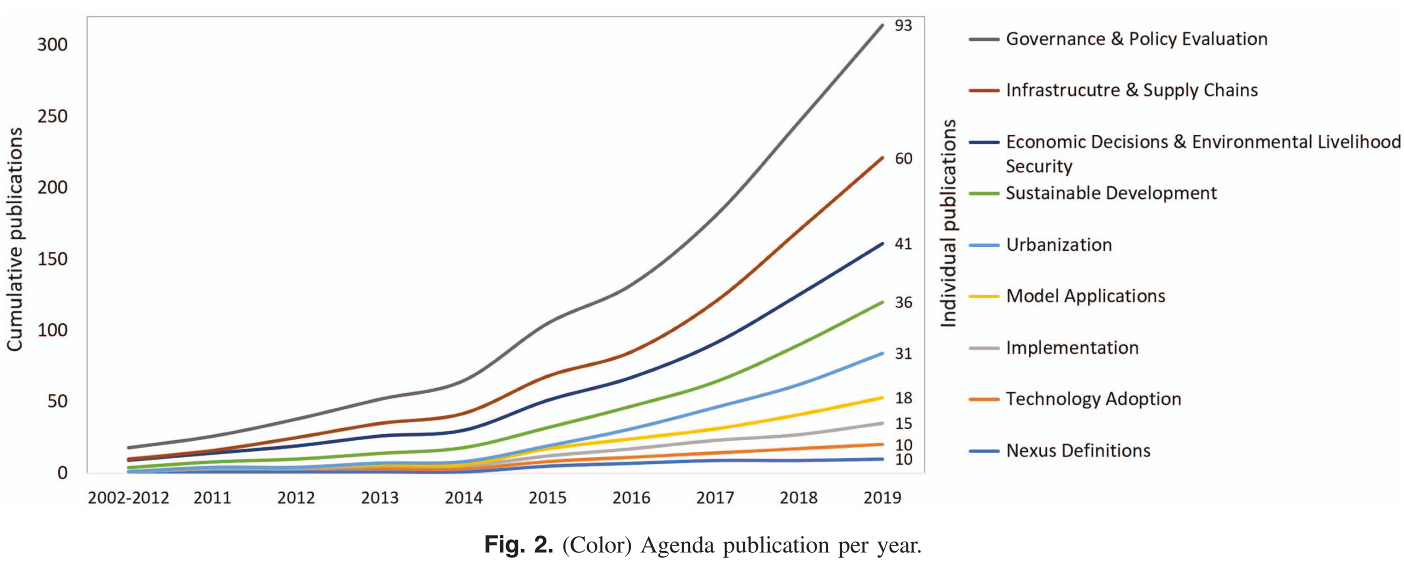

Fig. 2. (Color) Agenda publication per year.

with implementation studies is that they are predominantly qualitative, either focused on governance or conceptual. Implementation and technology adoption are interrelated, with technology adoption forming an internal part of broader implementation efforts. Given the vast disproportion of nexus studies that overlooked these concerns, in particular economic viability, cost recovery efforts, and power dynamics, we find that the implementation gap is significant.

> Deduction 1: The dominant agenda efforts were applied toward policy evaluations with attention to urbanization, sustainable development, and economic decision making. However, the main gap is studies aimed at understanding technology adoption and nexus implementation considerations, specifically financing, cost recovery, and public–private partnerships.

Modeling, Boundaries, and Data Framework

This section discusses the modeling approaches and how they were applied toward the study agendas. It also sheds light on boundary levels and their prevalent models, data availability and aggregation, how the different nexus scales are integrated, and uncertainty and sensitivity.

Modeling and Agendas

Fig. 3(a) shows the total distribution of approaches on top and a heat map with colors ranging from red (low frequency) to green (high frequency). This shows that over 60% of papers were quantitative, with MFA the most prevalent method, followed OPT, CAS, ABM, SD, and REG. However, the count for AA, the aggregate category of nonstandard approaches, supports previous claims on the plurality of nondistinct approaches. Governance, the semiquantitative approach of policy and management analysis, represents 10% of the literature.

Some modeling patterns were observed. First, MFA was used predominantly for infrastructure and supply chains, and for urbanization. Comprised of SAM and life cycle analysis, MFA offers valuable sector-based performance and their interdependencies. The emphasis on urbanization is through the impact of regional urban dynamics. The limitation of MFA, looking at feedback between sectors, can be mitigated via complementary model pairings. Second, optimization was applied toward governance and policy evaluations and infrastructure and supply chains under the lenses of uncertainty and risk impacts to resource allocation and economic benefit analyses. Table 2 indicates that the optimization studies included single-objective and multiobjective approaches, and these are grouped by type of objective function, form, decision variables, and constraints.

Single-objective problems aimed to either maximize economic benefit in the form of net present value and/or profit or minimize costs and use of resources. Both objectives were approached using linear, nonlinear, and mixed-integer programming, with the most common decision variables including land and water allocation, crop type, energy production, and technology expansions. The multiobject studies maximized economic benefits while minimizing environmental impacts such as CO_2 or greenhouse gas (GHG) emissions. The constraints across all optimization problems included groundwater and surface water supply and demand, energy supply and demand, production characteristics, food security requirements, and investment and economic limits.

Optimization approaches also offered the flexibility to complement other methods in multimodel approaches. For example, optimization coupled with ABM was used to model policy introductions of technology and regulation in a mixed integer linear programming (MILP) for resource allocation and technology investments (Bieber et al. 2018). With OPT and MFA, regional FEW priorities were evaluated through use of different biofuels (Yuan et al. 2018). Combining OPT and CAS, the impacts of hydropower projects on economic development, flood control, and irrigation were explored through an evaluation of 11 dam projects in the Himalayan River Basin, finding a need to compensate communities and reforest the region through the economic benefits of hydropower (Amjath-Babu et al. 2019). Utilizing OPT and SD, a water-food model explored the linkages of water scarcity, economics, and agricultural impacts of various food and water scenarios (de Fraiture 2007). Relying on CAS, OPT, and SD, Tian et al. (2018) evaluated ecosystem services, economics, and climate impacts to capture environmental degradation, economic costs, and excess resource use (Tian et al. 2018).

Lastly, although GOV methods accounted for 10%, they made up over half of implementation problems, and 17% of governance and policy evaluation problems. As indicated by previous research, a leading challenge in nexus studies is implementing and actualizing research findings.

Thus, complementing a governance approach with a quantitative method could yield results more readily transmutable to decision makers. The distributions of model applications for the various nexus problems strengthen the perspective that no single modeling approach is superior to another. Rather, scholars and decision makers can select the most appropriate approach and combinations for their problem. It is evident that the implementation and technology adoption studies could further benefit from quantitative studies. The contribution of each modeling approach is summarized in Table 3.

Modeling and Boundary Frameworks

Fig. 3(b) shows single-boundary analyses. A third of the studies were multilevel, with cities and river basins forming the majority of multilevel efforts. However, there are significant challenges to implementation, including cross-disciplinary collaboration, complexity, politics, and incompatibility of institutions, which require more precise quantification of nexus links and case studies–based recommendations (Beck and Walker 2013; Leck et al. 2015; Al-Saidi and Elagib 2017; Howarth and Monasterolo 2016; Lawford 2019). This partially explains why multilevel studies were predominantly qualitative, around 70%, as seen in the heat map.

With only a minor difference, regional studies were the most prevalent, followed by national and then local. Although the local level accounted for 19% of the studies, 80 studies (25%) covered the local boundary as part of multilevel frameworks. With 60 studies (19%) on regional levels, there were 118 (37%) that included the regional level in a multilevel framework. The fact that multiboundary research represented only 38% of the literature is a cause to pause and think of future work. The shift from centralized development and planning to decentralized sheds light on the importance of multiboundary thinking.

Table 4 offers a guide to observe prevalent agenda and modeling pairings and the boundary levels considered. These pairings point to the multimodel pairings that are beneficial to each agenda. Additional reference examples of different modeling applications are given in Table S2. A MFA study could be the preliminary phase of the project to identify synergies and trade-offs; then, an optimization model could be built to determine optimal resource use for technology investments, and an ABM model could simulate agent behavior concerning the adoption choices. Similarly, a willingness-to-pay study could help with accurate representation of agent decision making by fine-tuning model parameters and constraints. Creative thinking will lead the next phase of nexus cross-disciplinary

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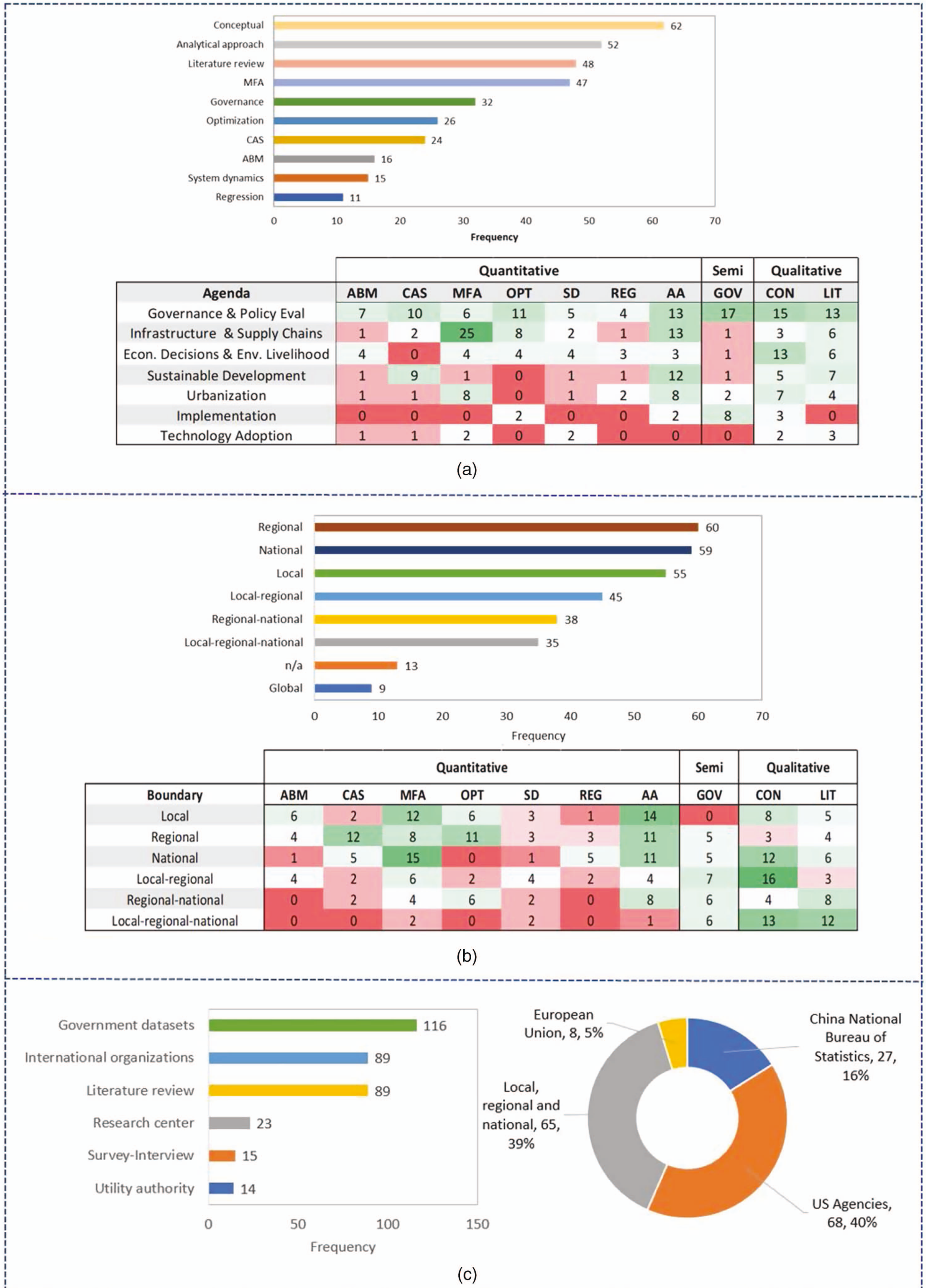


	Quantitative							Semi	Qualitative	
Agenda	**ABM**	**CAS**	**MFA**	**OPT**	**SD**	**REG**	**AA**	**GOV**	**CON**	**LIT**
Governance & Policy Eval	7	10	6	11	5	4	13	17	15	13
Infrastructure & Supply Chains	1	2	25	8	2	1	13	1	3	6
Econ. Decisions & Env. Livelihood	4	0	4	4	4	3	3	1	13	6
Sustainable Development	1	9	1	0	1	1	12	1	5	7
Urbanization	1	1	8	0	1	2	8	2	7	4
Implementation	0	0	0	2	0	0	2	8	3	0
Technology Adoption	1	1	2	0	2	0	0	0	2	3

	Quantitative							Semi	Qualitative	
Boundary	**ABM**	**CAS**	**MFA**	**OPT**	**SD**	**REG**	**AA**	**GOV**	**CON**	**LIT**
Local	6	2	12	6	3	1	14	0	8	5
Regional	4	12	8	11	3	3	11	5	3	4
National	1	5	15	0	1	5	11	5	12	6
Local-regional	4	2	6	2	4	2	4	7	16	3
Regional-national	0	2	4	6	2	0	8	6	4	8
Local-regional-national	0	0	2	0	2	0	1	6	13	12

Fig. 3. (Color) Models, boundaries, and data: (a) count of papers by the approach and model type with agenda-model heat map; (b) count of papers by boundary analyses with boundary-model heat map; and (c) count of papers by data sources and agencies.

Table 2. Overview of optimization studies

Objective	Optimization goal	Examples	Form	Decision variables	Constraints	References
Single objective	Maximize economic benefit	Net present value, profit	LP, NLP, MILP, MINLP	Land allocation, crop type, water allocation, energy production, resource expansion	Water supply and demand, energy supply and demand, food security, crop production	de Amorim et al. (2018), Saif and Almansoori (2017), Amjath-Babu et al. (2019), Jalilov et al. (2018), Suthar et al. (2019), Allam and El-tahir (2019), Jalilov et al. (2016), Sun et al. (2019), and Avraamidou et al. (2018)
		Multiagent benefit (profit)		Water allocation	Water supply and demand, agent interactions	Yang et al. (2011, 2009)
	Maximize environmental benefit	Environmental impact reduction (spatial optimization)	LP	Land and crop allocation	Land availability, water consumption, food demand and supply	Yuan et al. (2018)
	Minimize total cost	System and energy cost; Discounting	LP, NLP, MILP	Land and water allocation, technology investment, energy production	Water supply and demand, energy supply and demand, production consumption, investment balance	Karan et al. (2018), Martín and Grossmann (2015), Bieber et al. (2018), Zhang et al. (2018b), and Dubreuil et al. (2013)
	Minimize resource gap	Crop yield gap				Tian et al. (2018)
	Maximize economic benefit, food, and energy production	Maximize net present value, crop yields, and energy generation; maximize profit and crop yield	LP, MILP, MINLP	Land and crop allocation; energy alternatives; crop allocation; livestock allocation	Food/energy output sustainability limits; economic constraints; energy/water supply and demand	Hanes et al. (2018), Zhang et al. (2018a), and Nie et al. (2018)
Multiobjective	Minimize environmental impact	Minimize water and energy use, environmental impact	—	—	—	—
	Maximize economic benefit; minimize environmental impact	Maximize profit; minimize negative environmental impacts and CO_2 emissions	LP, NLP	Irrigation area, water allocation, land allocation, energy production	Water supply and demand, energy supply and demand, economic constraints, food security, resource allocation policy	Li et al. (2019a, b)

Note: LP = linear programming; NLP = nonlinear programming; MILP = mixed integer linear programming; and MINLP = mixed integer nonlinear programming.

Table 3. Summary of modeling contributions

Modeling	Contributions	References
Agent-based modeling (ABM)	Economic decisions on local and regional levels focus on impact of information sharing and coordination, as well as irrigation decisions and economic adaptation plans. Agent interactions enable the evaluation of payment of ecosystem services, ecological preservation, hydropower trade-offs, and governance responses to climate change. Watershed management focuses on water trading, groundwater policy and systemwide benefits.	Chen et al. (2012), Giuliani and Castelletti (2013), Bitterman (2017), Pope and Gimblett (2015), Foran (2015), Berger and Troost (2014), Berger and Ringler (2002), Bieber et al. (2018), Yang et al. (2011), Mulligan et al. (2014), Yang et al. (2009), and Gai and Shittu (2021)
Complex adaptive systems (CAS)	Watershed management evaluates water provision, ecosystem services, climate change impacts, hydropower planning. Energy and biofuels considerations consider agriculture and land-use decisions, GHG emissions, and carbon trading.	Karabulut et al. (2016), Nelson et al. (2009), Yang et al. (2016), Momblanch et al. (2019), Amjath-Babu et al. (2019), Hermann et al. (2011), Karlberg et al. (2015), Welsch et al. (2014), and Weirich (2013)
System dynamics (SD)	Household/firm level models focus on security of energy, food choices, water and wastewater systems. Socioeconomics, e.g., poverty alleviation, are increasingly modeled in both causal loop and stock-and-flow models. The focus in infrastructure models is resource expansions and investments in energy and water systems.	Wa'el et al. (2017, 2018), Scott et al. (2011), Dong et al. (2019), Givens et al. (2018), Kulat et al. (2019), and Wicaksono and Kang (2019)
Material flow analysis (MFA)	MFA is predominantly used for evaluating embodied resources in regional networks, e.g., infrastructure improvements in demand-side strategies for resource reduction and improved water management. A promising field of exploration is the opportunity for energy and nutrient extraction from wastewater.	Liu et al. (2017), Fang and Chen (2017), White et al. (2018), Wang and Chen (2016), Chen and Chen (2016), Wang et al. (2017, 2019a), Owen et al. (2018), Okadera et al. (2015), Walker et al. (2014), Valek et al. (2017), Liang et al. (2018), and Feng et al. (2019a, b)
Governance (GOV)	Highlights the importance of incorporating and mitigating uncertainty, addressing stakeholder coordination, providing guidelines for private sector inclusion, and economic solutions with cost recovery.	Yung et al. (2019), Dombrowsky and Hensengerth (2018), Weitz et al. (2017a, b), Hoff et al. (2019), Visseren-Hamakers (2015), Kurian (2017), Gain et al. (2015), and Bizikova et al. (2013)
Optimization (OPT)	Focuses on optimal decisions under different policies for land and resource allocation, irrigation economics under drought scenarios, crop choices, energy and GHG emissions. Infrastructure expansion projects evaluate changes to energy, water and food systems, capacity expansions, and reaching optimal economic benefits. Table 2 describes objectives, goals, form, decision variables, and constraints.	Li et al. (2019a, b), Sun et al. (2019), Zhang et al. (2018a), Hanes et al. (2018), Jalilov et al. (2016), Allam and Eltahir (2019), Dubreuil et al. (2013), Saif and Almansoori (2017), Zhang and Vesselinov (2017), Jalilov et al. (2018), Dhaubanjar et al. (2017), Martín and Grossmann (2015), and DeLuque and Shittu (2019)
Analytical approach (AA)	Focuses on the synergies and trade-offs between sustainable development goals and the FEW nexus. Uses specialized indices for prosperity mapping and geographic inequality. Education is key in behavioral and cultural change of nexus understanding. Trading schemes and investments influence nexus decisions. Improved resource management requires a holistic approach.	Saladini et al. (2018), Mahlknecht and González-Bravo (2018), Fader et al. (2018), Hake et al. (2016), Schlör et al. (2018), Terrapon-Pfaff et al. (2018), Hamiche et al. (2016), Kraftl et al. (2019), Le Noë (2019), Smajgl et al. (2016), Grindle et al. (2015), Bijl et al. (2018), Martins (2018), and Doggart and Meshack (2017)
Regression (REG)	Evaluates ecosystems and resource use through the willingness-to-pay for services, and analyzes scenarios using indicators of water quality and annual payment. Explores the health impacts of FEW related non-point-source pollution, and dietary habits. Assesses the correlation of FEW security and political stability.	Gurdak et al. (2017), Song et al. (2019), Khan and Zhao (2019), Ozturk (2015), Caixeta (2019), Hannibal and Portney (2019), and Abbott et al. (2017)

modeling because no single modeling approach satisfies all situations. Additional questions persist when determining which problem to focus on and how to model and address it, including data availability and effect of scale.

Data Availability and Aggregation

The modeling approach also depends on data availability, either from primary or secondary sources. The source and availability of data vary, depending on project and region. To better understand the data profile of the models used, six data categories were determined after reviewing the data sections of the modeling studies, including government data sets, international organizations, literature reviews, research centers, utility authorities, and surveys-interviews. The data analysis focused on the seven quantitative modeling approaches excluding the literature review, and conceptual and governance studies. Although some governance studies were quantitative, they had existing sources and did not require extensive data inputs. In total, 175 studies had their data sources analyzed as presented in Fig. 3(c).

The largest sources of data are government databases. Fewer than 40% of quantitative studies relied on the data tracked and updated by local, regional, and national governments, in the form of SAM and consumption tables. A similar count of studies was dependent on the US federal agencies, mainly the USEPA, Department of

J. Water Resour. Plann. Manage., 2022, 148(6): 04022031

Table 4. Literature on agenda-model-boundary combinations

Agenda	Examples	Prevalent models	Main boundaries
Economic decisions and environmental livelihood security	Farmer adaptation plans, household decisions, and resource security	MFA/SD, ABM/OPT	Regional and local–regional
Governance and policy evaluation	Resource management, policy impacts, and transboundary relations	GOV, OPT CAS	Regional and regional–national
Infrastructure and supply chains	Infrastructure improvements, and synergies and trade-offs	MFA, OPT	Regional and national
Sustainable development	Climate change impacts, sustainable development goals, agriculture practices	CAS, GOV	National and regional
Urbanization	Sustainable cities, urban networks	MFA/ABM,CAS/SD/REG/GOV	Local and local–regional
Technology adoption	Technology introduction, adoption scenarios	ABM/SD, MFA	Local and local–regional
Implementation	Implementation process	GOV, OPT	Local–regional and regional

Agriculture, and Energy Information Administration. The China National Bureau of Statistics also tracks environmental, energy, economic, and emissions-related statistics.

Integrating Different Nexus Scales

The challenge with data is to determine if it is used appropriately and how to integrate multiscale nexus systems. The biggest difference in scaling effects is between climate projections and resource consumption. On regional and national levels, climate data rely on downscaling general circulation models (GCMs) to their respective regional climate models (RCMs), as well as specific climate simulation based on historic climate observations in various integrated assessment models.

These are sensitive to stochastic parameters implying a range of uncertainties when downscaling models. Resource consumption and input–output (SAM) tables, however, were not often simulated, but aggregated as total consumption and outcome, such as energy (kWh), amounts of water, tons of food, and others. Here, downscaling may overestimate or underestimate the resource use of localities. For example, taking the average household use of nexus resources from a river basin and applying it to a town without pursing additional efforts, such as analyzing utility data for energy, water, and waste collection, could provide skewed results if models were simulated with the average data.

The higher the boundary level, the greater the degree of data aggregation required, especially when using CAS, MFA, and SD models. In local–regional studies, although government data sets and literature reviews were common, there was a greater reliance on surveys, workshops, and water and energy utilities than in other multilevel studies. However, for the regional–national boundary levels, there was greater emphasis on international organizations, government data sets, and research centers. These differences allude to more accessible data on regional and national levels than on local. To capture the perspective of local boundaries, additional effort is needed to collect data. Such data collection methods were not common in the nexus, suggesting that important perspectives and dynamics such as social, cultural, and political dimensions may be sidelined.

Addressing Uncertainties

Considering the impact of scaling and the type of resolution needed for each modeling type is key to aggregating the most appropriate data. However, uncertainty and sensitivity have an important role in nexus studies. This is especially relevant to climate models with parameter distributions. Thus, scholars may incorporate these perspectives either by including a parameter distribution and probability function in the simulation, or by evaluating scenarios with different parameter values. For sensitivity, it is recommended that scholars test percent changes to key parameters and evaluate the outcome accordingly. Addressing uncertainty will translate to robust results with significant confidence in the solutions, whether on resource or financial metrics (Kamdem and Shittu 2017; DeLuque and Shittu 2019). Specifically, for studies using GCMs and RCMs for their climate components, the recommendation is to evaluate several scenarios associated with different climate projections.

> Deduction 2: The prevalent approaches across all multiboundary studies have been MFA, SD, and GOV. However, most multiboundary studies were qualitative. Future quantitative studies should aim at the use of interdependent multimodel approaches, in which the output of one model serves as the input for another, for cross-disciplinary research. Lastly, additional attention to parameter and scenario uncertainty should be incorporated in future studies.

Other Dimensions of the Nexus

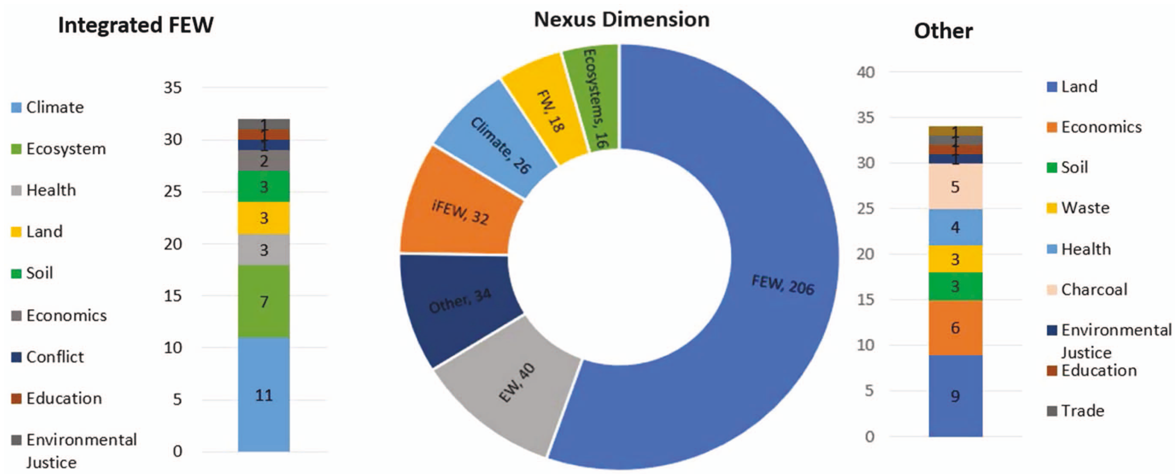
Analyzing the nexus dimension distribution provides a litmus test for research directions. The majority of studies reviewed were FEW focused, with 206 studies (64%). The integrated FEW (iFEW) nexus, corresponding to studies that identified additional dimensions alongside FEW, had 32 studies (10%). In total, 74% of the studies reviewed relied on the FEW nexus as core. Of the iFEW research studies, the two most common nexus additions were climate (12) and ecosystems (7). Broadly speaking, climate refers to mitigating GHG emissions as a core principle (Weirich 2013; Hermann et al. 2012; Howells et al. 2013), and *ecosystems* refers to enhancing and protecting ecosystem services (De Grenade et al. 2016; Hanes et al. 2018).

Aside from FEW, a range of additional subsystems have been explored and identified as core nexus, grouped under "Other" category: economics, land, charcoal, health, soil, waste, environmental justice, conflict, education, and urbanization. The dimensions and modeling distribution are shown in Fig. 4. Of the alternative dimensions, ecosystems, soil, health, and waste are lacking attention as core dimensions, representing only a small fraction of literature despite the many articles that consider the impacts on these subsystems. Expanding nexus research into these dimensions will enhance a holistic bottom-up approach that is human and ecological focused to balance the top-down technological- and economics-dominant approaches.

Ecosystems

Thriving ecosystems are the foundation for industries and sociopolitical processes. Understanding the impact of resource consumption

J. Water Resour. Plann. Manage., 2022, 148(6): 04022031



	Quantitative							Semi	Qualitative	
Dimension	ABM	CAS	MFA	OPT	SD	REG	AA	GOV	CON	LIT
FEW	6	10	23	19	12	7	35	27	49	30
iFEW	0	8	4	2	0	1	6	3	7	2
Climate	1	7	5	1	0	0	3	2	3	5
Ecosystems	2	4	1	1	1	1	2	0	1	2
F-W	5	2	1	2	1	1	2	0	1	6
E-W	3	4	17	3	1	1	5	1	2	6
Other	2	2	6	1	1	2	7	2	7	4

Fig. 4. (Color) Dimension and modeling distribution.

and technological development is paramount to mitigate ecosystem degradation, protect biodiversity, and ensure socioecological services (Karan et al. 2018; Tscharntke et al. 2012; Colloff et al. 2019; Dong et al. 2019). The dominant force of tapping into ecosystem services and resources is economics. Yet, the notion is to advance past nexus economic security, i.e., the availability of resources, and embrace the adaptive capacity instead (Ericksen et al. 2009; De Grenade et al. 2016). This capacity relates to the human behavior, leadership, and ability to adapt to nexus changes through learning and fair governance (Zhang et al. 2021). The inclusion of ecosystems as a main dimension will pave the way for a deeper understanding of resource-use impacts (Karabulut et al. 2016; Maass 2017; Sahle et al. 2019; Hanes et al. 2018).

A growing body of research is targeting valuation of ecosystem services. By exploring the economic value of these services, such as the natural filtration of water, pollination services, and fertile soil for increased productivity, it becomes possible to capture potential financial mechanisms to protect ecosystems in the form of cost-saving practices and payment for ecosystem services (Nelson et al. 2009; Chen et al. 2012; Mishra et al. 2019; Khan and Zhao 2019). By incorporating ecosystems perspectives into planning and life cycle analysis, a better resolution of policies is achieved.

Soil Function and Fertility

Soil degradation and erosion are major threats to nexus synergies, reduce productivity, increase reliance on fertilizers, and increase pollution (Hatfield et al. 2017; Campbell 2008; Kulmatov et al. 2018). The issue is that technological interventions are not always the solution, and a tipping point may be reached when they cease helping soil health. The challenge is that the role of soil is overlooked in favor of profitability and productivity. Complementary to technological interventions are functional land- and soil-management techniques that favor holistic soil approaches. Studies related to soil have relied more on specialized analytical tools for quantitative measurements, but most studies were conceptual, shedding light on the need for greater quantitative exploration of soil as a nexus component (Campbell 2008; Schulte et al. 2015; Hatfield et al. 2017; Roidt and Avellán 2019; Saladini et al. 2018; Kattel 2019; Ozturk 2015).

Health

Health-focused studies also had a broad approach, using regression, MFA, and analytical tools, with an equal amount of conceptual and literature review papers. MFA was the dominant approach for waste-related studies, given its advantages in capturing input-output relationships. It is arguable that nexus technologies are responsible for a large share of xenobiotic emissions, a group of synthetic materials that are foreign to ecosystems and the human body (Islas-Espinoza and de las Heras 2015). These emissions are driven by the intense use of pesticides and fossil fuels, causing respiratory, neurological, cancer, and endocrine-related damages. Yet, xenobiotic emissions are not the only threat because point-source and non-point-source pollution of many chemicals remain a significant obstacle (Gurdak et al. 2017), including agriculture waste such as nitrogen and phosphorous runoffs. On the social and cultural level, diets and urban food systems are a growing field of health-related nexus studies. These include the impact of urbanization, urban agriculture, and alternative diets (Song et al. 2019; Miller-Robbie et al. 2017; Gragg et al. 2018). The question of what people ought to eat, and whether such regulations should be made is a fierce political issue.

Waste

The literature focused significantly on wastewater. The opportunities in wastewater systems included reduction of primary resource consumption, nutrients recovery, and energy supply economic benefits (Gandiglio et al. 2017; Feng et al. 2019b; Kajenthira et al. 2012; Walker et al. 2014; Liang et al. 2018; Kulat et al. 2019; Kurian et al. 2019). Current focus points for upgrading wastewater systems included improved water and energy efficiency in treatment plants and nutrient recovery for reuse, as well as capturing methane for energy from the greater sewage system. Additional waste perspectives revolved around food waste, a significant problem around the world, jeopardizing sustainability efforts, wasting valuable resources, and causing economic loss (Hickey and Ozbay 2014; Vilariño et al. 2017; Scanlon et al. 2017). Addressing food waste requires technological as well as cultural and behavioral solutions and policy recommendations. On the technological side, increased efficiency of irrigation, processing plants, fuels, and agricultural practices can reduce primary-resource consumption on the operation side (Vlotman and Ballard 2014; Nikmaram and Rosentrater 2019). However, unaddressed in nexus studies was the impact on societal behavior.

Deduction 3: Although climate change has gained traction as a main dimension, especially with the focus on GHG emissions reduction, other dimensions, including ecosystems, soil function, human health, and waste, have not been sufficiently covered in the nexus literature. Although some studies considered these factors, they were not prioritized. Reorienting nexus dimensions toward these considerations will advance the holistic bottom-up approaches that are ecosystem-based over technology-focused analyses.

Proxies for Sociopolitical Dynamics

Modeling of political and social dynamics was not prevalent in the literature, in part because nexus research is driven by quantitative and resource-based thinking. When social and political dynamics were incorporated, they tended to be qualitatively introduced in a governance structure or as implications. In efforts to bridge the gap in social and political modeling, we aimed to elucidate ways to capture these dynamics using proxies identified in the literature.

Stakeholder Interactions

The realm of governance models offers examples that fit the first designation: stakeholder interaction proxies. For example, in GOV studies, understanding the role of various stakeholders in successful nexus coordination efforts led to improved platforms on how to incorporate political and social interactions (Dombrowsky and Hensengerth 2018; Weitz et al. 2017a, b). In a similar vein, guidelines for collaborating with the private sector aligned with technological and economic solutions, in which cost-recovery efforts could assist with governance structures and success (Hoff et al. 2019; Visseren-Hamakers 2015; Kurian 2017). In these examples, stakeholder dynamics and private–public collaborations served as proxies for building knowledge on how to represent social and political dimensions. Where research tends to focus on policy integration and overviews of existing links, as well as challenges and opportunities, integrated environmental governance can further shed light on platforms to address politics and social dimensions (Gain et al. 2015; Bizikova et al. 2013; Larcom and van Gevelt 2017).

Nexus Access, Security, Education

Access and security are established areas of concern (Bach et al. 2012; Kattel 2019; Allouche 2011; Misra 2014; Hanjra and Qureshi 2010; Scanlon et al. 2017; Hickey and Ozbay 2014), and from a modeling example, REG analysis was used to review access to improved water, electricity, and average protein supply, demonstrating a strong correlation between access to one dimension of the nexus and other dimensions (Caixeta 2019). With the use of AA, governance structure played a more substantial role than water availability (Huckleberry and Potts 2019). Through regression, security was found to be critical for political instability (Abbott et al. 2017). Specifically, a low nexus index correlated with lower stability. REG models showed that greater nexus connections between people and natural resources will further promote sustainability issues and reduce environmental inequality (Hannibal and Portney 2019).

From an educational perspective, it is imperative to bridge gap between academics and practitioners to enhance successful nexus projects (Bielicki et al. 2019). Education as a proxy is directly related to understanding the role of internal feedback loops, both qualitative and quantitative, that are often overlooked in the literature but appear to be flexible in modeling approaches. For example, SD was applied to socioeconomic influences, poverty alleviation, and power dynamics (Dong et al. 2019; Givens et al. 2018). To further explore feedback, there are benefits in SD models that target political and social understanding, even if qualitative with causal loop diagrams (CLD) or the quantitative stock and flow models.

Trade and Prosperity

Trading schemes have received some attention as potential strategies for mitigating water insecurity through virtual water trading and foreign direct investment (Grindle et al. 2015), spatial and production magnitude of resource consumption, and application of agriculture and energy sources through global trade patterns (Bijl et al. 2018). Although trade was rarely included as a nexus dimension, trade's multiple layers of political and economic influence have continued to be explored (Cao et al. 2018; Duan and Chen 2017; Lebel and Lebel 2018; Matthews and Motta 2015).

The prosperity proxy is influenced from work on urban studies, in which the idea was to use infrastructure and socioenvironmental metrics to assist in identifying future research based on a prosperity index and mitigate geographic disparities (Schlör et al. 2018; Hake et al. 2016). However, this proxy is in the early stages and not prevalent in the literature. The prosperity proxy may be reinforced by integrating the alternative dimensions of ecosystems, soil, health, and waste. Thus, studies focusing on prosperity may help to bridge political and social dynamics.

Deduction 4: The key proxies to integrate social and political dynamics in nexus studies are stakeholder interactions, nexus access, security, education, trade patterns, and prosperity. These proxies cover the realm of public–private interactions for projects and their financial considerations. Attention must be on capturing feedback loops, both qualitative and quantitative.

Geographic Distribution of Studies

Countries in Asia have received the most attention, with 89 studies (26%). China, especially countries in the Mekong River Basin, were frequent areas of study, along with several other large river basins in Central and South Asia. The prevalent geographies are global studies and countries in Africa, with 40 (12%) and 38 (11%), respectively. Global studies are studies that address at least one large region in every continent; otherwise, multiple locations were counted in their respective regions. North America (35) and Europe (34) each accounted for 10% of the distribution. The Middle East and North Africa (MENA) accounted for 16 studies (5%), followed by South America [15 (4%)], and Oceania [4 (1%)]. Some of the studies were non-geographic-specific.

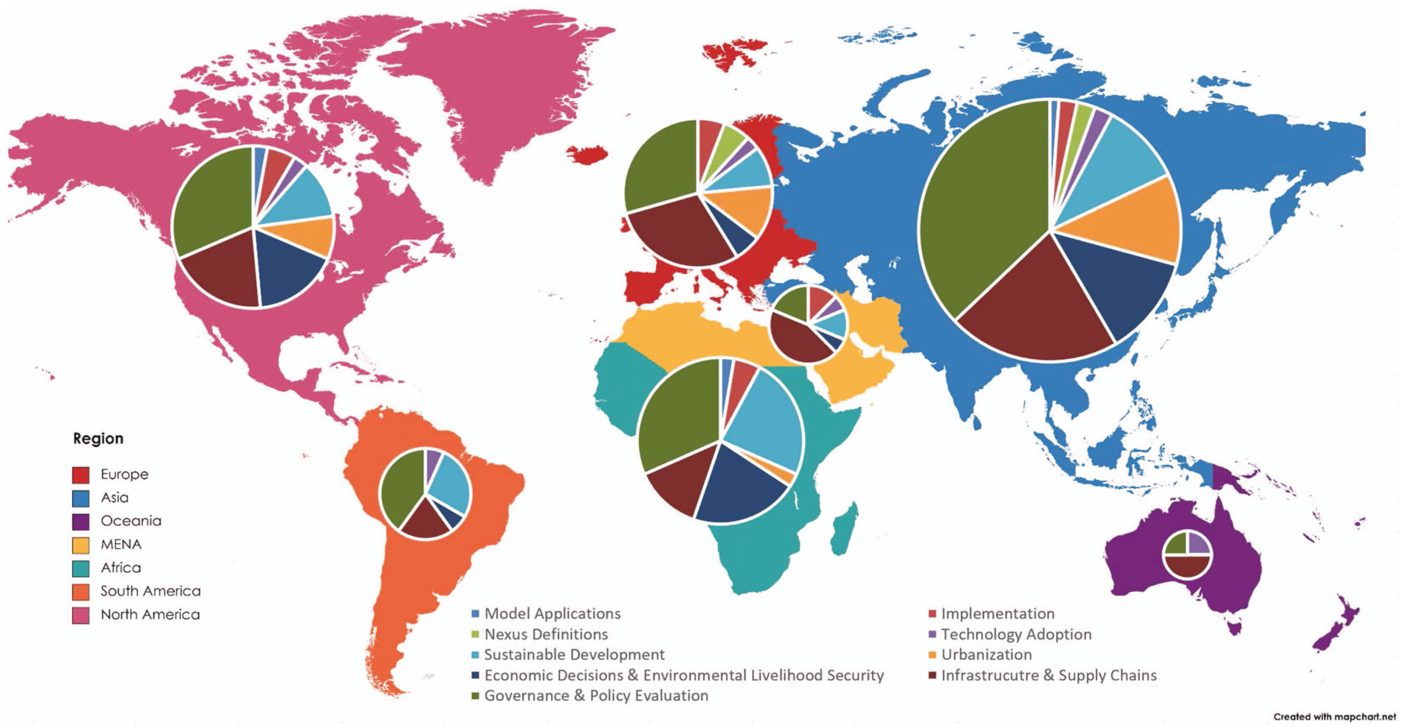


Fig. 5. (Color) Geographic distribution of agendas.

In terms of agendas, governance and policy evaluation was the most frequent research agenda across the different geographic regions, except for infrastructure and supply chains in MENA. Infrastructure and sustainable development were generally prevalent across all regions, which can be expected, given the prevalence of the top two agendas. The full geographic breakdown of agendas, excluding global and nonspecific regions, is presented in Fig. 5 with relative proportions of study volumes.

Economic decisions and environmental livelihood security vary substantially. In Africa, Asia, and North America, it was the third most prevalent. However, in MENA and South America, it was least common, and in Europe, it was second to last. On a global scale, it accounted for 12.5% of the studies. This is not to say that MENA, South America, and Europe do not value environmental livelihood security, but, rather, studies potentially prioritized other agendas. One possible reason is that Africa and Asia are already receiving much attention across the board and therefore more attention to livelihood security. However, because South America and MENA experience significant FEW stressors, it would be beneficial to further conduct livelihood security research in those regions. Another observation is that urbanization studies were clustered in Asia, North America, and Europe. Given the growing urbanization trends in South America, Africa, and MENA, additional efforts should explore the nexus considerations of urbanization in these regions.

What is evident from this comprehensive review is that from a geographic perspective, not enough empirical attention has been focused on MENA, South America, and Oceania. Although nongeographic-specific studies might use examples from South America, few studies conducted empirical reviews focused on South American countries. Additional work on island nations is warranted, given the impacts of climate change on those communities.

Deduction 5: The majority of nexus studies were applied toward countries in Asia, followed by Africa, North America, and Europe, generally in large river basins. Separating MENA from Africa suggests a shift in agendas, with MENA focusing on infrastructure and supply chains, and Africa on governance and economic decisions. In South America and Africa, urbanization requires attention, whereas environmental security is crucial in MENA and South America.

Data and Modeling as Pathways to Improved Decision Making

Having a better understanding of the modeling environment can directly help in making better decisions and effective nexus solutions. The steps necessary to achieve this gleaned from this review are discussed. First, it is important to map the stakeholders to the decisions in the ecosystem. For boundary levels, the recommendation is to capture local–regional and regional–national decision thresholds. For nexus dimensions, it is imperative to examine other sociotechnical aspects such as soils, health, and waste. Once the boundaries and dimensions are defined, a mapping of the stakeholders to the relevant inputs and outputs could be achieved.

Second, a mixed-methods approach should be sought after that integrates the quantitative approach of the research with the qualitative aspects of governance perspectives. This step is intended to be broadly understood and not dictate the type of quantitative models to pursue. Emphasis must be on including governance perspectives into input for scenario identification and the evaluation of trade-offs. The recommendation is to combine models as part of multiphase methodologies in which the output of one model feeds into the input for the second model. Such combinations could include MFA to identify resource synergies and trade-offs, while an optimization model could evaluate interventions or systems dynamics models with ABM techniques to evaluate resource feedback and user decision-making.

Although the goal is to differentiate complex models from complementary models, the challenge with complex adaptive models is that they require intensive granular data. If such data were easily accessible, the use of complex models could be expanded and generalized, leading to fine-tuned solutions. However, data of this nature may often be unique to a specific location, implying that replication in other domains may not be feasible. An outcome of this review is the need to highlight nonadaptive but complementary model combinations. This might ameliorate the shortfall of data granularity in favor of aggregate data. The main limitation in this approach is the loss of internal feedback dynamics across the sectors. However, this limitation can be mitigated by conducting uncertainty analyses. When understanding internal feedback is the goal of the research, such methodologies should consider the use of system dynamics models as part of the mixed-methods approach. These steps of stakeholder integration, mixed quantitative and governance models, and financial analysis (Gai et al. 2020; Ogunrinde et al. 2020) will ensure identification of efficient technological, policy, economic, or social solutions, and the results are relevant for all stakeholders.

Research Gaps

The outcome of this review illuminates the prevalent topics and methods across the literature, as well as those underrepresented. Fig. S5 shows the identified research gaps. These identified gaps follow the results of the main research questions guiding this paper. For the first question of agenda efforts, the main agendas are governance and policy evaluations and infrastructure and supply chains, with urbanization and economic decisions growing in the literature. From a geography perspective, there is a greater need for urbanization and economic decision studies in South America and Africa. The main gap, however, is in how to pursue implementation and understand the challenges of technology adoption. Several critical infrastructure topics are receiving heightened attention: nutrient and energy recovery across the sectors, extensive urban agriculture, and distributed renewable energy generation to support local and regional development. The challenge is in financing and implementing these projects. Therefore, future research exploring optimal implementation strategy would advance nexus potential by providing guidelines to take recommendations into practice.

Pertaining to modeling decisions of agendas and boundary analysis concerning the first and second research questions, the main underrepresented topics are implementation and technology adoption. The significant gap is addressing financial implementation that addresses capital investments and cost recovery. An integral component is to address all stakeholders in framework and collaboration efforts, in order to include social, cultural, and political perspectives into nexus project planning, design, and implementation. These considerations are central to both physical and social systems and across boundaries. Because the literature is saturated with material-focused research, which is paramount to understand what ought to be done, we now need to focus on how it ought to be achieved.

Our review highlighted modeling examples applied to different agendas and boundary levels for insights. There is no generic platform that captures all nexus components without limitations. Our model summary table and multimodel analysis would assist scholars in suggesting which complementary model pairings, based on desired agenda and boundary, are beneficial. The next phase of nexus research should prioritize model interactions across multiple boundaries, such as GOV interactions with CAS and ABM; MFA and OPT; REG and ABM; and SD with CAS. This list is not exclusive, and researchers are encouraged to identify further beneficial interactions that offer nexus benefits while minimizing limitations of each modeling approach.

Evaluating the different nexus dimensions, the third research question enabled the identification of important directions to reorient research to ecosystems, soil, health, and waste as core dimensions. The reorientation is significant. We find a growing push to ask bottom-up questions to steer research focus, especially the promotion of productive ecosystem services, fertile soil considerations, and health and waste as leading drivers. Placing people and the environment at the center is a natural extension, and a much needed one, to the dominant material-driven nexus work. This would also allow a greater flexibility in capturing local stakeholders and social and political dynamics, which we support with identifying proxies.

Illuminating the fourth research question provides the social and political proxies as opportunities to understand how to capture and study social and political dynamics. The proxies of stakeholder interactions, access, security, education, and trade and prosperity offer various perspectives, depending on their application. Although questions of access and security are increasingly incorporated in research, they are often of circumstantial relevance. The idea is to design research that would prioritize these proxies as drivers or objective functions as appropriate for the agenda and setting. These proxies are bridge points, and a balance is necessary, perhaps most seen with trade. Observing trade patterns alone will not promote social and political dynamics by itself, but rather illustrate which stakeholders hold greater influence. However, exploring trade patterns when access and prosperity are optimized could proxy the impact of social and political dynamics. These combinations are numerous, and it is up to future scholars to be creative and explore additional directions, especially when aligned with human-ecosystem-based research.

Lastly, exploring the geographic distribution of studies, the fifth research question suggests a greater need to focus on South America and Oceania. Special attention should be paid to urbanization, economic decisions, and environmental security in South America, Latin America, Africa (especially MENA), and Oceania.

Conclusion

The nexus concept is a valuable framework to address the challenges of managing the world's food, energy, and water resources. Although the main strand of literature is focused on food, energy, and water, growing attention has been aimed at re-evaluating the nexus into human-ecosystem perspectives. As the field developed, so did the modeling tools and approaches. Different modeling approaches are applicable to evaluate different nexus agendas, boundaries, and dimensions. Because regions around the world have their own unique characteristics and socioeconomic dimensions, no generic model or solution may be applicable to every situation. The key is to understand how to integrate complementary model approaches to capture the benefits of each and potentially reduce their limitations. Addressing the research gaps identified in this paper will lead the way for additional nexus research benefits as guidance for future work.

Our findings align with earlier nexus ideas that urge for a greater attention to implementation, deeper nexus dimensions that are focused on human and ecosystems, and inclusion of social and political dynamics. For example, implementation studies could explore the optimal ways to deploy and finance energy and nutrient recovery systems, extensive urban agriculture, or river basin ecosystem management practices, and integrate the social and political perspectives needed for successful adoption practices. Our contribution is in capturing the current prevalent and underrepresented agendas, boundaries, dimensions, opportunities to include social and political dynamics, and geographic distributions. The new directions of human-ecosystem-centered perspectives and implementation-thinking endeavors will pave the way forward to an increasingly holistic field of knowledge and practice.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

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Supplemental Materials

Figs. S1–S5 and Tables S1 and S2 are available online in the ASCE Library (www.ascelibrary.org).

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