



Stakeholder Perspectives on Sustainability in the Food-Energy-Water Nexus

Jeffrey M. Bielicki^{1,2,3*}, Margaret A. Beetstra⁴, Jeffrey B. Kast³, Yaoping Wang³ and Shaohui Tang⁵

¹ Department of Civil, Environmental, and Geodetic Engineering, The Ohio State University, Columbus, OH, United States, ² John Glenn College of Public Affairs, The Ohio State University, Columbus, OH, United States, ³ Environmental Science Graduate Program, The Ohio State University, Columbus, OH, United States, ⁴ School of Environment and Natural Resources, The Ohio State University, Columbus, OH, United States, ⁵ Department of Agricultural, Environmental, and Development Economics, The Ohio State University, Columbus, OH, United States

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*Correspondence:

Jeffrey M. Bielicki
bielicki.2@osu.edu

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Interest in the various dimensions of environmental, economic, and social sustainability for food, energy, and water (FEW) systems, independently and collectively (i. e., the FEW nexus), has spawned an increasing amount of literature that seeks to understand the various linkages within the FEW nexus and provide guidance to inform decision-making to enhance sustainability. While the use of science and data can generate important and relevant information, it is not clear how important they are relative to relevant policy and the integration of policy within and across the individual FEW domains. In this work, we assessed perspectives on various considerations that pertain to sustainability in the FEW nexus. To do so, we identified numerous stakeholder groups who have interests throughout the FEW nexus, and conducted a survey of a subset of these groups. Although the responses differed across the stakeholder groups that we surveyed, the consistent result was that stakeholders generally understand that FEW systems are physically connected at high levels, and that policy is less integrated than desired. When forced to choose between priorities for science and data or for integrated policy to enhance sustainability, respondents from Academia and Extension preferred more science and data, whereas respondents who are, or more frequently interact with, practitioners and policy-makers preferred integrated policy. Overall, with other results and findings that are relevant for advancing sustainability and improving communication the FEW nexus, we conclude that the importance of science, data, and integrated policy depends on the context in which the stakeholders operate in the FEW domain.

Keywords: food-energy-water nexus, sustainability, stakeholders, perception, integrated policy, data, science, survey

INTRODUCTION

Due to their vital roles in providing essential resources, goods, and services to society, there is great interest in the functioning and sustainability of the resources and systems that provide food, energy, and water (FEW). The “FEW nexus” includes the necessary natural resources and their systems, the associated physical infrastructure, the institutions, and socio-economic systems that develop, use, guide, benefit from, and impact conditions in FEW (Hoff, 2011). Understanding the

linkages within dynamic, nested, hierarchical, and evolving systems that comprise the FEW nexus, and considering them in decision-making and appropriate policy, could increase the efficient use of scarce resources, improve the quality and security of food, energy, and water supplies, as well as provide opportunities to grow economies and provide support for livelihoods (Hoff, 2011; World Economic Forum, 2011; Tidwell et al., 2014; Biggs et al., 2015; Wang et al., 2017).

Stakeholders in the FEW nexus typically have sector-specific goals and make decisions in silos (Howarth and Monasterolo, 2016; White et al., 2017) with a tendency to focus on short-term outcomes (Sterman, 2012). These motivations can lead to practices like desalination and first-generation biofuels (e.g., corn ethanol) that can increase the supply of one resource (e.g., water, energy) at the expense of another (e.g., energy, food) (Hussey and Pittock, 2012), or activities in one FEW domain (e.g., fertilizer application for agriculture) that can negatively affect the ability of systems in another FEW domain to provide usable resources (e.g., reduced water quality due to harmful algal blooms from agricultural runoff). Policy can be used to influence the direction of activities, but, despite the physical interconnections, policies in one FEW domain are often isolated from policies in another FEW domain and there is often limited effort to account for and manage the links (Hussey and Pittock, 2012). Such policy fragmentation across FEW systems is a governance problem that can lead to unintended consequences (Weitz et al., 2017). Greater policy coherence is critical (Rasul, 2016), and when the interactions and feedbacks between FEW sectors are understood and considered, policies that focus on one FEW sector can reduce negative effects, or create co-benefits, in another sector (De Strasser et al., 2016). As such, some have concluded that there is a need to increase the integration of policy for food, energy, and water so that policy considers components from more than one FEW system (Scott et al., 2011; Hussey and Pittock, 2012; Siddiqi et al., 2013).

Understanding the interactions and feedbacks in the FEW nexus should be informed by data, but, without roughly equal representations in the data of each of the elements of the FEW nexus (Howarth and Monasterolo, 2016), decision-making could emphasize one component of the FEW nexus, and the existence and collection of data does not alone provide the proper context for the appropriate formulation of policy (McCool and Stankey, 2004). There must be some translation of that data into knowledge and policy. Some tools that support decision-making in the FEW nexus include integrated assessment models, which may be developed with stakeholder inputs, and can perform scenario analyses to inform policy-making (Kraucunas et al., 2015; Miralles-Wilhelm, 2016). Tools that are suitable for sector-specific and short-term analyses include sector-specific optimization models with land, energy, and water constraints and tools for financial investments (Zhang and Vesselinov, 2016; Kaddoura and El Khatib, 2017). The calibration of decision-making tools is a data-intensive process, though, and there have been calls for more and better data on the FEW nexus (McCarl et al., 2017). Larger and more readily available data sets have the potential to be used by stakeholders in many ways, including for research to develop useful knowledge as well as

by those who are likely to benefit from the data and knowledge directly. For example, the increased availability of data—especially that which is highly-resolved and individualized—has influenced how farmers make decisions in areas such as planting, nutrient management, and financial record-keeping (Wolfert et al., 2017). Yet addressing trade-offs and improving policy integration across FEW sectors is a political process that requires negotiation amongst stakeholders with distinct perceptions, interests, ideologies, and practices, as well as preferences for how to address issues within the FEW nexus (Weitz et al., 2017).

The concept of sustainability has environmental, economic, and social dimensions (Geissdoerfer et al., 2017). Various indicators of sustainability have been developed in order to gain insight into the functioning of individual components of FEW systems and to provide evidence of progress toward sustainability goals. Early development and selection of indicators were mostly oriented around scientific and technical conditions (McCool and Stankey, 2004), but have more recently addressed all three dimensions of sustainability (McBride et al., 2011; Dale et al., 2013; Efromymson et al., 2013; Biggs et al., 2015; Santiago-Brown et al., 2015). Yet it is often unclear what are the relative roles of various stakeholders—scientists, the public, and policy-makers, to be specific—in selecting and using sustainability indicators, which can result in conflict and confusion (McCool and Stankey, 2004). In some cases, the social aspects of sustainability goals have been less addressed than the environmental and economic aspects, in part due to disconnects between the early stages of the policy cycle, poor identification of issues and formulation of policy tools, and the latter stages of implementation and evaluation (Chapman et al., 2016). Other policies have emphasized the economic dimensions of development at the expense of environmental sustainability (Oñate and Peco, 2005).

The design of integrated policy can be challenging, in part due to the varying interests of relevant stakeholders who may prioritize different types of information and data, may have complex relationships with each other, and may be directly or indirectly affected by the policy and its outcomes. The FEW nexus, and its various components, is perceived by stakeholders in many ways (Petit and van der Werf, 2003; Lamarque et al., 2011; Cairns and Krzywoszynska, 2016), which can vary spatially (Lawford et al., 2013) and by stakeholder interest and involvement (Jacobs and Buijs, 2011; White et al., 2017) in individual FEW domains. Using Johnson et al. (2013) as a point of departure for identifying the roles of stakeholders in complex systems where environmental, economic, and social systems where sustainability is a concern, **Table 1** contains a conceptual presentation of the interests of various stakeholder groups that are relevant to the FEW nexus.

The varying perceptions of the FEW nexus among stakeholders necessitates increased integration of different perspectives, which can be achieved by incorporating stakeholders from a variety of backgrounds in research (Voinov and Gaddis, 2008; Kalcic et al., 2016; Inouye et al., 2017) to co-produce knowledge (Howarth and Monasterolo, 2017) and to provide data and inputs to policy-making. Involving stakeholders in policy-making processes can increase

TABLE 1 | Stakeholder classification table identifying relevant FEWS stakeholder groups, their primary interests in each domain of FEWS, and their relevant involvement in each domain of FEWS.

Stakeholder group	Interests in agriculture/food	Interests in energy	Interests in water	Involvement in FEWS		
				AG/food	Energy	Water
DIRECT ACTORS						
Producers of agricultural outputs	Profit; competition; regulation; markets; technology	Input and output prices and supply	Regulation; input supply; output quality	X	X	X
Producers of agricultural inputs	Profit; competition; regulation; technology	Input and output prices and supply	Regulation; input supply, quality, and price	X		X
Producers of energy inputs	Profit; competition; regulation; technology	Profit; regulation; input and output prices and supply	Regulation; input supply, quality, price, and availability; output quality		X	X
INDIRECT ACTORS						
Agricultural supporting role	Profit; professional and business relationships; access to markets	Input and output prices and supply	Regulation	X		X
Agricultural product sellers	Profit; professional and business relationships; access to markets; product supply	Input and output prices and supply	Regulation	X		
Energy product sellers	Profit; product supply	Profit; input and output prices and supply; professional and business relationships	Input supply and availability		X	
Transportation companies	Profit; competition	Profit; input and output prices and supply; professional and business relationships	Regulation; input and output supply and availability	X	X	X
Utility companies	N/A	Input and output prices; output demand, professional and business relationships	Regulation; input supply, output quality		X	X
Engineering and construction firms	Profit; regulation	Input and output prices and supply	Regulation; input and output supply and quality	X	X	X
OVERSIGHT OFFICIALS						
Regulatory agencies	Regulation; educational opportunities; professional and business relationships	Regulation; educational opportunities; professional and business relationships	Regulation; compliance; input and output prices; professional and business relationships	X	X	X
Policy-makers	Regulation; professional and business relationships	Regulation; professional and business relationships	Regulation; compliance; professional and business relationships	X	X	X
CONCERNED PARTIES						
The public	Agricultural product supply, price, and quality; ecological impacts, health impacts,	Input and output prices, supply, and quality, health impacts	Input supply and quality; output quality and prices; health impacts	X	X	X
Agricultural commodity groups	Professional and business relationships; access to markets	Input and output prices	Regulation; input supply, quality, and availability; output quality	X		X
Public health agencies	Regulation; output quality	Input and output supply	Input supply, quality, and availability; output quality, health impacts	X		X
Emergency services	N/A	Energy operations safety	Input and output quality		X	
Recreation industries	Profit; regulation	Input and output prices and supply	Regulation; input supply, quality, and availability; output quality	X	X	X
Researchers	Data; professional and business relationships	Data; professional and business relationships	Data; professional and business relationships	X	X	X
Restaurants and supermarkets	Profit; input quantity, supply, prices, and availability; professional and business relationships	Input and output prices and supply	Regulation; input supply, quality, and availability; output quality	X	X	
Environmental conservation groups	Regulation	Regulation	Regulation; professional and business relationships	X	X	X
Non-governmental organizations	Profit; professional and business relationships	Input and output prices	Regulation; input supply, quality, and availability; output quality; professional and business relationships	X	X	X

(Continued)

TABLE 1 | Continued

Stakeholder group	Interests in agriculture/food	Interests in energy	Interests in water	Involvement in FEWS		
				AG/food	Energy	Water
Lobbyists	Regulation; professional and business relationships	Regulation; input and output supply; professional and business relationships	Regulation; input supply, quality, and availability; output quality	X	X	X
Academic extension officials	Professional and business relationships	Regulation; input and output prices	Regulation	X		X
Home and community developers	Regulation	Input and output prices and supply	Input supply, quality, and availability; output quality and price		X	X
Military and national security officials	Input prices, supply and demand; output prices, supply and demand; access to markets	Energy operations safety	Water quality and quantity safety	X	X	X

Based on Johnson et al. (2013).

understanding of system-wide FEW issues (Keskinen et al., 2015) and provide local knowledge and information about different types of needs that are not necessarily apparent to decision-makers (Carey et al., 2007; White et al., 2010).

There are substantial tensions in developing effective analytical frameworks that transcend the disciplinary boundaries that are associated with FEWS (Leck et al., 2015), and decisions that are made are often characterized as scientific, objective, and free of values, even though they mask particular systems of belief, in addition to conveying that issues of sustainability are related to physical and technical considerations rather moral, ethical, or political issues (McCool and Stankey, 2004; Fischhoff, 2018). Conflict between stakeholder groups can emerge because of different experiences and knowledge that various stakeholders bring to policy discussions, and issues for communication in the FEW nexus arise in part as a result of the cross-sectoral and transdisciplinary nature of the nexus—including potential differences in vocabulary, sets of skills, and expertise (Howarth and Monasterolo, 2016). Since competing belief systems are barriers to communication between stakeholders in science, in policy, and in the public (McCool and Stankey, 2004), the development and consideration of knowledge about differences in preferences for conducting science and research and generating data relative to integrated policy is important for advancing sustainability.

When stakeholder groups have varying views about aspects of policy, some may not be satisfied with the result (Adams et al., 2003). But this dissatisfaction can be partially mitigated if stakeholders experience some level of involvement and control throughout the policy development process (Khan and Gerrard, 2005), which they can do by providing input throughout the formation of policy (Wilsdon and Willis, 2004; Hering et al., 2013), responding to almost complete policies (Wilsdon and Willis, 2004), and engaging with other stakeholders (Elgin and Weible, 2013; Heikkila et al., 2014). Without stakeholder involvement, policies may not be implemented because of the lack broader support (Hering et al., 2013). Policy that is informed by science requires engagement between practitioners and academics (Bakker, 2012), because science for the development of

useful knowledge that is conducted in silos can lead to outcomes that are not tethered to the needs of those who could benefit from the knowledge (Howarth and Monasterolo, 2016). It is beneficial for scholars to co-produce knowledge with practitioners and other stakeholders (Clark and Dickson, 2003), and to accept the political context of their work (Clark et al., 2016), in part because local knowledge that is paired with goals to maximize stakeholder responsiveness, rather than forcing prescribed policy on stakeholders, can increase engagement and acceptance (White et al., 2010).

There are a number of barriers to better integration of policy, including (a) missing, incomplete, and proprietary data; (b) fragmented existing policy and regulatory frameworks; and (c) inertia and path-dependency in the research community (e.g., academic silos) and the emphasis on solutions that are optimal technically in lieu of those that are holistic (Hussey and Pittock, 2012). While increased collaboration across individual FEW domains can help to address needs for data and for policy (Keskinen et al., 2015), and between those that conduct research or develop policy and those that implement and are affected by that policy, it is unclear if the conduct of more research and science to develop more data on the FEW nexus is a priority over the development of integrated policy that is relevant to the FEW nexus. Stakeholders throughout the FEW nexus engage with data and policy in many ways, and for multiple benefits: policy and data can help stakeholders make better-informed decisions, whereas feedback from stakeholders can facilitate more comprehensive and informed research and policy (Johnson et al., 2013).

Since stakeholders in the FEW nexus engage with policy and data in a variety of ways, what should inform decision-making within the FEW nexus? Should effort be invested in developing useful data and knowledge and—perhaps to relevant sustainability indicators or combinations of them—or should the decision-making be implicitly encouraged to consider the linkages and outcomes of more than one of the FEW systems?

To investigate the relevance of science, data, and integrated policy to enhance the sustainability of FEW systems, we conducted a survey of select stakeholder groups who

engage with the FEW nexus in different ways. Others have solicited perceptions that are pertinent to FEW systems from stakeholders in non-governmental organizations (NGOs), the U.S. government, relevant industry, academia, forest harvesting and management, environmental conservation, education and training, consulting, and others who focus on socio-economic conditions (e.g., Hickey et al., 2007; Dwivedi and Alavalapati, 2009). Here, we surveyed stakeholders from three major groups that tend to focus on research and the production of knowledge at a university, those whose role is to bridge the university with the people in the state, and those who are practitioners and engage with policy in numerous ways. These groups were chosen in part because of varying relationships with the production and use of data and of policy and to provide a diverse set of stakeholder groups, which is useful for communication (NAS, 2017). Section 2 provides information on the survey and the characteristics of the stakeholder groups who were surveyed. The results of that survey are presented in section 3. Section 4 contains a discussion of the relevance of stakeholder perceptions and involvement in the FEW nexus.

MATERIALS AND METHODS

As part of a project that is funded by the U.S. National Science Foundation, we established a Research Advisory Council (RAC) that is convened for a series of annual and semi-annual meetings. The RAC is a group of stakeholders who are involved in various capacities in FEW issues in the Great Lakes Region, which roughly lies at the intersection of the Great Lakes, the Eastern Corn Belt, and the Great Lakes Megaregion, and includes the U.S. states of Ohio, Indiana, Illinois, Wisconsin, and Michigan—from which members of the RAC were drawn. These states had a total population of 46.9 million in 2017. This area contains a variety of fossil and renewable energy resources, substantial agricultural activity, and watersheds that drain into the five Great Lakes in the United States and Canada. Some of the issues for sustainability in the region include the development of algal blooms in Lake Erie, the environmental and social consequences of fossil fuel development—including past coal production and present hydraulic fracturing for oil and natural gas—and the economic and social consequences of the decline in manufacturing jobs.

The members of the RAC were selected by a theoretically-based quota sample, with the intention to have a mix of people who could represent different key attributes (e.g., across FEW sectors, working at different scales) and to ensure some representation for each of the states in the region. Potential members were identified through peer and expert networks, and were invited to participate sequentially. After each wave of invitations, the composition of the RAC membership was recalibrated to ensure that the desired combinations of sectors, scales, and states were achieved. The RAC is comprised of 22 individuals who serve in a variety of roles and institutions, including state agencies, non-profits, and industry, and served a secondary role as one of the three samples for this case study. While the perspectives of those on the RAC are not

necessarily generalizable to all of the stakeholders throughout the FEW nexus (**Table 1**), the sample captured a variety of perspectives and represented many of the major players who are involved in FEW decision-making in the Great Lakes Region. The survey was administered in paper at the beginning of the first of a number of 2-day workshops, and RAC members who were not able to attend that meeting in person received an online version that was identical to the paper version.

We also administered the online survey to two other populations: (1) faculty associated with Extension for the land-grant university, and (2) faculty affiliated with the interdisciplinary program in environmental science that awards M.S. and Ph.D. degrees. These Academics have their primary appointments in departments and schools in the physical, natural, engineering, and social sciences across the university. Extension faculty were chosen in part because of their role in bridging activities between the academia and the citizens of the state, and in part because agricultural extension in the United States has encountered decreasing influence on the farming community; farmers have been receiving increasing amounts of information from retailers and other consultants, and use new technologies (e.g., mobile phones and apps) to access data (e.g., market prices, potential buyers) to help them make on-farm decisions (Dissanayeke and Wanigasundera, 2014). As such extension may be becoming less prominent, but many farmers still consider extension to be a reliable source of information (Prokopy et al., 2015). In theory, Extension should represent a middle-ground in perspective between the RAC members and the Academics, and our survey data illuminates if these boundary-spanning activities and perspectives are prevalent. As with the RAC sample, the Extension faculty and Academics who were surveyed do not necessarily represent all of the individuals in these types of roles, but they do represent a broad range of relevant perspectives on FEW decision-making in the Great Lakes Region.

Collectively, the survey population included stakeholders who are primarily engaged in research and teaching (Academics), primarily engaged in interfacing between the academics and the public who are served by the land-grant institution (Extension), and primarily engaged with organizations that control or engage with physical or policy inputs or outputs in one or more FEW domains (RAC).

Respondents answered a series of questions to assess their engagement in each FEW domain; their engagement with the dimensions of sustainability, the interaction with, and influence of, policy related to each FEW domain; and the governmental level at which policy-making is most impactful on their work. Other questions gauge barriers faced in working in the FEW nexus in addition to the groups of people that most influence them. All of the questions were assessed on Likert-type scales, and all responses were anonymous. The specific survey questions are included in the **Supplemental Information**. All of the survey materials were reviewed by content and methodological experts during their development, and the materials were approved by, and administered in accordance with, the guidelines of the Institutional Review Board.

To determine the significance of differences in the responses, we used non-parametric tests of significance to avoid assumptions about the distributions underlying the data. In particular, we used the Kruskal–Wallis test to detect if there are significant differences between the three groups of respondents for the same survey question, or between survey questions for the same group of respondents. If significance was detected at the 5% level and more than two samples were compared in the Kruskal–Wallis test, we used the Nemenyi *post-hoc* test to identify the individual significant differences between pairs of respondents or questions. We also used the Wilcoxon signed rank to determine if the responses from a stakeholder group was significantly different from neutral [i.e., 3 on a scale from 1 (low) to 5 (high)]. The Kruskal–Wallis and Wilcoxon signed rank tests were performed in Python 3.7.0 using the SciPy library (Jones et al., 2001). The Nemenyi tests are performed in Python 3.7.0 using the Scikit-Posthocs library (Pohlert, 2018). In the results that follow, we present the *p*-values from these statistical tests, with at most two significant digits. To avoid conclusions that are based on the use of a relatively arbitrary standard for determining statistical significance (i.e., $p \leq 0.05$), we highlight *p*-values that are less than or equal to 0.10. We chose this level in part because the focused size of the sample in this case study limits statistical power, and we sought to avoid conflating the lack of statistical significance with the lack of practical importance (Gelman and Stern, 2006).

RESULTS

Demographics of Respondents

In total, 57 stakeholders with diverse backgrounds responded to the survey. Prior published studies using surveys have had less or comparable levels of respondents (e.g., Andreu et al., 2009; Dwivedi and Alavalapati, 2009). The 18 respondents from the RAC (14 were on paper) included individuals who work for the government (5), a non-profit (9), industry (2), academia (1), and philanthropy (1). The 19 respondents from Extension come from four program areas: 4-H Youth Development¹ (2), Agriculture and Natural Resources (12), Community Development (3), Family and Consumer Sciences (1), and not indicated (1). The 21 Academics who responded to the survey are from primary disciplines in the natural sciences (7), engineering and physical sciences (9), and the social sciences (5). The response rates in each group resulted in comparable sample sizes across the three stakeholder groups.

Approximately half of the respondents from the RAC and from Extension reported that they highly engage with food issues, while almost two-thirds of the respondents from the RAC and over 80% of the respondents from Extension reported that they highly engage with agriculture. In comparison, the Academic respondents reported low levels of engagement with food and agriculture, with <20% of the sample engaged with food and one-third engaged with agriculture. Typically, food and agriculture are grouped together in the literature on FEW systems, but the

responses to the survey suggest that food and agriculture are in fact partial subsets of each other.

Overall, respondents from the RAC interact with a broader array of professionals than those from Extension or Academia. For example, RAC members interact with lobbyists and public utility staff while no one from Extension or Academia indicated involvement with these groups. Further, Academics expressed low frequency of engagement with the general public, while the respondents from the RAC and from Extension indicated very frequent involvement. In general, Academic respondents did not frequently interact with non-academics, and thus their sources of data and engagement with policy may differ from respondents in the other stakeholder groups.

Across the three stakeholder groups, only 15–30% of each group reported that they are highly engaged in the energy domain. This low level of involvement is in contrast to the response for the water domain; respondents from the RAC and from Academia indicated that they have high engagement with issues for water, but those from Extension indicated low engagement in this domain. The low reported engagement with water by respondents from Extension is interesting in light of their reported high engagement in agriculture and their assessment that physical systems for food/agriculture and water are highly integrated (Table 2). It is possible that these respondents did not believe that there are concerns to address with respect to water, due to the relatively abundant surface and groundwater resources in the region. But such a lack of concern would be in contrast to regional issues pertaining to harmful algal blooms that have increasingly been occurring in Lake Erie, and how Extension programming is focusing on adopting best management practices to limit the amount of nutrients that leave the agricultural field.

Stakeholder Perception of the FEWS Nexus

Table 2 shows how the respondents from each of the stakeholder groups assessed the physical integration of FEW systems. There was relatively high agreement that the physical components of FEW systems are interconnected, with 70% or more of the respondents from each stakeholder group assessing that all of the combinations of FEW systems are physically integrated. But the responses varied by group in the degree to which they assessed the physical interconnectedness. Academics tended to assess the physical integration at higher levels than the other stakeholders, with on average 90.4% of the respondents assessing the high physical integration, whereas respondents from Extension had the lowest average assessment of this physical integration (84.3%). The combinations of FEW systems that involve energy were the least likely to be considered to be physically integrated, particularly by respondents from Extension and from the RAC. Although, the RAC members who are affiliated with energy viewed energy systems to be more interconnected with the other FEW systems than those who did not identify as such.

Respondents from the RAC had different assessments of the degree to which the various systems are physically integrated (Kruskal–Wallis, $p = 0.016$), but the *post-hoc* Nemenyi test did not suggest that the responses for any specific pairs of systems were significantly different. The three groups of respondents

¹4-H is a youth development and mentoring program that includes about 6.5 million youth throughout the world.

TABLE 2 | Agreement of respondents that physical systems for FEW are integrated.

System 1/System 2	RAC	Extension	Academics	p-value
Food/agriculture and energy	82.4%	70.6%	87.5%	0.34
Food/agriculture and water	100.0%	94.1%	93.8%	0.085*
Food/agriculture and ecosystems	87.5%	94.1%	87.5%	0.26
Energy and water	82.4%	76.5%	93.3%	0.15
Energy and ecosystems	76.5%	76.5%	86.7%	0.31
Water and ecosystems	94.1%	94.1%	93.8%	0.023**
p-value	0.016**	0.36	0.19	

Percentages represent the proportion of respondents who indicated that the combinations are physically integrated at the two highest levels they could assess on the Likert-type scale: “a good deal” or “to a great extent”. The p-values are from Kruskal–Wallis tests on the H_0 : the different groups of respondents have the same response to the survey question (rows), or H_0 : the group of respondents have the same response to the various survey questions (columns). Significance: ** $\leq 5\%$; * $\leq 10\%$.

had different assessments on how well Water and Ecosystems are physically integrated (Kruskal–Wallis, $p = 0.023$) and on how Food/Agriculture and Water systems are physically integrated (Kruskal–Wallis, $p = 0.085$). The *post-hoc* Nemenyi test suggested that the significant difference was between the RAC and Academics ($p = 0.03$); while the percentages in **Table 2** appear to be similar, the aggregation of responses of “a good deal” and “to a great extent” mask that the Academics had more “to a great extent” responses than did the other two groups of respondents. Differences in the dispersion of the underlying data such as this explains the significance of these and other statistical tests, despite the percentages in tables appearing to be similar.

Much smaller fractions of the respondents assessed that current policy for FEW is highly integrated (dashed bars in **Figure 1**). At 35.6% of all of the respondents, current water policy and current environmental policy were most often considered to be highly integrated, whereas the other combinations of current policies with FEW had at most 12% of all of the respondents assess that they are highly integrated. Overall, Academics were the least likely to assess that current FEW policies were highly integrated (7.8% on average), and respondents with Extension were the most likely (20.1% on average). The respondents from Extension most often assessed that current policy for food/agriculture is integrated with current policy for the other components of the FEW nexus, which is likely to be consistent with the majority of the respondents being from the Agriculture and Natural Resources program area.

The Kruskal–Wallis test indicated that there was a difference in the assessments between the integration of current policy for energy and for environment, which was the only combination of FEW policy integration that had significantly different assessments from the respondents across the stakeholder groups ($p = 0.022$; see **Table S1** for the results of the significance tests). The subsequent *Post-hoc* Nemenyi test showed that the significant difference was between the RAC and Academics respondents ($p = 0.025$).

The combination of **Table 2** and **Figure 1** also shows that all of the stakeholder groups consistently assessed higher levels of physical integration than policy integration. This disparity does not necessarily suggest that there should be more policy, but **Figure 1** shows that the respondents assessed that there should be more integrated policy for FEW than there is at

present. Respondents from Extension consistently assessed less need for integrated policy relative to current policy, whereas respondents from the RAC assessed larger disparities between ideal policy integration and current policy integration for FEW systems involving food/agriculture than did the other stakeholder groups. Despite these general differences, the assessments of the difference between the current integration of FEW policy and the ideal integration of FEW policy were significant for all of the combinations of FEW policy and for all of the stakeholder groups, with the exception of the assessment of the difference between current and ideal integration of water and environmental policy by respondents from Extension ($p = 0.064$) (see **Table S1**).

Stakeholder Consideration of Sustainability and Interaction With Relevant Policy

Table 3 shows that at least 75% of the respondents from the RAC and from Extension consider all three dimensions of sustainability in their work. The respondents from Academia only considered the environmental outcomes at a similar level, but this may reflect the fact that these stakeholders are affiliated with an environmental science degree program and, by virtue of disciplinary specializations, only a subset would be interested in economic or social outcomes in their work. The consistently high consideration of economic and social outcomes among the respondents from the RAC and from Extension may suggest that these groups interact more directly and consistently with a broader array of the people and institutions in **Table 1** than the Academics.

The respondents from the three stakeholder groups had significantly different levels of consideration for the environmental and economic aspects of sustainability. The *post-hoc* Nemenyi tests indicated that the consideration of environmental outcomes differed between the RAC and the Academics ($p = 0.057$), and that the consideration of economic outcomes differed between the RAC and the Academics ($p = 0.036$) and between the Academics and those in Extension ($p = 0.004$).

Across the three groups of stakeholders, respondents reported being involved with, or influenced by, relevant policy at lower levels than the outcomes that they consider in their work

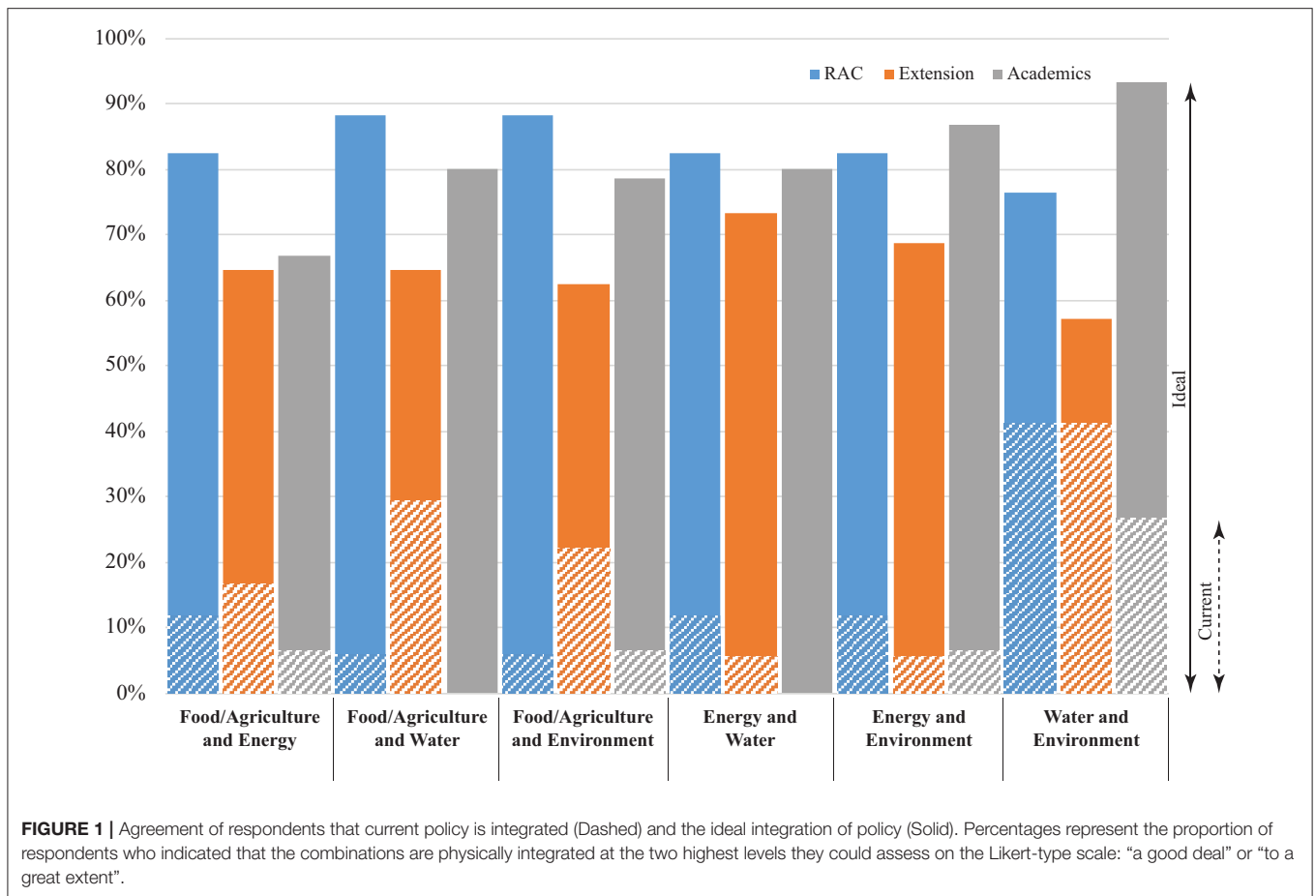


TABLE 3 | Respondents’ consideration of components of sustainability and their interaction with associated policy.

	Consider outcomes			Involved with or influence policy		
	Environmental	Economic	Social	Environmental	Economic	Social
RAC	82.4%	82.4%	76.5%	82.4%	64.7%	29.4%
Extension	75.0%	93.8%	75.0%	58.3%	50.0%	33.3%
Academics	87.5%	31.3%	43.8%	77.8%	23.5%	17.6%
p-Value	0.043**	0.002***	0.16	0.052*	0.070*	0.16

The values are percentages of respondents who selected one of the two highest levels on the 5-point Likert-type scale. For “Consider Outcomes”, these two highest options are “Frequently” or “Very Frequently”; for “Involved with or Influence Policy”, the scale ranged from “Not At All” to “A Great Deal”, and the percentages are the aggregation of responses in the two highest levels that are above the midpoint (“a moderate amount”). The p-values across the bottom row are from Kruskal–Wallis test of the significance between the stakeholder and their consideration of the components of sustainability and between their interaction with the associated policy. *H0*: the RAC, Extension, and Academic respondents have the same level of consideration on the components of sustainability or interaction with the relevant policies. Significance: *** $\leq 1\%$; ** $\leq 5\%$; * $\leq 10\%$.

(Table 3). Respondents from the RAC tend to interact more with policy than do respondents from the other stakeholder groups, with an average of 58.8% with high interaction relative to 47.2% for Extension and 39.7% for Academic respondents. All of the respondents across the three stakeholder groups interact most often with environmental policies, followed by economic policies, and finally social policies, but the respondents from Extension have more similar levels of interaction across the three types of policies than the RAC and Academic respondents.

The Kruskal–Wallis tests indicated that the Academics gave different consideration to the different components of sustainability ($p = 0.003$, see Table S2); the *post-hoc* Nemenyi test suggested that the difference between consideration of environmental outcomes and the social outcomes was significant ($p = 0.026$), as was the difference between consideration of the environmental outcomes and the economic outcomes ($p = 0.007$). The responses from the RAC and the Academics indicated that the respondents from these stakeholder groups are neither involved with nor influence policy for environmental,

economic, and social outcomes to the same degree ($p = 0.0006$ and $p = 0.018$ in **Table S2**). The *post-hoc* Nemenyi tests suggested that the difference for respondents from the RAC was significant between policies for social outcomes and policies for economic outcomes ($p = 6.2 \times 10^{-4}$), whereas for the Academic respondents the difference was between policies for social outcomes and policies for environmental outcomes ($p = 0.034$).

The p -values in **Table S2** show that there was no significant difference for any of the Stakeholder groups between the level of consideration for environmental outcomes and policy for those outcomes. In contrast, the level of consideration for the economic aspect of sustainability was different from the level of interaction with policies for economic outcomes by the Extension respondents ($p = 0.039$) and by the Academic respondents ($p = 0.097$). Further, the responses for the social aspect of sustainability were significantly different from the level of interaction with policies for those social outcomes for all of the stakeholder groups.

In general, while there was an acknowledgment of the need for more integrated policy (**Figure 1**), the results in **Table 3** suggest that the considerations for this policy could prioritize the environmental dimensions over the economic and social dimensions of sustainability.

Stakeholder Priorities for Science, Data, and Policy

Respondents were consistent in their assessments of the importance of, and need for more, science, data, and integrated policy FEW systems (**Figure 2**). Between 93.3% (Extension) and 100% (Academics) of the respondents agreed that “It is important to have more science and data on food, energy, and water,” and 64.7% (RAC) to 73.3% (Extension) of the respondents disagreed with, “There is enough science and data currently being generated on food, energy, and water.” For integrated policy, 73.3% (Extension) to 94.1% (RAC) of the respondents agreed that, “It is important to have better integrated policy for Food, Energy, and Water,” and 60.0% (Extension) to 70.6% (RAC) disagreed with, “There is enough integrated public policy currently being generated on food, energy, and water.” The Kruskal–Wallis test suggested that there was a difference between the stakeholder groups in their responses to the importance of more science and data ($p = 0.018$ in **Table S3**), and the *post-hoc* Nemenyi test identified this difference in the responses between the RAC and the Academics ($p = 0.019$). When the responses for more science and data were compared with those for more integrated policy within stakeholder groups, the respondents from Extension and from Academia each had different responses on the importance of more science/data vs. integrated policy.

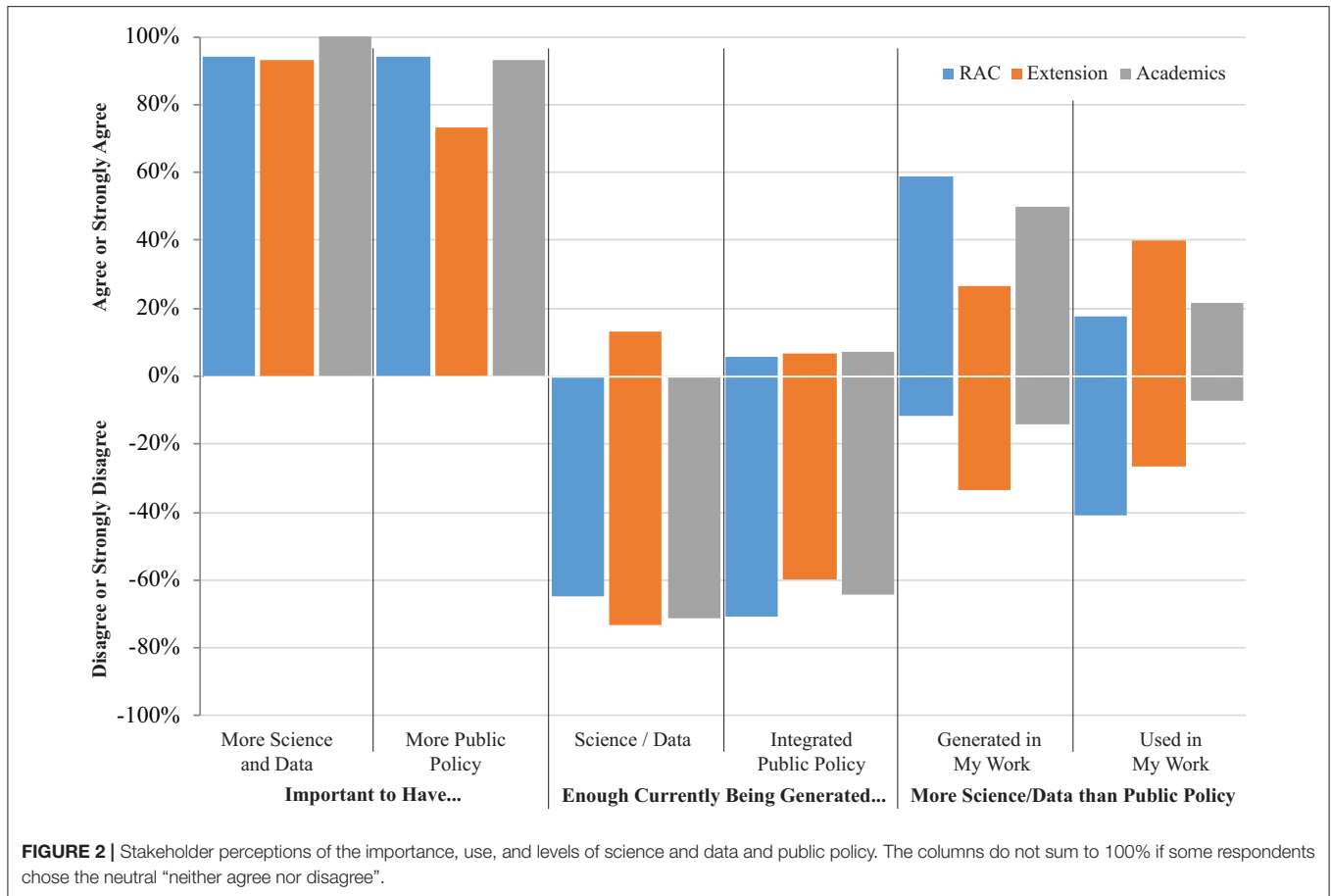
Respondents from the RAC and from Academia identified that they are generating more science and data than public policy in their work, whereas respondents from Extension were roughly split between the two dimensions. But, as **Table S3** shows, none of these responses were significant. In contrast, members of the RAC responded with the tendency to use more public policy than science and data in their work ($p = 0.016$), but the Academic respondents reported a tendency to use more science and data

than policy that was not significant. Extension did not show a preference either way. The generation of policy requires some degree of translation of science and data to inform the attempts to reach desirable outcomes, but **Figure 2** suggests that none of the three stakeholder groups are predominantly involved with this translation activity. These disparities might contribute to the low levels of integrated policy at present (**Figure 1**).

Consistent with the greater use of policy than science and data, the respondents from the RAC diverged from Extension and from Academia when forced to choose between spending on research and better data and better integrated policy (**Figure 3**). Respondents from Extension and Academia favored research and data for FEW, whereas members of the RAC were more disposed toward integrated public policy for FEW. This divergence may be explained by the more frequent use of public policy by the RAC than the other two stakeholder groups (**Figure 2**). In fact, 20–30% of Extension and Academic respondents, respectively, placed all of the importance on more research and data for FEW, and none of the members of these stakeholder groups placed all of the importance on more integrated public policy for FEW. Moreover, respondents could not choose to balance science and data equally with integrated public policy, and 60–70% favored more research and better data. In contrast, RAC members indicated a clear preference for integrated public policy. None of the respondents from the RAC placed all of their preference for spending on research and data, but 20% of these stakeholders did so for integrated policy and 73.3% favored spending on integrated policy. These differences were significant ($p = 0.0003$), and the *post-hoc* Nemenyi test indicated that the differences were between the RAC and the other stakeholder groups ($p = 0.0017$, RAC vs. Academics; $p = 0.0033$, RAC vs. Extension).

Stakeholder Assessment of Potential Barriers to FEW Sustainability

Figure 4 shows how the respondents assessed various potential barriers to science and data and integrated public policy across four groups: (1) the quality of the science and the data, (2) the quality of the policy, (3) outcomes of policy and governance, and (4) impediments to implementation. The responses suggest that the stakeholders are not concerned about the effects of the quality of the science and the data, with higher proportions consistently assessing that the potential barriers were low. The majority of the non-neutral responses from the stakeholder groups—which ranged from 41.2% (RAC) to 52.6% (Extension)—assessed that conflicting science/data is a low barrier. The p -values in **Table 4** indicate that the responses from Extension ($p = 0.078$) and the responses from the Academics ($p = 0.042$) differed from neutral. Similarly, more members of Extension and of the Academics assessed that the lack of good science was a low barrier (52.6 and 47.4%, respectively), whereas members of the RAC were relatively mixed on this assessment. These results from Extension and from Academia differed from neutral (at the 10% level, $p = 0.078$ and $p = 0.079$, respectively, in **Table 4**). Further, higher levels of respondents from the RAC (56.3%) and from Academia (52.6%) assessed inadequate science to make decisions as a low barrier, while the respondents from Extension

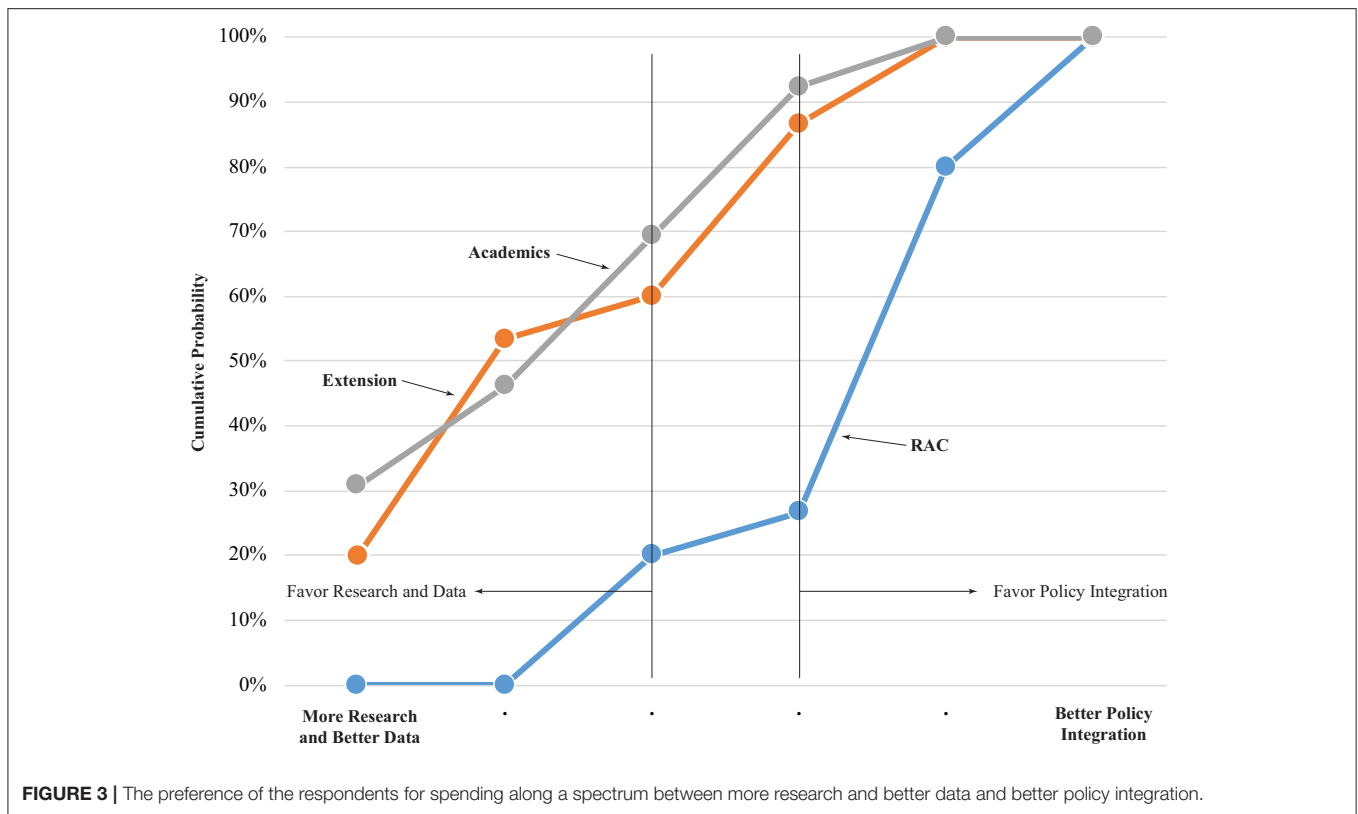


were relatively split, although none the responses from these stakeholder groups were significantly different from neutral. These mixed responses could be a result of the diversity of these stakeholders in a group and their varying roles within the FEWS nexus. For example, a RAC member who is involved with a commodity group could view good science differently than someone who works in a federal or state agency. As such, the use of data may vary by their varied roles and thus may be more of a barrier for some than others. Similarly, those in Extension have different roles, albeit with less heterogeneity than those in the RAC, and the assessments by those respondents could depend on their focus. For example, there is a plethora of salient data relating agricultural practices and nutrient management to the minimization of harmful algal blooms, but there is not as much present focus soil health; and those in 4H might be more interested in education. Responses regarding the barriers could partly depend on a respondent's role within Extension, and their participation in particular activities. Overall, however, these results could indicate that the stakeholders have faith that the quality of the science and the data that are generated is adequate for use in enhancing the sustainability of the FEWS nexus.

In contrast to the trend toward lower concern about science and data, respondents tended to assess the policy-related barriers to be high or the results were mixed. The lack of good policy was the only policy-related barrier that was assessed to be a

high barrier from all of the stakeholder groups, with a range from 41.2% (Extension) to 44.4% (Academics), but **Table 4** shows that these assessments did not differ from neutral. The majority of the respondents from the RAC assessed that all of the potential policy barriers were high barriers; in fact, their assessments of lack of policy integration efforts and lack of good policy differed from neutral ($p = 0.023$, $p = 0.016$, respectively). But the other stakeholder groups tended to be split in their assessments, although the Academic respondents seem to lean toward the assessment that potential policy-related barriers are low—with their assessment of policy fragmentation differing from neutral ($p = 0.081$). There was a difference between responses from members of the RAC and Academia regarding policy fragmentation and lack of policy integration (**Table S4**). The apparent divide between respondents from the RAC and from Academia may expose differences in how these stakeholders are involved with the FEWS nexus. For example, Academics may be more concerned with data because of their dominant role in generating knowledge from it, whereas those in Extension and the RAC in their boundary spanning roles may be concerned with other, and perhaps more numerous, factors (e.g., regulations, prices) that are more related to public policy.

The questions that were related to the outcomes of policy and governance and the impediments to implementation reflect several potential structural and systematic barriers. All of the



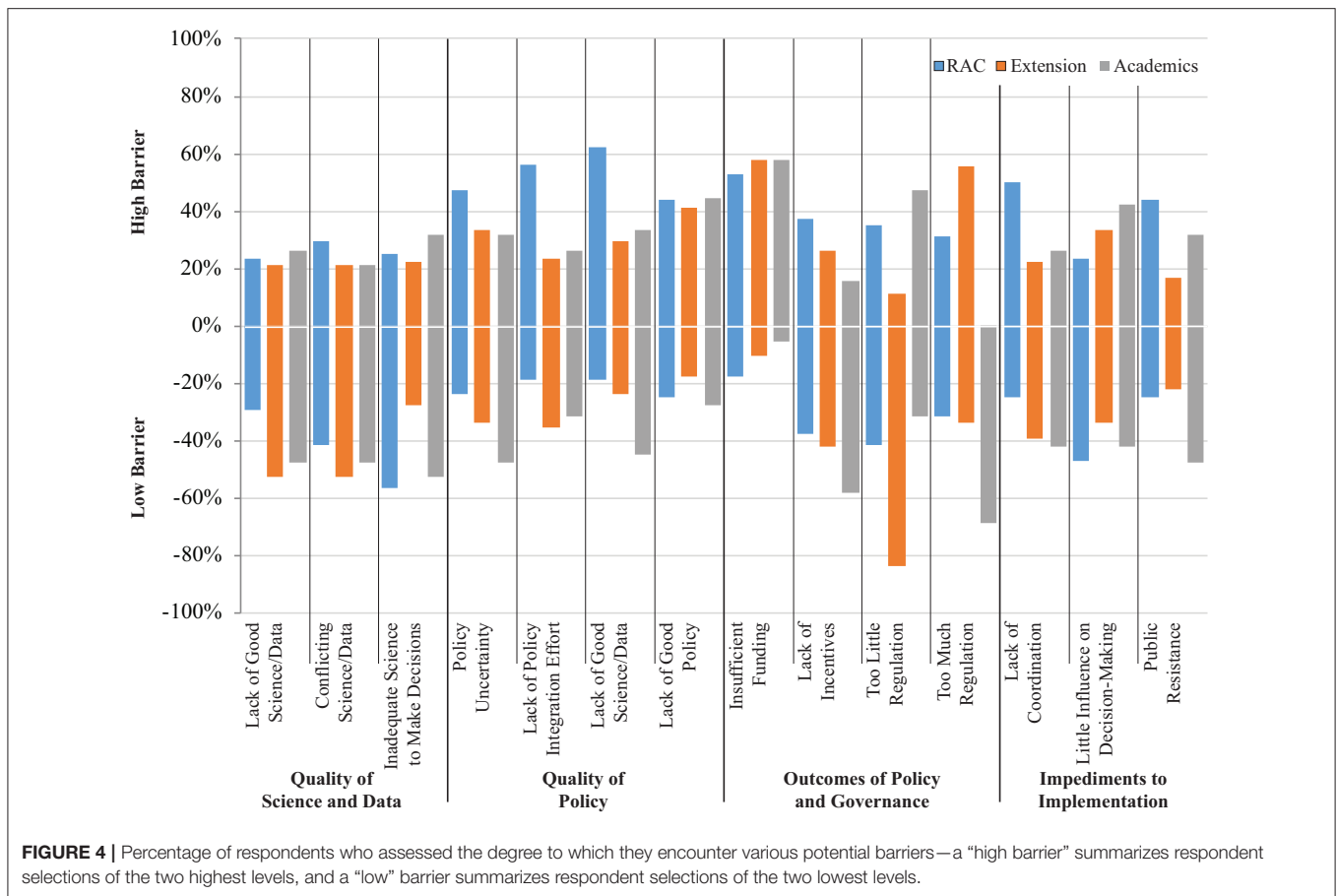
respondents assessed insufficient funding as a high barrier, with a range from 52.9% (RAC) to 57.9% (Extension and Academia), which differed from neutral for respondents from all of the stakeholder groups ($p = 0.042$, RAC; $p = 0.028$, Extension; $p = 0.002$, Academics). The lack of incentives could be perceived to be similar to insufficient funding, but the respondents appear to have understood some of the differences: 42.1% of the respondents from Extension and 57.9% of the Academic respondents assessed them to be low barriers, both of which differed from neutral ($p = 0.10$ and $p = 0.007$, respectively), but respondents from the RAC were split in their assessment. The assessments of the degrees to which too little or too much regulation were consistent within the stakeholder groups. Respondents from the RAC were tempered in their consideration of regulation—both of their assessments of too little and too much regulation were split between high and low barriers. But respondents from Extension tended to favor less regulation with their assessment that too much regulation was a high barrier (55.6%) and too little regulation was a low barrier that differed from neutral (83.3%, $p = 0.0005$). In contrast Academic respondents had the opposite assessment and tended to favor more regulation, with too little regulation being a high barrier (42.6%) and too much regulation being a low barrier that differed from neutral (68.4%, $p = 0.0004$). This difference between responses from members of Extension and of Academia on too little and too much regulation was significant ($p = 0.004$ and $p = 0.001$, respectively; **Table S4**), and could be due to the daily “on the ground” work that Extension pursues

with landowners who face regulatory impacts (e.g., permitting, inspections, operating procedures), while Academics do not consistently encounter regulations on issues pertaining to FEW in their daily research and work.

Assessments of the impediments to implementation were largely split between being high and low barriers. For example, respondents from the RAC considered lack of coordination with other organizations and agencies to be a high barrier (50.0%), which differed from neutral ($p = 0.074$), but respondents from Extension and from Academia leaned toward it being a low barrier (38.9 and 48.1%, respectively). Having little influence on decision-making had the same trend: respondents from the RAC assessed it as a low barrier (47.1%), and respondents from Extension and Academia were split. As with these other impediments to implementation, assessments of the effect of public resistance by respondents from the RAC differ from those by the other stakeholder groups: RAC assessed public resistance as a high barrier (43.8%), and Academics as a low barrier (47.4%), which differed from neutral ($p = 0.068$). The difference between RAC and Academics related to public resistance could reflect the fact that Academics tend not to interact with the public as much as the other stakeholders.

DISCUSSION

To enhance the sustainability of individual FEW systems as well as their linkages within the FEW nexus requires advances in scientific understanding of the systems and their components



(Bazilian et al., 2011) as well as integrated policy to guide the appropriation and use of the FEWS resources and address the resulting externalities (Rasul and Sharma, 2016). Success in communicating about, and within, the FEWS nexus requires a collaboration across disciplines, which is difficult in part because of the different norms and practices across disciplines, and between scientists and practitioners and other stakeholders (NAS, 2017; Fischhoff, 2018). We investigated how various stakeholders perceive and assess important characteristics of the FEWS nexus as a case study, with particular attention to issues for science and data and policy and its integration. This investigation involved an assessment of interests by various stakeholder groups who are involved in the FEWS nexus and a survey of three populations that contain various FEWS stakeholders. The stakeholders that were involved in this assessment are a small sample of all of the stakeholders within the entire FEWS nexus, and as such can provide a snapshot of the perspectives among different groups of relevant FEWS stakeholders in the Great Lakes Region.

Integrated management of FEWS systems must have collaborative action of diverse stakeholders (Helmstedt et al., 2018), and in this work we illuminated some similarities and differences in the perspectives of major stakeholder groups in the FEWS nexus. Other related studies that have elicited perceptions in the FEWS nexus have had findings such as:

regional and economic development are perceived to be major drivers of changes in water quality and effects on energy and food production, and that changes in political and economic systems are the major contributors to substantial changes in the FEWS nexus (Lawford et al., 2013); differences in assessments of how well forests are managed and whether the amount of data and information that is required by legislation is sufficient, and that information exchange is inhibited by the costs of monitoring and reporting (Hickey et al., 2007); and concerns that management measures are hindered by limited economic resources, an emphasis on scientific research over research on efficient management strategies, lack of public awareness and support, an absence of coordination among public agencies, insufficient legislation, and limited enforcement of legislation (Andreu et al., 2009). In our results, while there were differences between the stakeholder groups that we assessed, there was considerable agreement that the physical systems for FEWS are interlinked, and that related policy should be integrated at much higher levels than at present. Such results may not be unsurprising, given that it may be easier to envision resource flows, inputs, and outputs than it is to change the organization of the institutions that develop and enact regulations and policy—which tend to be organized often by the resource or the service (e.g., water, electricity) (Scott et al., 2011; Hussey and Pittock, 2012). But the emergence of the understanding

TABLE 4 | *p*-values from Wilcoxon signed-rank tests on barriers to FEWS sustainability.

		RAC	Extension	Academics
Quality of science and data	Lack of good science/data	0.61	0.078*	0.079*
	Conflicting science/data	0.54	0.078*	0.042**
	Inadequate science for decisions	0.22	0.24	0.14
Quality of policy	Policy uncertainty	0.17	0.50	0.15
	Lack of policy integration efforts	0.023**	0.16	0.16
	Policy fragmentation	0.016**	0.34	0.081*
Outcomes of policy and governance	Lack of good policy	0.17	0.12	0.12
	Insufficient funding	0.042**	0.028**	0.002***
	Lack of incentives	0.52	0.10*	0.007***
	Too little regulation	0.21	0.0005***	0.34
Impediments to implementation	Too much regulation	0.36	0.17	0.0004***
	Lack of coordination	0.074*	0.22	0.13
	Little influence on decision-making	0.49	0.67	0.35
	Public resistance	0.17	0.22	0.068*

H_0 : The responses are neutral (3) on the scale of 1 (low) to 5 (high). Significance: *** \leq 1%; ** \leq 5%; * \leq 10%.

that the regulatory and policy guidance should address the interactions between systems, implicitly or explicitly, in order to advance sustainability broadly suggests that there could be better integration of food/agriculture, energy, and water policy in the future.

Of the respondents from the stakeholder groups that we surveyed, Academics were typically least involved in policy overall, and they were also the least likely to view FEW policies as integrated. This lack of involvement with policy may be natural due to their predominant role as researchers and teachers, usually with a focus in an individual field of inquiry. The lower level of involvement with policy may also lead to the perception by the academic respondents that the policy is not well-integrated, but it is also possible that the lack of involvement with policy could provide Academic stakeholders with a more objective perspective. Regardless, the consistent assessment across the respondents of the disparity between actual and ideal levels of policy integration does not necessarily suggest that there should be more policy for FEW, but instead more *integrated* policy for FEW.

With some qualifications, there is evidence that the respondents considered the quality of policy to be a higher barrier to enhancing sustainability than the quality of the data. This evidence may be a product of how the determination and implementation of policy is mediated by ethics, values, compromises, and tradeoffs (Cochran and Malone, 2014), and the fact that data require analysis and interpretation before being translated into policy. With such mechanisms that intervene in the analysis and interpretation of data, and its subsequent codification into policy, it is perhaps probable that satisfaction with the quality of the data may be higher than satisfaction with the quality of related policy. These intervening mechanisms may also help to explain why the academic stakeholders considered “little influence on decision-making” to be a barrier to enhancing sustainability. It is also interesting to note that the Academics assessed too little regulation to be a barrier, whereas the respondents from Extension assessed too much regulation to be a barrier.

All of the stakeholder groups assessed that enhancing sustainability for the FEW nexus requires more science and data, and that doing so also requires more integrated policy. But when forced to choose between spending on creating more science and data or more integrated policy, the stakeholder group that uses more policy in their work (i.e., the RAC) preferred to spend more on policy, while the stakeholder groups that use more science and data in their work (i.e., Extension and Academia) preferred to spend more on science and data. Academics, who by virtue of their role as researchers seeking to develop knowledge, may be more likely to prefer an emphasis on science and better data. This preference may result from their daily interaction with, and understanding of, the research processes that over time relax assumptions and simplifications in the research questions and the methods. The preference for more science and data by respondents from Extension may also result from the typical role of Extension in connecting developments and understanding within the state university (e.g., from Academics) to citizens of the state. In fact, there is indication that extension may be successful in influencing some on-farm activities for larger sustainability concerns: behavioral data from farmers in the Maumee Watershed (Ohio, Michigan, and Indiana, USA) indicates that some conservation practices (e.g., soil testing) to reduce issues with nutrient loading into waterways and the negative effect on water quality are on the rise, while others (e.g., use of cover crops, subsurface placement of fertilizer) are constant over time (Wilson et al., 2018).

There may be institutional barriers that limit engagement in particular areas, or stakeholders may not make the connection between activities and outcomes, particularly when they are separated by time and place. For example, respondents from Extension did not assess the importance of their engagement with water issues, even though a number of the agricultural practices about which they inform farmers and landowners are motivated by concerns for water quality. Emphasis has been placed on “best management practices” (e.g., subsurface placement of nutrients, implementation of nutrient management plans, soil testing) to reduce the application and runoff of nutrients in order to reduce

the size and likelihood of downstream hypoxic zones (Mallin et al., 2006; Rabotyagov et al., 2010) and harmful algal blooms (Anderson et al., 2002; Kalcic et al., 2016).

The responses to the survey contain evidence that suggests that the considerations for FEW policy might prioritize the environmental dimensions over the economic and social dimensions of sustainability. But we caution against such an interpretation because the responses might reflect the makeup of the sample, corresponding concerns, and expertise rather than those of all of the stakeholders in a specific region. While we do not necessarily expect the trends to change much with a larger or broader sample from the Great Lakes Region, it is possible that different priorities or realms of engagement could emerge. For example, given less interaction with stakeholders outside of academia that was reported by the respondents from Academia, the low level of consideration for social elements of sustainability could reflect a desensitization by the Academic respondents to these issues (Howarth and Monasterolo, 2016). But it may also be that the environmental dimension may be more relevant to, or understandable by, the stakeholders than are the social or economic dimensions, even though those who work more closely with the public (Extension and RAC) reported that they consider the economic and social outcomes more than the environmental outcomes, and respondents from the RAC assess public resistance to be a high barrier to enhancing sustainability. Further, some specific issues in this region (e.g., harmful algal blooms in Lake Erie) have received a substantial amount of media coverage and prioritized funding, which may render some environmental dimensions more salient to the stakeholders in our sample.

Some of the results may also be products of the ways in which the respondents engage in the FEW nexus. In particular, the respondents from the RAC and from Extension were largely from food/agriculture sector (60–80%), but this sector was underrepresented in the Academic respondents (<20%). In addition, the energy sector was underrepresented in all three stakeholder groups (15–30%), which may result in responses that suggest that energy is less physically integrated with the other FEW systems.

Although this work is narrow in scope, given the selective sampling methods that we used, the conclusions could have wider implications. The general trends and directionality of the relationships are likely to exist in other FEW systems outside the Great Lakes Region because of the relative separation of practitioners, members of Extension, and Academics in their spheres of work. For example, we found that perspectives within Extension tended to be similar to the perspectives of Academics more often than with the more general members of the RAC. Extension is often perceived as a middle ground connecting Academia to practice. However, our findings suggest that Extension may occupy this role to a lesser extent than anticipated. Perhaps the home within state university systems positions members of Extension to be more in-line with Academics. Given the integrated nature of FEW systems, it may be important to carefully consider the role of Extension and how best to leverage their strategic position to help better bridge the gap between Academics and stakeholders like those represented on the RAC. Having the disconnects between different stakeholder groups

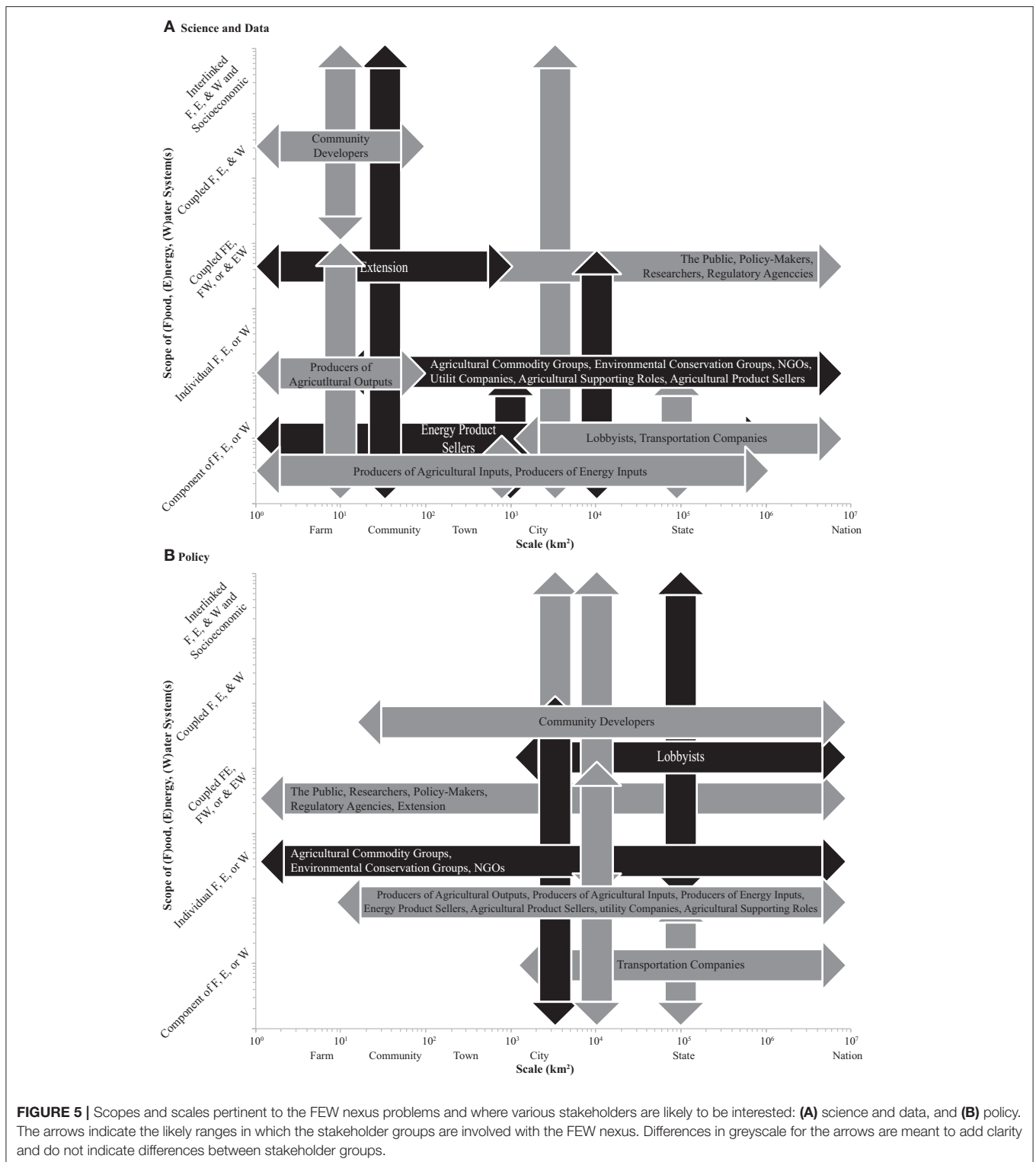
in their priorities, whether science and data focused or policy-focused, has the potential to impede innovative progress on FEW issues if each group is working toward different goals. There are many types of work within FEW nexuses, but further integration, understanding, and protection of the systems are likely to be goals that are shared by all of the stakeholders. Our results illuminate some distinctions between different stakeholder groups, but they also highlight the potential for missed opportunities for collaboration with members across stakeholder groups. Further integration of stakeholder groups may allow for more progress toward the common FEW nexus goals that underlie much of this work.

Integrating management of FEW systems requires resolving differences in spatiotemporal relationships over multiple scales, closing resource loops, and producing information that can be acted upon (Scott et al., 2011; Helmstedt et al., 2018). It is thus important to consider the scale of knowledge needs by stakeholders (Howarth and Monasterolo, 2016), otherwise messages that are tailored for stakeholders at one scale (e.g., regional) might not be useful by others that are relevant (e.g., local). Since the stakeholders whom we surveyed represent a subset of interests, involvement, and foci within the FEW nexus that we identified in **Table 1**, in **Figure 5** we present the likely ranges in scope (degree of interconnection of the system) and scale (spatial extent of consideration) in which the various FEW stakeholder groups may engage in issues that are related to FEW.

Stakeholders within the FEW nexus clearly have overlapping and nested interests and considerations in both science and data (**Figure 5A**) and integrated policy (**Figure 5B**). The scopes and scales in **Figure 5** are not independent; smaller scopes and scales are nested within larger scopes and scales, and the boundaries that separate consideration by stakeholders may be artificial and not consistent with the physical extents. For example, a watershed can extend into multiple states, and the jurisdictions of relevant agencies can also overlap but they may not be defined by the extent of the physical system. In addition, the individual components of the FEW nexus operate at different and overlapping spatial scales, such as when the water withdrawal of thermoelectric power plants responds to electricity demand on the grid, but affects the downstream water quantity and quality at the watershed level. Integrating management of FEW systems requires resolving differences in spatiotemporal relationships over multiple scales, closing resource loops, and producing information that can be acted upon (Helmstedt et al., 2018).

As the scope expands to include the social and economic contexts, and the scale tends to increase, defining and achieving sustainability in the FEW nexus may be more challenging. The lack of a commonly accepted definition of the concept of the FEW nexus (Stein et al., 2014; Cairns and Krzywoszynska, 2016) as well as the lack of a universal metric for evaluating the success of work conducted within the FEW nexus (Tevar et al., 2016) contributes to the heterogeneity of work currently considered to be a part of the FEW nexus. Accordingly, **Figure 5** indicates that interests in science and data may be related to smaller scopes and scales than interests in policy.

The depictions of the ranges of interests for stakeholders throughout the FEW nexus in **Figure 5** could be used as a



point of departure to discuss and further investigate how the joint outcomes of decision-making by multiple stakeholders depend on the relative importance of science and data vs. integrated policy promote decisions that induce better economic, environmental, or social outcomes. Such Pareto-improving goals

should seek to yield benefits that do not decrease environmental, economic, and social conditions or the welfare of FEW stakeholders.

Sustainability science entails the co-production of knowledge that occurs when doing work in complex, overlapping systems

(Clark et al., 2016), such as the FEW nexus. The FEW nexus also includes human actors, and as such the purposeful production of knowledge for action is best-served by incorporating stakeholder input in order to more fully understand the issues, trade-offs, and dynamics of the complex system(s) (Cash et al., 2003). Depending on the scope and scale of consideration within the FEW nexus, there may be opportunities for self-organized practices that enhance the sustainability at multiple levels if actors are aware of the scarcity of the resources, they have good knowledge of the system, and the social backdrop is favorable (Ostrom, 2009). Interactions at different organizational levels can lead to emergent properties that the individual components do not (Liu et al., 2015), as such it is necessary to scientifically understand the characteristics of these properties and incorporate them into policy—which by definition must be integrated. Overall, given the feedbacks and interactions between science, research, data, and policy for sustainability in FEW nexus, in combination with varied roles and interests of relevant stakeholders, this work suggests that distinctions between the importance of one aspect (e.g., data) and another (e.g., policy) may be artificial, and that proper attention must be given to the nuances of the issues, the policies, the people and their interests, and the physical, economic, or social systems that are involved.

ETHICS STATEMENT

This research was conducted with the approval of the Institutional Research Board at Ohio State University (2018E0285 and 2018E0361). The Ohio State University holds Federalwide Assurance (FWA) #00006378 from the Office

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AUTHOR CONTRIBUTIONS

JB: conceptualization, methodology, investigation, writing original draft, writing review and editing, visualization, supervision, project administration, and funding acquisition. MB: conceptualization, methodology, investigation, writing original draft, writing review and editing, and project administration. JK: conceptualization, writing original draft, and writing review and editing. YW: conceptualization, formal analysis, writing original draft, and writing review and editing. ST: conceptualization, writing original draft.

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SUPPLEMENTARY MATERIAL

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