
PRACTICE BRIDGE

Developing leaders to tackle wicked problems at the nexus of food, energy, and water systems

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The multiscale, complex challenges at the nexus of food, energy, and water systems (FEWS) demand approaches to graduate education beyond traditional disciplinary training. Here, we present a vision for training FEWS leaders developed by faculty and students from interdisciplinary graduate training programs focused on the FEWS nexus. We discuss the imperative to create interdisciplinary, next-generation FEWS leaders and the core skills and proficiencies such leaders need: employ systems thinking, thrive in interdisciplinary teams, communicate effectively, and engage diverse stakeholders and communities. These skills will prepare students to connect science to innovative, actionable solutions and to successfully lead across a variety of careers. Graduate training that integrates these approaches must, on the one hand, overcome structural, cultural, and financial barriers in higher education, but on the other hand, will help develop a community of practice capable of developing sustainable solutions for the FEWS nexus and other vexing environmental challenges.

Keywords: Graduate education; Food-energy-water nexus; Sustainability; Systems thinking; Science communication; Co-production

1. The imperative: Interdisciplinary leaders to solve wicked problems at the nexus of food, energy, and water systems

The challenge of building sustainable and secure food, energy, and water systems (FEWS; D'Odorico et al., 2018; Jones et al., 2017) requires a new generation of leaders trained in interdisciplinarity and innovation (Ledford, 2015). The FEWS nexus epitomizes “wicked problems”; i.e., those that resist definitive formulation and clear-cut solutions and whose complexity demands new modes of inquiry (Rittel and Webber, 1973). Addressing wicked problems requires deep integration across fields and transcendence of disciplinary boundaries (Harris et al., 2010; Irwin et al., 2018). FEWS are multiscale and interdependent, and they combine biophysical and social sciences, engineering, humanities, and other disciplines. Transforma-

tional leaders are needed to envision innovative and cross-disciplinary solutions in partnership with other stakeholders (Burns and Rechy, 2004).

Graduate education continues to be critiqued, however, for its shortcomings in developing STEM (science, technology, engineering, and math) professionals who can offer solutions for complex, multidisciplinary problems (Gropp, 2018; Hancock and Walsh, 2016; NASEM, 2018; NSB, 2014). Similarly, traditional STEM graduate education is seen as being mismatched with workforce demands, in part because it trains students for academia despite evidence that most graduate students pursue non-academic and/or non-research careers (Lautz et al., 2018; NSF, 2018). Other disruptors also pose challenges to traditional models of graduate STEM education, including shifts in demographics and in the nature and availability of work, a broader set of occupations demanding STEM expertise; and the ongoing, substantial changes in technologies and methods for STEM research (NASEM 2018). Graduate education must therefore adapt in order to prepare students for multiple career pathways, emphasizing interdisciplinary and experiential learning that includes a mix of core competencies, broad technical literacy, and deep specialization (NASEM 2018). Further, preparing students for a range of career pathways requires career-related experiences, project-based learning, and understanding of the ethical issues of their work and of their ethical responsibilities as STEM professionals (NASEM, 2018).

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In this paper we identify and examine core elements of interdisciplinary and experiential graduate education aimed at developing leaders with specific skills and proficiencies necessary to address environmental challenges, including but not limited to those at the FEWS nexus. We provide several specific examples of how these skills could be integrated into graduate education. We also review several of the key barriers to interdisciplinary and experiential graduate education. Finally, we suggest that building a community of practice, wherein new leaders share learning and mentorship, is necessary to transform graduate student training and, ultimately, effect a sea change in FEWS management and sustainability (**Figure 1**). We recognize that implementing lofty plans for educational transformations outlined in journal manuscripts may be stymied by the realities of time, financial, and institutional constraints. Academic breadth and depth can be at odds, faculty and graduate students are already typically overextended, and solving wicked problems at the FEWS nexus will depend on more than innovative graduate training programs. Nevertheless, our own efforts to achieve the vision we propose here, as students, faculty, and staff who have participated in U.S. National Science Foundation Research Traineeships (NRTs) focused on Innovations at the Nexus of Food, Energy, and Water Systems (INFEWS; NSF, 2020), not only inform our proposals but also underpin our optimism that innovative, interdisciplinary graduate training programs can be realized.

2. The training: Core skills and proficiencies for FEWS leaders

Next-generation sustainability leaders must be able to:

2.1. Employ systems thinking

In an increasingly complex and interconnected world, future FEWS leaders must address problems that transcend

a single discipline and have profound societal implications (Randle and Stroink, 2018). A foundational competency required to address these challenges is systems thinking (Bazilian et al., 2011; Garcia and You, 2016). Although definitions vary (Buckle Henning and Chen, 2012), systems thinking is generally identified as a cognitive paradigm emphasizing holism, whereby one recognizes how phenomena emerge from a collection of dynamic, often complex, interactions between interdependent components (Ballew et al., 2019; Lezak and Thibodeau, 2016; Randle and Stroink, 2018). Systems thinking acknowledges that systems are constantly changing, yielding outcomes that are not always intuitive or predictable (Lezak and Thibodeau, 2016; Randle and Stroink, 2018).

The benefits of systems thinking have been documented in many disciplines, including agriculture and public health (Bawden, 1991; Leischow et al., 2008). Systems thinking is often viewed as fundamental to addressing multifaceted global environmental problems (NRC, 2012), especially climate change (Ballew et al., 2019), sustainable development (Martin, 2005), and FEWS challenges (Gunda and Tidwell, 2019). The FEWS nexus is inherently interdisciplinary and demands innovative problem solving that spans resource sectors, often across large spatial and temporal scales. As such, it is vital to recognize and understand the connections, feedbacks, and concomitant effects between interdependent resource systems. Systems thinking is required to address the biophysical and technological aspects of these problems in a way that is integrated with the social, economic, and political components of the system (Ballew et al., 2019).

While the value of systems thinking for FEWS leaders is clear, most people have a limited understanding of systems thinking (Dawidowicz, 2012). Fortunately, it is a teachable skill (Lezak and Thibodeau, 2016; Sterman, 2010). FEWS-related systems thinking can be advanced by

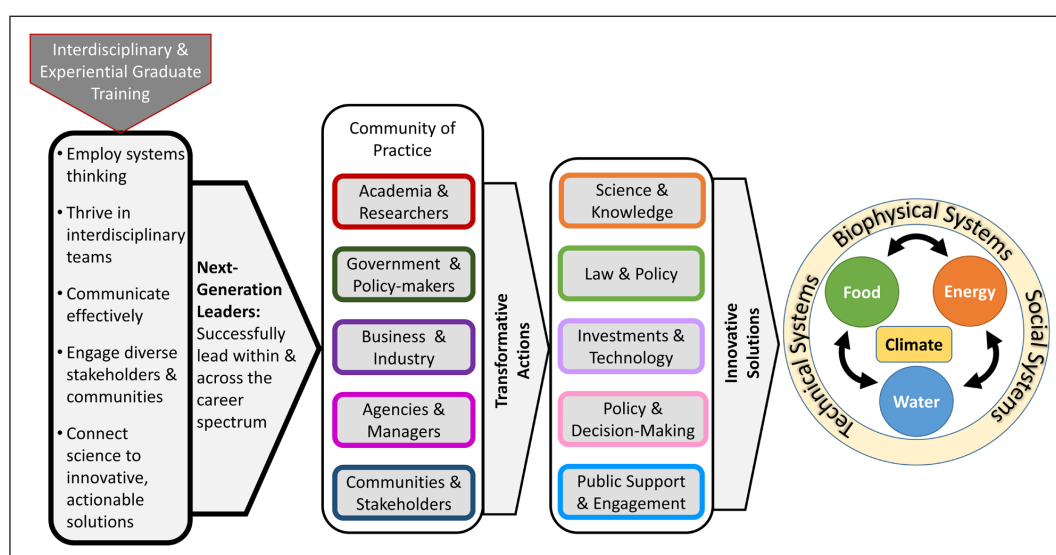


Figure 1: Developing leaders to solve wicked problems at the nexus of food, energy, and water systems via interdisciplinary and experiential graduate training. Food, energy, and water systems (FEWS) are interconnected and embedded within technical, social, and biophysical systems. Interdisciplinary and experiential graduate training is needed to build the necessary skills to allow next-generation leaders, working across the career spectrum, to transform FEWS. Creating a community of practice can provide mentorship and shared learning for emerging and developed leaders to create lasting, innovative solutions. DOI: <https://doi.org/10.1525/elementa.407.f1>

teaching skills that integrate social and biophysical data and methods, including social-ecological systems dynamics modeling, agent-based modeling, integrated hydrological and economic optimization, science-policy analyses, and life-cycle analysis (Fiksel, 2006). Applying concepts such as cross-scale linkages, boundary effects, and trade-offs to specific case studies provides an understanding of the relationships between physical, biological, and social components of particular system. Case studies on wicked problems at the FEWS nexus provide opportunities for students to apply these concepts and skills (**Box 1**).

Box 1: FEWS case-study examples.

Below are two examples of interdisciplinary challenges at the FEWS nexus that demand systems thinking. These examples provide current, real-world scenarios and are useful subjects for case studies, thought exercises, or activities for graduate courses aiming to advance FEWS-related systems thinking.

Drought adaptation on rangelands in the western United States: Agricultural producers are particularly vulnerable to climate change impacts, such as increases in the frequency and severity of drought (Thornton et al., 2014). On rangelands, drought can result in expansion of invasive plants, novel shifts in vegetation, altered fire regimes and soil water availability, and decreased forage production and quality (Briske et al., 2015). In response to these changes, ranchers can employ a range of strategies, including reducing herd size, adopting more efficient grazing systems, developing new water sources, restoring rangelands, and diversifying incomes streams. Ranchers' decisions about drought adaptation are influenced by both the specific biophysical changes occurring on their rangelands as well as social and economic processes, including commodity prices, trade policy, government drought relief programs, family finances, risk perception, available technology, and social norms. In some cases, experiences with past drought, skepticism about climate projection, risk aversion, and social norms interact in ways that reduce investments in long-term adaptation (Yung et al., 2015). Understanding drought adaptation on rangelands requires examining the ways that biophysical, economic, and social processes interact across multiple scales to both enable and constrain decisions about drought adaptation, which can be facilitated by asking the following questions: How do past ecosystem responses to drought influence the assumptions that producers make about future change? How can climate projections and ranchers' local knowledge be integrated to provide actionable information that agricultural producers trust and utilize? In what ways do political economic processes at non-local scales discourage drought adaptation on farms and ranches?

Nutrient management scenarios in the Upper Mississippi River watershed: Nitrogen (N) and phosphorous (P) loads in the Upper Mississippi River watershed drain to the Gulf of Mexico where they drive formation of a low-oxygen dead zone ("Gulf hypoxia") unable to support aquatic life (Turner and Rabalais, 1994).

Nutrient pollution is linked to the heavy use of fertilizer in corn and soybean production, a large fraction of which is used for ethanol production mandated by the Renewable Fuel Standard (Donner and Kucharik, 2008), in states like Iowa and Illinois (Goolsby et al., 2000; Jones et al., 2018). Global shifts toward high-protein diets have also intensified animal agriculture (e.g., pigs) in the region, generating N- and P-rich manure that is applied as fertilizer and can contribute, even more significantly than commercial fertilizers in some cases, to nutrient pollution of waterways (Jones et al., 2019). Opportunities for sustainable nutrient management must integrate fundamental understanding of nutrient transport and storage processes; systems-scale modeling of nutrient flows linking changes in land use to water quality; more efficient approaches to manure management [e.g., pre-application analysis of crop N availability in soil and manure; Jones et al., 2019] and development of on-farm technologies (e.g., anaerobic digesters for resource recovery) that incentivize limiting manure application; broader adoption of practices including cover crops and edge of field controls (e.g., bioreactors, wetlands, and riparian buffers) for non-point source pollution; and a deeper appreciation for how policies and programs for food and energy production influence water quality. Example discussion questions include: How can modeling and mass balance be used to better understand sources, sinks, and transformations of nutrients across watersheds that differ in land use, population (urban vs. rural), and size? What does an integrated food, energy, and water policy framework look like that promotes more sustainable agriculture and biofuel production while more proactively protecting water quality?

2.2. Thrive in interdisciplinary teams

Creating effective interdisciplinary research teams has boldly been called *the* solution to solving the world's most complex problems (Ledford, 2015), and there has been a specific call for increased interdisciplinarity to solve FEWS problems (Albrecht et al., 2018; Rodríguez et al., 2019). Interdisciplinary team science is collaborative research by two or more scientists that integrates data, techniques, and perspectives from two or more disciplines to solve problems whose solutions are beyond the scope of a single discipline (NAS et al. 2005). There is evidence that interdisciplinary team science is more innovative, productive, and impactful than discipline-specific science – both within and across specific disciplines (Hall et al., 2012; Uzzi et al., 2013; Wang et al., 2015). Systems thinking requires interdisciplinarity, and even more powerful is transdisciplinary research, which transcends disciplinary boundaries to develop wholly new and unprecedented frameworks for novel science (Choi and Pak, 2006). Here, we focus on interdisciplinary training and research, although the ultimate goal is transformative, transdisciplinary solutions.

Innovative graduate training is recognized as central to increasing interdisciplinary research capacity (Borrego and Newswander, 2010). Graduate education should

provide students with in-depth, applied team-science experiences (**Box 2**, **Box 3**) as well as targeted training in relevant interpersonal and team-related skills (Committee on the Science of Team Science et al., 2015; Hall et al., 2018). Training should include:

- Methods for developing shared language. Jargon is a barrier to interdisciplinary collaboration (IoM, 2000). Disciplinary terms, paradigms, and theoretical frameworks need to be understood by team members (Nielsen-Pincus et al., 2007), and methods such as mind-mapping can be taught and applied to illustrate varied perspectives (e.g., Winowiecki et al., 2011).
- Strategies for effective team development and function. Team members should be familiar with the stages of team development (e.g., Hall et al., 2012) as well as best practices for successful team building, such as developing a shared mission statement containing quantifiable objectives and proactively dealing with conflict. They should also be exposed to the science of team science, the body of research examining what factors contribute to the success of such efforts.

Box 2: Co-labs: Interdisciplinary laboratory experiences.

Participation in co-labs – collaborative, interdisciplinary, product-driven research efforts among students that are formed, guided, and mentored by faculty from different disciplines (Bosque-Pérez et al., 2016) – are effective means of providing experience in conducting team science. For example, a co-lab could entail faculty and students from biophysical (e.g., geosciences) and social (e.g., economics, sociology) science disciplines working together to review relevant research, discuss disciplinary assumptions, define a shared gap in the literature, and combine data to produce a review paper on an interdisciplinary FEWS topic such as prediction of how changes in hydrology may affect working agricultural landscapes.

Box 3: Experiential learning for innovative solutions.

Experiential learning provides particularly important opportunities for students to develop skills in innovation (Neck and Greene, 2011) and actionable science (Evans et al., 2015). Getting students out of the laboratory and into the field provides opportunities to interact directly with FEWS practitioners and systems. Client-based and use-inspired FEWS training exercises can be particularly effective, leveraging opportunities to engage with decision makers, practitioners, and innovators, both on and off campus. These experiences promote learning and application of key FEWS concepts, as well as professional development and networking. Local field trips to FEWS-related locations are a simple approach that can spur new thinking. There are also existing organizations that provide deeper opportunities to expose students to entrepreneurialism; for example, students could participate in NSF's I-Corps program or intern with small businesses involved in the Small Business Innovation Research (SBIR) program.

- Qualities of an interdisciplinary collaborator. A good collaborator must show a willingness to engage. Exposure to team science can help students overcome discomfort or distrust of interdisciplinarity (Nielsen-Pincus et al., 2007), and help them become a “T-shaped” team member wielding both the requisite depth and breadth of disciplinary expertise to work in interdisciplinary collaborations. “T-shaped” aptitudes, such as empathy building, analytical thinking, and problem solving, can be taught through experiential learning (Conley et al., 2017). Team scientists understand how to work with different personalities and value trust and self-reflection (Costley and Pizzolato, 2017).

2.3. Communicate effectively

By honing their science communication skills to share their science with non-scientists, leaders can better use science to inform decision-making and policy (NASEM, 2017; Smith et al., 2013). Many decisions rely on scientific knowledge; there is a need for scientists to serve as “honest brokers” in discussing the pros and cons of policy alternatives (Pielke, 2007). Furthermore, when science is communicated well, the public's appreciation and understanding of science can increase (NASEM, 2017). In contrast, poor or ineffective communication can be costly to both science and society, as continued scientific progress relies on public support (Fischhoff and Scheufele, 2013). Finally, emerging leaders can become recognized experts more quickly through building buzz around their research – an additional benefit of effective science communication.

Research to improve the efficacy of science communication is needed (NASEM, 2017), and many evidence-based best practices for science communication and training are emerging. Science communication training should start with the science of science communication and a review of effective techniques, which are sometimes counterintuitive (Fischhoff and Scheufele, 2013; Jamieson et al., 2017). For example, people's perceptions and use of science are influenced by their beliefs and ideologies (Eveland and Cooper, 2013; Fiske and Dupree, 2014). FEWS leaders must therefore practice refining key messages for specific audiences (Cooke et al., 2017; Mercer-Mapstone and Kuchel, 2017) and selecting communication frames that resonate with the belief systems of the intended audience (e.g., Dixon et al., 2017). Other key elements of science communication training include using the principles of narrative storytelling (Dahlstrom, 2014); crafting a clear, pithy message without jargon and focused on the “so what” (Baron, 2010); effectively communicating uncertainty (Friedman et al., 2012); employing a diverse portfolio of communication approaches (Cooke et al., 2017), such as policy briefs, public lectures, science cafes, and elevator pitches; and maintaining clarity and scientific rigor (Brossard and Scheufele, 2013; Klahr, 2013).

Further, scientists often envision that they are educating the public (Dudo and Besley, 2016). However, the “knowledge-deficit model” – the assumption that non-scientists would integrate scientific information into decision-making if they simply knew more – has been largely refuted (Simis et al., 2016). Instead, people's perceptions and use of science are influenced by their beliefs and ideologies (Eveland and Cooper, 2013; Fiske

and Dupree, 2014). FEWS leaders must therefore learn to target messages to specific audiences (Cooke et al., 2017; Mercer-Mapstone and Kuchel, 2017) and to select communication frames that resonate with the belief systems of the intended audience (e.g., Dixon et al., 2017). Perhaps the most underdeveloped skill in training good science communicators is building trust and relationships (Kearns, 2012). Two-way dialogue is essential to science communication, and that requires listening and humility, cultural competency, and ethics and empathy (Priest et al., 2018), themes that we echo in the stakeholder and community engagement section below.

2.4. Engage diverse stakeholders and communities

Decision-making in linked ecological and social systems, such as FEWS, demands the inclusion of diverse stakeholder interests. Stakeholder participation can lead to more innovative, decision-relevant results and publicly accepted solutions (Caves et al., 2013; Johnson et al., 2013). Critically, stakeholder engagement precipitates social learning – individuals learning through social interactions leading to societal change (Reed et al., 2010) – which results in greater consensus and likelihood of concerted action toward a solution (Collins and Ison, 2009). Stakeholder engagement relies on dialogue rather than one-way communication of research results to stakeholder groups (Jolibert and Wesselink, 2012). Building relationships allows stakeholders to invest personally and professionally, sustains complex projects over time, and better incorporates the science built by stakeholders and communities into planning and policy.

Although there is no single method for engaging stakeholders, Talley et al. (2016) identify five features of engagement that benefit both stakeholders and researchers. Engagement must: 1) set clear objectives, 2) systematically represent stakeholders, 3) use relevant methods (such as public meetings, focus groups, advisory panels), 4) create opportunities for co-ownership of process and knowledge, and 5) reflect on processes and outcomes. Key elements of stakeholder engagement also include creating physical and mental space for interaction; aligning motivations through understanding of values, goals, and benefits; and building trust (Schoonover et al., 2019).

Training in research ethics, intellectual property agreements, cultural competency, power dynamics, and group negotiation can prepare students for effective stakeholder engagement. Students should understand how to engage non-academics in setting research objectives, discussing and assisting with data collection and analysis, dissemination of research results, and how each role differs (Phillipson et al., 2012). Targeted training in working with regionally important, but often underrepresented cultures or populations – such as indigenous groups – can improve understanding of different knowledge systems and help build new partnerships. Students should understand the concepts of implicit and confirmation bias, the effects of worldviews on understandings of and participation in science, and the tools and methods to address these challenges (McInerney et al., 2014). Students must also acknowledge that there are tradeoffs for stakeholders – their participation is time consuming and

they may not be compensated for their intellectual property (Garnett et al., 2009). Knowing when not to engage is as important as knowing when and how to engage (Reed et al., 2018). Training in effective stakeholder engagement can be advanced by having a diverse student cohort and faculty, promoting insight from and access to diverse knowledge bases and philosophies.

2.5. Connect science to innovative, actionable solutions

Actionable, decision- and policy-relevant science must define the coming decade of sustainability science (Miller et al., 2014; Rose et al., 2018). Leaders who know how to create and apply innovative, solutions-oriented information can help society adapt technologies toward more sustainable FEWS systems. Universities and graduate education are key to training leaders in innovation and entrepreneurship toward solutions for the world's most complex issues (Thorp and Goldstein, 2013). The ability to connect science to solutions is the culmination of the skills discussed above.

Policy- and decision-relevant science must be timely, trusted, and rigorous, both in the eyes of researchers and decision makers (Cook et al., 2013). This means scientists need to work closely with decision-makers (**Box 4**) to build trust and ensure that research responds to the needs of end-users (Pannell and Vanclay, 2011). In addition, FEWS leaders must not only consider whether their science is locally relevant and culturally appropriate, but also envision FEWS sustainability from local to global scales (Blewitt, 2010).

To effectively produce actionable science, FEWS leaders need to recognize that they are working within 1) complex systems – requiring that they negotiate tradeoffs between ecological, social, and economic needs; 2) adaptive systems – giving rise to new social and technological innovations; 3) innovation systems – such that new research can generally only be translated to useable solutions when it can be integrated with existing technologies and local and social norms for a given place and problem; and 4) political systems – because “power is knowledge” and research

Box 4: Co-production for actionable science.

Co-production of knowledge is perhaps the most intensive but effective means of developing policy-relevant science (Beier et al., 2017). Co-production involves collaboration between diverse actors, including scientists and practitioners, who connect science and other types of knowledge with specific decisions and visions of the future, and then co-design a process to formulate questions, methods, and outputs. Ideally, co-production advances the kinds of societal transformations required by wicked FEWS problems by shifting the relationships between science institutions, sustainability governance, and society at large (Wyborn et al., 2019). Students should understand the time commitment required for co-production specifically as well as the greater likelihood that co-produced research will be used by decision-makers (Reed et al., 2018). Ultimately, co-production can be best taught by doing and requires faculty support and patience throughout the research project.

results are often viewed as supporting some and threatening others, understanding and accepting the political context is key (Clark et al., 2016). To account for these realities, students should be trained to create science that is both useable and *used* by collaborating and engaging with a range of stakeholders, fostering social learning by prioritizing learning as much as knowing, as well as recognizing how their research is situated within a broader knowledge governance system where social norms and political processes influence how information is produced and decisions are made (Clark et al., 2016).

Novel, innovative solutions may be as important as decision-relevant ones when tackling wicked problems. Innovative solutions arise when scientists believe innovation is appreciated, are given a safe space to discuss ideas without judgement, and are provided with a diverse intellectual community with whom to discuss the ideas further (Anderson and West, 1998). Training leaders to innovate requires exposure to the systems-thinking skills described above and to the detailed complexities of FEWS problems, such as spatio-temporal disconnections between food, energy, and water systems at local to regional scales, as well as being fully fluent in the input/output and tradeoffs of food-energy-water interactions (Helmstedt et al., 2018).

2.6. Successfully lead across the career spectrum

Effecting transformative change in FEWS will require leaders that excel at the five skills listed above. But they must also combine those skills with effective and transformative leadership. Further, that leadership must permeate research, engineering, management, and policy-making. As such, graduate education should seek to provide the skills, knowledge, and competencies to pursue and succeed in a range of STEM careers. Many non-academic employers find that employees straight out of graduate school lack necessary skills for job success (CGS and ETS, 2012). Employer-identified skills for job success include professionalism and work ethic, teamwork and collaboration, critical thinking and problem solving, ethics and social responsibility, oral and written communication, and leadership (TCB, 2006). Only about one-quarter of employers found that 4-year college graduates were proficient in the first four skills, and about one quarter thought graduates were deficient in the last two (TCB, 2006).

Developing leaders ready to tackle difficult FEWS problems from within the varied organizations in which they will make their careers requires a broader view of what graduate education entails (St. Clair et al., 2017). Graduates who enter the workforce with professional and leadership skills are more valuable than employees who must learn these skills on the clock. Indeed, several of the critical skills we highlight above are necessary for transformational leaders – innovation, communication, and engagement; FEWS inherently provides the other key ingredient – conflict (Burns and Rechy, 2004). As such, conflict-resolution skills are another critical element for developing leaders across the career spectrum.

3. The challenge: Overcoming barriers

Interdisciplinary, experiential, and career-based training in FEWS transcends the traditional organizational and incentive structure associated with most universities. Thus, institutional change and buy-in is necessary to overall program success (**Box 5**). Barriers to such change may be 1) structural, such as challenges working across discipline-specific departments, lack of support for interdisciplinary team teaching, or lack of incentives for interdisciplinary or community-based research; 2) cultural, such as biases about specific disciplines, lack of experience with and knowledge about effective interdisciplinary or experiential teaching, or lack of long-term planning to institutionalize the courses and opportunities for altered graduate education; and/or 3) financial, in particular insufficient resources (Blanco-Portela et al., 2018; Coops et al., 2015; Marchesi and Rolls, 2016).

The conventional disciplinary structure of higher education both reinforces and is reinforced by a culture that privileges discipline-specific research (IoM, 2000). Most institutions lack guidelines and incentives for research and training across units including how to navigate disciplinary differences related to publishing, teaching, or team-teaching outside of the faculty's home unit and co-advising and/or training students from other departments. As noted above, many STEM programs are designed for future academics, and there is a lack of support for experiential-learning or career-planning.

Box 5: Programmatic actions to overcome barriers.

The initial nine NRT programs identified the following actions for gaining and growing institutional support for FEWS training programs:

- Secure institutional commitment. Build relationships early in the planning process with administrators who can allocate resources and provide long-term commitments.
- Explicitly and openly discuss the need for incentive structures that reward interdisciplinary, community-based, and experiential research and training.
- Build ongoing support through community. FEWS training programs can leverage relationships with organizations that support interdisciplinary, experiential learning including non-profits, tribal colleges, extension agencies, and local businesses. External advisory boards can provide advice regarding skills needed for multiple career pathways and promote the value of FEWS training to university administrators. Combined with faculty and affiliates from across campus, these multiple stakeholders can form a community of practice for knowledge sharing, continued learning, and program support necessary to sustain the program for the long term, as discussed in section 4.1.
- Establish clear objectives, track progress, and adapt. Begin training programs with a strategic plan or a "Theory of Change" process (Weiss, 1995), then use rigorous evaluation to adapt and improve (**Box 6**).

A final barrier specific to interdisciplinary FEWS training is that very few universities have training programs focused on food, energy, and water systems, and new programs must be created from scratch, even when supported by the NSF NRT program. Published literature regarding examples, evidence, and best practices for teaching FEWS is limited. There are few turnkey FEWS training resources available, and nearly all FEWS courses require new preparation by faculty.

4. The reward: Community of leaders to transform FEWS

4.1. A community of practice to transform FEWS toward sustainability

Effecting transformative and lasting changes to FEWS requires more than just rethinking graduate education, or even developing a cadre of future leaders. Lasting changes to FEWS will also require a framework to grow and sustain

Box 6: Strategic FEWS training from plan to evaluation to outcomes.

Beginning with a “Theory of Change”, whereby planning includes a clear statement of objectives and an explicit and detailed explanation of how those objectives will be reached, is an effective means for building a new program. Objectives can be tied directly to core skills, but also to more intangible goals such as whether the new training program is effecting institutional or community change, increased STEM diversity, or the creation of actionable science. A Theory of Change can also provide a framework for a formal assessment plan, linking training activities to intended outcomes through iterative evaluation and program improvement (**Figure 2**).

a critical mass of leaders who can drive global change. The next generation of FEWS leaders will need an ecosystem of mentors and peers to foster life-long learning in FEWS and innovation throughout their careers. These needs can be met by developing a FEWS-focused Community of Practice (CoP), which will act as a network of people with a shared passion for FEWS who learn from and support each other through regular interactions (**Box 7**).

Communities of Practice provide ideal landscapes for sharing information and data, disseminating best practices, brainstorming and commenting on new ideas, and identifying existing knowledge and knowledge gaps

Box 7: A budding FEWS Community of Practice.

A FEWS-inspired CoP can maximize the return on investment for NSF and FEWS-focused NRTs. The workshop that served as the impetus for this paper kicked off a new FEWS CoP. This budding CoP seeks to share resources for improved interdisciplinary FEWS training as well as create the intellectual and career network for a cadre of new FEWS leaders. Methods for sustaining a FEWS CoP include informal time to build relationships through meet-ups at conferences, with opportunities for students, as well as virtual events through video conferencing and webinars. Developing a CoP will also be advanced by sharing of resources, including infrastructure to house shared datasets and methods toolboxes; coordinated internship opportunities across universities and partnerships; job and funding opportunity lists; teaching materials, case-study examples, and turnkey training modules; alumni-profiles and contacts for career networking; and a publication clearing house. Opportunities for collaboration on proposals, publications, and trainings can also help build, and arise from, a CoP.

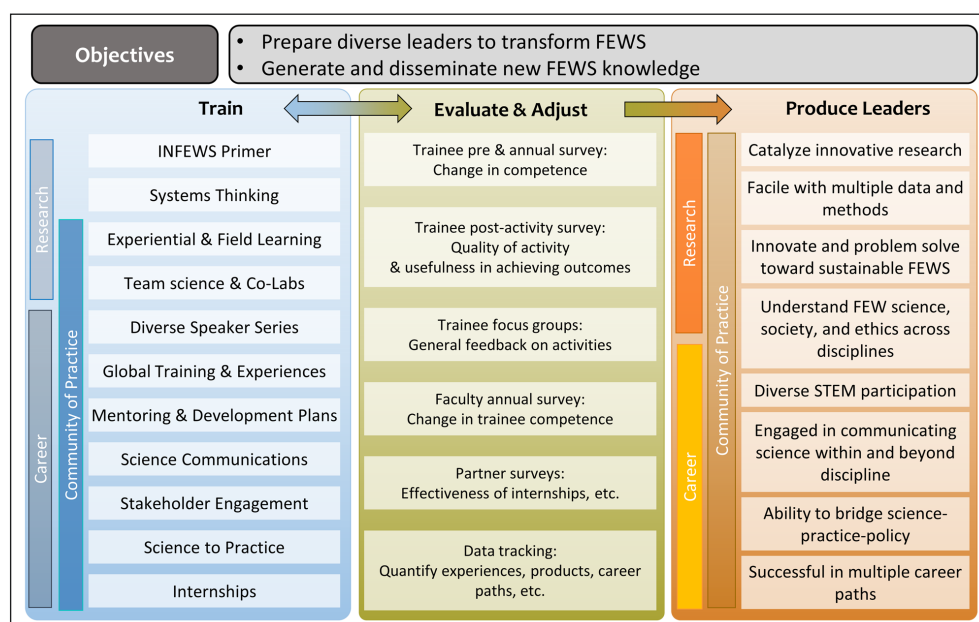


Figure 2: Schematic of “Theory of Change” as a road map for innovative, interdisciplinary graduate education. Effective programs will be guided by governing objectives and link training elements (left column) and evaluation and adjustment mechanisms (center column) to produce leaders with core skills. DOI: <https://doi.org/10.1525/elementa.407.f2>

(Wenger and Snyder, 2000). Within graduate training programs, CoP offer opportunities for universities to leverage their relative strengths, find synergies, and disseminate information across different campuses (Pharo et al., 2014). For example, through a CoP, participating students could select from a suite of FEWS-related workshop modules all of which a single campus could not offer because of limited resources. Sharing of syllabi, FEWS case studies, grading rubrics, and evaluation materials would obviate the necessity of creating new programs from scratch at budget-limited institutions.

Beyond training, CoP can provide a career and support network for innovative FEWS research and leadership. CoPs are essential in supporting interdisciplinary approaches to innovative solutions (Cundill et al., 2015). A FEWS-focused CoP would address the need to move from theory to practice in operationalizing FEWS nexus goals (Leck et al., 2015). A broader-scale CoP can be facilitated through virtual infrastructure, allowing widespread connectivity and participation among members (Ardichvili, 2008). This type of virtual community would provide a place where FEWS leaders at any stage in their career from around the globe could gather not only for mentoring, support, and continuing education, but also to use their collective expertise for solving wicked problems at the FEWS nexus (Mohtar and Lawford, 2016). A broad FEWS-focused CoP may also be better positioned to collaborate and engage with diverse stakeholder communities to identify, analyze, and solve problems (Mohtar and Lawford, 2016). Moreover, because there is the expectation of continued participation in the CoP over time, participants can also create new partnerships for learning and knowledge generation that help grow the CoP and make it self-sustaining (McDonald and Cater-Steel, 2017).

4.2. New training approaches for new leaders

Strategic training of FEWS leaders is needed to produce lasting change in FEWS sustainability. Students who can think in complex systems, thrive in interdisciplinary teams, and communicate effectively with diverse stakeholders and communities will be prepared to connect science to solutions and address wicked problems throughout their careers. Future FEWS leaders must recognize and address the structural, cultural, and financial barriers to achieve these goals. Joining forces across universities, institutions, and stakeholders will enhance this training and create a much-needed FEWS CoP.

The concepts and themes identified in this paper reflect several of the U.S. National Science Foundation's 10 "Big Ideas", which focus research investments and address emerging opportunities and challenges (NSF, 2019). For example, the ideas presented here directly address "transforming education and career pathways to help broaden participation in science and engineering." Indeed, FEWS issues tend to attract diverse students – from different disciplines, political perspectives, and nationalities – creating a broader research community. Additionally, NSF is committed to "growing convergence research," recognizing that tackling grand challenges, including those at the nexus of FEWS, requires:

"the merging of ideas, approaches and technologies from widely diverse fields of knowledge to stimulate innovation and discovery.... Convergence builds and supports creative partnerships and the creative thinking needed to address complex problems (NSF, 2019)."

Convergence research will require not only an interdisciplinary, but ultimately a diverse, transdisciplinary community of practice that can envision creative solutions for emergent issues. Innovative graduate training programs, such as NRTs, are essential for preparing a new generation of leaders to tackle present as well as future global challenges. Society demands a new cadre of leaders, and graduate training programs must rise to these demands.

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The authors have no competing interests to declare.

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