Board 390: Student-Led Collaboration for Data-Driven Decisions in Food, Energy, and Water Systems

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Background and Problem Statement

Sustainable provision of food, energy and clean water for the long term requires understanding of the interdependencies among supporting systems. Stakeholders such as government bodies, consumers and investors may focus too much on short-term fixes, while researchers tend to focus too narrowly on tractable problems with limited scope. Providing implementable solutions requires understanding the motivations and incentives of farmers and rural policy makers. Expanding the scope and fostering a long-term perspective in research efforts aimed at effective innovations at the nexus of these food, energy and water systems (FEWS) exposes the need for data-rich system modeling with analytic capabilities for diverse types of data.

Agriculture occupies the epicenter of the FEWS nexus. It is an increasingly energy intensive enterprise, but is also a potential source of energy. Agriculture places large demands on water supplies while poor practices can degrade water quality. Crop and livestock production for food uses water and generates runoff that degrades water quality with implications for public health, water treatment costs, and downstream ecosystems. It also requires energy to power vehicles, maintain livestock habitats, and manage wastes. Renewable energy production from biomass can compete with food production for land and water resources. Management of water supply and quality requires an intricate balance between demand from agriculture and energy for water and other societal and ecosystem needs for water. Each of these interactions creates opportunities for modeling driven by sensor-based and qualitative data collection to improve the effectiveness of system operation and control in the short term as well as investments and planning for the long term. However, the large volume and complexity of the data collected creates challenges for visualization, decision support, and stakeholder communication.

A National Research Traineeship (NRT) program nearing its conclusion aimed to build a community of researchers that explores, develops and implements effective data-driven decision-making to efficiently produce food, transform primary energy sources into energy carriers, and enhance water quality. We focused on the impacts of agricultural practices in the Midwestern US on the interactions of food, energy, and water systems. The goals and associated objectives were:

Goal 1. Foster interdisciplinary research based on data-intensive methods.

- *Objective 1.1*. Increase collaboration between researchers in FEWS domains and those in decision modeling and analytics.
- *Objective 1.2*. Expand research that leads to workable, synergistic solutions for food production, renewable energy and clean water in the social, economic and geographic context of Midwest agriculture.

Goal 2. Educate STEM graduate students for a range of research, research-related and entrepreneurial careers employing data-driven modeling at the FEWS nexus.

- *Objective 2.1*. Train students in the effective use of systems modeling to understand the interactions among food production, renewable energy generation and water quality along with their business and policy contexts.
- *Objective 2.2*. Improve decision science and analytics skills in FEWS researchers to improve their use of heterogeneous data from biological, hydrological, chemical, thermal, social and economic processes.

Goal 3. Prepare STEM graduate students to work effectively in multidisciplinary teams, communicate effectively with stakeholders, and identify economically sustainable innovations.

- *Objective 3.1*. Develop and test mechanisms and structures for mentoring, social support and team-building that aid retention, productivity and timely degree completion of STEM graduate students.
- *Objective 3.2*. Develop and test mechanisms and structures for providing professional and communication skills relevant to careers in academia, government, or industry, including startups.

As the project progressed, we continually grappled with one over-arching question: how to induce busy graduate students to engage in the training and community-building activities that would produce our desired outcomes – particularly, multidisciplinary collaboration on FEWS-related research? The solution we increasingly adopted was to involve trainees in the leadership of nearly all program components. Ultimately, this sharing of program ownership has resulted in the final cohort choosing to engage in multidisciplinary collaboration as a way to satisfy a requirement we designed for documenting individual trainee learning outcomes.

This paper is organized as follows. The next section describes the structure of the program and its grounding in scholarship. Then we describe project outcomes in the context of each goal, with emphasis on how student leadership modified our initial plan and helped to attain the outcomes. We conclude with results of the project evaluation and lessons learned.

Program Structure

The structure of the traineeship program was based on Golde and Walker's "Stewardship framework" for doctoral education [1], which posits that PhD holders (in industry, academia, or elsewhere) act as stewards of their particular disciplines, with their stewardship activities described as: *Conservation, Generation,* and *Transformation. Conservation* of disciplinary knowledge is passed to students through coursework and other foundation-laying academic inquiry. *Generation* takes place when stewards produce new knowledge that contributes to the field. *Transformation* is the translating of expertise to a variety of audiences. We used the key actions derived from interviews with PhD

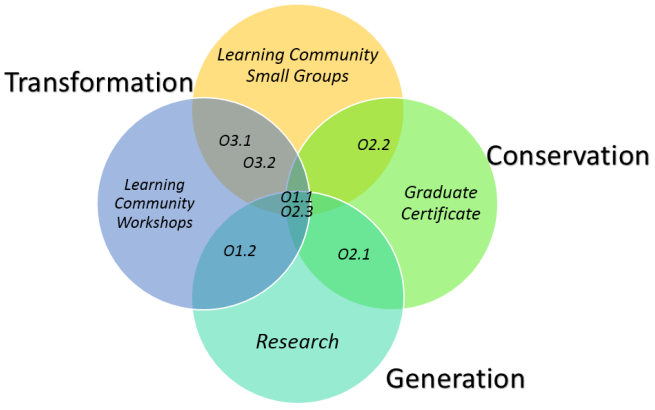

Figure 1. Project objectives mapped to components of the Traineeship under the Stewardship framework.

holders [2] as guidelines to design Traineeship activities (see Fig. 1). In this context, the "discipline" is defined as core competencies in data analysis, synthesis, and decision-making for FEWS.

The key components of the traineeship program are (Figure 2):

1) The student's thesis or dissertation research on a FEWS issue for the *generation* of new knowledge;
2) A graduate certificate in Data-Driven Food, Energy and Water Decision Making, which consists of 2.5 credits of core courses and 9 credits of electives, as described in Table 1, that represents *conservation* of knowledge;
3) A Graduate Learning Community [3] for *transformation* of knowledge that includes
    a. a two-year series of monthly workshops, and
    b. weekly small-group activities designed to enhance the trainees' interdisciplinary communication and collaboration skills;
4) An e-portfolio that contains artifacts from research or coursework that demonstrate attainment of key competencies;
5) An annual symposium convening trainees, faculty advisors, and the external advisory board.

To avoid extending the time to degree completion, the certificate coursework was designed to be flexible enough to integrate seamlessly into each trainee's primary degree program of study. The two years of the workshop series could be taken in either sequence, so that the whole traineeship program could be completed in two years.

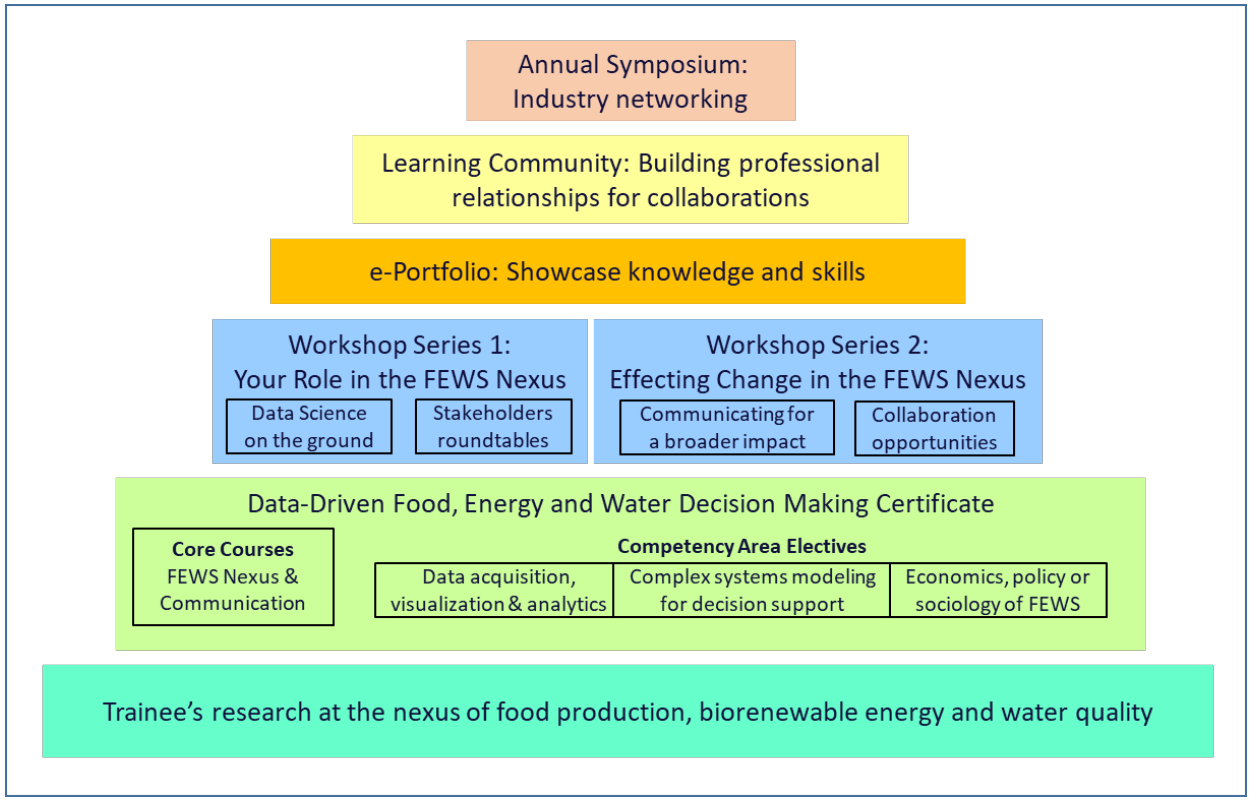

Figure 2. Components of the traineeship program.

Evolution

We spent a planning year on developing the traineeship components and recruiting the first cohort of trainees [4]. Over five years beginning in Fall 2019, four cohorts of trainees, totaling 31 MS and PhD students from 16 graduate programs at [blinded] University (approximately half drawn from five different engineering disciplines) have completed the major components of the two-year program (the fourth cohort will complete its second year in May 2024).

The interdisciplinary research targeted by Goal 1 relies on the team-building and soft skill development addressed by Goal 3. The knowledge and skills at the focus of Goal 2 enable a common platform for effective research, while its attention to career preparation provides motivation for gaining experience in multidisciplinary work as a student. Thus, because Goals 3 and 2 lay the groundwork for Goal 1, we discuss the project evolution for each goal in reverse order. Our planned approaches and activities to achieve the goals and objectives, shown in Table 2, evolved and gained effectiveness with increased student leadership.

Table 1. Input-output portion of logic model, color coded to match Figure 2.

Project Goals	Inputs	Activities	Outputs
G1. Foster interdisciplinary research based on data- intensive methods.	• Trainees • Interdisciplinary Faculty/Mentors • Institutional Support/Infrastructure • Investigators' Knowledge/Expertise • NSF Funding • Industry Advisory Board	Collaborative research in (Theme 1) Technologies and practices to increase agriculture's contributions to energy supply while reducing its negative impacts on water quality and human health; (Theme 2) Data science to increase crop productivity within the constraints of sustainable intensification; (Theme 3) Decision sciences to manage tradeoffs and promote best practices among diverse stakeholders.	•Proposals to external funding agencies •Conference papers and presentations •Reports to funding agencies •Journal publications •Seminars •Stakeholder workshops •Research symposium •Theses/dissertations
G2. Educate STEM graduate students for a range of research, research-related and entrepreneurial careers employing data-driven modeling at the FEW nexus.	• Trainees • External Evaluator • Interdisciplinary Faculty/Mentors • Institutional Support/Infrastructure • Investigators' Knowledge/ Expertise • NSF Funding • Program Coordinator • Academic Advisory Board	•Develop certificate curriculum •Develop new core courses •Develop co-curricular career preparation workshops	•Graduate certificate approved by Graduate College •Curricula for ABE 585, GR ST 566, Entrepreneurship course •Trainees' ePortfolios •Trainees' IDP & CV
G3. Prepare STEM graduate students to work effectively in multidisciplinary teams, communicate effectively with stakeholders, and identify economically sustainable innovations.	• Trainees External Evaluator Industry Advisory Board Diversity Advisory Board • Interdisciplinary Faculty/Mentors Institutional Support/Infrastructure Investigators' Knowledge/Expertise NSF Funding • Program Coordinator	•Develop Graduate Leaning Community (GLC) model •Implement & adjust GLC activities based on feedback loop •Hold annual symposium •Develop ePortfolio structure •Develop recruiting practices and trainee selection procedures that promote diversity •Develop professional & communication core competency matrix	•GLC workshop model •GLC small group reflections •Trainees' ePortfolios •Symposium content •Professional & communication core competencies matrix •Recruiting and retention practices •Mentoring models •Application prompts •Trainee selection rubric

Goal 3: Community and Communication as a Foundation for Multidisciplinary Teams

Our plan: Following a day-long orientation including Clifton Strengths training [5] and team-building activities, the weekly small-group meetings were led by the trainees on a rotating basis. In the first semester for the first cohort, the meetings featured peer-review activities similar to those described by Cunningham [6]. Based on trainee feedback, in the second semester they included more opportunities for the initial cohort to present their research and identify collaboration possibilities. From the time when the second cohort joined in Fall 2020 until the third cohort concluded in Spring 2023, these weekly sessions mainly provided opportunities for trainees to share their areas of expertise such as data analytics methods and familiarity with various databases or software tools.

To develop skills for communication with diverse audiences, we included sessions on science communication in the orientation sessions for the first two cohorts and worked with our university's Graduate College to revive a half-semester course on this topic. In consultation with the external advisory board, we also focused the first annual symposium, scheduled for April 2020, to focus on communication and soft skill development.

Modification with student leadership: The COVID-19 pandemic caused postponement of the first symposium to January 2021, conducted in a virtual format. Meanwhile, the second cohort joined the first one in Fall 2020 and the learning community moved mostly online (throughout the 2020-21 academic year, our university was holding some face-to-face classes and activities, while many remained hybrid or virtual). We instituted working groups of trainees with faculty leadership to help plan the symposium and workshops. Student leaders were especially effective in selecting and customizing an online platform for the virtual symposium. Trainee feedback in Spring 2021 suggested the need for more community-building activities and earlier sharing of research interests to integrate two cohorts. In response, we held a networking weekend offsite for the second and third cohorts in early Fall 2021. Planned mostly by the cohort 2 trainees, this event was received very enthusiastically, and repeated for the trainees in cohorts 3 and 4 in Fall 2022.

Several elements of the communication course were also revised after its first offering in response to trainee feedback. In particular, the workload was adjusted and more emphasis was placed on communication basics, instructor-led content dissemination, and hands-on training to scaffold learning of technology and software for creating communication projects. In Fall 2021, two trainees who had completed the course advanced to the finals of the university's Three Minute Thesis competition. In Fall 2023, fewer than 25% of the students enrolled were trainees from our program, evidence of our program's impact on our graduate education in our institution.

Goal 2: Data-Driven Modeling for Impactful Research and Diverse Career Preparation

Our plan: The two vehicles for building trainee skills in data analysis and systems modeling were the related electives in the certificate program (see Table 2) and some of the monthly workshops. In addition, we included the ePortfolio requirement as a means for the trainees to

informally certify their attainment of data and modeling skill, and potentially advertise these to prospective employers.

Modification with student leadership: The success of the working groups with the first networking weekend motivated us to expand them to help plan the workshops and small group activities as well. Workshop sessions on data-related topics were added to the second and third annual symposia, while the trainees identified preferred topics for monthly workshops: data visualization and geographic information system (GIS) tools. A workshop on entrepreneurship was added in Fall 2022 to replace the course in the certificate program. Fall workshops on decision analysis conducted by an engineering faculty member enticed non-engineering trainees to enroll in his course the following spring semesters. One resulting course project expanded into a cross-disciplinary journal article [7].

Table 2. Requirements for the graduate certificate in Data-Driven Food, Energy and Water Decision Making

Knowledge Area	Requirement	Courses
Fundamental understanding of interactions in the FEW nexus	Core Course	ABE 585X: *Biosystems for Sustainable Development* (2 credits)
Communication	Core Course	GR ST 566: *Communications in Science* (0.5 credit)
Entrepreneurship	Core Course*	*BCB 590 / EE 690X: Entrepreneurship for Graduate Students in Science and Engineering* (1 credit)
Data acquisition, visualization, and analytics	Elective (Choose One)	8 options in Engineering or Statistics (3 credits)
Complex systems modeling for decision support	Elective (Choose One)	11 options in Engineering or Agronomy (3 credits)
Economics, Policy, or Sociology of FEWS	Elective (Choose One)	11 options in Economics, Sociology, Political Science or Discipline-specific Policy (3 credits)

*After the first two years, this requirement was dropped based on student feedback and a related workshop was conducted instead.

Goal 1: Interdisciplinary Research on FEWS

Our plan: Because the NRT program is "dedicated to effective training of STEM graduate students in high priority interdisciplinary or convergent research areas,"[1] we placed a high priority on encouraging and equipping trainees to conduct interdisciplinary research. In the program design, we focused on the FEWS core course as the primary opportunity for students to work across disciplines. The catalog description for this course is:

> Understanding and appreciation of sustainable development issues related to food, water, energy, and climate change nexus and its implications for environmental sustainability, nutrition security, one health, and economic development of communities in the US and other countries. Application of basic agricultural,

[1] https://new.nsf.gov/funding/opportunities/national-science-foundation-research-traineeship

> biological, math, and engineering/applied sciences to solve society's problems for water, food, energy, and environment systems. Emphasis placed on learning from case studies and developing sustainable solutions for communities. Students will learn to lead by example, improve their leadership and communication skills to understand local conditions and motivate themselves and others to improve the world around us.[2]

Because of its focus on developing solutions in case studies, we intended that trainees would collaborate on FEWS-related projects within this course. Several course projects produced substantial contributions [8-10], but they were all conducted by individual trainees.

At the same time, a few members of the first two cohorts objected to their perceived worldview of the course instructor and requested substitutions for this course. We offered two alternatives that both produced interdisciplinary work. The first was participation in a "Cohort Challenge" offered by another NSF-funded project [11]. Two trainees from the first cohort joined a team of graduate students from multiple institutions to conduct stakeholder analysis of a livestock management issue [12]. The second was the opportunity to propose their own interdisciplinary project, supervised by a faculty member on our leadership team, and evaluated by the whole team using a rubric we developed. One three-member team of trainees from cohort 2, also supervised by their individual faculty mentors in environmental engineering, sustainable agriculture, and environmental science, conducted a systematic literature view of FEWS research emphasizing their shared interest in social equity [13].

Modification with student leadership: At the beginning of their second year of the traineeship, the final cohort of trainees proposed an agenda for the weekly learning community meetings and an alternative way to complete their e-portfolio requirements. The twelve members of the cohort divided into four-member teams to collaborate on projects concerned with each of the three FEWS areas.

- The food team is studying food systems in Iowa to assess inequality in access to nutrition. They combine production, distribution, consumption, and nutritional data at the county level to assess causes of poor health outcomes of state residents, while incorporating climate change components in their analysis to assess the sustainability of current food systems. This team comprises students in agricultural and biosystems engineering, animal science, economics, and nutritional science.
- The energy team, combining three engineering disciplines (agricultural and biosystems, chemical, and materials science) is analyzing data collected from a microgrid that combines solar photovoltaic generation and storage to power a livestock feeding facility. Their goal is to assess the cost effectiveness of installed capacity relative to power purchased from the grid.
- The water team is studying how climate change affects regional drought and flood conditions, with the objective to produce an online, interactive map linked to low-income communities. These majors in civil engineering, agricultural meteorology, and environmental science are combining meteorological, climate, and demographic data to identify hot spots of vulnerability to water excess or deficit.

[2] Catalog link blinded

Each team aims to develop a product (e.g., interactive data visualization or economic evaluation) that will demonstrate each member's attainment of the core competencies in each knowledge area of the certificate.

Table 3. Outcome portion of the logic model.

Project Goals	Short-Term Outcomes	Mid-Term Outcomes	Long-Term Outcomes
G1. Foster interdisciplinary research based on data- intensive methods. .	•Trainees with primary FEWS focus effectively apply data-driven decision modeling •Trainees with primary data-driven decision modeling focus produce meaningful FEWS applications	•Funded proposals •Completed theses/dissertations •Stakeholder consideration of innovation adoption	•Interdisciplinary research sustained by external funding •Stakeholder adoption of innovations
G2. Educate STEM graduate students for a range of research, research-related and entrepreneurial careers employing data-driven modeling at the FEW nexus.	•Trainees attain specified competencies from certificate coursework. •Trainees demonstrate understanding of relevant stakeholder concerns in FEWS context. •Trainee demonstrate awareness of diverse career paths	•Trainees complete certificate requirements. •Non-trainees complete certificate requirements. •Trainees explores various career path opportunities such as by completing internships.	•Certificate well-established with healthy enrollments. •Trainee graduates placed in relevant positions. •Businesses started. •Relevant technical groups in existing businesses, NGOs, or agencies established or expanded.
G3. Prepare STEM graduate students to work effectively in multidisciplinary teams, communicate effectively with stakeholders, and identify economically sustainable innovations.	•Diverse trainees recruited and retained •Trainees demonstrate team building & leadership skills •Trainees demonstrate professional and communication competencies relevant to multiple career options •Trainees are able to articulate the interdependencies among FEW systems in the context of Midwest agriculture •Trainees demonstrate successful interactions with and understanding of stakeholders	•Second year trainees are effective mentors to incoming trainees •Trainees identify economically sustainable innovations to FEWS •Trainees demonstrate effective use of ePortfolio in furthering their careers in various markets •Diverse trainee graduates successfully placed in starting positions	•Increase of STEM professionals who understand and can navigate across expertise boundaries to effectively communicate with stakeholders and identify economically sustainable innovations in the FEWS nexus. •Diverse former trainees rise to leadership positions

Outcomes, Evaluation and Conclusions

Table 3 shows the outcomes we envisioned to occur in various time frames as a result of the activities undertaken in the logic model. Here we summarize one mid-term outcome highlighted for each goal.

- *Completed theses/dissertations*: As of March 2024, nine former trainees have completed their doctoral dissertations and one completed a master's thesis. Nine additional current or former trainees have passed their doctoral preliminary exams, which signifies approval of their dissertation proposals and substantial progress towards completion.
- *Completed certificates*: Of the 31 total trainees who have completed the program or are on track to do so by May 2024, 18 have completed the certificate program.
- *Trainee graduate placements*: One alumnus is a tenure-track assistant professor overseas, three are in postdoctoral positions at universities (two domestic, one

international), and one holds a university extension appointment. Two of the PhD alumni work in government agencies, one is employed by a private foundation, and one works in industry, as does the MS graduate.

As articulated in Objective 3.2, the trainees have demonstrated productivity and made timely progress towards degree completion despite the coursework requirements for the certificate and time devoted to participating in the learning community and symposia.

Our external evaluator has conducted annual trainee surveys to gain their feedback on program elements and gauge the extent to which the project goals are met. Figure 3 shows the proportions of trainees who agreed at least somewhat with statements describing the attainment of each goal.

The lower evaluation scores for Goals 1 and 2 by the first two cohorts in Spring 2021 (end of year 2 for cohort 1 and end of year 1 for cohort 2) could be attributed to the impact of the COVID-19 pandemic. A lagged pandemic effect might also explain the less positive responses by cohort 3 concerning Goal 3 at the end of their first year (Spring 2022). Although causation is difficult to establish, the positive trend in the results for Goal 1 and high values for Goal 3 by cohorts 3 (Year 2) and 4 (Year 1) in Spring 2023 match our subjective impressions that giving trainees more ownership of the program has contributed to achieving its goals.

Specific steps we took to involve the trainees in program leadership were to:

- Include an elected representative from each cohort on the leadership team for our monthly meetings;
- Form student-faculty working groups to plan the networking weekends, symposia, workshops, and learning community agenda, as well as to award travel/publication grants;
- Allow a collaborative independent study alternative to the core FEWS course; and
- Entertain petitions for additional elective course beyond the initial set proposed, and replace one required course with a workshop based on trainee feedback.

Allowing the final cohort the freedom to devote their learning community time to working across disciplines on projects of their own design, in self-selected teams, seems to have been the most effective way to promote the collaboration we sought.

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Figure 3. Proportion of trainees who responded Strongly Agree, Agree, or Somewhat Agree in a year-end survey to the statement that the program "is preparing me to …" (a) Engage in interdisciplinary research based on data-intensive methods [Goal 1], (b) Succeed in a range of careers employing data-driven modeling at the food-energy-water nexus [Goal 2], (c) Work effectively in multidisciplinary teams [Goal 3].

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