ASEE 2022 ANNUAL CONFERENCE
Excellence Through Diversity
MINNEAPOLIS, MINNESOTA, JUNE 26TH-29TH, 2022 ASEE
Paper ID #37350

Developing Cohort Challenges: An Innovative Program for Training Graduate Students to Work in Transdisciplinary Teams

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Abstract: "Wicked problems" in science and engineering demand transdisciplinary approaches drawing on multiple disciplines and perspectives, yet we continue to conduct graduate training largely within the confines of a single discipline. The INFEWS-ER is an NSF-funded virtual resource center designed to provide transdisciplinary graduate education to students working on problems at the intersection of food-energy-water systems. Relying on a conceptual framework that identifies several competencies -- the skills, knowledge, and pedagogical methods that are vital for successful transdisciplinary teamwork -- we designed an approach that capitalizes on faculty expertise, student interests, and teamwork.

In this paper, we offer a model of an innovative approach to training graduate students -- Cohort Challenges offered by the INFEWS-ER. Specifically, we describe the fundamental elements that each Cohort Challenge shared: a broad theme related to a wicked problem that gives graduate students the flexibility and independence to formulate their own research questions and design their own projects; training in competencies for conducting transdisciplinary research; mentorship from faculty and peer experts outside their departments and outside their disciplines; and collaborative learning in a virtual environment. We also focus on important dimensions of the process of conducting a Cohort Challenge, including intentional team-building practices that foster trust and accountability among participants; meaningful stakeholder engagement throughout the research process, from design to sharing final products; and learning to communicate about science across varied audiences. We also describe some of the final projects

the Challenges produced, including journal articles, conference presentations, and social media campaigns, all outside of the students' more traditional course of study. We conclude by offering several final observations about the opportunities and obstacles to successful Cohort Challenges, as well as our future plans to support others who want to design and deliver this mode of graduate education.

I. Introduction

The interest in "wicked problems" in science and engineering reflects a growing recognition that the most pressing technological needs of the 21st century do not fall neatly into any single discipline. Because they sit at the intersection of many competing disciplines and interests, wicked problems defy easy definition or solution [1]. Rather, they demand challenge-centered research that requires the collaboration of the full range of traditional scientific fields, as well as an understanding that those challenges arise in particular social, political, and economic contexts [2]. Challenges are real problems, experienced by real people, where technological solutions, if implemented, could vastly improve the quality of life of many members of society. To meet these challenges, then, research teams have to reflect the scope of expertise implicated by the problems themselves. To prepare graduate students to work on these wicked problems and grand challenges, we need innovative graduate training that helps them navigate transdisciplinary teams [3]–[6].

The Cohort Challenges developed by the NSF Program, Innovations at the Nexus of Food, Energy, Water Systems Educational Resources (INFEWS-ER) offer a model of transdisciplinary training for graduate students [7]. Grounded in mentored graduate student research in food-energy-water systems (FEWS), Cohort Challenges also offer students training in competencies widely recognized as being necessary to conduct transdisciplinary team research.

Since 2018, the INFEWS-ER has sponsored nine Cohort Challenges on broad topic areas addressing wicked problems, described in Table 1.

TABLE 1: INFEWS-ER Cohort Challenges, 2018-2022

Academic Year	INFEWS-ER Cohort Challenges and their 'Wicked Problems'
2018-2019	Dairy Carbon Nutrient Loss Reduction, Recovery and Reuse
2019-20	Dairy Nitrogen Disaster Relief and Resiliency Livestock and Local Communities
2020-21	Food Waste Disaster Relief and Resiliency Livestock and Local Communities
2022	INFEWS-ER Virtual Resource Center

In this paper, we offer a framework for designing a Cohort Challenge for transdisciplinary graduate education. The authors of this paper have all participated in Cohort Challenges in a variety of roles as:

- faculty organizers of these unique experiences,
- graduate student participants in the Cohort Challenges, and
- graduate student mentors helping to guide the process.

The framework we describe emerges from our observations and reflections on the process. Specifically, we describe the fundamental elements that each Cohort Challenge shared: a broad theme related to a wicked problem that gives graduate students the flexibility and independence to formulate their own research questions and design their own projects; training in competencies for conducting transdisciplinary research; mentorship from faculty and peer experts outside their departments and outside their disciplines; and collaborative learning in a virtual environment. We also focus on important dimensions of the process of conducting a Cohort Challenge, including intentional team-building practices that foster trust and accountability among participants; meaningful stakeholder engagement throughout the research process, from design to sharing final products; and learning to communicate about science across varied audiences. We conclude by offering several final observations about the opportunities and obstacles to successful Cohort Challenges, as well as our plans to support others who want to design and deliver this mode of graduate education.

II. Elements of a Cohort Challenge

Cohort Challenges are designed with the goal of transdisciplinary training in mind. By participating in these unique experiences, graduate students have the opportunity to combine their disciplinary expertise and develop new technical and communication skills as they explore new approaches to a wicked problem in FEW systems. In this section, we describe the basic elements that all the Cohort Challenges had in common – the formulation of the broad research topic; the emphasis on competencies of transdisciplinary team-based research; the significance of mentorship; and considerations for a virtual environment (Figure 1).

Figure 1. Elements of a Cohort Challenge. There are four key elements that have comprised successful cohort challenges.

A. Formulating a Theme

The original Cohort Challenges emerged from wicked problems in FEWS research, with a broad range of scenarios that focused on particular aspects of those systems. They were topics drawing on organizers' expertise in a range of natural, physical, and social sciences and engineering in areas where there are no fixed set of solutions. Intentionally open-ended, Cohort Challenges invite graduate students to identify and design their own collaborative and transdisciplinary projects over the course of several months. In formulating a Cohort Challenge, organizers avoided charting solutions stemming from their own scholarly agendas and disciplines. Rather, organizers focused on sharing the problem and engaging in some transdisciplinary thinking themselves to ensure multiple fields and perspectives can play a role in the solution.

Learning objectives in Cohort Challenges have encompassed transdisciplinary skills, but have to be flexible, reflecting the fact that there is no predetermined project or output. Beyond

these more traditional disciplinary skills, the Cohort Challenge's learning objectives encourage students to apply their knowledge to specific problems, to work effectively as a team, and to develop a shared language to make research questions understandable across the cohort as well as to lay audiences. If necessary, participants are encouraged to learn new skills to meet the needs of challenges. Faculty advisors and mentors for the Cohort Challenges must be attentive to student goals and activities; their supervision makes it possible to have learning outcomes that are adaptable on the one hand, and still allow advisors to hold students accountable for achieving those outcomes. Although less fixed than learning objectives in traditional graduate education, this component is an important element of a successful Cohort Challenge.

B. Competencies of Transdisciplinary Research

In a recent paper, Heemstra et al. (2022) described and organized the broad spectrum of competencies for transdisciplinary research in graduate education [8]. All the Cohort Challenges featured training in several competency subdomains, recognizing the process and product would support a broader set of competency domains. Specific competencies that emerged in syllabi and essential training in most cohorts included: 1) team-based skills where participants work efficiently and hold each other accountable; 2) competence in project management to identify and complete tasks; 3) systems-thinking to map out the scope of the "wicked problem;" 4) engagement with stakeholders interested in both the problem and relevant solutions. Underpinning all the competency domains is effective communication to a number of audiences – multi-disciplinary team-members, stakeholders, policymakers, other scientists and even the general public. Traditionally graduate programs do not offer specific training in these areas. Indeed, students may have contact with stakeholders during their graduate programs, or they may

develop project management skills by observing the work done in their labs. As with most acquired abilities, students must apply these techniques in actual situations before they can claim to be skilled in their use. The Cohort Challenge provided a meaningful context for these skills as well as a real situation in which to repeatedly apply them.

To support training in these competencies, the INFEWS-ER developed a series of on-line modules – "Toolbox Modules" – that facilitate practice and application of specific skill sets for use among multiple cohorts [9]. The competencies are in and of themselves the subject of extensive research, and "best practices" have emerged in the scientific communities that implement these skills. Toolbox Modules offer students in Cohort Challenges brief introductions to the relevance of the skill to transdisciplinary teamwork in the form of readings, exercises, and activities. As "plug-and-play" options, ready-made modules were pulled into one or more cohorts to develop specific skills, but also to contribute to the larger purpose of the cohort challenge [9]. In most cases, modules were considered in syllabus development by advisory teams, but cohorts had the opportunity to "plug-and-play" additional modules per their charted path needs. In their paper, Rodriguez et al. (2019) and his colleagues detail the variation in why, how and when specific modules played into past cohort challenges, but also how competencies emerged in the process and deliverable for different cohorts [9].

C. Mentorship

The extracurricular nature of the INFEWS-ER cohort challenges and the participation of individuals from multiple institutions strain typical definitions of mentorship. In a recent report, the National Academies of Sciences, Engineering, and Medicine describe mentorship as formal or informal, neither of which quite fit the INFEWS-ER model [10]. Formal mentors are assigned

and have authority over the educational outcome of the one being mentored; informal mentorship relationships develop organically based on common interests and interpersonal interactions. Neither of these criteria are met. Yet from a broader perspective of mentorship as a mutually beneficial relationship focused on personal and professional growth of the partners, the faculty and cohort participants clearly are in a mentorship relationship.

The faculty who plan the Cohort Challenges serve as mentors in a group model [11] but also fill roles of facilitator and advisor. In designing the challenge, they offer students some context on the general topic. As the Cohort Challenge gets started, the faculty provide basic instruction on the background science and engineering. And finally, they offer guidance to students as they take leadership over defining and executing their project. Faculty provide an environment for students to safely test and develop skills as transdisciplinary scientists. The emphasis is on the learning process and not the delivered product. As such, the focus is on encouraging students to develop their skills in engaging across disciplines and resolving difficult problems. The environment is open-ended and requires students to deliberate extensively to identify and justify the problem to be solved, identify, and justify the methods to be employed, and implement their solution. Many rounds of deliberation are required, and participants may experience frustration with the lack of structure to open-ended problem solving.

Faculty advisors and mentors are generally expected to allow the students to ideate and deliberate on their own, while encouraging participants to be faithful to the process. This can be similarly challenging for the advisors as they may see many viable pathways that could be rewarding, but the advisors typically have enough experience to see that any one of several pathways may provide successful outcomes. Advisors may be tempted to direct participants to

follow a path. This should be avoided since successfully navigating the deliberation process is an opportunity for the team of participants to develop key competencies.

In addition to faculty mentors, graduate student mentors have provided guidance to students participating in the Cohort Challenges. Graduate student mentors are recruited from participants in the previous year's Cohort Challenges. Their exposure to some of the more demanding aspects of the process allows them to provide much-needed support to students navigating their first Cohort Challenge. For example, graduate student mentors have offered reassurance to students who are learning to ask transdisciplinary questions and formulate a project on their own. They also offer concrete advice to resolve logistical issues, like strategies for building an agenda and leading a meeting. Finally, their presence emphasizes the importance of building trust in teams through social interactions with peers rather than relying on faculty advisors to provide answers.

Beyond the support they provide graduate student participants in Cohort Challenges, the graduate student mentors are themselves acquiring skills by occupying the role of mentors. Graduate programs in traditional disciplines offer little in the way of formal training in the skill set that researchers need to be successful mentors. Yet success in academia and in the private sector often depends on having the capacity to supervise the work of junior colleagues. By participating in this role, graduate students develop valuable experience in offering mentorship to transdisciplinary team members.

D. Virtual Learning Environment and Collaborative Tools

Working online with digital resources presents both practical/logistical and pedagogical advantages. The flexibility afforded by asynchronous learning is essential when cohorts and collaborators live and work in many different time zones. But there are also pedagogical reasons

to promote flexible learning using digital tools and resources. Using tools for asynchronous communication and collaboration enables students to integrate their learning into busy and sometimes unpredictable schedules, and to work at the times and places that best suit their own learning styles, putting both "night owls and early birds" on an equal footing [12]. Our students are also increasingly "reading" digital hypermedia texts and producing the same as part of their professional workflow, especially if their work includes engagement with stakeholders in the community who do not engage regularly with traditional scholarly genres. Working regularly with the tools and resources available on the web, including those developed as Toolbox Modules, reinforces digital literacies, and invites active remixing and repurposing of content. The use of these open educational resources and self-directed learning, such as the Toolbox Modules, also democratizes the learning process and encourages students to situate themselves in communities of practice and not merely the particular institutions in which they are enrolled [13].

The Cohort Challenges were designed, before the COVID pandemic, to be offered online to accommodate teams assembled across different disciplines and different universities. Thus, accessible, online tools that allow collaboration have been a feature of every Cohort Challenge. Team meetings occurred on Zoom before Zoom became a standard meeting tool across US universities. Beyond email, team members used Slack channels to plan agendas, share information, and ask questions. Course materials for Toolbox Modules were made available through the Moodle learning management system, though such materials were often stored or hosted on various ancillary servers and sites (e.g. Google, YouTube). In addition, team members collaborated on shared bibliographies using Zotero and worked on basic systems modeling using Plectica. These online tools created a virtual learning environment that promoted collaboration

and cooperation across time zones and around the world. These tools were again proven useful when some cohort participants were impacted by COVID-19 travel restrictions and participated from their home countries while waiting for the initial travel to the US-based campus to start in-person instruction.

III. The Cohort Challenge Process

Since 2018, our team has sponsored numerous cohort challenges. The following process has proven successful, and repeatable, despite the differences in the subject matter and leadership associated with a cohort challenge. The process flows from recruitment; to launch; to the development of teams, stakeholder engagement skills, and communications skills; all culminating in a closing symposium (Figure 2). Many cohorts continue to work on products after the symposium. In this section, we describe the processes reflected in Figure 2 and the way that Cohort Challenges build transdisciplinary skills.

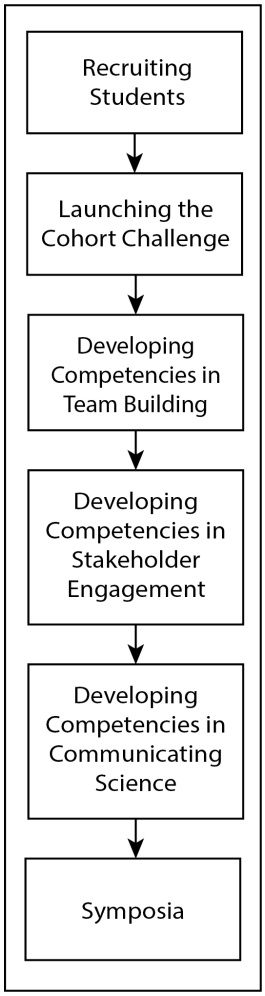

Figure 2. The Cohort Challenge Process. There are five key phases to the Cohort Challenge Process.

A. Recruiting Students

Students for the Cohort Challenges were recruited from a wide range of different disciplines. The summer before the Cohort Challenge launched, organizers circulated a project description of each Cohort Challenge to colleagues in the FEWS community, including the PIs of recipients of NSF and USDA FEWS-related funding, as well as other colleagues in the sciences, engineering, and agricultural extension networks. We asked recipients to circulate the

project descriptions widely, to their own students as well as the students in their department's graduate program.

Students submitted brief applications that asked them to identify the Cohort Challenge they were interested in, along with their field of study, their specific research interests, and any transdisciplinary experience they might have had prior to working in the Cohort Challenge. Participating students have come from universities all across the United States, and each year, at least one cohort had a student from outside the US. In putting together cohorts, the organizers have sought different disciplinary expertise, and have been largely successful in that effort. Participants have included chemical, civil, agricultural, computational data science engineers; chemists; environmental, animal and soil scientists; economists, ecologists; informatics; anthropologists; as well as graduate students in agricultural education and social work. Figure 3 is a word cloud made up of all the departments of the student participants in the 9 Cohort Challenges. The word cloud reflects the significance of engineering, especially in agriculture and biology, as well as a diversity of other areas, including communication and education.

Figure 3. Word Cloud of departmental homes of students participating in Cohort Challenges.

Thus far, organizers of cohort challenges have not had to engage in a selection process; we have been able to accommodate every student who was interested in participating. However, each of the Cohort Challenges experienced attrition, as a handful of students began the project but did not complete it. Thus, the size of the cohorts varied over the course of the project, but generally ranged from 6 to 12.

So far, Cohort Challenges have been extra-curricular activities for the graduate students who have participated. They are told to expect the workload to be roughly the equivalent of an approximately 1-credit semester-long course, spread over an academic year. They are also told that the faculty organizers would cooperate in their efforts to get credit for independent studies, and several students have taken advantage of that offer. And finally, students who complete the project are eligible for a Certificate of Completion. For most students, however, Cohort Challenges have offered opportunities to work on projects that result in products that can be captured on their CVs, including publications and conference presentations described below.

B. Launching the Cohort Challenge

Once the cohort participants were settled, the organizers of the Cohort Challenge searched for a suitable meeting time, frequently a difficult task that required the balancing of different time zones and busy schedules. Organizers also developed a syllabus that introduced participants to basic background on the specific FEWS challenge/problem, including readings, discussions, and guest speakers from different disciplines, offering multiple perspectives on the general topic of the challenge. Over time, organizers came to realize that students also needed an early introduction to team building, as cohort members are largely unknown to each other; for

the most part, their studies are in different disciplines and different universities. Thus, intentional focus on team-building in a virtual environment early in the process has been an important feature of all the Cohort Challenges.

In their early stages, all participants – both advisors and students – must also prepare for the different expectations associated with Cohort Challenges. In traditional graduate education, the faculty advisor is an expert in a discipline who shares knowledge and develops projects and exams designed to assess whether students can absorb and apply that knowledge. As a result, students are relatively passive, following the direction and performing the tasks laid out in a syllabus. In a Cohort Challenge, students must take leadership as soon as possible over the research questions and projects that will drive their activities over the course of the academic year. This switch in roles can be confusing to both the organizers and students in a Cohort Challenge. Advisors must resist the temptation to assert control over the students' efforts to identify a project, and students must understand that advisors and peer mentors will not provide them with answers. While this part of the process can be frustrating, it is crucial to the overall goal of training students to be leaders in conducting transdisciplinary research.

C. Developing Competencies in Team-Building

Many graduate students have some experience working on teams in the labs associated with their graduate programs, but working in transdisciplinary teams across multiple institutions provides a unique opportunity to hone effective team-building skills. Those skills include, but are not limited to, communication, accountability, and goal setting. For example, developing an awareness of jargon within disciplines can facilitate finding a common language to share information and conceptualize projects among team members. A flexible communication plan

that includes identification and use of various technology platforms to meet team needs is also critical to team-building and management. The plan should function across multiple time zones and may include group chat, email, and document organization. This teamwise communication is particularly important for expressing expectations both individually (i.e., what do I want to get out of this cohort challenge?) and collectively (i.e., how can I contribute to the challenge?).

To this end, some teams also used ice-breaker sessions or various personality assessments for team-building. These practices allowed members to identify, share, and combine their individual strengths, experience, and passions to promote cohesiveness. This allows students to forge strong relationships within the team quickly, improving productivity and accountability among team members. Accountability is a critical component of a high-performing team regarding individual contributions but also in sharing responsibility for group management and accomplishing project tasks. Role assignments that cater to individual strengths seem to improve the efficiency and confidence of individual team members.

Goal setting is another team-building exercise that helps students identify the needs and constraints of their cohort challenges projects. Because the challenge descriptions are often broad and unstructured, it is up to the cohorts to investigate the problem and identify what their contribution will be. Brainstorming among team members often results in multiple project ideas that must then be narrowed down to a single plan of action with clearly stated goals and objectives. This goal setting process further helps students improve their communication skills, including consensus-building. Goal setting also contributes to accountability by identifying any missing expertise or experience within the team to achieve goals, and the inherent need to develop a timeline by which to do so. This in turn promotes stakeholder engagement and network building skills to enhance the team's strengths and help meet its objectives.

Effective teams do not happen by accident; they are the product of intentional practices that can be taught. Remote collaboration introduces additional challenges, particularly for forging strong relationships quickly. While the Cohort Challenges begin with structured, regular meeting times, each team has realized that they need to meet more often, both to plan tasks and report progress, and to build bonds beyond simply working on the project. Teams have also cultivated connections using social media and various asynchronous communications tools and platforms. Those closer connections make for better communication across the team.

D. Developing Competencies in Stakeholder Engagement

Many of the syllabi for Cohort Challenges included material on stakeholder engagement given that the very definition of a "wicked problem" is one that implicates multiple societal sectors. The most brilliant solutions generated by scientists and engineers will be rendered ineffectual if they are not adopted by industry, regulators, farmers, and the general public, all of which are sectors that might have interested stakeholders. While working in their labs under the supervision of their advisors, they may have occasion to interact with some stakeholders. Yet graduate students, often focused on developing expertise in their own fields, may not think through the impact their research has on the rest of society. The Cohort Challenge experience encourages them to think broadly about social, political, and economic actors in relevant communities who might encourage adoption and implementation of their innovative solutions or who might create obstacles to that implementation.

Most of the Cohort Challenges offered students an opportunity to brainstorm about the relevant stakeholder groups and sectors that were affected by the broad general problem they were addressing, using the Community Capitals framework as a guide [14]. That framework

identifies different sectors of a community that have resources that could be brought to bear in implementing projects. That capital comes from sectors including financial institutions, social groups, politics and governance, human resources, and cultural organizations. Students discussed how stakeholders from these different sectors might react to the projects they were considering. This exercise demonstrated that stakeholders come from a wide range of different segments of society, not just industry. In addition, the discussion also encouraged cohorts to think carefully about the kind of influence that stakeholders might bring to bear on the project. Students realized that some stakeholders might prefer the status quo and resist any changes, including changes that enhanced sustainability. Finally, the exercise asked them to think through the relative influence that stakeholders might have to enable or to block change and to anticipate a strategy for winning the support of the most significant parties.

E. Developing Competencies in Communicating Science: Cohort Challenge Products

As students define and develop their projects in the Cohort Challenge process, they are frequently advised to draw on the expertise of the entire team and to ensure that relevant stakeholders are invested in the outcome. During the deliberations identifying a project, cohort members often find that their final products require that they convey scientific and engineering information to a range of different audiences, both within and outside of scientific communities.

Students in the Cohort Challenges are often interested in having final projects that are helpful in pursuing academic careers. Thus, many of the Cohort Challenges have produced manuscripts for publications [15]–[17] and presentations at professional conferences, including annual meetings of the Community Informatics Research Network and ASA-CSSA-SSSA International Conference[18], [19]. In preparing academic papers, students take the lead in

identifying journals and conferences that are interested in interdisciplinary work; they manage the logistics of preparing the manuscript; they communicate with the editors; and they decide how to respond to reviewers' comments. For many of the students, this is their first experience with leadership in publication and the peer review process. It jump-starts their careers in publication and prepares them for a vital component of an academic career.

In keeping with the transdisciplinary nature of the problems they worked on, the Cohort Challenges have also generated several products for audiences beyond the scientific community. One Cohort Challenge generated a white paper evaluating the impact of a policy intervention on nutrient loss reduction in Illinois. Another Cohort Challenge developed a database of publications that an NGO could use to support its efforts to apply for grants. And several Cohort Challenges have created resources to inform the general public about the "wicked problem," including a social media campaign about food waste and a storymap about disaster resilience in Puerto Rico.

While working on these products, cohort members obtain first-hand experience with the difficulties of communicating science across disciplines and across interested communities. As they edit manuscripts or presentations, they are repeatedly called on to imagine how the information might be received by others working with different levels of knowledge and different interests. This experience with tailoring communication is an important foundation for successful transdisciplinary collaboration.

F. Symposia

The INFEWS-ER also sponsors meetings and events that emphasize team-building and networking across the cohorts. By encouraging students to reflect on the work that they are

doing, these events consist of presentations about their projects, which enhance their skills in communicating science to a transdisciplinary audience. In addition, students interact in small groups where they describe some of the obstacles they have faced in working on the Cohort Challenges and strategies for dealing with those obstacles. In addition, some discussions focus on professional development, such as developing "elevator pitches" to describe Cohort Challenge activities to prospective employers.

These symposia are scheduled at the mid-point of the Challenges, sometime in January, and near the end when students are wrapping up their final projects. In addition to offering students reinforcement in the transdisciplinary skills that they are building, the midpoint meeting has also been motivational. When hearing about how other projects are developing, students can assess their progress and determine how to move forward with their work. The year-end symposium offers participants an opportunity to summarize the work they have completed and reflect on how they might have improved the process and the products.

Although the Cohort Challenges are designed to operate in a virtual environment, the organizers have found that a face-to-face meeting near the end of the experience offers many benefits. Before COVID-19, the INFEWS-ER offered a symposium near the end of the Cohort Challenge in 2019. Faculty sponsors and graduate students were able to meet in person and get to know each other in a more informal setting. Stakeholders were able to attend and offer specific advice about ongoing projects.

IV. Cohort Challenges in Action: Livestock and Local Communities and Disaster Relief and Resiliency

In this section, we provide brief summaries of how Cohort Challenges worked in practice. We focus on two Cohort Challenges – Livestock and Local Communities and Disaster Relief and Resiliency – both of which were offered in 2019-20 and 2020-21.

A. Livestock and Local Community

The organizers of the Livestock and Local Community (LLC) Cohort Challenge – John Classen, Erin Cortus, Alison Deviney, and Jacek Koziel – all had experience conducting agricultural research in livestock production. During their research, they recognized the many ways that livestock production, regulations (primarily associated with environmental protection), local communities, and economics are inextricably linked. Thus, through both iterations of LLC, the organizers offered prospective students the following challenge:

> Your challenge is to (1) identify factors that influence food animal production in several counties in a state, highlighting differences; (2) document the historical cause-effect relationships that influenced change in livestock development among counties; (3) provide recommendations for processes that influence stability in the relationships and resilience in the system/community (and define scope of recommendation).

Both LLC Cohort Challenges attracted graduate students from different disciplines. LLC-2019 had students pursuing graduate degrees in animal science, agronomy, applied ecology, biological and agricultural engineering, among other fields. LLC-2020 had students studying agricultural communication, agricultural education, animal and food science, agronomy, and other natural resource sciences.

In both iterations of the LLC Cohort Challenge, the organizers emphasized team-building exercises early in the process, encouraging students to assume ownership over the project as quickly as possible. They supported team-building with a variety of tools, including personality assessments that gave them perspective on the talents that individuals brought to bear on the work they were planning. As the challenge progressed, students traded leadership roles and assumed responsibility for accomplishing different tasks. As they balanced competing demands on their time, students in both cohorts learned the importance of stepping in for teammates and being accountable to others for staying on task.

The organizers also introduced both cohorts to stakeholders who had varying perspectives on sustainability in the livestock industry. For example, students met with professional consultants who offered producers and potential producers advice about how to run a profitable operation, community planners and/or officials who focused on the state and local regulatory environment for livestock farms, and a conservation advocate. These interactions with stakeholders offered students in both LLC Cohorts much-needed background to help them refine their research questions and to collect data for their final projects.

While both Cohorts began the same way, students in the two versions of LLC formulated very different research questions to meet their challenges. LLC-2019 emphasized the different influences on siting decisions by analyzing the political, economic, and social factors influencing siting new and expanding livestock farms in South Dakota. Drawing on research methods developed in the social sciences, the team collected quantitative data in the form of census data and economic indicators for each of five South Dakota counties over a 25-year period. In addition, they collected qualitative data from interviews with stakeholders in the relevant areas. Using both qualitative and quantitative data, they adapted qualitative comparative analysis [20]

[19] to find common contextual conditions that influenced the viability of the livestock industry in the locations they studied. Published in the interdisciplinary journal, *Sustainability* [15] their analysis demonstrated the complexity of the systems influencing siting decisions and the risks of trying to generalize in the absence of a sophisticated understanding of the surrounding context.

LLC-2020 focused on questions surrounding the adoption of innovative technologies on North Carolina swine farms. Specifically, they asked why producers were slow to adopt alternative manure management practices that could both increase capacity and mitigate some of the environmental impact associated with swine production. This research question led the team to consider the competing demands of different stakeholder groups on producer's decision-making with respect to adoption of new practices. Through interviews with representatives of different sectors of stakeholders, the team developed a unique model of adoption that emphasizes producers' "means, motive, and opportunity" in choosing manure management strategies. Their manuscript was recently accepted for publication by the journal *Elementa:Science of the Anthropocene* [16].

In both iterations of the LLC Cohort Challenge, students asked research questions that got at the heart of why the conditions of livestock production present "wicked problems" where food production systems intersect with many aspects of society and where solutions depend on the active cooperation of many different constituencies. In each version, students worked with different kinds of data and analytic strategies demanded by the problems they were addressing. In addition, communication with stakeholders were at the heart of the research both teams performed. Both teams produced new analytical techniques applicable to a broader set of wicked problems. Moreover, over time, the team built trust in each other, allowing for mutual cooperation in the face of obstacles and collaborative problem-solving when challenges emerged.

It is noteworthy, that one faculty advisor has also commented on their own learning and growth, capturing the wonder of collaboratively developing novel and fresh solutions in a transdisciplinary teamwork that were beyond their own initial and limited disciplinary genre.

B. Disaster Relief and Resiliency

The Cohort Challenges on Disaster Relief and Resiliency were both led by Luis Rodriguez of the University of Illinois, Urbana-Champaign. The Cohort Challenges were part of a substantial portfolio of teaching experiences, leading both undergraduate and graduate students to participate in projects in Puerto Rico in the aftermath of 2017 Hurricane Maria. Rodriguez's extensive network of contacts in Puerto Rico and his deep understanding of the complex systems compromising disaster recovery led to the following challenge statement:

> Students will work with local communities, aid organizations, and peer institutions in the identification and implementation of resilient responses in the context of natural disasters. Students will document their assessments providing a prioritized action plan for future development efforts.

The students for DRR-2019 came from diverse backgrounds, seeking degrees in agricultural engineering, civil engineering, natural resource sciences, applied sociology, as well as an interdisciplinary program in water resources. Similarly, the students for DRR-2020 had different disciplinary interests in agricultural engineering, civil engineering, sustainability sciences, and social work.

In both iterations of DRR, the teams worked closely with an NGO in Puerto Rico, Caras con Causa [21], an organization working on issues related to community development, citizen science and STEM education for young people. Both years, students supported Caras con Causa programs that aim to build community resilience in the face of recovery from disasters that

compromise FEW systems. Members of the cohort were introduced to the leadership and staff for Caras con Causa early in the process, and discussions about the definition of the respective projects and the final products was an ongoing feature of the Cohort Challenge each year. The manner of stakeholder engagement and accountability were crucial to team interactions early in the Cohort Challenge process.

After several conversations with Caras con Causa's staff about their educational programs, the team members for DRR-2019 proposed preparing a set of interactive maps that identify infrastructure, nearby nature preserves, and other features shaping resilience to natural disasters. The maps were designed to include community input, thus supporting the citizen science Caras con Causa conducts. Through the course of developing the maps, the team members learned the challenges of working in a virtual environment with stakeholders who lived in a place they had never visited; frequent meetings were necessary to clarify the goals of the project and the scope of the team's activities for their community partners. Those interactions led group members to create tools to encourage regular communication and accountability for outcomes. They have prepared a manuscript for publication that analyzed the pathways of stakeholder engagement; the manuscript has recently been accepted for publication in *Global Environmental Change* [17].

DRR-2020 worked on a very different project. Based on the experience the previous year, Caras con Causa's staff had a better idea of what to expect from participating in a Cohort Challenge and formulated a relatively specific request to enhance two of its programs. The first, Urban Roots, promotes sustainable reforestation and restoration of the local ecosystem through the cultivation of mangroves. The second, The Community Laboratory, provides school children with access to laboratory equipment to conduct various science activities and exercises. Knowing

that grant funding is available to support citizen science, Caras con Causa staff needed assistance developing literature reviews to support their efforts to attract those funds. The diversity of disciplinary experience the students in the DRR-2020 cohort helped them get creative in developing this literature review, and the bibliographic database they assembled reflected many different possible avenues of research. In addition, several of the team members were personally familiar with life in Puerto Rico; their ability to communicate with Caras con Causas staff in both English and Spanish helped promote effective communication. The participants in DRR-2020 have presented a case study of their experience at the annual meeting of the Community Informatics Research Network and at the ASA-CSSA-SSSA International Annual Meeting [18], [19].

V. Reflections / Future Directions for Cohort Challenges

"Cohort Challenges" provide a rich and rewarding transdisciplinary experience by individuals and teams of students that complements traditional graduate training. This paper outlines an approach for providing this experience. Like any curriculum or educational program, the prescription of competencies or skill sets can be met through a broad range of exercises, applications or practices. Yet the Cohort Challenges have offered particularly impressive results in developing those competencies. The graduate students who have participated have built effective teams applying transdisciplinary skills to identify and create solutions to wicked problems. In doing so, they have expanded their professional networks to include faculty, peers, and stakeholders they might not have otherwise met in the course of their graduate education. Yet even considering these successes, we hope to enhance and expand the capacities of Cohort Challenges.

For example, the INFEWS-ER team envisions making Cohort Challenges more accessible by enabling students to secure course credit for their participation. Because Cohort Challenges are mostly extra-curricular activities, students may not be able to join because they are juggling other commitments. Yet securing course credit is complicated given that Cohort Challenges draw students from many departments and universities with widely different curricular requirements. The INFEWS-ER team continues to identify indicators to support students who want to build a case for claiming independent study credit, including formal assessment measures. Designing formal assessment is complicated, however, by a program where students are responsible for identifying the learning objectives – that is, the final project – and it is hard to specify in advance the knowledge they need to master and the skills they need to develop. Still, the INFEWS-ER team has identified a battery of questions that offer students the opportunity to engage in self-assessment about the transdisciplinary skills that Cohort Challenges are supposed to foster. Students in the 9th Cohort Challenge took that self-assessment at the beginning of their program and will take it again at the end when their project nears completion. In addition to these self-assessments, the publication of papers generated in Cohort Challenges is a good measure of the quality of the students' work. And finally, while the short- and long-term impact of the Cohort Challenges on the graduate student's careers is not known at this time. However, the advisors and participants continue to provide informal feedback on how this new form of graduate training has enhanced their own scholarship of teaching and learning, teamwork, communication, research, and funding opportunities. While fragmented and informal, the overall positive feedback warrants continuation of efforts to develop and offer transdisciplinary training to graduate students.

We also hope that the Cohort Challenge model will be adopted more widely, beyond FEWS systems, on large-scale projects pursuing transdisciplinary research and education. For example, the National Science Foundation funds several convergent research centers which focus on complex, "vexing" research problems focusing on societal needs. These centers emphasize collaborative, transdisciplinary team research where both faculty and students are expected to work across disciplinary boundaries and connect their research agenda with others across the center. Cohort Challenges would be an excellent mechanism for training graduate students working in such multi-disciplinary settings. Such centers are grounded in the broad research areas that generate many possible projects that require many kinds of scientific and engineering expertise. Cohort Challenges advance research center goals by bringing faculty mentors and graduate students together, by showing students and faculty how to work as a team, and by encouraging them to demonstrate leadership in asking questions and designing solutions.

For example, one such center, Science and Technology for Phosphorus Sustainability (STEPS) encompasses approximately 40 faculty investigators across 28 disciplines and nine institutions and approaches phosphorus sustainability across 17 orders of magnitude in length scale. [22]. The Center is organized in three themes based on scale, materials, human / farm interaction, and global / modeling. Research activities are allocated to teams working across disciplines and across at least two of the length scales. Two of the authors (Classen and Marshall) are STEPS investigators and plan to propose a 2022-2023 cohort challenge that will employ graduate students from several of these internal projects with the goal of integrating the project results with the needs and goals of other projects. Consistent with the cohort challenges described above, the process is more important than the product, but one possible outcome is a list of proposal ideas for the next round of internal funding. Other outcomes are certainly

possible, but the most important result will be the enhanced skill set of the students that complete the process. The concepts and processes described in this paper can be adapted to a wide range of issues, teams, and educational settings.

Finally, to expand the availability of Cohort Challenges, the INFEWS-ER team is developing a virtual resource center (VRC) that will assist faculty organizers in designing their own Cohort Challenges. The current plan is to provide access to Toolbox Modules and other materials to that provide training in transdisciplinary skills. The VRC will showcase the processes and products of previous Cohort Challenges. Importantly, we expect the VRC to be interactive so that future Cohort Challenge participants can make their own contributions, including adding Toolbox Modules to the menu and creating spaces to trade insights into what works and what needs further development.

The fodder for Cohort Challenges is all around us, if we are willing and able to scope out problems, as opposed to jumping to solutions. Some of society's most pressing problems are of the wicked nature we describe above. These situations present some of the most interesting cohort challenges precisely because of the need for transdisciplinary approaches, fresh interpretations of the problem, and a willingness to accept uncertainty of the solution during the process. In this vein, cohort challenges may not always mesh well with time-sensitive grant programs with limited flexibility in protocol, particularly where a specific product is necessary. However, the skills developed here are transferable to programs like these where timely products must be procured.

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