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Experiential Graduate Course Prepares Transdisciplinary Future Leaders to Innovate at the Food-Energy-Water Nexus

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Abstract: Food, energy and water (FEW) systems are critically stressed worldwide. These challenges require transformative science, engineering and policy solutions. However, cross-cutting solutions can only arise through transdisciplinary training of our future science and policy leaders. The University of Maryland Global STEWARDS National Science Foundation Research Traineeship seeks to meet these needs. This study assessed a foundational component of the program: a novel, experiential course focused on transdisciplinary training and communication skills. We drew on data from the first two offerings of the course and utilized a mixed-method, multi-informant evaluation that included validated pre–post surveys, individual interviews and focus groups. Paired Mann–Whitney–Wilcoxon tests were used to compare pre- and post-means. After the course, students reported improvements in their ability to identify strengths and weaknesses of multiple FEW nexus disciplines; articulate interplays between FEW systems at multiple scales; explain to peers the most important aspects of their research; and collaborate with scientists outside their field. Students also reported improvements in their oral and written communication skills, along with their ability to critically review others' work. Our findings demonstrate that this graduate course can serve as an effective model to develop transdisciplinary researchers and communicators through cutting edge, experiential curricular approaches.

Keywords: graduate education; interdisciplinary; transdisciplinary; food–energy–water nexus; communication; collaboration; program evaluation

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1. Introduction

Population growth and climate change are crippling our global food, energy and water (FEW) resources, jeopardizing both ecological and human health [1,2]. For instance, high-quality freshwater sources used to irrigate food crops are dwindling worldwide [3,4], and modern farming practices aimed at increasing yields to feed ever-expanding populations have exigent needs for energy [5]. Our current food production systems continue to deplete natural resources and pollute ecosystems, thereby compromising the ability to feed future generations [6].

1.1. The Food-Energy-Water (FEW) Nexus

The interconnections between a changing climate, an increasing global population, dwindling freshwater supplies, growing energy demands and changing food production systems have given rise to a new area of interdisciplinary research within the last two decades known as the FEW nexus [7]. The origins of FEW nexus thinking can be traced back to the World Economic Forum of 2011, where the global challenges related to economic development were recognized from the perspective of linkages among food, energy and

water [4]. The Bonn 2011 Nexus Conference later that year also popularized FEW nexus thinking, presenting evidence for how such an approach can enhance FEW security by increasing efficiency, reducing trade-offs, building synergies and improving governance across sectors [7]. This spurred a global awareness that food, energy and water challenges can no longer be addressed in isolation or within sectoral boundaries. Many scholars have since shown the interdependence of the water, food and energy sectors, demonstrated their complex relationships and outlined ways of addressing them in a more systematic manner under a nexus approach [8–15].

1.2. Critiques of FEW Nexus Thinking

As quickly as FEW nexus thinking gained popularity over the past decade, so too did arguments arise that it is not a novel concept and is merely a rebranding of existing environmental governance approaches and previous systems' frameworks, such as integrated water resource management (IWRM) and integrated natural resource management [16,17]. Wichelns (2017) even contends that the attention given to the FEW nexus in the scholarly literature is somewhat surprising, particularly as the nexus is not a clearly defined construct or tested framework [18].

Other scholars refer to the term "FEW nexus" as a buzzword, arguing that it has no real definition and lacks focus on the problem itself despite widespread popularity of the term within stakeholder groups in government, academia and international development and conservation organizations [19,20]. Foran (2015) describes the FEW nexus as an "immature concept" that requires more critical conceptualization [21]. Both Cairns and Krzywoszynska (2016) and Foran (2015) emphasize critical social science as a necessary tool to be used to help the concept of the FEW nexus mature outside of typical quantitative analysis [19,21]. Wiegleb and Bruns (2018) also discuss the misconception of the FEW nexus as a neutral and apolitical concept while its managerial framing is critiqued for masking power relations and social inequalities [22]. These authors deem it necessary to critically investigate the nexus approach before further endorsing it as an analytical or resource governance framework [22].

1.3. Enhancing Knowledge of the FEW Nexus

Nevertheless, FEW nexus research to date recognizes that food, energy and water systems are inextricably linked and emphasizes an interconnected approach to policy, science and practice focused on FEW nexus solutions [2,23]. This approach is based on the awareness that these systems are interdependent, and it is not possible to effectively address problems regarding food, energy or water resources in isolation without considering the impacts on the other two [6,7]. Hence, there is an urgent need to develop educational models that focus on the interdependencies among FEW systems [24] and train the next generation of FEW nexus professionals in transdisciplinary research (e.g., research integrating different disciplines in a holistic manner to create new knowledge and innovations beyond discipline-specific approaches to address critical problems) and systems thinking [25,26].

While systems thinking approaches are not novel concepts in interdisciplinary curricula [27–30], we believe that this type of training is particularly important for educating future leaders poised to address many of the global challenges currently facing humanity. The application of systems thinking to FEW nexus training, particularly at the graduate student level, is imperative to the success of future FEW nexus researchers.

1.4. Graduate Student Training

Research universities and most graduate education programs typically focus on traditional science, technology, engineering or mathematics (STEM) education models that emphasize expertise in highly specialized fields [31–33]. Through this approach, graduate students focus on a small, specific segment of science, often through densely packed curricula and highly targeted scientific investigations within their field of study [32,34,35].

However, problems at the FEW nexus span complex geographic, temporal, socioeconomic and governance scales, requiring integration of physical, biological and social sciences, as well as engineering, along with effective stakeholder engagement [36,37]. This need for the integration of diverse perspectives requires innovative STEM graduate education models that focus on transdisciplinary training in order to prepare a FEW workforce across multiple sectors [38]. Additionally, graduate programs that are rooted in traditional disciplines may not offer the training necessary to develop skills needed for transdisciplinary collaboration. Furthermore, the majority of STEM graduate programs have significantly underdeveloped formal professional training for skills such as technical writing, communicating to diverse audiences, budget and project management, leadership, mentorship and conflict resolution. As a result, recent graduates are often unprepared to be successful across a wide range of career settings [33].

1.5. The UMD Global STEWARDS Program

In an effort to address these educational gaps, we developed a transdisciplinary, experiential graduate education program focused on innovations at the FEW nexus from local to global scales: the University of Maryland (UMD) Global STEWARDS (STEM Training at the Nexus of Energy, WAter Reuse and FooD Systems) program. UMD is a public, research-intensive university located on the east coast of the USA with nearly 40,000 students enrolled in over 200 undergraduate and graduate programs. UMD Global STEWARDS is supported by a National Science Foundation (NSF) National Research Traineeship (NRT) grant, and embraces the NSF definition of STEM fields, including the biological, physical and computer sciences, engineering and the social and behavioral sciences (e.g., sociology, anthropology, political science). The program has multiple elements, including a novel experiential introductory course on the FEW nexus, a data practicum course, weekly seminars, outreach and mentoring, an optional domestic internship, an optional short-term faculty led study abroad trip and an annual intensive professional development workshop series (Figure 1).

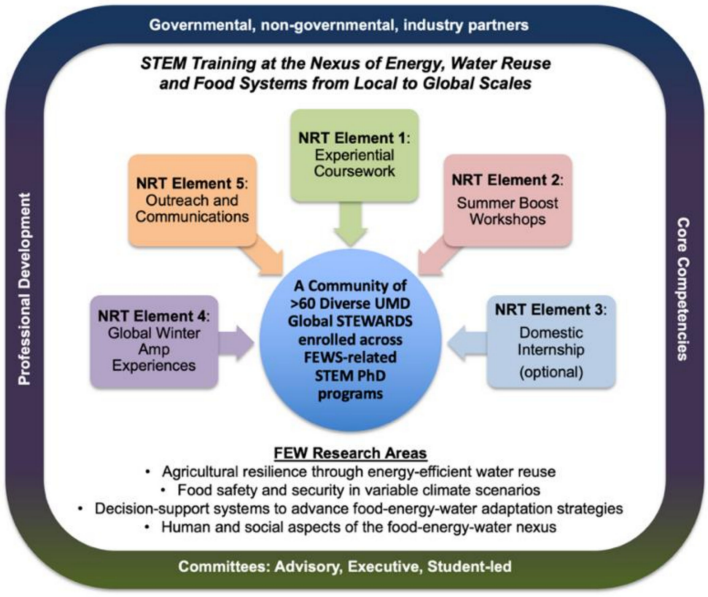

Figure 1. Overview of the UMD Global STEWARDS NSF NRT [39].

The UMD Global STEWARDS NSF NRT was created to be a national model for the preparation of lifelong learners, stellar science communicators and distinctive professionals prepared to create transdisciplinary FEW nexus solutions that ensure food, energy and water security for future generations. Specifically, the program focuses on developing students' skills in collaborative transdisciplinary research to address challenges at the

FEW nexus [25,40]. The program also emphasizes refining students' written and oral communication across disciplines.

The purpose of this study was to assess the effectiveness of the program's experiential introductory graduate course focused on interdisciplinary FEW research training and communication of research to diverse audiences. This course is entitled Experiential Exploration of Innovations at the Nexus of Food, Energy, and Water Systems (INFEWS) (hereafter denoted as the "introductory course"). The introductory course is a cornerstone of our program and is designed to familiarize students with broad food, energy, water (FEW) nexus topics, focusing on how integration across the biological, physical, social, behavioral, computer and engineering sciences will be critical in solving FEW systems challenges. To frame our assessment, we posed the following specific research questions:

(1) What was the rationale for creating this course and the specific course components?
(2) How beneficial did the students find each of the activities, assignments and course components in developing their skills as interdisciplinary researchers?
(3) To what extent did students report that the course overall contributed to their growth in interdisciplinary research skills, communication skills and career preparation?
(4) Did students' confidence in their ability to conduct interdisciplinary research grow over the duration of the course?

2. Materials and Methods

2.1. Course Description and Participants

The UMD Global STEWARDS NSF NRT was designed to attract doctoral students from any graduate department, as long as their research focus is related to two or more aspects of the FEW nexus. To date, students have been drawn from the life and public health sciences, earth system sciences, engineering, social behavioral sciences, natural resource management studies and public policy, to name a few. The program runs on a calendar year schedule, with new cohorts joining the program in January. Students take the introductory course during their first semester in the program.

The introductory course (Table 1) consists of lectures, expert guest speakers, student-led discussions and presentations, hands-on activities, field trips and case studies focused on domestic and international FEW challenges. The course components (Supplementary Materials) emphasize how integration across the biological, physical, social, behavioral and computer sciences is critical in solving FEW systems challenges. We aim to strike a balance between presenting perspectives and data from each of these different sciences, exposing the students to both quantitative and qualitative study design and data analysis approaches, along with policy implications. In each course session (Table 1), we specifically aim to integrate varying perspectives. For example, in session 3, "Water–Food Intersections: Interdisciplinary Research within the CONSERVE Center of Excellence", students engage in a panel discussion with a microbiologist, extension specialist, social–behavioral scientist and lawyer, regarding their interdependent work in the CONSERVE Center. As outlined in Table 1 and in the alignment map presented in Table 2, students also gain an appreciation for different writing styles in science communication through class assignments such as writing policy memos, Op-Eds and short research papers. The course is designed as part one of a two-course series, providing the foundation for students to be successful in the subsequent data practicum course where they put these skills to use, working on an interdisciplinary FEW research project with fellow students.

We collected data from the first two iterations of the course over two consecutive years, in Spring 2019 and Spring 2020. Due to the COVID-19 pandemic, the latter half of the second iteration was taught online. This research was approved by the University of Maryland Institutional Review Board (IRB).

Table 1. Summary of the introductory course components.

* Lecture Topics and In-Class Activities	Uncovering the Food–Energy–Water Nexus Systems Thinking at the Food–Energy–Water Nexus Water–Food Intersections: Interdisciplinary Research within the CONSERVE Center of Excellence ** Food/Waste–Energy Intersections Energy–Water Intersections Economics of the Food–Energy–Water Nexus * Global Perspectives: Emerging FEW Innovations in Nepal and Israel FEW Systems as an Opportunity for Mitigation and Adaptation Climate Change Impacts on FEW systems Policy and Governance at the FEW Nexus Stormwater Reuse and Treatment for Irrigation and Other Applications ** Introduction to Group Dynamics ** Social/Behavioral Dimensions of the Food–Energy–Water Nexus ** Forests, The Future of Food Systems
Student Activities: In-Class	5-min lightning round presentations on their research 5-min lightning round presentations on their two-page policy memos Systems Thinking Game 20-min presentation on interdisciplinary FEW nexus case studies (group project of 3 students per group) * 15-min group project pitches that will become the interdisciplinary FEW nexus team projects that students complete in the fall semester ***
Student Activities: Outside of Class	Post comments on the online discussion board Write a two-page policy memo on a chosen topic Interdisciplinary FEW nexus case studies (group project of 3 students per group) * Short research paper
Field Trips	On-campus field trip: exploration of on-campus sites employing stormwater treatment and water reuse for food production and other irrigation activities **** Off-campus field trip to a forest farm **** Off-campus field trip: energy–water innovations in the Town of Emmitsburg, MD ****

Note: The content included in this table reflects course content that was offered in at least one iteration of the course. There were slight variations in the topics and method of delivery in response to both student feedback from the first offering as well as due to the COVID-19 pandemic. * Topic/activity completed in first iteration of class only. ** Topic covered in second iteration of class only. *** New course component integrated into the second iteration of the class. **** Cancelled in second iteration of course due to COVID-19 pandemic.

Table 2. UMD Global STEWARDS Introductory course alignment map.

Course Objectives **At the End of the Course, Students Will Be Able to:**	**Activities**	**Assessment**
(1) Identify major FEW challenges and conceptualize and articulate interplays between FEW systems from local to global scales	(1) Multiple guest lectures from FEW nexus experts (2) Field trips to demonstrate real-world applications of important FEW nexus concepts (3) Interdisciplinary FEW case studies (cohort 1 only) (4) Lightning round presentations of written policy memos	(1) Short research paper (cohort 1 only) (2) Short research paper oral presentation (cohort 1 only) (3) Written policy memos (4) Interdisciplinary FEW case studies (cohort 1 only) (5) I Interdisciplinary FEW systems project pitches (projects completed in subsequent semester) (cohort 2 only)
(2) Begin to collaborate as a member of an interdisciplinary research team to analyze and offer solutions to specific FEW system challenges	(1) Interdisciplinary FEW case studies (cohort 1 only) (2) Forming interdisciplinary FEW systems project teams	(1) Short research paper (cohort 1 only) (2) Interdisciplinary FEW systems project pitches (projects completed in subsequent semester) (cohort 2 only)

Table 2. *Cont.*

Course Objectives At the End of the Course, Students Will Be Able to:	Activities	Assessment
(3) Build science communication skills: communicating your research to scientific disciplines outside your field and to the general public, both written and orally	(1) Introductory Lightning round presentation on students' individual dissertation research (2) Lightning round presentation on written policy memos	(1) Short research paper (cohort 1 only) (2) Short research paper oral presentation (cohort 1 only) (3) Written policy memos
(4) Recognize and translate the language of multiple disciplines working at the food–energy–water nexus from molecular to societal levels	(1) Guest lectures from UMD faculty and other non-academic experts in Systems Thinking and the FEW nexus (2) Systems thinking game (3) Off-campus field trip to a forest farm (cohort 1 only) (4) Off-campus field trip: Energy–water innovations in the town of Emmitsburg, MD (cohort 1 only) (5) Forming interdisciplinary FEW systems project teams (cohort 2 only)	(1) Written policy memos (2) Interdisciplinary FEW case studies (cohort 1 only) (3) Interdisciplinary FEW systems project pitches (projects completed in subsequent semester) (cohort 2 only)
(5) Identify strengths and critique weaknesses of multiple FEW nexus disciplines	(1) Multiple guest lectures from FEW nexus experts (2) Field trips to demonstrate real-world applications of important FEW nexus concepts	(1) Written policy memos (2) Interdisciplinary FEW case studies (cohort 1 only) (3) Interdisciplinary FEW systems project pitches (projects completed in subsequent semester) (cohort 2 only) (4) Written Policy memos (5) Short research paper (cohort 1 only)

2.2. Data Collection and Analysis

We draw upon data from the ongoing UMD Global STEWARDS internal evaluation program which utilizes a mixed-method, multi-informant evaluation that includes surveys, individual interviews and focus groups. The evaluation team consists of an expert evaluator (a research professor in science education) and a graduate assistant. The evaluation team is not involved in planning or teaching the course and the team is presented to the students as "evaluators of the UMD Global STEWARDS program". The consent forms for the interviews and surveys include the following sentence: "Only the evaluation team will have access to the data, and the leadership team [which includes the teachers of this course] will have access only to de-identified data".

To collect baseline data and end-of-semester data, we used an adapted version of a validated pre–post survey [41]. Face validity of the adapted survey was established by the evaluation team, the course instructor and the UMD Global STEWARDS program manager. For the Likert scale questions, responses were collected using a 5-point scale ranging from 1 = "not at all" to 5 = "to a great extent", and we calculated means (M) and standard deviations (SD). Paired Mann–Whitney–Wilcoxon tests were used to compare students' pre- and post-course ratings of their confidence in developing multiple skillsets. Missing data (n = 1) were handled using pairwise deletion. All values designated as significant remained so after correcting for multiple comparisons using Holm's Step-Down Procedure.

Following the Spring 2019 course, the evaluation team used two methods to collect feedback in addition to the survey: a focus group with the students and course instructors and, in order to ensure feedback was not influenced by the presence of the instructors, individual student interviews only with the evaluation team. The focus group in the Spring 2019 semester was held in person and audio recorded. The evaluation team conducted the individual semi-structured interviews in person with six fellows who were specifically selected to represent the population of the course in terms of demographics (gender and

race/ethnicity), field of study and year in the program (Table 3). Each interview lasted for one hour and was audio recorded after receiving permission from the interviewees. Interviews were transcribed verbatim. Individual profiles of each interviewed student are not reported here to protect the students' anonymity.

Table 3. Student demographics.

	Spring 2019	2019 Interviewees	Spring 2020
	(*n* = 12)	(*n* = 6)	(*n* = 11)
Years in Program			
<1	2 (17%)	1 (17%)	4 (36%)
2	6 (50%)	2 (33%)	5 (45%)
3	2 (17%)	2 (33%)	2 (18%)
4	2 (17%)	1 (17%)	-
Gender			
Male	7 (58%)	4 (67%)	2 (18%)
Female	5 (42%)	2 (33%)	9 (82%)
Race/Ethnicity			
White	3 (25%)	2 (33%)	7 (64%)
Black/African American	1 (8%)	-	1 (9%)
Asian/Asian American	5 (42%)	3 (50%)	2 (18%)
Hispanic/Latino	1 (8%)	-	1 (9%)
American Indian or Alaska Native	1 (8%)	1 (17%)	-
Other	1 (8%)	-	-
Field of Study			
Anthropology	-	-	1 (9%)
Architecture, Planning & Preservation	-	-	1 (9%)
Atmospheric and Oceanic Science	2 (17%)	1 (17%)	-
Biological Science	-	-	1 (9%)
Engineering	-	-	2 (18%)
Environmental Sciences	4 (33%)	2 (33%)	1 (9%)
Geographical Sciences	1 (8%)	1 (17%)	2 (18%)
Plant Sciences	2 (17%)	-	-
Public Health	2 (17%)	1 (17%)	3 (27%)
Public Policy	1 (8%)	1 (17%)	-

At the end of the Spring 2020 semester, the evaluation team streamlined the feedback process and conducted an hour-long semi-structured focus group interview where the course instructors were not present. The focus group in the Spring 2020 semester was conducted via Zoom video conferencing software [42] (since, at this point, all classes and meetings were being conducted virtually due to the COVID-19 pandemic) and recorded using the Zoom recording feature. Interviews were transcribed verbatim. Responses to the open-ended questions from the interviews and the surveys were analyzed qualitatively using an inductive approach [43] and related responses were grouped into themes that could be quantified. Due to the relatively small sample size, two members of the evaluation team (the expert evaluator and a graduate assistant) simultaneously reviewed the responses to identify themes. First, the team reviewed all the responses and identified the main themes. All themes identified by both team members were included. Next, each member coded each response as corresponding to one or more of the identified themes. The team members discussed discrepancies in their coding until they reached a consensus for each response. Prior to the discussion, their interrater agreement was estimated to be around 90% [43]. At the end of the Spring 2019 semester, the evaluation team also interviewed the course instructor (who is also the UMD Global STEWARDS program director) to ascertain the overall motivations for the program and the instructor's views on the success of the course.

3. Results

We draw upon the data from student surveys, student and instructor interviews and focus groups to assess the research questions outlined above. Overall, 23 students participated in the two courses (12 in 2019 and 11 in 2020). The participants were diverse in terms of race/ethnicity, gender, core discipline and year in their program (Table 3).

RQ 1: What was the rationale for creating this course and the specific course components?

To accurately assess the course, it was important first to ascertain insight into the motivation to create the course and the reasons for developing the specific course structure. To this end, following the first iteration of the course, the evaluation team interviewed the instructor of the course. The instructor referred to the current high national and international priority regarding FEW nexus research as a motivation for the development of the course, and highlighted the challenges of teaching this topic mainly due to its interdisciplinary nature and the fairly recent emergence of the FEW nexus as a combined research area.

> " . . . For food–energy–water nexus traineeship programs, it is necessary to have a broad course about the topic because you have students coming from multiple disciplines, and you have limited information about their previous knowledge concerning the food–energy–water nexus. Even if they work on energy issues, for example, they might not have a firm understanding about this new framing. NSF clearly focuses on training more interdisciplinary leaders in this area, because we know that if we want to successfully address critical FEW nexus challenges, we have to simultaneously consider all areas of the nexus."

The instructor further asserted that the complex nature of the FEW nexus, coupled with the variety of students from such diverse fields of study, influenced the course planning and eventually the course structure.

> "This is a very difficult course to teach and plan because you have students from so many different disciplines participating. There are also multiple aspects of the food–energy–water nexus that you have to cover . . . from local to global scales and across multiple fields from microbiology to policy and governance issues, so it is a very difficult course to plan."

The first step in planning the course was to explore similar FEW-nexus-focused NRT programs that were already created by other universities and adopt some of their ideas. However, the structure of the course was mainly inspired by John Dewey's educational philosophy that promotes student learning through high-quality experiential activities [44,45]. The instructor remarked, "I apply John Dewey's model for all of my graduate courses. I try to schedule as many field trips, experiential and hands-on activities in the class as possible".

Regarding the decision to include specific components in the course, the instructor explained that field trips and guest speakers were secured first (in an order that considered first availability and then the specific topic). Other components (such as the policy memos, case studies, assignments in diverse small groups, short research papers and lightning talks by students) were implemented to increase students' ability to communicate (orally and in writing) with diverse audiences (e.g., the general public, policy makers, scientists in other fields) and to support students' development as interdisciplinary researchers.

> "An overall theme of the NRT, of any NRT, is being able to communicate your science to a diverse audience. This is especially critical at the food–energy–water nexus. FEW research has immediate policy ramifications, and thus, our students, regardless of their individual fields, need to be able to talk about their science in lay terms and be effective in helping to translate their science to policy . . . ."

> " . . . So, the idea was that students could work with folks that were not in their discipline . . . I specifically paired them in groups of three with people who were

> from a different college, different department, difference discipline, so they could work together on an interdisciplinary FEW nexus problem."

RQ 2: How beneficial did the students find each of the activities, assignments and course components in developing their skills as interdisciplinary researchers?

Figure 2 shows student reports of how useful each of the course activities was on a 5-point scale with the following levels: 1 = not at all, 2 = not much, 3 = somewhat, 4 = to a good extent, 5 = to a great extent. Students found the opportunities to learn about fields that were previously unknown to them to be the most useful activity (M = 4.61, SD = 0.58), followed by learning different perspectives on scientific approaches and communication (M = 4.39, SD = 0.50) and access to role models of interdisciplinary thinking among faculty members (M = 4.30, SD = 0.64).

The survey ratings were consistent with students' feedback during the interviews and focus groups. For example, in one individual interview following Spring 2019, a student described their experience learning about fields that were previously unknown to them:

> " . . . I loved learning about other discipline's nexus problems because as we all talk about, these problems are very siloed. I only research water-related interdisciplinary problems. I don't look at waste problems, I don't look at agriculture problems, even though they're all related, I don't focus—I only have so much time. So, it was really nice just carving out time in my week to look at these other angles, and I think that made me more proficient in talking about the nexus as a whole."

On average, students reported that they perceived course activities as more than somewhat useful in providing opportunities to learn new research skills (M = 3.83, SD = 0.54) or help rethinking/or reshaping their research (M = 3.7, SD = 0.51). Noteworthy here is that the second course in this series, taken in the following semester, provides more opportunities for working on group research projects.

In the focus group following the second iteration of the course in Spring 2020, one student shared:

> "I feel that I kind of crowbarred my research interests into the FEW nexus. And so it was really good to see how broad and diverse the FEW nexus actually is. Other than just kind of the targeted food, energy, water like direct linkages that I had looked into in order to like apply to the program. So, I think it definitely opened up the frame and allowed me to see how my research fits into the nexus."

In the individual interviews, when asked if, through the course activities, they gained skills and knowledge that they were able to share with their lab peers and or advisor, one student commented:

> "So, I have, I've definitely let the food, energy, water nexus here take over my thought process as I'm working my way through my first year here of PhD studies. And so every paper that I've done has a food energy water nexus component to it. And so I'm putting in a genuine effort to utilize the skills and the readings and research that we're doing [in the course], and finding a way to tie it to my research and I truly feel that it's an approach that could really have a strong impact in my field . . . "

The course discussion board was rated as the least useful activity (M = 3.26, SD = 1.29). In the focus group with the instructors and the evaluation team following the first iteration of the course, students had a long conversation about why the discussion board did not work for them. One student said, "For me, a discussion board is not conducive to giving feedback. I'm better at in-person feedback and bouncing ideas off of people . . . ". Another student referred to the assignment structure that required students to post their comment before reading other students' comments saying:

" . . . You had to write first and then you could see everybody else's comments. I think it would be nice if we could see everybody else's comments first and if they say something where you're like oh that's interesting then you could try to build off of that . . . "

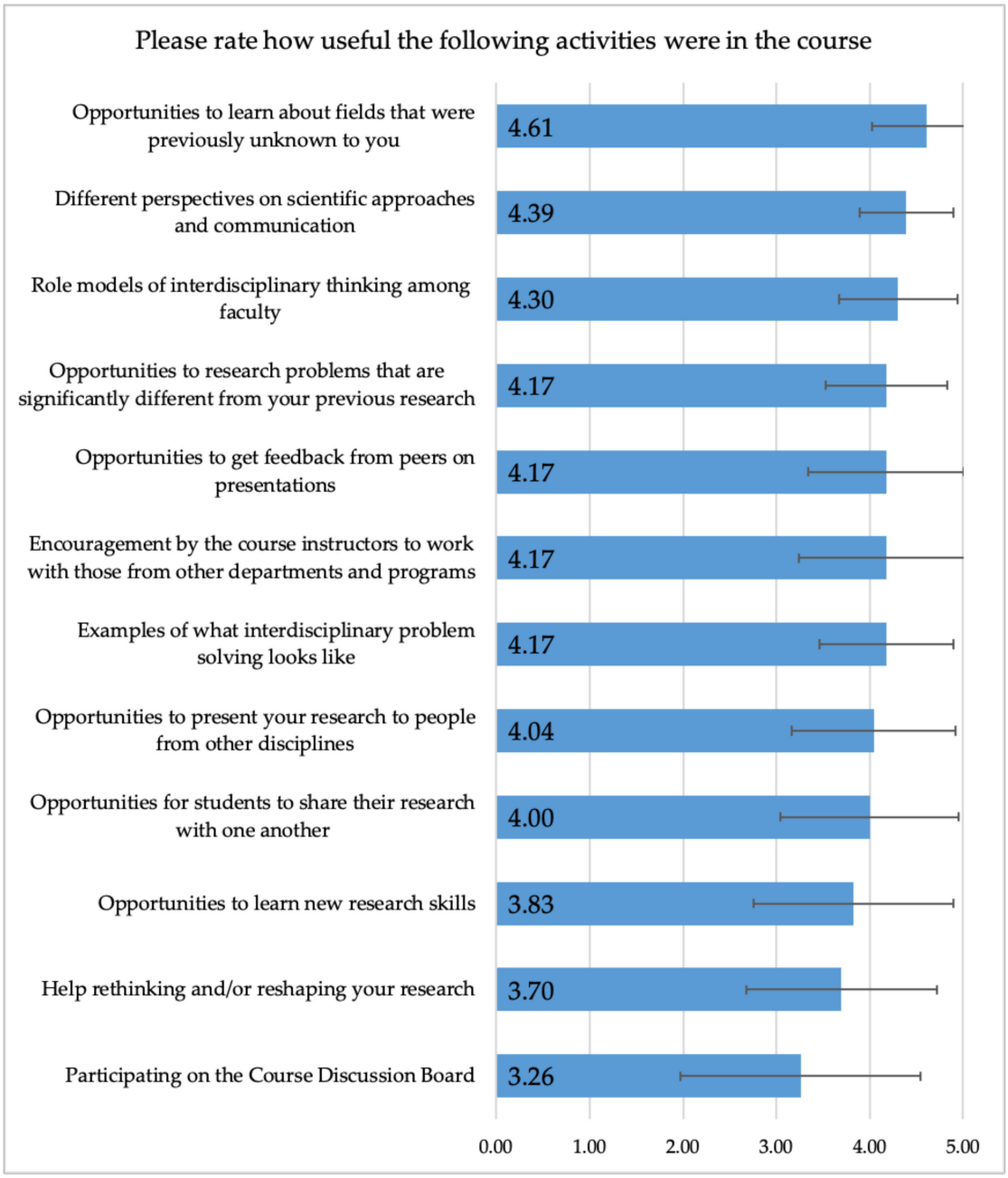

Figure 2. Average and standard deviation of student reports of the usefulness of each course activity (n = 23). Error bars represent ± *SD*, which corresponds to a 95% confidence interval for each item. (1 = Not at all, 2 = Not much, 3 = Somewhat, 4 = To a good extent, 5 = To a great extent).

The instructor explained that the discussion board served as a Just-in-Time teaching approach [46,47], and its purpose was to identify what her students are struggling with before each class, saying " . . . the whole idea was to understand where everyone was coming from". In the latter half of the Spring 2020 course when all course instruction shifted online, a student expressed during the focus group that the discussion boards were

useful because the class was unable to meet in person, but that discussing ideas online did not have the same effect as the dynamic that naturally occurred in class.

Figure 3 shows student reports of how beneficial each of the assignments and course components were to their development as interdisciplinary researchers. Students in both course iterations generally found that all of the assignments and components were helpful (averages > 3.7 out of 5), with again the exception of the course discussion board, which was on average "somewhat" beneficial (M = 3.09, SD = 1.28). The aspects of the course rated as most beneficial were the short research paper (M = 4.57, SD = 0.90) and the in-class group discussions (M = 4.43, SD = 0.45).

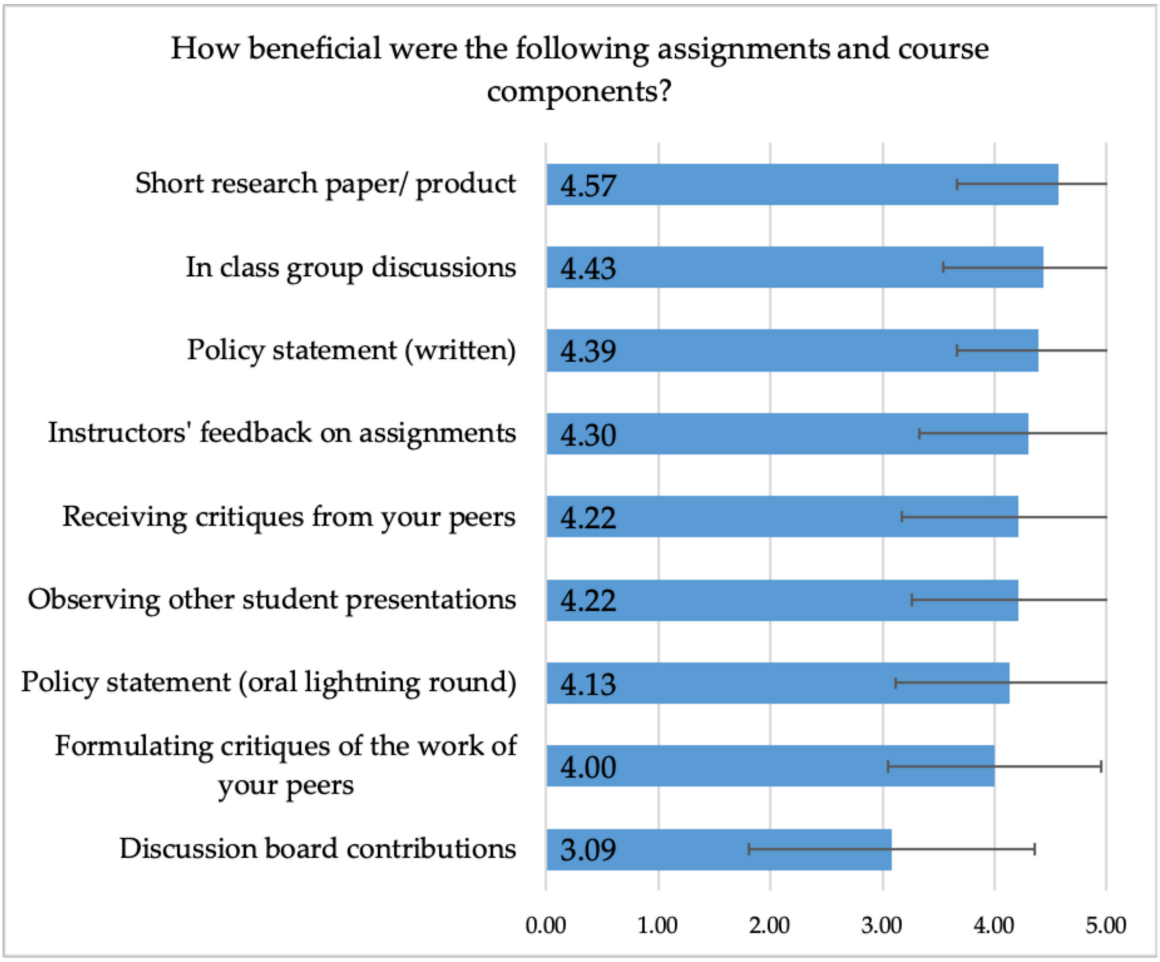

Figure 3. Average and standard deviation of student reports of the usefulness of each assignment and course component (n = 23). Error bars represent ± SD, which corresponds to a 95% confidence interval for each item. (1 = Not at all, 2 = Not much, 3 = Somewhat, 4 = To a good extent, 5 = To a great extent).

During individual interviews, students elaborated on how they benefited from the different course components. These responses varied somewhat based on students' home discipline in that those students from more of a research science background found the policy content to be challenging, but beneficial. Meanwhile, those from policy or policy-adjacent backgrounds, who were in the minority, were challenged by the more technical and scientific content. These students found the policy assignments somewhat routine to complete but they described benefitting from the insight into how their scientist peers approach policy. For example, the following quote from one student from a focus group following the Spring 2019 semester is reflective of the feedback expressed by most of the class, the majority of whom came from research science backgrounds:

> " . . . Doing the case studies was like an opportunity to really dive deep in particular areas, so getting to know like things that I knew surface level. . . . I've never written a policy memo before, and again, that stepping into a new field, it was really enlightening to me . . . [the paper] allowed me to question some of the ideas that I had about the food, energy, water nexus a little bit more rigorously and has actually led to a bit of a transformation in terms of the way that I see the food, energy, water nexus."

Another comment from a student in the focus group following the Spring 2020 semester concerned the value of the written assignments (e.g., the short research paper, the team project):

> "I think that for the written communication, especially the team writing, I haven't done a whole lot of team writing before, so this was a good opportunity to do that. Between the short term paper and then also the group project that we're working on . . . there were a lot of opportunities to do this kind of collaborative writing, collaborative project work. So, definitely I feel a lot stronger now as a result of being a part of the class than I was before."

Another student mentioned how the case study exercise was useful even outside of the Global STEWARDS program: "I basically handed over the case study that I developed for this program to my advisor so that she can use it in her class. Because . . . it was an insight from actually teaching her class that sparked the case study so it fits right into her curriculum".

Overall, students provided largely positive feedback on the course activities, assignments and components, with the exception of the discussion board activity. Otherwise, students only provided negative feedback after the evaluation team probed for suggestions for improvement. This was consistent in the first focus group that the instructors attended, as well as in all of the interviews and focus groups conducted by the evaluation team alone in which student responses were kept anonymous from the instructors. Students' suggestions for improvement were largely minor and included wanting more non-academic guest speakers and wanting those speakers to discuss their career path (a change that was implemented for the second iteration of the course after the instructors received the suggestion), holding a discussion of the readings at the beginning of class meetings in case not all students completed or understood the readings, and including more of a focus on quantitative studies. Quotes from the Spring 2019 focus group are representative of the type of suggestions for improvement from students:

> "A lot of times I hear the same sorts of research data stories, and after a while . . . there's sort of the same thing over and over again. But hearing people's stories about how they found themselves in positions, how they interacted with the different bureaucracies or, you know, social contacts is something that we almost never get access to. And it's something that I think would be really, really valuable."

One student suggested the following: "In the case of reading, I prefer to have more of the quantitative papers to get a good idea of the tradeoffs, because in some cases what we actually think may not be happening". Another student responded: "More like applied ones, because most of the papers we get are like a theory, white paper, or review paper".

RQ3: To what extent did students report that the course overall contributed to their growth in interdisciplinary research skills, communication skills and career preparation?

Students reported that the course helped them gain or improve all the skills outlined in the learning outcomes of the course (averages > 3.48 out of 5; Figure 4). They reported the most improvement in their ability to identify strengths and critique weaknesses of multiple FEW nexus disciplines (M = 4.26, SD = 0.75), followed by their ability to conceptualize and articulate the interplays between and identify challenges within FEW systems from local to global scales (M = 4.09, SD = 0.73).

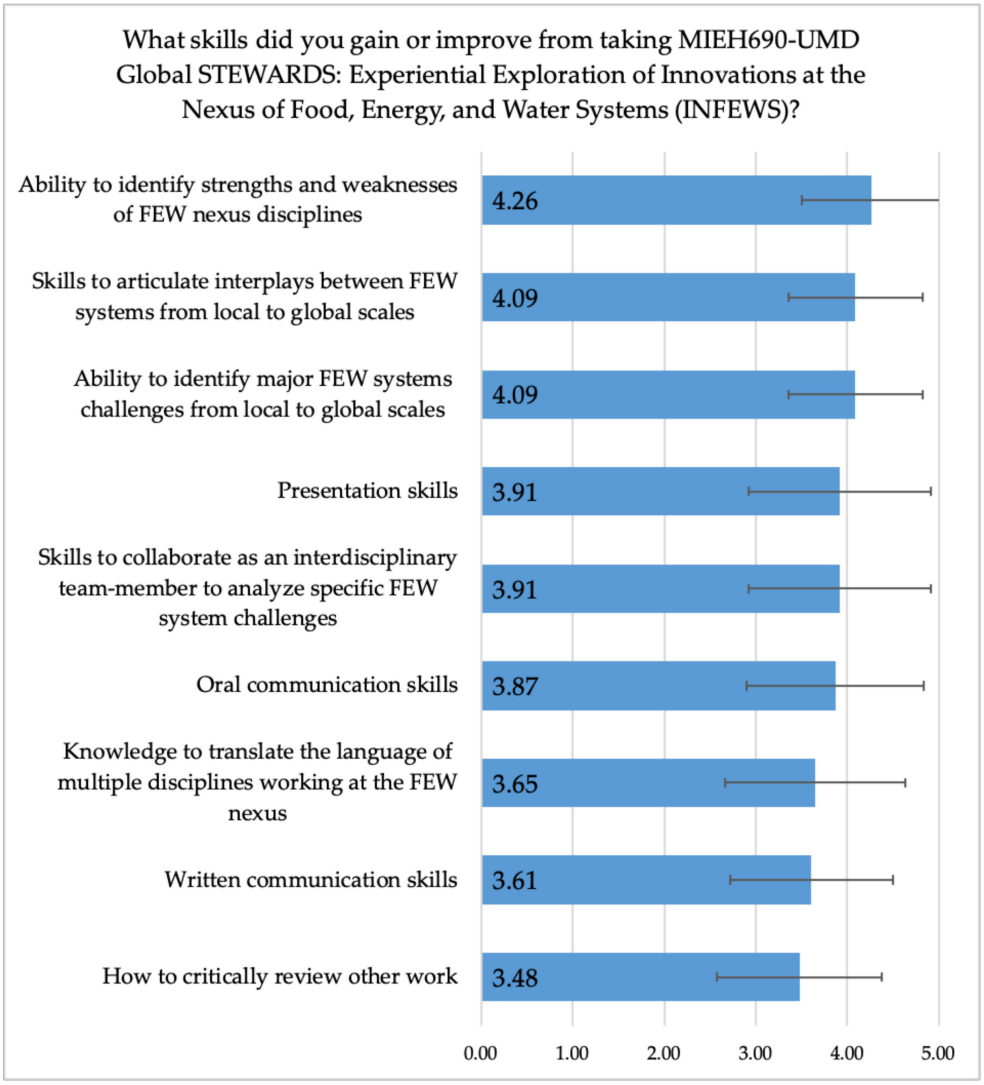

Figure 4. Average and standard deviation of student reports of the degree (1 = Not at all, 2 = Not much, 3 = Somewhat, 4 = To a good extent, 5 = To a great extent) to which the course helped them gain or improve skills (n = 23). Error bars represent ± *SD*, which corresponds to a 95% confidence interval for each item.

These findings were further supported by the qualitative responses from students both in their responses to open-ended survey questions as well as the feedback students provided during the interviews and focus groups. Table 4 shows that in response to the open-ended survey question about gains, most students (n = 13) related to growth in communication and giving presentations, followed by (n = 8) broadening content knowledge. Students also mentioned improvements in their interdisciplinary experience (n = 8), application of FEW concepts to their own research (n = 5), writing (n = 3) and application to potential career paths (n = 2). Regarding potential career paths, one student in the focus group indicated, "This material has really rekindled my excitement about environmental research and opened my eyes to alternative career paths in the field, which is really exciting". In the individual interviews, another student commented:

> "Actually, this is very interesting, we always hear about interdisciplinary groups, multidisciplinary work, but in theory pen and paper I have never experienced it myself. But here we can involve students from different departments and study areas, and it was great how they're thinking and how to communicate with them and how to collaborate with them."

Table 4. Themes and quotes from responses to the end-of-semester survey question regarding the most important things students gained from the course.

Theme	Number of Responses (n = 23)	Student Quote Examples
Communication and Presentation Skills (*especially to diverse audiences*)	13	"How to do presentation in front of people from other discipline " . . . communication skills in regards to drawing parallels between language/jargon of different disciplines." "I appreciated the emphasis on communication, and the opportunity to practice and receive peer feedback."
Content Knowledge (*especially in FEW Nexus*)	8	"A great overview of FEW Nexus research both at a microscopic and macroscopic scales." " . . . case study: very interesting and helpful to me to understand the Nexus better." "Broad knowledge in FEW nexus areas which were new to me before I joined the program."
Interdisciplinary Experience	8	" . . . the course was a good introduction to thinking about issues across sectors, and why interdisciplinary research is important." "Ability to think critically about work outside of my field and ask the appropriate question . . . " "Content and perspective of how other disciplines do research/analysis/methods."
Collaboration	5	"Forming connections outside of my department with professors and students who have different perspectives on FEW issues I deal with in my own work." "Working with people who have very different research interests and finding common ground has also been awesome." "opportunity to collaborate on projects was helpful in developing group research skills. For me the entire purpose of this program is to meet and work with other researchers."
Apply FEW to [My] Research	5	"I have become exposed to and interested in adopting system-based approaches in my research." "The course provided insights on how to take my research discipline/ideas and apply them to (or within) complementary frameworks (e.g., environmental justice at the FEW Nexus)." " . . . the creativity regarding potential research endeavors moving forward."
Writing	3	" . . . writing: writing is challenging but I love the feedback from the instructor. It is really helpful."
Other	2	"Experience working with the human element behind a lot of scientific problems—this was neglected in much of the scientific coursework I've taken in the past." "This material has really rekindled my excitement about environmental research and opened my eyes to alternative career paths in the field, which is really exciting."

RQ4: Did students' confidence in their ability to conduct interdisciplinary research grow over the duration of the course?

Results of paired Mann–Whitney–Wilcoxon tests (Figure 5) showed that students reported higher confidence across a variety of interdisciplinary research aspects. Encouragingly, students reported significant growth not only in their confidence regarding working independently on research within their field of study ($W = 0$, $Z = -3.55$; $p < 0.001$), but also in their confidence in explaining to peers the most important aspects of their research ($W = 5$, $Z = -2.73$; $p < 0.01$) and collaborating with scientists outside their field of expertise ($W = 13$, $Z = -2.71$; $p < 0.01$).

In the interviews, students explained how the course activities and diversity of disciplines helped them to become more confident in these areas. One student said:

> "During these classes and during . . . the policy memo, research study, case study, research paper, all of this we have to go through one by one like we have to do all of this work in a team . . . [this] will train us how to do it for the different disciplines, and of course during working on this team we have to communicate with one discipline to another academic researcher, and communicate interdisciplinary research to non-academic audiences."

Yet another student commented:

> "Even if I wouldn't be able to expertly talk on anything, I am enthusiastic and have examples and have case studies to point to. So, if it was a discipline that I've heard of or was in a seminar or even guest talk I could say 'Well I heard this talk from this person in your field and they were discussing this case study and I found it fascinating' so I can pull examples now which I wouldn't have been able to do before."

Another student expressed that the program has made them more comfortable in working with researchers from other disciplines, and highlighted the necessity of this skill in problem solving:

> "I'm comfortable now working in a group with diverse disciplines . . . I see this as very essential for [working on] real world problems. Because out there, there will be diverse problems and diverse people to come with the solution to existing problems."

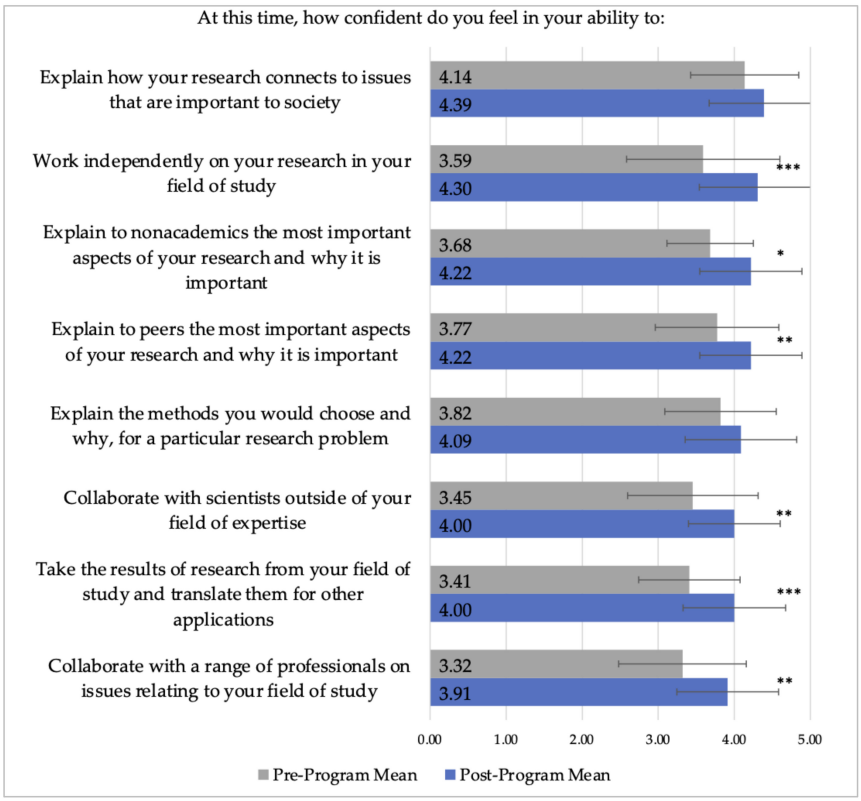

Figure 5. Average and standard deviation of student reports of their own confidence (1 = Not at all, 2 = Not much, 3 = Somewhat, 4 = To a good extent, 5 = To a great extent) in interdisciplinary research skills before and after taking the course (n = 23). Paired Mann–Whitney–Wilcoxon tests were used to compare pre- and post-means. Error bars represent $\pm$ SD, which corresponds to a 95% confidence interval for each item. *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

4. Discussion

Our findings demonstrate the efficacy of a core curricular component of a transdisciplinary, experiential graduate education program, the UMD Global STEWARDS NSF NRT, which was designed to foster innovations at the nexus of food–energy–water systems. FEW nexus researchers have recognized that transdisciplinary research and building the accompanying skillsets in students are critical to our ability to solve the FEW nexus challenges of our time and in the future [36,48]. To this end, the UMD Global STEWARDS program creates a solid foundation for graduate students in transdisciplinary training at the FEW nexus. Students come to the program from a wide range of disciplines (Table 3), and their first interaction with one another is during the required introductory course that was evaluated during this study.

The goals of the introductory course are to formalize training around FEW nexus topics from local to global scales, provide opportunities to collaborate as a member of an interdisciplinary research team and bolster communication skills, all of which are typically deficient in traditional, siloed graduate programs [48]. Following the example of other interdisciplinary graduate programs, we aimed to fit this course into students' already densely packed curricula while avoiding extending their time to degree [49].

To understand the overall effectiveness of the instructors' approach, we focused the present assessment on the four key research questions outlined previously and drew upon data from the program evaluation team's mixed-method assessment. This method provided a robust evaluation of the course as it utilized both quantitative survey data and qualitative focus groups, interviews and survey questions. Quantitative survey data allowed students to anonymously rate the different aspects of the course according to how the course was designed by the instructors and to measure changes in student responses over time. At the same time, the qualitative data provided insights into students' survey responses, allowed for follow-up questioning and gave students the opportunity to describe the course as they experienced it; that is, students could bring up the points they found most important as opposed to points the instructors and evaluators anticipated would be important.

Our first research question concerned the rationale for the course. An interview with the course instructor, who is also the Director of the UMD Global STEWARDS program, revealed that the course was created to address the current global priority of furthering transdisciplinary research at the FEW nexus. Students gain an understanding of the fundamental concepts of the FEW nexus and are introduced to innovations that are implemented to address FEW nexus challenges from local to global scales. Additionally, recognizing that students benefit from learning from multiple perspectives, the course was also motivated by a need to assist doctoral students in enhancing their collaborative interdisciplinary research skills. Students also benefit from a wide variety of opportunities to share their research with different audiences. The INFEWS-ER (Innovations at the Nexus of Food, Energy, and Water Systems—Educational Resources) program, housed at the University of Illinois at Urbana-Champaign and including partners at many other universities and organizations across the country, described a similar motivation for creating their program and its components [50]. The INFEWS-ER seeks to provide educational opportunities to supplement graduate students, especially in their development of transdisciplinary competences, since this is critical to addressing FEW nexus challenges [36]. Comparing the UMD Global STEWARDS to INFEWS-ER, the programs' core components are different; however, the rationale for creating both programs and the skills they both aim to impart on students are similar.

With regard to the effectiveness of activities, assignments and course components, our findings demonstrate that the course has provided avenues for students to work with others who have very different research interests to their own, and that making these connections has been positive (Table 4). Participating in the program has also allowed the fellows to form connections with professors and students outside of their home departments, providing different perspectives on FEW nexus issues that they also encounter in their own work (Table 4). Students also highly rated the opportunity to learn about fields

previously unknown to them (4.61 out of 5) and the opportunity to research problems that are significantly different from their previous research (4.17 out of 5, Figure 2), thereby demonstrating their appreciation for the interdisciplinary nature of the course activities and components. Students' descriptions of which assignments were more challenging varied somewhat depending on their discipline, though we lacked the power to explore these differences empirically. Notably, however, students described benefitting also from assignments that were not new to them because they gained perspective on how their peers from other disciplines approached the assignment. This is consistent with the instructors' intent to provide students with interdisciplinary exposure not only through students' own work but also through interactions with their peers.

In terms of how the course contributed to students' growth in interdisciplinary research skills, communication skills and career preparation, we found that students reported increases in their abilities centered around these core competencies of the course. The course provided students with a safe and encouraging environment to share their ideas and their research with their peers, and to practice the skill of communicating their research to diverse audiences. Students also expressed an appreciation of the emphasis that the program places on these skills by highly rating course assignments that required the practice of written and oral communication as outlined in Figure 3, such as in-class group discussions (4.43 out of 5), writing policy statements (4.39 out of 5) and participating in oral lightning round presentations of their work (4.13 out of 5). Overall, students reported improvements in their presentation skills (3.91 out of 5), oral communication skills (3.87 out of 5) and written communication skills (3.61 out of 5) as a result of participating in the introductory course (Figure 4). These course components not only served to improve students' communication skills, but also to enhance their career preparation since students will be expected to be effective communicators and presenters when they enter the workforce. The inclusion of guest speakers who are experts in FEW nexus research (Supplementary Materials) also provided insight into possible careers in the field.

Another goal of the course, which is aligned with previous studies on interdisciplinary research [51,52], was to improve students' ability to conduct interdisciplinary teamwork. Regarding changes in students' confidence in their ability to conduct interdisciplinary research, we observed that, collectively across both cohorts, students reported statistically significant improvements in their ability to collaborate with scientists outside of their field of expertise (3.45 pre-program mean vs. 4.00 post-program mean), and to collaborate with a range of professionals relating to their field of study (3.32 pre-program mean vs. 3.91 post-program mean), demonstrating the ability of our program to foster interdisciplinary collaboration (Figure 5). Fellows also appreciated being a member of a diverse cohort of students, and the perspectives that this brought to their own work. This was demonstrated by their rating of the opportunities to receive feedback from peers on their presentations (4.17 out of 5), and opportunities for students to share their research with each other (4.00 out of 5), as shown in Figure 2. In listing the most important things gained from the course, students also indicated that the ability to think critically about work outside of their field and ask the appropriate questions was very important to them (Table 4).

A particular strength of our study is that we utilized a robust, mixed-methods research design. We recognize that our study is limited by the small sample size of 23 students. However, this number encompasses all of the fellows who have been accepted into the program thus far in its first two years of existence. It is also notable that the ongoing evaluations of the course and program as a whole allow for insights into the components of the introductory course that can be improved. Thus far, students have provided overwhelmingly positive feedback about the course and generally required additional probing to suggest improvements. Because this is consistent across all data collection methods (i.e., anonymous surveys, focus group with instructors and interviews and focus groups without instructors), we believe that our results are valid and unbiased. Even still, students' suggestions for improvement are valuable, as we are continually making changes to enhance students' experiences (see Supplementary Materials). Moreover, we plan to conduct

follow-up surveys of alumni as they transition into the workforce, explore how students' experience in the course varies by discipline and demographic factors as more students enroll in the course and continue to share our findings. Sustained contact with UMD Global STEWARDS alumni is important to assess how their interdisciplinary training has impacted their career and to determine the perceived value of the program to the workforce.

We hope that our results encourage other graduate training programs to incorporate the use of interdisciplinary skill building in their design and embrace transdisciplinary concepts, and that UMD Global STEWARDS course materials become a valuable resource for both students and faculty working at the FEW nexus. Additionally, we hope that members of the FEW research community may draw upon the program elements and course structure as components for their own programs and course offerings.

5. Conclusions

Problems at the FEW nexus are among the most challenging that we will face in the 21st century. It is therefore imperative that we restructure our graduate training models to emphasize interdisciplinary collaboration, communication and transdisciplinary approaches that will be needed to meet these challenges. There are limited examples of how to train graduate students to become transdisciplinary researchers and stellar science communicators. However, our results demonstrate the efficacy of the introductory course of the UMD Global STEWARDS program as an educational model for supporting transdisciplinary research at the graduate student level. Specifically, we found that the introductory course promotes the development of students' interdisciplinary research skills and science communication skills, skillsets that are necessary to engage in transdisciplinary research focused on solving the critical challenges of our time. This course can serve as a model for graduate training programs that seek to develop strong interdisciplinary researchers and communicators through cutting edge, experiential curricular approaches.

Supplementary Materials: The following are available online at https://www.mdpi.com/2071-1050/13/3/1438/s1, Table S1: Introductory FEW Nexus Course Schedule Summary.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data is contained within the article and supplementary material.

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