An integrated food-energy-water systems course that builds systems thinking skills among graduate students in STEM

Mirit Shamir, Matthew Sanderson, Rebecca Cors, Nathan Hendricks, Stacy Hutchinson, Prathap Parameswaran, Melanie M. Derby

Kansas State University/ Kansas State University/ University of Wisconsin-Madison / Kansas State University/ Kansas State University/ Kansas State University/ Kansas State University

Keywords
Systems thinking skills, Interdisciplinary, Systems thinking curriculum, STEM graduate students

Abstract
Current and future global challenges present complex, interrelated problems. Some of these global issues are related to the Food, Energy and Water (FEW) nexus. To address these global challenges and for the United States' economic and technological competitiveness, there is a need for systems thinkers. This paper will detail the graduate-level, one-credit interdisciplinary Integrated Systems course structure that may become a framework for teaching systems thinking at the graduate level and for the development of systems thinkers in STEM disciplines.

The NRT Integrated FEW Systems course is part of the Rural Resource Resiliency NSF Research Traineeship (the NRT) at Kansas State University. The NRT prepares master's and doctoral students from STEM disciplines to solve the grand challenges of creating a more resilient food, energy, and water systems in semi-arid regions. Systems thinking framework provides concepts and tools to understand complex problems that link society, economy, and the environment at multiple scales.

The NRT Integrated FEW Systems course is a cross-listed course that has been taught annually in the fall semester by faculty from the College of Engineering, the College of Agriculture, and the College of Arts and Sciences since 2019. This course is an introduction to systems thinking, with specific application to the FEW nexus. The course explores the natural-environmental systems, the human-social systems, and their interactions.

This paper will discuss course format, content team teaching strategies, grading structures, and evaluation. The course lectures combine theory and practice, and design to establish knowledge base in system thinking concepts and tools. Course grading includes reflections and analyses, system component maps, and a final project, an integrated system map. The evaluation results through the four (4) cohorts show that student ratings about their perceived ability to perform FEW systems tasks improved from the beginning to the end of the course, from 'somewhat able' to 'very able.' Students rated most course activities as "very useful".

Introduction
Systems thinking is an approach for examining complex events and systems in a holistic way [1]. Its origin dates back thousands of years ago to indigenous cultures [2], and it is a framework for better understanding linkages and connections between systems [3]. Systems thinking as a concept has been developed in different disciplines [4] – [6]. In engineering, systems thinking examines the system's structure, behavior, and their interactions to reach an optimal function [7].

In social sciences, systems thinking considers interactions between human-social systems and the built environment [8].

Systems thinking is a core ability for understanding complex systems. Issues at the Food, Energy, and Water (FEW) nexus (e.g. production, distribution, and use) are interrelated problems and to solve these problems systems thinking approach is needed [9]. The Rural Resource Resiliency NSF Research Traineeship (The NRT) curriculum builds interdiciplinary and systems thinking abilities to help students address complex FEW systems problems. The report by the National Academies of Sciences, Engineering, and Medicine on Graduate STEM Education for the 21st century noted that current and future global challenges, such as creating more resilient communities, present scientific, technological, and societal challenges that require systems thinking abilities to solve these challenges [10]. In addition, employers from different sectors attested to the value of systems thinking abilities in the workforce and for future global competitiveness [10].

Since 2013, the United States National Science Foundation through its Research Traineeship program has supported graduate students in STEM with interdisciplinary training, thereby preparing them to enter the national workforce [11]. The NRT at Kansas State University prepares graduate STEM students to solve the grand challenges of creating resilient Food, Energy, and Water (FEW) Systems in rural communities. Problems at the nexus of FEW systems are complex and solutions to these problems integrate systems thinking. The NRT Integrated FEW Systems course is a required one-credit course for NRT trainees/students. It was developed as part of the NRT requirements in the 2019-2020 academic year and has been taught every fall semester since 2019. The course objectives are to enhance graduate students' systems thinking abilities and establish a knowledge base for students to build upon through the educational and experimental elements of the NRT.

This paper aims to describe the NRT Integrated FEW Systems course, which may become a framework for teaching systems thinking at the graduate level and for the development of systems thinkers in STEM disciplines. The paper presents the course structure, the course learning experience, and evaluation. This study received an Institutional Review Board approval and appropriate guidelines were followed. The author team includes faculty, administration, and staff. The author team includes four people who identified as women. Two of these women are engineers, and two are social scientists. The author team also includes three people who identified as men. One of these men is an engineer, and two of these men are social scientists. Several author team members have experience in systems thinking in engineering and social sciences as well as experience implementing systems thinking to solve complex systems problems in the FEW nexus. These experiences allow us to develop an integrated systems thinking curriculum at the graduate level.

Course Structure

The NRT Integrated FEW Systems course introduces students to systems thinking, with specific application to the FEW nexus in Southwest Kansas. Course materials integrate the natural-environmental systems (i.e. water, energy, waste) and the human-social systems (i.e. economic, social, cultural, and political systems). The course runs as a mix of lectures co-taught by faculty from the College of Engineering, the College of Agriculture and the College of Arts and Sciences or guest speakers form different disciplines, class discussion, and class activity. It also includes readings, individual reflection assignments, individual system component maps, and a final individual project, an integrated system map. Since fall 2019, thirty seven (37) NRT students participated in the course and completed it. Out of the 37 students, 19 were master's students and 18 were doctoral students.

The NRT Integrated FEW Systems course is dynamic, iterative, and cumulative. It uses a conceptualize tool, Loopy, to practice systems thinking theory [12]. Systems modelling and simulations promotes understanding of complex systems by conceptualization [13] – [15]. Loopy allows students to draw system components using circles and their interactions using arrows and then press play to simulate how the system behaves. Students use positive and/or negative feedbacks to balance the system. The expected learning outcomes for the course are for students to: 1) conceptualize key FEW systems' elements, links, process, and dynamics; 2) interpret system elements, links, processes, and dynamics from multiple perspectives, using narrative and visual tools; 3) cultivate an awareness of diverse perspectives of FEW system stakeholders; 4) translate scientific, disciplinary knowledge for diverse audiences, and communicate across disciplinary boundaries; and 5) work collaboratively with interdisciplinary partners to diagnose and address FEW system challenges.

Course Assignments and Grading

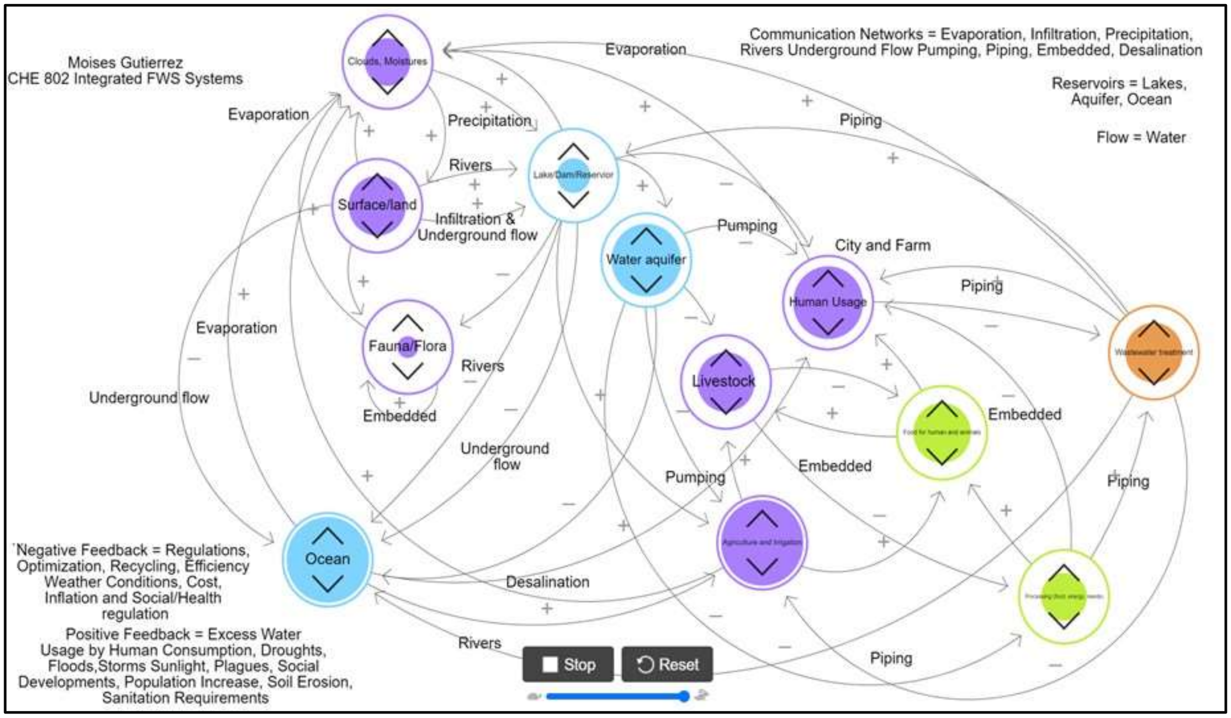
Course assignments include reflections and analyses, system maps, and a final project, an integrated system map, as shown in Table 1 below. To prepare for class, students read the material assigned for a session ahead of class, and submitted written responses to questions through Canvas. Readings were assigned from the open-source textbook, The Macroscope: A New World Scientific system [8] and journals. The faculty, who assigned the reflection or analyses, graded it. For the system component maps, students created a map of the system component that was discussed/presented in class using Loopy, a web based interactive tool for thinking in systems [12]. The systems that were discussed in class are the natural-environmental systems (i.e. water, energy, waste) and the human-social systems (i.e. economic, cultural and political). With Loopy, students created a map of the system by drawing circles and arrows. The maps included at least one positive feedback loop (i.e., moves the system away from an equilibrium) and one negative feedback loop (i.e., brings the system to an equilibrium), at least one flow (e.g. water, energy, money, data), and one reservoir (e.g. river, atmosphere). Students saved the map as a link or file and submitted it via Canvas. An example of a system component map using Loopy is shown in Figure 1. For the final project, the integrated system map, students at the end of the semester created a map using Loopy that integrates all of the system component maps they created throughout the semester. Students also submitted a narrative interpretation of the systems. The systems component maps were graded by the faculty, who taught the system, and the integrated map was graded by the systems thinking course lead faculty.

Table 1: NRT Integrated FEW Systems weighted assignments

Reflection and Analyses	40%
Systems Component Maps	40%

Final project – Integrated System Map	20%

Figure 1: Water System Map Components



In Figure 1, components of the water system are human usage, agriculture and irrigation, livestock, industrialization, energy, and food production, wastewater, the flora, and the fauna. Furthermore, piping, pumping, and embedded are added as additional network communications. The flow is water. There are number of feedbacks, positive and negative (e.g., use of water by humans, droughts, flooding will continue to disturb the equilibrium, and policy, optimization projects, and climatic condition will move the system towards equilibrium.

Students' Learning Experiences

To understand NRT students' experiences in the course, the NRT team asked students to complete a post-course survey. The aim of the survey was to elicit students' feedback about their experiences with the NRT program. Several items in the survey focused on the NRT Integrated FEW Systems course, asking students about how they thought their abilities had changed from before to after the course and asking them to rate the usefulness of course activities. Initial development of the survey occurred in December 2019. The NRT program external evaluator drafted the survey based on the NRT logic model, team priorities for the NRT educational and research activities, and initial interviews and discussions with the NRT leadership team. The NRT external evaluator worked with several team members to review and test the survey and to update it each year.

As shown in Table 2 the NRT external evaluator administered the survey to four cohorts of NRT students from 2019 to 2022, after they completed the fall semester and the course. Responses to the post-course survey across cohorts resulted in a response rate of 75% or greater.

Table 2: Administration of the Annual NRT Trainee Survey

Course time	Post-course survey administration	# of surveys completed	# of students enrolled in course	Response rate
Fall 2019	February 2020	11	14	79%
Fall 2020	December 2020	6	7	86%
Fall 2021	December 2021	7	8	88%
Fall 2022	December 2022	6	8	75%

Each fall, after closing the survey, the evaluator downloaded response data from Qualtrcis survey software to Microsoft Excel and analyzed them. To improve validity of the analysis, and to support planning and decision-making for the course and the NRT program, results were discussed during a co-interpretive session with NRT program leaders [16]. Noticeable from these annual review sessions, was that responses changed little from year to year. For this paper, quantitative data analysis involved aggregating survey responses from four cohorts and then depicting totals in a bar graph or table.

To gain insights into how students were building systems thinking skills critical for FEW work, the post-course survey asked them to rate their ability to perform a short list of key tasks before and after participating in the course. The tasks are: Collaborate on interdisciplinary teams; Communicate scientific, disciplinary knowledge to diverse audiences; Communicate across disciplinary boundaries; Be aware of diverse perspectives of FEW stakeholders; Conceptualize key FEW systems' elements, links, processes, and dynamics; Use narrative and visual tools to interpret FEW systems; and Collaborative diagnose FEW systems challenges. Survey respondents selected ratings from a five-point scale: 1=not at all able, 2=a bit able, 3=somewhat able, 4=very able, 5=extremely able.

As findings in Table 3 show, students felt that their skills for these seven tasks improved over the time they participated in the course. For example, before participating in the course, only 10% of students felt 'very' able, 3 % felt 'extremely' able, to conceptualize key FEW systems' elements, links, processes, and dynamics. After participating in the course, these ratings increased to 60% of students who felt 'very' able and to 13% of students who felt 'extremely' able carry out the task.

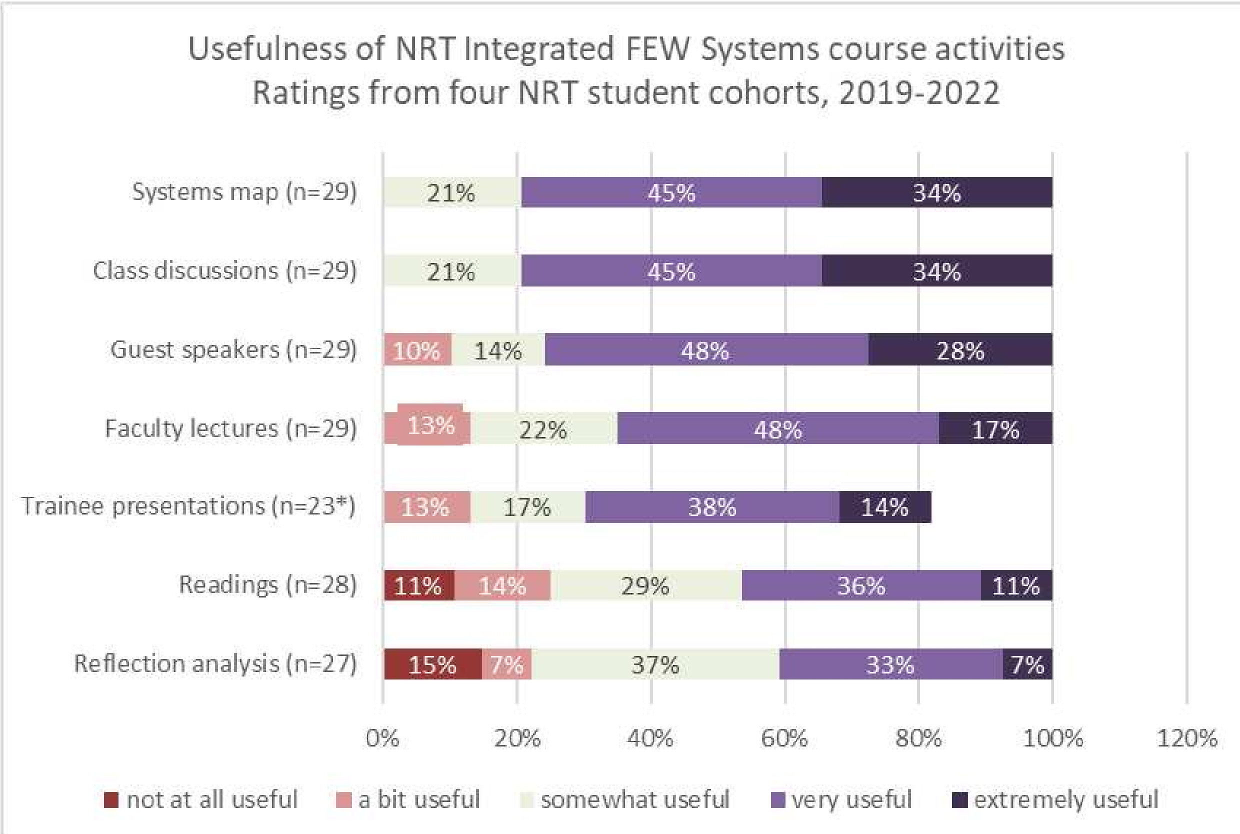
Table 3: Students' perceived gains in seven abilities to carry out integrated systems tasks *improved* from before to after participating in the NRT Integrated FEW Systems course (self-report from four student cohorts, 2019 to 2022).

Perceived Abilty for Key Skills BEFORE (retrospectively) & AFTER course ratings *Four NRT trainee cohorts, 2019 to 2022*	not at all able	a bit able	somewhat able	very able	extremely able
Collaboratively diagnose FEW system challenges BEFORE (n=30)	13%	47%	33%	3%	3%
Collaboratively diagnose FEW system challenges AFTER (n=30)	0%	0%	37%	50%	13%
Be aware of diverse stakeholder perspectives BEFORE (n=31)	19%	39%	32%	3%	6%
Be aware of diverse stakeholder perspectives AFTER (n=30)	0%	7%	37%	40%	17%
Use narrative & visual tools to interpret systems BEFORE (n=30)	7%	47%	27%	17%	3%
Use narrative & visual tools to interpret systems AFTER (n=30)	0%	7%	37%	43%	13%
Conceptualize FEW system elements, links, processes BEFORE (n=30)	10%	27%	50%	10%	3%
Conceptualize FEW system elements, links, processes AFTER (n=30)	0%	3%	23%	60%	13%
Communicate across disciplinary boundaries BEFORE (n=29)	7%	21%	38%	31%	3%
Communicate across disciplinary boundaries AFTER (n=30)	0%	0%	33%	50%	17%
Communicate science to diverse audiences BEFORE (n=31)	0%	32%	35%	26%	6%
Communicate science to diverse audiences AFTER (n=30)	0%	0%	37%	47%	17%
Collaborate on interdisciplinary teams BEFORE (n=29)	7%	34%	31%	21%	7%
Collaborate on interdisciplinary teams AFTER (n=30)	0%	3%	30%	37%	30%

To find out how useful students found course activities for preparing them to carry out the systems tasks tabulated in Table 3 above, a survey item asked students to rate a short list of course activities: Class discussions, Faculty lectures, Guest speakers, System map, Trainee presentations, Readings, and Reflection analysis. Figure 2 shows ratings from all four-student cohorts. There are fewer responses about trainee presentations, because that activity did not take place in the 2022 course.

As findings in Figure 2 show, students thought most course activities were quite useful for helping them develop abilities for working with integrated FEW systems. More than half indicated that the *Systems map*, *Class discussions*, *Guest speakers*, *Faculty lectures*, and *Trainee presentations* activities were 'very' or 'extremely' useful. For example, 45% of students ranked the *Systems map* activity as 'very' useful and 34% rated it as 'extremely' useful. In contrast, students' ratings for *Readings* and *Reflection analysis* were more varied. A closer look at *Reflection analysis*, for example, shows a few more that one-third of students, 40% (33%+7%), rated this activity as 'very' or 'extremely' useful, another one-third, 37%, rated the activity as 'somewhat' useful, and 22% rated it as 'a bit' or 'not at all' useful.

Figure 2: Students found activities from the NRT Integrated FEW Systems course activities were useful for helping them develop their abilities. Ratings from four cohorts, 2019-2022.



* cohort 4 did not experience Trainee presentations

Challenges

There were a few challenges, from students' perspectives, with the course. For a few students, using Loopy to create system maps was a challenge. Loopy was selected because it allows users to simulate how the system behaves and it is free. In the first version of Loopy's interface users could not zoomed in, which made it difficult to navigate and to make a large map. The second version, Loopy v.2.0, was released in time for the third course offering. It allowed the students to better navigate the interface and included more controls, two aspects that addressed concerns from students in the first two cohort students.

At meetings with faculty, a few students from the first two cohorts voiced concerns about how the textbook, the Macroscope, from the 1970s, was outdated and the significant reading load. The mixed survey ratings from students about course readings, which comprised most readings for the course, reflects that a few students did not think the textbook was useful. The textbook was kept because it is an open-source resource and still has relevant content that introduces systems thinking fundamentals using examples from the natural-environmental systems and the human-social systems. The amount of reading from the textbook was adjusted to reflect a one-credit course load in future semesters.

From faculty perspectives, co-teaching and developing an integrated curriculum about FEW systems requires communication among faculty from different disciplines so that lessons are sure to relate to, and build on each other, and relate to the integrated system as a whole. The modular approach to the course was well-suited to team teaching; most modules were 2-3 weeks and included a Loopy diagram. Team teaching is a viable approach for exposing students to different disciplinary thoughts and ideas; however, there are some differences between departments in how this teaching was acknowledged and integrated into course loads. The interdisciplinary nature of the course required faculty to consider what pre-requisite knowledge the students may or may not have, including basic equations and concepts; however, faculty expressed positive comments regarding the vibrant discussions engaging from the diverse disciplines and backgrounds of the students.

Conclusions

The NRT Integrated FEW Systems course has been offered in the fall semester since 2019 to a total number of 37 students. The course combined theory and practice, with lectures, class discussion and Loopy assignments throughout the semester. It incorporated readings, lectures, and assignments that enhance students' systems thinking abilities. Student feedback indicated that through the NRT Integrated FEW Systems course, they gained in their abilities to perform tasks that support FEW systems thinking work. In addition, students found most course activities to be very useful for this skill building, in particular: faculty lectures, guest lectures, class discussion, and the systems map.

Acknowledgment

This work was supported by the National Science Foundation Research Traineeship (NRT) grant # 1828571.

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Mirit Shamir, LL.M., MS

Mrs. Shamir is the Academic Services Coordinator for the Rural Resource Resiliency NSF Research Traineeship housed in the Alan Levin Department of Mechanical and Nuclear

Engineering at Kansas State University. She holds an M.S. in Environmental Policy from Michigan Tech where she was an IGERT scholar, and an LL.M from Tel -Aviv University. As the academic services coordinator, she actively recruits diverse prospective graduate students, and manages the day-to-day administrative and program functions of the graduate traineeship in rural resource resiliency for food, energy and water systems.

Dr. Matthew R. Sanderson

Dr. Sanderson is Randall C. Hill Distinguished Professor of Sociology, Anthropology, and Social Work and Professor of Geography and Geospatial Sciences at Kansas State University. He is a social scientist working in the areas of population, environment, and development. His work has been supported by the USDA, NSF, EPA, and the Australian Research Council. He has been a Visiting Professor and Research Fellow at the Center for Environmental Resource Management at the University of Texas at El Paso and the Hugo Centre for Population Research at the University of Adelaide in Australia. Dr. Sanderson is Editor-in-Chief of *Agriculture and Human Values.*

Dr. Rebecca Cors

Dr. Rebecca Cors is a scientist and evaluator who works at the Wisconsin Center for Education Research. For the last 10 years, her work has focused on supporting program managers to study and improve training, education, and outreach programs focused on science and nature learning, and also on environmental sustainability. Before this, Dr. Cors studied and published research about how organizational learning and systems thinking strategies can improve natural resources management. This work was carried out primarily at the Wisconsin Department of Natural Resources and the Institute for Environmental Decisions at ETH Zurich, a contributor to the European Sustainable Phosphorous Platform.

Dr. Nathan Hendricks

Dr. Hendricks is a Professor in the Department of Agricultural Economics at Kansas State University. His research program focuses on production economics, agricultural policy, and the interaction between agriculture and the environment. A signification portion of his work is related to the economics of land and water. His research has received several awards and has been cited in major media outlets. Dr. Hendricks also teaches courses at the undergraduate and graduate levels.

Dr. Stacy Lewis Hutchinson

Dr. Stacy Lewis Hutchinson is the Associate Dean for Research and Graduate Programs and a professor of Biological and Agricultural Engineering at Kansas State University. Her research focuses on the development of sustainable stormwater and land management techniques, the use of vegetated systems for mitigating non-point source pollution, and the remediation of contaminated soil and water. Prior to joining the faculty at Kansas State University, Dr. Hutchinson worked for the United States Environmental Protection Agency, Ecosystem Research Division in Athens, GA.

Dr. Prathap Parameswaran

Dr. Parameswaran is an Associate Professor in the Department of Civil Engineering at Kansas State University. His expertise is in the broad area of Resource recovery from wastes and wastewaters through the application of Environmental Biotechnology principles, with specific focus on anaerobic digestion and anaerobic membrane bioreactors towards a circular bioeconomy. He also performs interdisciplinary research that transcends agriculture, engineering, and economics and his research is supported by funding from federal agencies and private industry.

Dr. Melanie M. Derby

Dr. Melanie Derby is an Associate Professor at Kansas State University and holds the Hal and Mary Siegele Professorship in Engineering. Her research focuses on heat and mass transfer and the Food, Energy, and Water Nexus and has been sponsored by NSF, NASA, ASHRAE, ONR, and industry. She currently directs the KSU NRT, which focuses on interdisciplinary FEW research and graduate education. Dr. Derby is a recipient of an NSF CAREER Award, KSU College of Engineering Outstanding Assistant Professor Award, and ASME ICNMM Outstanding Early Career Award.