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An integrated systems thinking graduate course that prepares students to solve the complex problems of the food-energy-water nexus

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An integrated systems thinking graduate course that prepares students to solve the complex problems of the food-energy-water nexus

Abstract

Current and future global challenges, such as creating more resilient and sustainable communities; developing renewable energy; improving public health; and addressing climate change present complex scientific, technological, and societal problems. Thus, to tackle these global challenges and for the United States' economic and technological competitiveness, there is a need for systems thinkers. Recent efforts to prepare graduate students to use systems thinking to address these problems are promising. This paper will detail the graduate-level, interdisciplinary Integrated Systems course structure that can be beneficial to the implementation of teaching systems thinking framework at the graduate level and the development of systems thinkers in STEM disciplines.

The NRT Integrated FEW Systems course is a 1-credit course, and part of the NSF Research Traineeship (NRT) at our university. The NRT prepares master's students and doctoral students from STEM disciplines to address the grand challenges of creating food, energy, and water systems in semi-arid regions that are more resilient. Solutions to resiliency problems often require systems-thinking frameworks. Systems thinking 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. Faculty from the College of Engineering, the College of Agriculture, and the College of Arts and Sciences have co-taught this class annually in the fall since 2019. This course is an introduction to systems thinking, with specific application to the food-energy-water (FEW) nexus. The course explores two basic types of systems and their interactions: natural-environmental systems and human-social systems. The course emphasizes the importance of systems thinking in developing effective policy to enhance resilience in FEW systems.

This paper will discuss course format, content team teaching strategies, grading structures, evaluation, and lesson learned from teaching the course four years. The course lectures combine theory and practice, and design to establish knowledge base in system thinking concepts and tools, and focus on the unique challenges for management, governance, communication, and policy in the FEW nexus. Course grading includes reflections and analyses, creating system component maps with Loopy (a free online tool for thinking in systems), and a final project, an integrated system map. All assignments are individual assignments. The NRT external evaluator designed an annual NRT survey that assesses the NRT program at our university, including the impacts of the NRT Integrated FEW Systems course. Student ratings about their perceived ability to perform interdisciplinary 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 a core ability for understanding complex 'wicked' challenges, which are intractable issues that we have not been able to solve with a single approach. Wicked challenges are complex, unclear, changing, and entangle [1]. In a time where global challenges are becoming wicked challenges and STEM-based systems, such as Food, Energy, Water (FEW) systems, are becoming more complex, the need for systems thinking ability has grown. The criteria of Accreditation Board for Engineering and Technology (ABET) include systems thinking concepts as part of the education program [2]. ABET supports our call to include systems thinking as part of the NRT curriculum because what applies to undergraduate studies certainly applies to graduate studies and more so when students from different disciplines are enrolled. The decision to include systems thinking course as part of the NRT was to build skills to deal with 'wicked' 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, improving public health, and mitigating climate change present scientific, technological, and societal challenges that require systems thinking abilities to solve these challenges [3]. In addition, employers from academia, industry, and government attested to the value of systems thinking abilities in the workforce [3]. Thus, systems thinking abilities are vital for future competitiveness, and college graduates should gain systems thinking abilities through their education training.

Systems thinking is an approach for examining complex events and systems in a holistic way [4]. Its origin date back thousands of years ago to indigenous cultures [5], and it is a framework for better understanding linkages and connections between systems [6]. Systems thinking as a concept has been developed in several disciplines including engineering, social sciences, and natural sciences [7]– [9]. In engineering, systems thinking examines the system's structure, behavior, and their interactions to reach an optimal function [10]. In social sciences, systems thinking considers interactions between human-social systems and the build environment [11].

Since 2013, the United States National Science Foundation Research Traineeship (NRT) program has supported graduate students in STEM with their interdisciplinary training, and has prepared them for the national workforce [12]. The NRT at our university prepares graduate STEM students, master's and doctoral students, to solve the grand challenges of creating resilient FEW Systems in rural communities. Problems at the nexus of FEW systems are 'wicked' and solutions to these problems must integrate systems thinking. The NRT Integrated FEW Systems course is a required one-credit course for the NRT in FEW systems at our university. 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 competency and establish a knowledge base that students build upon through the educational and experimental pillars of the NRT at our university. These pillars include field experiences in Southwest Kansas, policy experiences at the state capital, course work, and a subsequent 2-credit capstone, project-based course.

This paper aims to describe the experience gained from the NRT Integrated FEW Systems course, which may be beneficial in the implementation of a systems thinking course at the graduate level in other four-year institutions. The paper presents the course structure, the course learning experience, assessment, and lessons learned. This study received IRB approval and appropriate guidelines were followed.

The author team is an interdisciplinary team and includes faculty, administration, and staff from the Colleges of Engineering, Agriculture, and Arts and Sciences. The author team includes four people who identified as women. Two of these women are engineers, and the other 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 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 Western Kansas. The course establishes a knowledge base that students build upon through educational and experiential components of the NRT traineeship. Course materials integrate engineering, economic, and social sciences systems, with focus on the unique challenges of enhancing rural resource resiliency in FEW systems. This course is a one-credit hour required course to NRT students that meets once a week for 50-minute class. It has been offered every fall semester since 2019, and it is co-taught by engineering and social science faculty. The course explores the natural-environmental systems and the human-social systems, and their interactions, and runs as a mix of lectures co-taught by faculty 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. Five Master's students and nine Ph.D. students from the College of Engineering, the College of Agriculture, and the College of Arts and Sciences participated in the NRT Integrated FEW Systems course in fall 2019 semester. Three Master's students and four Ph.D. students from the College of Engineering, the College of Agriculture, and the College of Arts and Sciences participated in this course in fall 2020 semester. Three Master's and five Ph.D. students from the College of Engineering, the College of Agriculture, and the College of Arts and Sciences participated in this course in fall 2021 semester. Eight Master's students from the College of Engineering, and the College of Agriculture participated in this course in fall 2022 semester.

The NRT Integrated FEW Systems course is organized to be dynamic, iterative, and cumulative. It uses a conceptualize tool, Loopy, a web based interactive tool for thinking in systems [13], to teach systems thinking. Systems modelling and simulations promotes understanding of complex material by conceptualization [14] – [16]. 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 NRT Systems Thinking course are 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. 5. Work collaboratively with interdisciplinary partners to diagnose and address FEW system challenges.

The NRT Integrated FEW Systems course format, content team teaching strategies, and grading structures encouraged a systems thinking approach to investigating FEW systems problems. Students attended faculty guided seminar lecture designed to introduce systems thinking with specific application to the FEW nexus. Topics that were discussed in the NRT Integrated FEW Systems seminars/classes were systems basics, natural-environmental systems, human-social systems, and the interactions between these systems as shown in Table 1. In fall 2019, fall 2021, and fall 2022 the class was taught in person. Following the university COVID guidelines, in fall 2020 the class was taught in a hybrid mode with some students attending in person and some students attending online simultaneously. Course grades were based on individual assignments that included reflections and analyses, system maps and a final project.

Table 1: NRT Integrated FEW Systems course schedule

Date	**Topic**
Week 1	INTRODUCTION AND OVERVIEW: The Ogallala High Plains Region: Overview
Week 2	INTRODUCTION AND OVERVIEW: Systems Basics
Week 3	INTRODUCTION AND OVERVIEW: Systems Basics cont.
Week 4	Introduction to LOOPY
Week 5	FEW NATURAL SYSTEMS: Engineering/Technical Aspects - Water
Week 6	FEW NATURAL SYSTEMS: Engineering/Technical Aspects - Water
Week 7	FEW NATURAL SYSTEMS: Engineering/Technical Aspects - Energy
Week 8	FEW NATURAL SYSTEMS: Engineering/Technical Aspects - Energy
Week 9	FEW HUMAN SYSTEM: FEW Economic Aspects
Week 10	FEW HUMAN SYSTEM: FEW Economic Aspects
Week 11	FEW NATURAL SYSTEMS: Engineering/Technical Aspects – Waste
Week 12	FEW NATURAL SYSTEMS: Engineering/Technical Aspects - Waste
Week 13	FEW HUMAN SYSTEM: FEW Social, Cultural, Political Aspects
Week 14	FEW HUMAN SYSTEM: FEW Social, Cultural, Political Aspects
Week 15	FEW SYSTEM: Bringing it all together

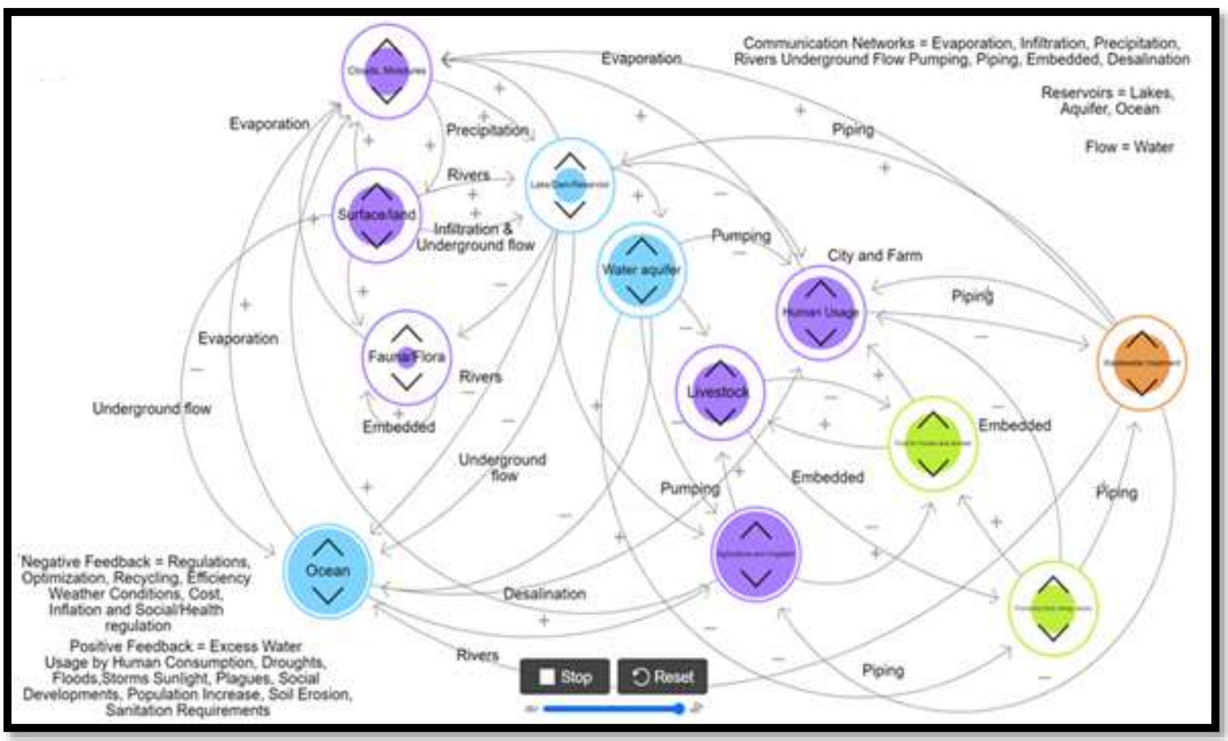
Course Assignments and Grading

Course assignments include reflections and analyses, system maps, and a final project, an integrated system map, as shown in Table 2 below. For the reflections and analyses, students read the material assigned for a session ahead of class, and submitted written responses to questions prior to class through Canvas. Readings were assigned from the open-source textbook, The Macroscope: A New World Scientific system [11] and journals. The readings and reflections allowed students to come ready to class, discuss, and analyze the material with the instructor. 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 [13]. The systems that were discussed in class are the natural-environmental systems and the human-social systems. With Loopy, students created a map of the system by drawing circles and arrows. The maps included at least one positive feedback loop (Moves the system away from an equilibrium) and one negative feedback loop (Brings the system to an equilibrium), at least one flow (e.g. water, energy, money, data), and one reservoir (e.g. river, atmosphere). The map was saved as a link or file and was submitted to 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 the system component maps they created throughout the semester. An example of an integrated system map is shown in Figure 2. In addition to drawing the map using Loopy, students submitted a narrative interpretation of the system component and a narrative interpretation of the integrated system. 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. As the NRT Integrated FEW Systems course is an introduction to systems thinking and establishes a knowledge base that students build upon through the NRT traineeship, the graded assignments were individual assignments, and the class discussion were interdisciplinary and integrated engineering, social science, and economic perspectives.

Table 2: NRT Integrated FEW Systems course weighted assignment

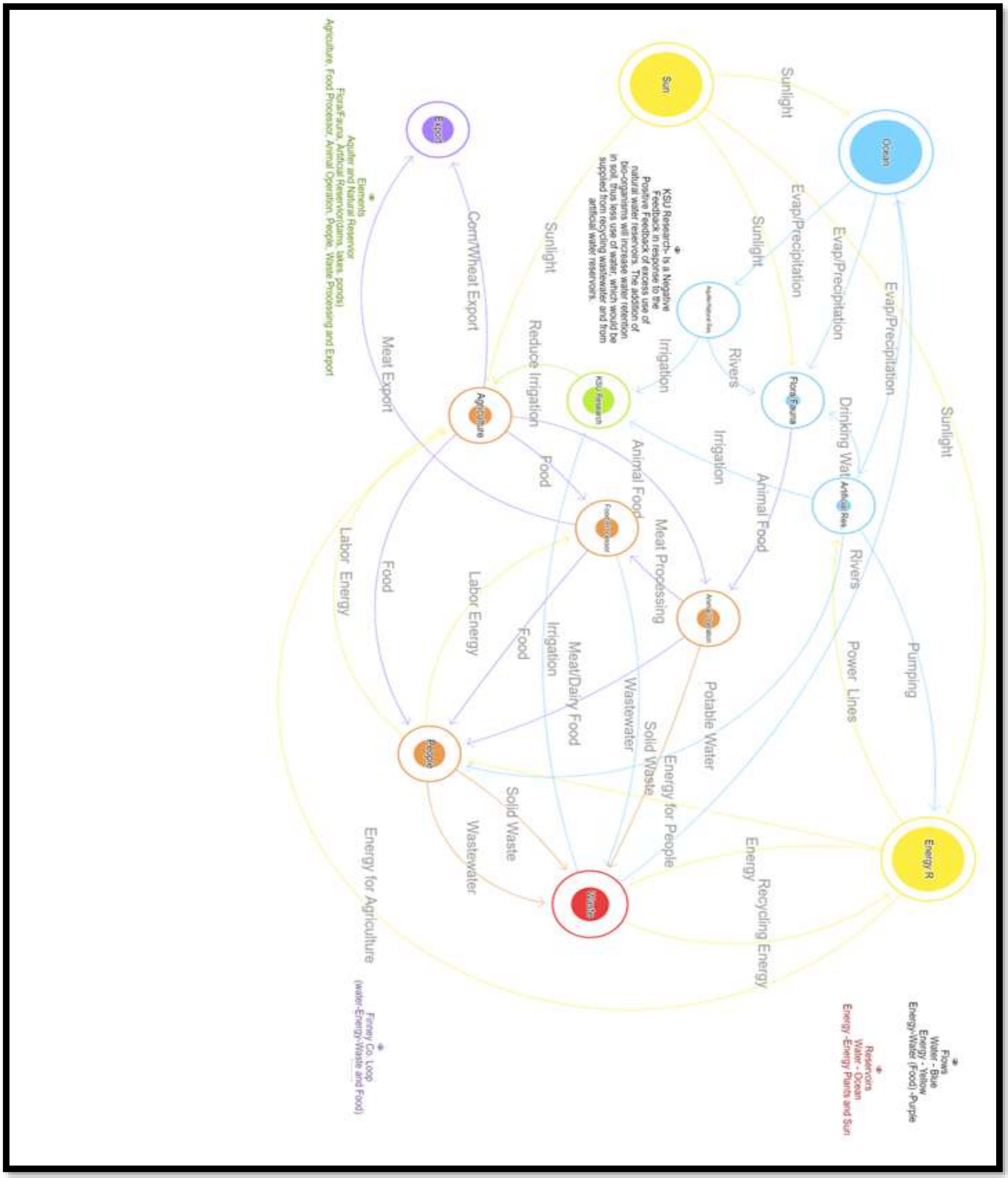
Reflection and Analyses	40%
Systems Component Maps	40%
Final project – Integrated System Map	20%

Figure 1: Water System Map Components



In Figure 1, human usage, agriculture and irrigation, livestock, industrialization, energy, and food production, wastewater, the flora, and the fauna are components of the water system. 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.

Figure 2: An Integrated System Map



In Figure 2, the integrated map demonstrates how water, energy, and food flow thru the FEW systems. The elements (system components) are aquifer and natural reservoir, flora/fauna, artificial reservoirs (dams, lakes, ponds) agriculture, food processor, animal operation, people, waste processing and export. The water, energy and food flow by evaporation, infiltration, precipitation, irrigation, rivers, underground flow, pumping, piping, food commodities, power lines, embedded energy in waste. The integrated system also includes negative and positive feedbacks. Negative feedback: Soil Water Retention, regulatory enforcement, optimization, recycling, efficiency, weather conditions, cost, inflation, social/health regulation, daylight saving, new energy sources, educational courses in energy, water savings, new government requirements, and export and import regulations. Positive feedback: Excess water usage from the natural reservoirs, excess energy usage, droughts, floods, storms, sunlight, plagues, social developments, population increase, soil erosion, sanitation requirements, food waste, energy waste, social events, night operations, excess exports and imports, economics disequilibrium and recession.

Students' Experiences

To better understand NRT students' experiences during, and takeaways from, the Integrated FEW Systems course, the 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, results described below, focused on the Integrated FEW Systems course, asking them 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.

The NRT external evaluator administered the survey to four cohorts of NRT students from 2019 to 2022, after they completed the fall semester NRT Integrated FEW Systems course. As shown in Table 3, administration during the first year took place in February. In the following years, administration occurred in December, just days or hours after students completed the course. Most students from each cohort responded to the post-course survey, with a response rate of 75% or greater.

Table 3: Administration of the Annual NRT Trainee Survey

Course time	Post-course survey administration	Sample (surveys completed)	# 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 Qualtrics 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 [17]. Noticeable from the annual review sessions is 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 bar graphs and tables to allow for comparisons.

To gain insight into how students were building skills critical for their work, the post-course survey asked them to rate their ability to perform a short list of key tasks before (retrospectively [18]) and after participating in the NRT Integrated FEW Systems course. The tasks: 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 results in Figure 3 and Table 4 show, students felt that their skills for these seven tasks improved over the time they participated in the NRT Integrated FEW Systems course. For example, before participating in the course, only 3% students felt 'very' able, 3 % felt 'extremely' able, to *Collaboratively diagnose FW systems challenges.* After participating in the course, these ratings increased to 50% of students who felt 'very' able and to 13% of students who felt 'extremely' able carry out the task. In the bar chart, the visual pattern is more dark and medium purple on the right side of the chart for AFTER ratings than for BEFORE ratings.

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

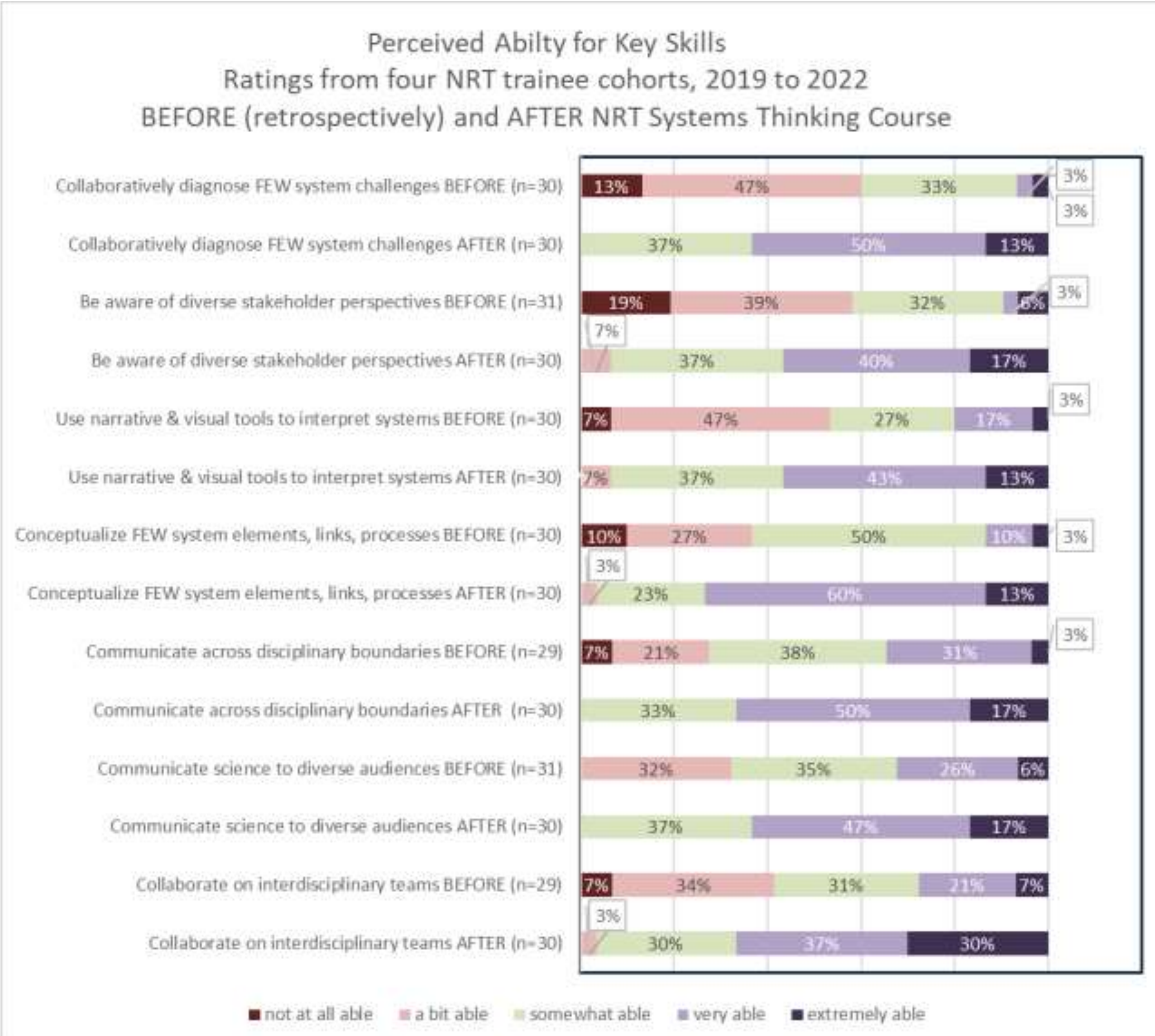

Perceived Abilty for Key Skills
Ratings from four NRT trainee cohorts, 2019 to 2022
BEFORE (retrospectively) and AFTER NRT Systems Thinking Course
Collaboratively diagnose FEW system challenges BEFORE (n=30)
Collaboratively diagnose FEW system challenges AFTER (n=30)
Be aware of diverse stakeholder perspectives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

Table 4: Students' perceived gains in seven abilities to carry out interdisciplinary 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%

We also wanted to know how useful students found the NRT Integrated FEW Systems course for preparing them to carry out the systems tasks shown in Figure 3 above. To elicit this feedback, 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 4 shows ratings from all four student cohorts, 2019 to 2022. There are fewer responses about trainee presentations, because that activity did not take place in the 2022 course.

As results in Figure 4 and Table 5 show, students thought most course activities were quite useful for helping them developing 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 4: 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.

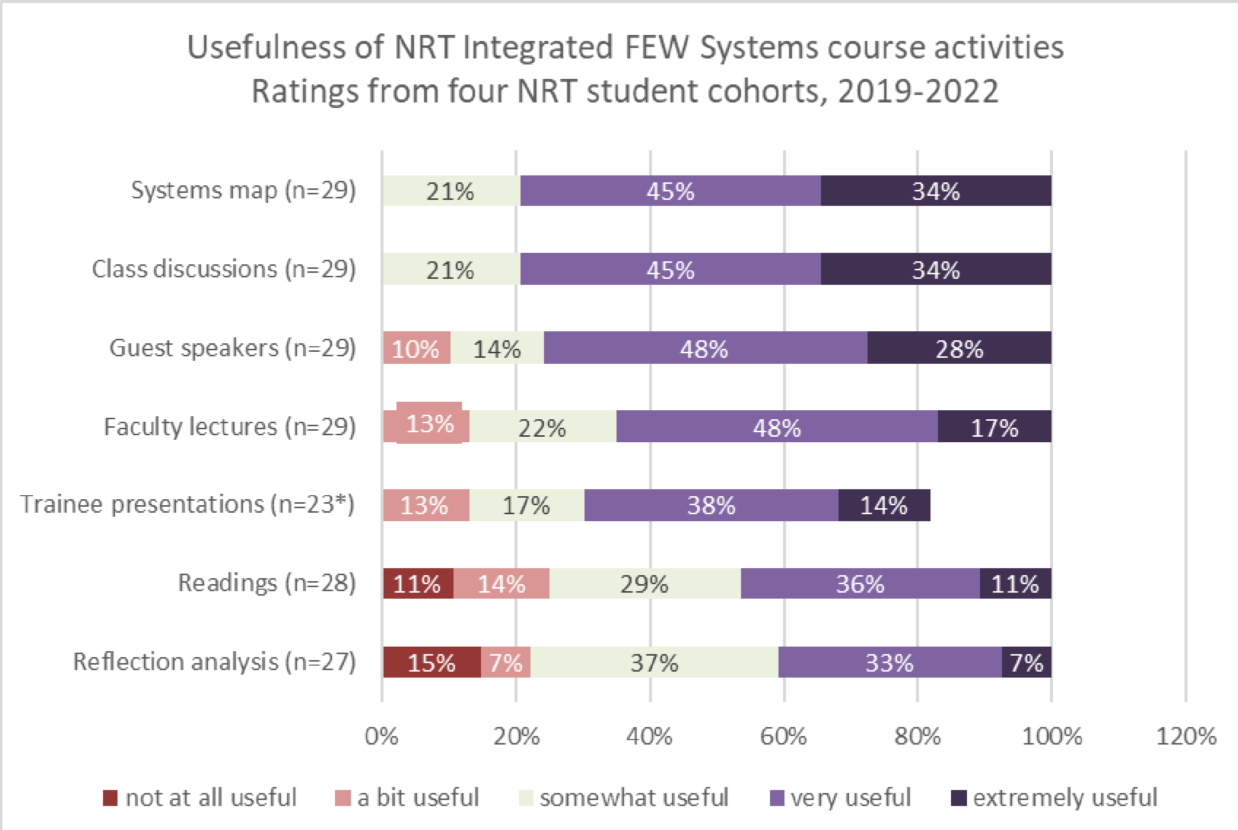


Table 5: Students found activities from the NRT Integrated FEW Systems course activities were useful for helping them develop their abilities. Ratings from four cohorts, 2019-2022.

Ratings for course activities *Four NRT cohorts, 2019-2022*	not at all useful	a bit useful	somewhat useful	very useful	extremely useful
Reflection analysis (n=27)	15%	7%	37%	33%	7%
Readings (n=28)	11%	14%	29%	36%	11%
Trainee presentations (n=23*)	0%	13%	17%	38%	14%
Faculty lectures (n=29)	0%	13%	22%	48%	17%
Guest speakers (n=29)	0%	10%	14%	48%	28%
Class discussions (n=29)	0%	0%	21%	45%	34%
Systems map (n=29)	0%	0%	21%	45%	34%

** cohort 4 did not experience Trainee presentations*

Discussion - Challenges and lessons learned

There were a few challenges, from students' perspectives, with the NRT Integrated FEW Systems course. One challenge for some students was using Loopy to create system maps. Faculty selected Loopy for use in the course, because it allows one to simulate how the system behaves. However, even though most students from the first two cohorts indicated through the survey that the systems maps supported building skills for systems thinking, some students found it challenging, because the interface could not be enlarged, making it difficult to navigate and to make a big map. The students described this problem with faculty after class. The second version of Loopy 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. Faculty were glad to be able continue using Loopy in a way that worked for all students,

A second challenge a few students from the first two cohorts voiced at meetings with faculty had to do with concerns about how the textbook, the Macroscope, from the 1970s, was outdated and the amount of reading. 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 has relevant content that introduces systems thinking 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 in future semesters.

From faculty perspectives, co-teaching and developing an integrated curriculum about a systems topic requires communication among faculty from different disciplines, so that lessons are sure to relate to each other, and to the integrated system. Developing an integrated FEW systems course requires faculty to move beyond their own comfort zone of teaching and to connect lecture material to other topics.

Conclusions

The NRT Integrated FEW Systems course was offered in fall 2019, 2020, 2021, and 2022 to class groups of 14, 7, 8, and 8 students, respectively. The course combined theory and practice, with lectures, class discussion and Loopy development of system maps throughout the semester. It incorporated readings, lectures, and assignments that enhance students' understanding of different disciplines through a systems thinking lens. Student feedback indicated that through the NRT Integrated FEW Systems course, they gained in their abilities to perform tasks that support 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. The Loopy-created system maps, which provided conceptualization of FEW systems and their linkages and interactions were a challenge for some students and useful for most students. Further research could explore barriers and enablers to system map production and how students use system maps for their work to develop FEW system solutions.

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