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Implementing interdisciplinary sustainability education with the food-energy-water (FEW) nexus

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Growth in the green jobs sector has increased demand for college graduates who are prepared to enter the workforce with interdisciplinary sustainability skills. Simultaneously, scholarly calls for interdisciplinary collaboration in the service of addressing the societal challenges of enhancing resilience and sustainability have also increased in recent years. However, developing, executing, and assessing interdisciplinary content and skills at the post-secondary level has been challenging. The objective of this paper is to offer the Food-Energy-Water (FEW) Nexus as a powerful way to achieve sustainability competencies and matriculate graduates who will be equipped to facilitate the transformation of the global society by meeting the targets set by the United Nations Sustainable Development Goals. The paper presents 10 curricular design examples that span multiple levels, including modules, courses, and programs. These modules enable clear evaluation and assessment of key sustainability competencies, helping to prepare graduates with well-defined skillsets who are equipped to address current and future workforce needs.

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The sustainable development goals and food-energy-water nexus

Reducing poverty, addressing inequalities, and providing sustainable access to food, water, and energy, for billions of people are grand challenges for humanity (Wade et al. 2020). As a response to these complex challenges, much of the world is committed to pursuing the targets of the United Nations' Sustainable Development Goals (SDGs). The urgent need to meet these targets when the speed of global environmental damage is rapidly accelerating demands effective global stewardship, education, and governance for sustainable development (Folke et al. 2021; Henriques and Brilha, 2017; Scown et al. 2023). As stated in a UNESCO report (Rieckmann, 2017, pg. 7): *"Embarking on the path of sustainable development will require a profound transformation of how we think and act. To create a more sustainable world and to engage with sustainability-related issues as described in the SDGs, individuals must become sustainability change makers. They require the knowledge, skills, values, and attitudes that empower them to contribute to sustainable development. Education, therefore, is crucial for the achievement of sustainable development."* Universities are responding to this call for educating "sustainability change makers" by embracing interdisciplinary environmental and sustainability programs as part of their mission (Beynaghi et al. 2016; Rosenberg Daneri et al. 2015; Trencher et al. 2014; Wals, 2014). The objective of these interdisciplinary environmental and sustainability (IES) programs is to train students in sustainability problem-solving and *"produce graduates who can help societies and governments solve pressing technical, management, and policy problems involving natural resources, environmental quality, and social justice"* (Clark et al. 2011, pg. 702).

We argue that the Food-Energy-Water (FEW) Nexus (sometimes referred to as the Water-Energy Food, or WEF Nexus in recognition of the critical role and lack of substitutes represented by water specifically; FAO, 2023) is a powerful arena in which to educate sustainability change makers who will be equipped to facilitate societal transformation and address the SDGs. FEW systems are highly interconnected and are fundamental to the health and well-being of societies (Anandhi et al. 2023; Karabulut et al. 2016; Ringler et al. 2013). The FEW Nexus explicitly recognizes these interdependencies (Albrecht et al. 2018; Bazilian et al. 2011; Ojeda Matos, 2023; Wolfe and Riggs, 2017; Yadav et al. 2021), and approaching challenges through this nexus will allow us to meet the food, energy, and water demands of a growing population in more sustainable and equitable ways that do not further stress earth systems (Anandhi et al. 2023; D'Odorico et al. 2018; Ojeda Matos, 2023). The complexity and scale of FEW Nexus issues demand a workforce and citizenry who are prepared to understand and make decisions beyond a specific discipline. The potential contribution of FEW Nexus education is to the development of students who can tackle complex issues at the intersection of sustainability and social justice. This need has been highlighted by a joint report of the U.S. National Academy of Engineering, the U.S. National Research Council, the U.S. Committee on Integrated STEM Education (NAE et al. 2014), and the U.S.' 2012 President's Council of Advisors on Science and Technology (PCAST) (PCAST, 2012).

The FEW Nexus directly refers to SDG 2 (food), SDG 6 (water), and SDG 7 (energy) and is relevant in meeting the majority, if not all, of the other SDGs, though FEW as an inter-related system is not an SDG in and of itself. Given the inter-connections of these systems, students need to learn about the FEW Nexus holistically, as opposed to investigating each system individually, as is often the case in educational settings dictated by siloed disciplinary programs. Through consideration of the interrelated dependencies of these core resources, the FEW Nexus

recognizes the importance of impacts, trade-offs, and competing interests (D'Odorico et al. 2018; Food and Agriculture Organization of the United Nations (FAO), 2023). The FEW Nexus is a timely, real-world educational context for framing interdisciplinary environmental and sustainability education and the critical role of the FEW Nexus in meeting the SDGs. The FEW Nexus also provides powerful and meaningful connections to help students see the relevance of their disciplines to real-world 21st-century issues in achieving the SDGs. In this paper we provide concrete examples and discussion of how the FEW Nexus can be used to achieve the learning outcomes of key sustainability competencies.

Disciplinary and multidisciplinary approaches for the education of key sustainability competencies with the FEW Nexus

Currently, most IES programs are structured around specific disciplines, sometimes with the integration of other disciplines into their core disciplinary home. For example, an analysis of a representative sample of 363 IES programs in the United States found three prevalent approaches to curriculum design: emphasis on natural systems, societal systems, or integration of natural and social sciences as well as humanities and professional fields such as planning and technology (Vincent, 2013). In another review of 127 IES programs, 75 consisted of 75% courses in natural sciences, while 7 programs consisted of 75% or more courses in social sciences, and 45 were completely interdisciplinary (Romero, 2016). While a deep dive into a particular disciplinary focus can be valuable, students may then struggle to connect and apply disciplinary learning to complex, interdisciplinary settings. A commonly identified skill for environmental programs is knowledge integration across disciplines, even though the majority of these programs are focused primarily on natural or social sciences. There have been several calls to more formally synthesize and integrate disciplines that comprise environmental programs for more rigorous curriculum development and evaluation (Wallace and Clark, 2018; Vincent, 2017). A uniting framework, such as the FEW Nexus, could provide a tool to link discipline-focused courses with broader, cross-cutting problems. FEW Nexus topics also hold the potential to effectively bridge disciplinary gaps at scales that balance the need for complexity and manageability. There is a need for education research and collaboration specifically within the FEW Nexus, as demonstrated by (1) the U.N. Food and Agriculture Organization initiative to define the FEW Nexus in the context of water and agriculture security (FAO, 2023), and (2) the recently funded U.S. National Collaborative for Research on Food, Energy, and Water Education (NC-FEW). Also, although they may not share specific curricular foci and content emphases, environmental programs often share skill development learning objectives (e.g., problem-solving, systems thinking) (Vincent et al. 2013) for which the FEW Nexus provides a context for developing and applying those skills.

Connections between the FEW Nexus and the SDGs are long-intertwined as both concepts have increased in relevance in recent decades (Simpson and Jewitt, 2019; Pandey and Shrestha, 2017). For example, as noted by Simpson and Jewitt (2019), the U.N. Brundtland Commission (1987) report that defined sustainability also recognized the rise of "interlocking crises" spanning across nations, sectors, and societal issues that had been often addressed separately, including food security and energy among others. Subsequent publications, particularly Hoff (2011) and World Economic Forum (2011), as well as the Bonn 2011 Nexus Conference further refined and highlighted the FEW Nexus while the international community focused on implementing the SDGs

(Albrecht et al. 2018). Today, the FEW Nexus provides a valuable applied model for investigating interconnections across resources that informs sustainable development more generally (Albrecht et al. 2018; Adom et al. 2022). As such, the FEW Nexus also offers an approachable pedagogical entry point for teaching complex and demanding interlinked environmental and social challenges present across the broader SDGs. We find that a FEW Nexus approach provides a means for an engaged inquiry-based approach that can be readily adopted across multiple topics and disciplines addressing sustainability.

Alongside these studies that have analyzed content and disciplines in IES programs, another body of work has identified key competencies for sustainability education. A competency-based approach focuses on developing the knowledge and skills necessary to successfully perform a complex task and thus combines well with a content-based approach. Since the early 2000s, scholars have been identifying diverse competencies in sustainability, which have been synthesized, through a comprehensive literature review and expert deliberation, into a framework of key competencies in sustainability to guide sustainability education (Wiek et al. 2011). The key competencies were identified as Systems thinking, Anticipatory, Normative, Strategic, and Interpersonal (Wiek et al. 2011). A 2016 study by Wiek et al. (2016) added a sixth competency—Integrated problem-solving. A 2017 UNESCO report adapted the key competencies framework in support of education for sustainable development (UNESCO, 2017).

Ten years after the first synthesis by Wiek et al. (2011), Brundiers et al. (2021) conducted a Delphi study to assess consensus among the sustainability education research community on the framework of key competencies in sustainability education. The conclusions of the Brundiers et al. (2021) study revealed agreement among sustainability excerpts in the six key competencies identified by Wiek et al. (2016) study, recommended updated, more nuanced definitions and nomenclature, and the addition of two additional competencies—Intrapersonal and Implementation. Redman and Wiek (2021) also conducted a review of the literature, which indicated convergence on these final eight key sustainability competencies. Table 1 lists the eight key competencies along with definitions (Redman and Wiek, 2021) and indicates in brackets alternate nomenclature for some of these competencies.

Redman and Wiek (2021) detail the complementary relationships between the key competencies in sustainability education and disciplinary knowledge and content areas, which together build upon foundations prioritized by most academic programs, including general academic competencies (e.g., critical thinking, creativity, learning) and professional skills (e.g., communication, project management). Most recently, the Global Council for Science and the Environment (GCSE) published a proposal statement on accreditation of sustainability-related higher education programs (Brundiers et al. 2023), which builds on the literature since the early 2000 and synthesis efforts by Brundiers et al. (2021) and Redman and Wiek (2021). The objective of the proposal statement is to provide dynamic guidance on the design and evaluation of sustainability programs and a potential foundation for an accreditation system for sustainability programs.

When deployed as part of the IES curriculum development process, the key sustainability competencies elucidate what the program aims to achieve in terms of skills development as learning outcomes. However, we still lack clarity on how these key sustainability competencies are operationalized in real-world contexts and how they are combined with pertinent interdisciplinary and disciplinary content knowledge (Redman and Wiek, 2021). In other words, students need to be able to see how they can directly apply what they are learning to real-world

situations that support sustainable development and the targets set by the SDGs. Achieving this, we argue, is where the FEW Nexus provides a powerful, real-world context that requires integration of the key sustainability competencies with content knowledge and provides opportunities for multi-, inter-, and trans-disciplinary learning (see Pennington et al. [2016] for definitions of these terms). In “Teaching and Learning in the FEW Nexus to build key competencies in sustainability”, and referenced in the final column of Table 1, we provide specific examples of achieving the key competencies of sustainability grounded in the FEW Nexus.

From dialog to paper: fostering interdisciplinary education insights.

This paper was originally conceived during conversations with the post-secondary working group of the U.S. National Collaborative for Food-Energy-Water Education Research (NC-FEW) about how best to attend to the needs of a multiple discipline education community that included disparate disciplines conducting research on this topic, but not well networked with each other. The purpose of NC-FEW is to serve as a hub to advance education research grounded in the FEW Nexus, established with funding through the U.S. National Science Foundation Research Coordination Network Program (NSF Award # 2242276). Discussions originally centered around FEW as distinctly supportive of sustainability education goals and during an invited workshop in May 2023 and subsequent virtual group meetings, participants realized that there was congruence among our approaches to (1) anchoring socio-environmental concepts and sustainability competencies in the FEW Nexus (“Anchoring concepts and sustainability competencies in the FEW nexus”), (2) engage values thinking to address tension inherent to the FEW Nexus (“Anchoring socio-ecological systems in the FEW Nexus”), and (3) support students to develop skills to integrate multiple disciplines (“Developing skills to integrate multiple disciplines across the curriculum”).

This paper was written by scholars representing disciplines that include biology, chemistry, physics, psychology and educational psychology, science education research, anthropology, ecology, and interdisciplinary degree programs such as sustainability, geography, resilience, environmental studies and environmental sciences, tourism and outdoor recreation, biological systems engineering and environmental sociology. The authors also represent 2-year colleges, small liberal arts colleges, teaching-focused universities, and research-intensive universities. Our case study boxes in the next section provide examples from our range of disciplinary backgrounds, interdisciplinary scholarship, and institution types.

Here we take a retrospective approach to synthesize existing work across institutions and disciplines to show the ways that sustainability competencies are achieved with the use of the FEW Nexus. Case studies were identified by requesting program, course, or module examples from the NC-FEW listserv from anyone interested in participating in a synthesis project. To be included in the paper, case studies had to address the FEW Nexus in a way that integrated one or more of the Key Sustainability Competencies (Table 1). Authors were also asked to provide insights into the development of their approach, how this evolved over time, and what changes were made to address lessons learned in the process. The case studies are organized by three categories; (1) Anchoring Concepts and Sustainability Competencies in the FEW Nexus, (2) Engaging Values Thinking to Address Conflicts Inherent in the FEW Nexus, and (3) Developing Skills to Integrate Multiple Disciplines Across the Curriculum. Each case study

Table 1 Application of FEW Nexus to key competencies in sustainability (columns 1–3 replicated from Table 1 from Redman and Wiek, 2021).

Competency	Definition	Descriptors from the literature	Application of FEW Nexus
(1) Systems Thinking Competency	Ability to collectively apply modeling and complex analytical approaches: 1) to analyze complex systems and sustainability problems across different domains (environmental, social, economic) and across different scales (local to global), including cascading effects, inertia, feedback loops, and other system dynamics; 2) to analyze the impacts of sustainability action plans (strategies) and interventions (how they change systems and problems)	Understand, identify, describe, analyze sustainability challenges and problems, complex issues, effects, relationships, impacts, patterns, structures, unintended consequences, feedback loops, context, interactions, etc. across different domains (environmental, social, economic), scales (local to global), and perspectives (interdisciplinary), Etc (Connell et al. 2012; Sandri, 2013; Gray, 2018; Levy et al. 2018; Schuler et al. 2018; Mahaffy et al. 2019). Exploring and developing effective action in complex contexts thereby enabling systems change.	• Box 1: Anchoring Socio-Ecological Systems in the FEW Nexus. • Box 2: Anchoring the Anthropocene in the FEW Nexus • Box 3: Anchoring Systems Thinking in the FEW Nexus • Box 4: Anchoring Resilience Thinking in the FEW Nexus • Box 5: Values Thinking Connections to Food Justice in the FEW Nexus • Box 9: Teaching Integrative Food and Water Systems with the FEW Nexus
(2) Futures Thinking Competency (Anticipatory Competency)	Ability to collectively carry out or construct simulations, forecasts, scenarios, and visions: 1) to anticipate future states and dynamics of complex systems and sustainability problems; 2) to anticipate how sustainability action plans (strategies) might play out in the future (if implemented).	Anticipate, foresight, envision, craft, analyze, and evaluate long-term future consequences, scenarios (multiple futures), and visions regarding intergenerational equity, future generations, uncertainty, etc. (Withycombe, 2010; Gardiner and Rieckmann, 2015; Ojala, 2017). Divergent thinking is used to elicit many possible answers and acknowledge uncertainty.	• Box 1: Anchoring Socio-Ecological Systems in the FEW Nexus. • Box 4: Anchoring Resilience Thinking in the FEW Nexus • Box 7: Teaching Values Thinking using Structured Decision-Making • Box 8: Teaching Climate Change Across Disciplines with the FEW Nexus
(3) Values Thinking Competency (Normative Competency)	Ability to collectively identify, map, specify, negotiate, and apply sustainability values, principles, and goals: 1) to assess the sustainability of current and/or future states of complex systems; and 2) to construct sustainability visions for these systems; (3) to assess the sustainability of action plans (strategies) and interventions.	Identify, assess, negotiate, reconcile, reflect on, map, apply sustainability principles, morals, norms, ethics, goals, integrity, justice, conflicts, trade-offs, etc. (Remington-Doucette et al. 2013; Verma et al. 2016; Komarinski and Ishimura, 2017)	• Box 2: Anchoring the Anthropocene in the FEW Nexus • Box 3: Anchoring Systems Thinking in the FEW Nexus • Box 4: Anchoring Resilience Thinking in the FEW Nexus • Box 5: Values Thinking Connections to Food Justice in the FEW Nexus • Box 6: Values Thinking in FEW Nexus Trade-offs in Water Use • Box 7: Teaching Values Thinking using Structured Decision-Making • Box 9: Teaching Integrative Food and Water Systems with the FEW Nexus
(4) Strategic Thinking Competency (Action-oriented)	Ability to collectively construct and test viable strategies (action plans) for interventions, transitions, and transformations toward sustainability.	Design, create, develop, test transformative, innovative, viable, feasible interventions, transitions, strategies, action plans, solutions, etc. considering barriers, inertia, path dependence, carriers, assets, etc. (de Haan, 2006; Wesselink et al. 2015; Fukushima et al. 2017)	• Box 2: Anchoring the Anthropocene in the FEW Nexus • Box 3: Anchoring Systems Thinking in the FEW Nexus • Box 5: Values Thinking Connections to Food Justice in the FEW Nexus • Box 10: Interdisciplinary Strategic Thinking with the FEW Nexus for Rural Development

Table 1 (continued)

Competency	Definition	Descriptors from the literature	Application of FEW Nexus
(5) Implementation Competency	Ability to collectively put sustainability strategies (action plans) into action, including implementation, adaptation, transfer and scaling, in effective and efficient ways.	Implement, enact, adapt, manage, transfer, scale action plans, strategies, change plans, intervention plans, governance initiatives, etc. (de Haan, 2006; Perez Salgado et al. 2018; Schank and Rieckmann, 2019)	• Box 2: Anchoring the Anthropocene in the FEW Nexus • Box 3: Anchoring Systems Thinking in the FEW Nexus • Box 5: Values Thinking Connections to Food Justice in the FEW Nexus • Box 10: Interdisciplinary Strategic Thinking with the FEW Nexus for Rural Development
(6) Interpersonal Competency (Collaboration)	Ability 1) to collaborate successfully in interdisciplinary and professional teams; and 2) to involve diverse stakeholders, in meaningful and effective ways, in advancing sustainability transformations.	Enable, motivate, facilitate interdisciplinary, transdisciplinary, cross cultural collaboration in teams and among stakeholders through listening, compassionate communication, negotiation, conflict resolution, empathic leadership, etc. (Ulrich, 2016; Brundiers and Wiek, 2017; Sarpin et al. 2018)	• Box 4: Anchoring Resilience Thinking in the FEW Nexus • Box 6: Values Thinking in FEW Nexus Trade-offs in Water Use • Box 8: Teaching Climate Change Across Disciplines with the FEW Nexus • Box 9: Teaching Integrative Food and Water Systems with the FEW Nexus • Box 10: Interdisciplinary Strategic Thinking with the FEW Nexus for Rural Development
(7) Intrapersonal Competency (Mindset)	Ability to avoid personal health challenges and burnout in advancing sustainability transformations through resilience-oriented self-care (awareness and self-regulation)	Reflect, motivate, have respect for, be responsible, be empathetic, self-care for identity, commitment, feelings, burnout, personal boundaries, limits of capacity, etc. (Glasser, 2016; Lozano et al. 2017; Giangrande et al. 2019)	• Box 8: Teaching Climate Change Across Disciplines with the FEW Nexus • Box 9: Teaching Integrative Food and Water Systems with the FEW Nexus
(8) Integration Competency	Ability to collectively apply collective problem-solving procedures to complex sustainability problems: 1) to develop viable sustainability strategies (action plans); and 2) successfully implement them, in collaborative and self-caring ways.	Develop, apply, promote, make decisions to advance sustainability by using viable, equitable, and inclusive solution processes, procedures, frameworks, schemes, etc. (Jegstad and Sinnes, 2015; Hull et al. 2016; Wiek et al. 2016)	• Box 2: Anchoring the Anthropocene in the FEW Nexus • Box 3: Anchoring Systems Thinking in the FEW Nexus • Box 4: Anchoring Resilience Thinking in the FEW Nexus • Box 5: Values Thinking Connections to Food Justice in the FEW Nexus • Box 6: Values Thinking in FEW Nexus Trade-offs in Water Use • Box 7: Teaching Values Thinking using Structured Decision-Making

author has highlighted which sustainability competencies are best represented in their module. We acknowledge there may be additional connections between the cases and the competencies, but in the interest of conciseness and clarity, we highlighted the most salient connections between each case and its targeted competencies.

Teaching and learning in the FEW Nexus to build key competencies in sustainability

In an educational context, the FEW Nexus integrates the key competencies in sustainability to address a range of complex, global, and interconnected real-world contexts. Discipline-based knowledge provides the core content and concepts

relevant for understanding FEW systems and the inter-connections between FEW variables while the key sustainability competencies establish a procedural framework for how to apply content knowledge in ways that support sustainable development through application of the FEW Nexus (Fig. 1). Real-world examples ground the key sustainability competencies and content-based knowledge so that students see the relevance of how their education can support action and solutions in support of sustainable development to meet the targets and goals set by the SDGs. In this section, we present examples from our own IES programs of how the FEW Nexus can serve as this crucial link between developing key sustainability competencies in students to meet sustainable development goals.

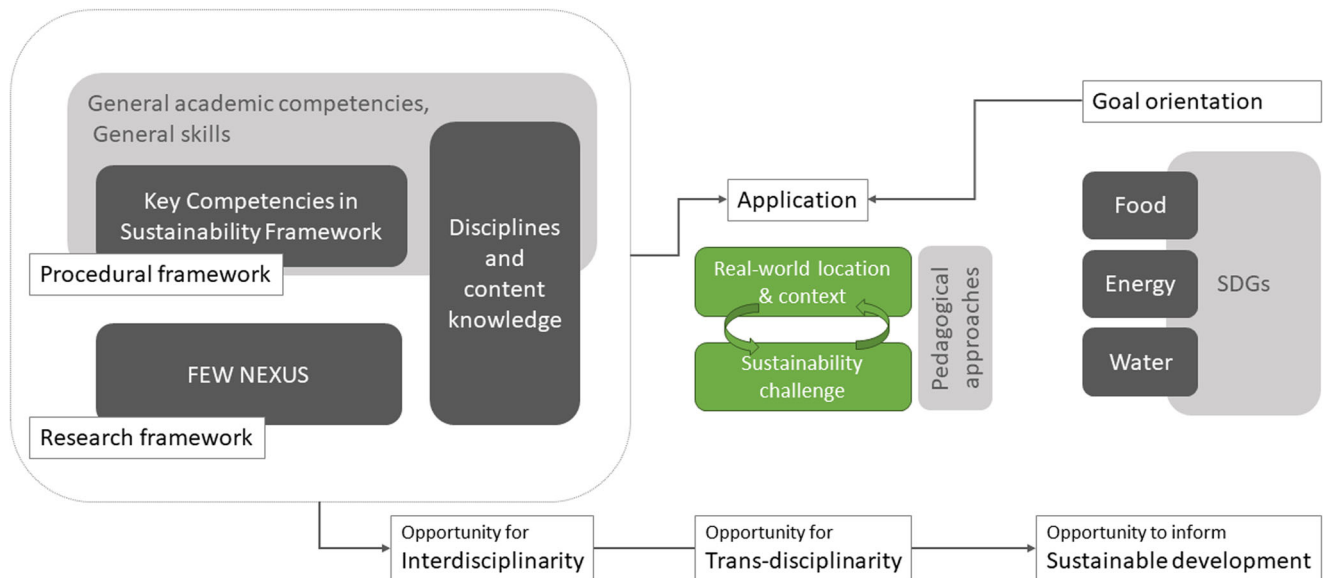


Fig. 1 Schematic representation of the relationship between, research, education, and action in the FEW Nexus. The key competencies in sustainability provide a framework for integrating discipline and content knowledge with the FEW Nexus and grounded through applications of real-world contexts. The goal is to help students see the relevance of the key sustainability competencies in identifying solutions and approaches that achieve the SDGs.

Anchoring concepts and sustainability competencies in the FEW Nexus. This first set of examples from our IES programs demonstrate how to anchor abstract concepts in concrete situations (i.e. “the real-world context” in Fig. 1). FEW aids student mental models and thinking development regarding abstract concepts by using concrete phenomena or events that students can relate to from their daily lives. Clear and coherent anchoring of concepts supports student learners to see connections across course content and systems. The curricular modules demonstrate the use of the following abstract concepts:

- Box 1: Anchoring Socio-Ecological Systems in the FEW Nexus
- Box 2: Anchoring the Anthropocene in the FEW Nexus
- Box 3: Anchoring Systems Thinking in the FEW Nexus
- Box 4: Anchoring Resilience Thinking in the FEW Nexus

For each example, we first discuss the anchored concept and then present a specific course or module in which the FEW Nexus anchors the abstract concept and supports the integration of key sustainability competencies with content knowledge.

Anchored concept: socio-ecological systems. Socio-Ecological synthesis considers the interactions of human activities and the environment holistically, rather than as separate systems. The concept of Systems Thinking is considered a key competency of sustainability (Table 1) with specific skills related to synthesis, analytics, and application of research to decision-making (specific skills described in the Definitions and Literature columns of Table 1). The regional, national, and global importance of food, energy, water, and the connection of FEW to other socio-environmental systems such as ecosystem services systems demands an understanding of how FEW systems respond to stress—developing resilience, and an educational system that addresses these fundamental challenges that involve FEW resource management and ecosystem services production, but also access, equity, agency, availability, and connections to other systems. Often economic development has taken precedence in decision-making over ecological impacts (Eisenmenger et al. 2020), showing the difficulty of cross-scale trade-offs among the ecosystem services upon which we depend

(Anandhi et al. 2023). The FEW Nexus provides a framework for understanding the socio-ecological relationships between FEW systems by providing a focused set of resources to consider and specific socio-economic connections to evaluate (Box 1).

Anchored concept: the anthropocene. Recent scholarship around earth systems has emphasized not only the human interactions with those systems but also assessed how our actions are altering fundamental earth system processes that support human societies (Rockström et al. 2023; Steffen et al. 2015). Generally, this concept has been referred to as “The Anthropocene”, with formal discussion of whether this constitutes a geologic epoch over the past 15 years by The Anthropocene Working Group of the International Commission on Stratigraphy (Max Planck Institute for the History of Science, 2023 C.E.). The adverse impacts of human activities on these Earth system boundaries hinder global progress toward the UN Sustainable Development Goals. This recognizes the interconnections between earth system boundaries and the 12 social foundations derived from the SDGs (Raworth, 2017). Food, energy, and water constitute three of these social foundations, and each is experiencing resource scarcity and distribution concerns. FEW allows the abstract concept of the Anthropocene to be anchored in specific situations where human actions change earth systems that impact how these resources can be sourced (Box 2). Approaching earth system boundaries from a FEW perspective supports the key sustainability competencies listed in Table 1, including systems thinking, futures thinking, and values thinking by considering human justice and equity in devising strategies that promote sustainability.

Anchored concept: systems thinking. Systems thinking is one of the key competencies for sustainability (Wiek et al. 2011), but we have also included it as an anchor concept in our framework because it is perhaps the most widely recognized and foundational competency associated with sustainability and STEM. For example, systems thinking is identified as a key competency in STEM education by the U.S. National Science Foundation 2020 visioning report (NSF, 2020), the 2020 U.S. National Academies of Science, Medicine and Engineering Report on Strengthening

Box 1 | Anchoring socio-ecological systems in the FEW Nexus**Biosphere 2 Case Study**—University of Montevallo

Institution Type: Public, 4-year, Carnegie Classification: Master's College and University (medium programs)

Level: Undergraduate major/minor course for Environmental Studies

Scale: 2 Multi-day activity

Case Location(s): United States

Description: In Principles of Sustainability, Environmental Studies students are introduced to social-ecological systems. The students first read about systems properties and social-ecological resilience, and then groups of students are given example diagrams of social-ecological systems—examples come from varied systems, like pike fisheries, soil health management, and ecotourism (see Caplow, 2023 for a full description). The groups identify key stocks and flow within the diagram and interpret their system for the rest of the class. To culminate the activity, students watch a video and read materials describing the Biosphere 2 case. Students are then each given their own piece of information related to the case, and then one student volunteers to present their information first—after that, each student presents their information sequentially by connecting it to the previous student's information, constructing a narrative in which historical and spatial connections between information encourages them to consider ways in which air, water, food, energy, waste, and social dynamics are connected within the Biosphere 2 system.

Competencies and the FEW Nexus: Students interpret and create visualizations of social-ecological systems (1-Systems Thinking Competency). Students imagine how perturbations in the system will create feedback within the system (2-Futures Thinking Competency).

Insights gained by the instructor: In previous iterations, this case was not framed as a FEW case, but rather, one more broadly about social-ecological systems. However, pivoting towards an explicit focus on the FEW Nexus focuses the expectations regarding systems interactions, and makes the content more manageable for students. In particular, within Biosphere 2, FEW system interactions represent a significant portion of the challenges associated with the project. The FEW Nexus will be central to future iterations of this activity.

Box 2 | Anchoring the anthropocene in the FEW Nexus**The FEW Nexus in the Anthropocene**—Binghamton University, The State University of New York

Institution Type: Public 4-year Carnegie Classification: Doctoral Universities: High Research Activity

Level: Undergraduate course for Biology, Environmental Science, and Studies and Graduate course for Food and Health for Biology, Environmental Science and Studies

Scale: Semester

Case Location(s): United States and Italy

Description: Students in this course conduct inquiry-based projects that incorporate experiential learning opportunities into FEW Nexus and the SDGs. The learning queries are meant to foster dialog among students from diverse fields around the most pressing scientific obstacles to implementing sustainable solutions related to the FEW Nexus, while also understanding the myriad environmental, economic, infrastructural, and social constraints that define the boundaries of both challenges and potential opportunities within the FEW Nexus. The course serves as a leading course to community-engaged capstone projects and capstone courses as well as graduate courses in sustainable communities. Having students explain and assess social, historical, and ethical issues to community stakeholders further helped students further develop skills in research, writing, and communication.

Competencies and the FEW Nexus: Students understand FEW systems individually and link systems through ecosystem services (1-Systems Thinking Competency). They then conduct life-cycle analyses of a typical grocery list (3-Values Thinking Competency) by further examining risks and opportunities in a regional FEW system. Students work in project-based learning (PBL) teams to identify localized governance gaps (5-Interpersonal Competency) finally linking to capstones to further research outcomes and engage stakeholders (8-Integration Competency).

Insights gained by the instructor: Given the experiential and community engagement learning, students were able to analyze contemporary global issues and apply them to local FEW systems. This allowed them to assess the relationship that science and technology have with issues of social justice locally. The course fulfills the following core curricular goals of addressing the SDGs by,

1. Analyzing a contemporaneous global issue from a multidisciplinary local perspective.
2. Formulate the relationship matrix between FEW systems and science and technology.
3. Emphasize cross-dependency of goals with singular emphasis on social-environmental issues.

Sustainability Programs and Curricula at the Undergraduate and Graduate levels (NAS et al. 2004), the U.S. Next Generation Science Standards for K12 education (NGSS Lead States, 2013), and by various discipline-specific and interdisciplinary researchers (Anandhi et al. 2017; Blatti et al. 2019; Hmelo-Silver et al. 2007; Mambrey et al. 2020; Momsen et al. 2022; Ravi et al. 2021). Sustainability and systems are critical to understanding in a world where food, energy, and water scarcities and inequities are driven by population growth, climate change, and resource consumption (Anandhi et al. 2023). Understanding the complex trade-offs and interlinkages between these environmental and human systems is a prime example of systems thinking (Bentley and Anandhi, 2020) that is also an important public policy educational task (Sanford et al. 2017), but remains pedagogically difficult (Silva de Vasconcelos, 2016). Part of the difficulty stems from the sheer volume of topics that are highly variable across courses,

programs, and institutions of IES programs (Vincent, 2013), coupled with the challenge of teaching abstract concepts. The FEW Nexus provides a concrete anchor for developing the skill of systems thinking (Box 3).

Anchored concept: resilience thinking. Resilience refers to the capability of a system to cope with disturbance without collapsing and transitioning to a less desirable or productive state (Holling, 1973). Resilience is a salient attribute of FEW systems, and requires specific integration of social, ecological, and economic aspects of FEW (Sundstrom et al. 2023). Collapses following the loss of resilience have been well documented in FEW systems, often with catastrophic effects on humanity. However, most disturbances affecting systems don't cause collapse, and return time (also called bounceback, or resiliency) is an important feature of FEW systems (Allen et al. 2019).

Box 3 | Anchoring systems thinking in the FEW Nexus**Conceptualizing Systems Thinking in a FEW Nexus Course**—Florida A&M University

Institution Type: Public, 4 year, HBCU Carnegie Classification: Doctoral Universities: High Research Activity

Level: Graduate elective course for Agricultural Sciences, Environmental Science and Engineering

Scale: Semester Course

Case Location(s): Various (student-led projects)

Description: Students in this course apply systems thinking using conceptual models highlighting the FEW Nexus through student projects. The students explore existing frameworks/models such as FAO framework, Bonn 2011 Nexus Conference framework, World Economic Forum, 2011 framework, ICIMOD framework, and IISD framework, to understand what are included in the existing models. The students explore existing relevant definitions related to the FEW Nexus and what factors are currently included in each definition. They then decide how the FEW Nexus should be defined and conceptualized for a project or application and what the consequences are of choosing particular components in the definition and conceptualized model.

Competencies and the FEW Nexus: Students acquire the ability to apply systems thinking to adapt a definition and develop conceptual models, relate to the FEW Nexus for an application a stakeholder can use (1- Systems Thinking Competency, 4—Strategic Thinking Competency, 5—Implementation Competency). Students reflected on diverse definitions and conceptual models of FEW Nexus concepts existing in literature (3- Values Thinking Competency, 8- Integration Competency).

Insights gained by the instructor: The teaching approach had several features. The students' understanding of the complexity of FEW Nexus concept improved when various definitions and conceptual models existing in peer-reviewed literature were provided to them. The experiential learning exercise to create their own definitions and conceptualizations based on certain guidelines brought excitement when the theories and knowledge were connected to real-world situations. They applied system thinking in the process. They (students and faculty) were provoked/surprised/kindled when they explored the reasoning behind the differences in the definitions and conceptual models. The course material being published open access in a reputed peer-reviewed journal brought credibility to the course (Anandhi et al. 2023) and reduced the cost of textbooks. Our pedagogy also acknowledges the limits of the published material requiring constant updating, the need for a course focusing on FEW Nexus case studies in different continents of the world.

Box 4 | Anchoring resilience thinking in the FEW Nexus**Foundations of resilience**—University of Nebraska-Lincoln

Institution Type: Public, 4-year, Carnegie Classification: Doctoral Universities: High Research Activity

Level: Graduate course for U.S. NSF National Research Trainees (required) and other graduate students (elective) interested in interdisciplinary science.

Scale: Semester-long course

Case Location(s): Various (student-led projects)

Description: This graduate class was developed as a synthesis class on resilience theory and applications and convergence approaches for a U.S. NSF National Research Traineeship focused on resilience in working landscapes. Students register for this semester-long course preferably at or near the beginning of their graduate program. Non-linear change and non-stationarity are used as introductory concepts, and complex adaptive systems as an approach to understanding social-ecological change. Resilience is introduced as a recent example of convergence science. Background and history of resilience are provided, as are the various ways in which resilience concepts are currently utilized in different disciplines. Once a basic understanding of resilience concepts such as alternative stable states, thresholds, transformation, non-equilibrium systems, and social-ecological systems were covered, individual students led discussions once a week focused on applications within their disciplinary domains. Students also work together on a student-led, student-selected project of their collective choice, to provide the opportunity for collaborative work in the spirit of convergence science.

Competencies and the FEW Nexus: Students explore resilience through complex systems theory and application (1-Systems Thinking Competency). Students also imagine transformation within the system (2-Futures Thinking Competency) and the concept of alternative stable states which may or may not be desirable (3-Values Thinking Competency). Students collaborated across diverse cohorts to execute a whole-class project selected by the students, most recently focused on ecological drought (6-Interpersonal Competence Competency and 8-Integration Competency).

Insights gained by the instructor: Students crave multidisciplinary classes but struggle with the concept, and with initiating diverse collaborations required by such an approach. Case studies help elucidate the approach and its importance. Working across disciplines takes effort and work, and concepts such as FEWs and resilience serve as natural bridges to interdisciplinary learning.

Resilience-focused and FEW Nexus approaches have been combined to build on the strengths while addressing the weaknesses of each approach. In past studies, resilience focus has been on shock-absorbing capacity (Stringer et al. 2018) or vulnerability (Bentley and Anandhi, 2020), with the advantages and disadvantages of combining both approaches (Anandhi et al. 2023). Regardless, resilience is an exemplary integrative topic for cross-disciplinary education because resilience does not reside in any single domain, but emerges from the interaction of multiple facets of both ecological and social systems. Feedback between social and ecological realms must be considered deeply, and feedback, and the concept of resilience itself, requires understanding at multiple scales.

There are several U.S. NSF National Research Traineeships (NRTs) that have focused on FEW Nexus education,

synthesized in Wade et al. (2020). Convergence approaches are often applied in resilience (Box 4; Sundstrom et al. 2023), and are well-suited to cross-disciplinary training because convergence addresses complex (or “wicked”) problems affecting humanity, requiring integration of multiple disciplines, and multiple perspectives, knowledge, methods, and tools (*Learn About Convergence Research—Research Approaches*|U.S. NSF—National Science Foundation, n.d.). Convergence requires the synthesis of multiple frameworks to generate science—and understanding—that transcends the traditions of any given discipline. Resilience science and theory is a convergent science in that it addresses a fundamental challenge in social-ecological systems, rapid non-linear change, that requires input and synthesis from multiple disciplines, such as ecology, social sciences, and economics.

Engaging values thinking to address conflicts inherent in FEW nexus. The inherent interconnections and systems dynamics of the FEW Nexus can mean that identifying holistic approaches or solutions may be fraught with conflicts and tensions and what is often considered “trade-offs.” For example, restricting the withdrawal of groundwater from a rapidly depleting aquifer could potentially impact an agricultural community, or a planned installation of a solar photovoltaic utility scale plant may impact local biodiversity. However, from a sustainability perspective there must be attention paid to minimizing and mitigating and ideally identifying solutions that avoid such trade-offs. As (Gibson, 2006, p172) argues “*Sustainability is not about balancing, which presumes a focus on compromises and trade-offs. Instead, the aim is multiple reinforcing gains. Trade-offs are acceptable only as a last resort when all the other options have been found to be worse.*”

Values Thinking Competency, which focuses on the application of skills such as identifying, mapping, and clarifying values, goals, and targets, as well as supporting negotiation and reconciliation around sustainability values through ethical and decision-making approaches, is central to identifying approaches and solutions that center principles of sustainability and sustainable development in just and equitable ways. Students must be educated on how to navigate these complex relations, holistically consider trade-offs, and identify ideally “win-win” interventions. Combining new, “out-of-the-box” systems-thinking competency with values-thinking competency enables students to intentionally identify potential trade-offs. Having done this, Values Thinking Competency requires identifying approaches which in the words of Gibson aim to be “multiple reinforcing gains” and “net positive” where no one community or system bears the burden. Where such an approach may not be deemed possible or realistic, values thinking competency allows for intentionally identifying the benefits and the negative impacts,

and who might bear these impacts. In combination with strategic-thinking competency, students can then explore ways to minimize mitigate or distribute impacts before execution of the solution (Jimenez et al. 2023).

The FEWs nexus also allows for Values-thinking Competency to help students engage in what may be challenging, political debates. Students regardless of their backgrounds and political beliefs, must feel comfortable sharing their values and perspectives, and be heard respectfully. Explicitly supporting students in perspective-taking, defined as engagement with others or their circumstances, a shift from an outsider “etic” to insider “emic” viewpoint, and a moral context guided by conscience, is a key component to reasoning and problem-solving within FEWs nexus issues (Kahn and Zeidler, 2019; Newton and Zeidler, 2020; Kirk, 2023). Despite many instructors feeling wary or uncomfortable with how to incorporate values into instruction, and have a perception that instruction should be “value free” or “objective” (Cross and Price, 1996; Beatty et al. 2023), it is possible to take a pluralistic approach (Biesta, 2020; Öhman, 2008) and use values-centered reasoning to help students autonomously engage in personal and societal sensemaking and reflect on their own values and others—which is essential to navigate FEWs nexus topics. Values-thinking competency can support finding common ground and compromises such that solutions may be deemed acceptable across diverse perspectives.

We elevate this particular key competency of sustainability because it has been proposed that the Values-thinking Competency is a critical competency from a justice and equity perspective for decision-making (Schneider et al. 2019) and how normative power structures result in inequitable values represented in current decision-making (Fritz and Binder, 2020). Similarly, values-thinking competency plays a lead role in processes aiming to co-construct solutions to sustainability challenges (Brundiers et al. 2021). The FEW Nexus framework combines the key

Box 5 | Values thinking connections to food justice in the FEW Nexus

Environmental Biology and Film as Art Coupled Courses—College of DuPage

Institution Type: Public, 2-year, Carnegie Classification: Associate's Colleges: High Career & Technical-High Nontraditional

Level: Undergraduate general education course

Scale: Two semester-long courses taught in an interdisciplinary format (students take 2 courses together in one semester)

Case Location(s): Global Concepts and Examples with Local Contexts to Illinois, USA

Description: Students registered in two general education courses—Environmental Biology and Film as Art—that were integrated and thematically centered around exploring food systems. Food justice was used as an organizing principle, and the learning community was structured around systems thinking. Using the film *Food Inc.*, as a starting point early in the semester, we introduced the industrial food system, identifying its key features and the consequences they bring. Through additional films (both documentary and feature), lab activities, and experiential field learning, we discussed topics related to the FEW Nexus embedded in the industrial food system, applying an interdisciplinary framework as we constructed our understanding of the challenges and complex issues in feeding the world. We also asked students to complete a *visioning activity* where they think aspirationally to conceptualize an alternative food system, using ecological principles and key points of environmental and social justice as a foundation. Concept maps were used as a learning tool, adding an interactive visual element, as students mapped our current food system, side by side with the alternative one they envisioned. Additionally, students were asked to develop and implement a civic engagement project, which provided them with opportunities to take individual action related to building a sustainable food system (Adelman and Ajaonkar, n.d.).

Competencies and the FEW Nexus: Students interpreted and created visualizations of both the existing and aspirational food system (1- Systems Thinking Competency). Students reflected on diverse perspectives and values towards FEW issues in the context of food systems (3-Values thinking Competency). Students put sustainability strategies into action by developing and implementing a personal civic engagement project connected to food systems (4-Strategic Thinking Competency and 5-Implementation Competency). Students applied collective problem-solving procedures to develop the aspirational food system to address the issues inherent in the current one (8- Integration Competency).

Insights gained by the instructor: Our pedagogy acknowledges the limits of our individual disciplines, recognizes that each offers a unique lens through which to make sense of the world, and that both are necessary to find our place within it. We approach teaching with the understanding that we (faculty and students) are responsible for the knowledge that we construct and the world we co-create. Additionally, the lessons students take from studying our current food system and how food intersects with energy and water demands within the FEW Nexus are not abstractions for them but part of their lived experience. Despite the limits of a semester, students can (and do) leave with an understanding of how food justice could be used as a guide for making food consumption choices, and how our individual and collective food choices impact water and carbon footprints. Thus, they come to understand that through the everyday act of eating they can engage in the practice of rebuilding the world (Excerpted and adapted from Adelman and Ajaonkar, 2023).

Box 6 | Values thinking in FEW Nexus trade-offs in water use**Floridan Aquifer Case Study**—University of Florida

Institution Type: Public, 4-year, Carnegie Classification: Doctoral/Research Universities-Extensive

Level: Undergraduate major and non-major courses in Environmental Science

Scale: Multi-day activity

Case Location(s): United States

Description: Instructors developed two case studies to enhance student learning in water resource units in undergraduate non-major and major-track Environmental Science courses. Instructors developed one local case, focusing on a controversy surrounding the extraction of groundwater by a private company from the Floridan Aquifer, which is highly stressed by agricultural water use and home/industrial consumption. For the other case, instructors used a similar groundwater extraction scenario that was removed from the local context. Instructors led activities with each case scenario in separate sections of both the non-major and major-track courses in order (1) to enhance student learning using case-based, FEW Nexus activities and (2) to test empirically whether student learning outcomes were impacted by local contextualization of the case scenario. During the activities, students were assigned stakeholder roles across a variety of potential perspectives and tasked with conducting multi-stakeholder negotiations to determine sustainable outcomes for each controversy (Pappo et al. in prep).

Competencies and the FEW Nexus: Students reflected on diverse perspectives and values towards FEW issues (3-Values thinking Competency) and practiced listening, group decision-making, and conflict management (6-Interpersonal Competency) in their multi-stakeholder negotiations. The result of the negotiation was the collaborative development of a theoretically viable action plan in response to the case study controversy (8-Integration Competency).

Insights gained by the instructor: Case studies in the FEW Nexus can help students achieve sustainability competencies, regardless of whether they are situated in a local context. However, selecting a scenario that integrates local species, ecosystems, and ways of knowing (Semken, 2005; Semken and Freeman, 2008) may also provide other benefits for students including a more robust connection to place in the classroom and improved critical thinking skills (Cincera et al. 2015; Pappo et al. 2022; Ernst and Monroe, 2004).

Box 7 | Teaching values thinking using structured decision-making**Science and decision-making for a complex world**—University of Nebraska-Lincoln

Institution Type: Public, 4-year, Carnegie Classification: Doctoral/Research Universities-Extensive

Level: Required for all undergraduate STEM majors and non-STEM majors in the College of Agricultural Sciences and Natural Resources

Scale: Semester-long course

Case Location(s): United States

Description: In this core introductory course for the college, undergraduate students use FEW Nexus issues to develop media literacy and practice systems thinking and science-informed decision-making (for a full course description see Dauer et al. 2022). Students explore topics like water conservation in Nebraska in a transdisciplinary way throughout the course using a structured decision-making process (Hammond et al. 2015): they define the issue, select alternative solutions to the issue, formulate objectives as valued outcomes, use scientific and other evidence to inform how the FEW Nexus system works (i.e. if we enact a particular alternative will we achieve our objectives?), consider trade-offs among our objectives, choose an alternative and reflect on the decision and decision-making process. The “decision” is oriented around policy decisions in two examples: increasing research and development for sustainable technology, and enacting policies that restrict farmers’ use of water. Students discover that while there is no one “best” way to address FEW Nexus challenges, and that trade-offs are inherent to the process, decisions are improved by the inclusion of interdisciplinary information to capture system complexity and the incorporation of diverse perspectives.

Competencies and the FEW Nexus: Students take multiple perspectives on a FEW Nexus issue and consider how values should ultimately drive decision-making (Keeney, 1996; 3- Values thinking Competency). Working through structured decision-making asks students to consider how FEW Nexus systems would be impacted by different types of policy solutions and asks them to use scientific, reasoning, and other kinds of information to compare how each alternative performs to solve the problem (2-Futures Thinking Competency).

Insights gained by the instructor: Our goals for our students are to remain internally consistent with their own stated values and objectives, engage in perspective-taking, and avoid “value judgements” or quick decision-making shortcuts that are based on a single objective or priority (values-focused education research results from the course design are available in several publications: Sutter et al. 2018; Alfred and Dauer, 2019; Dauer et al. 2017; Jimenez et al. 2023). Structured decision-making allows students to the important yet separate roles of values and scientific information and incorporate both into decision-making in ways that are thoughtful and transparent. FEWs issues provide contexts that bridge the local and global, allowing for potentially transformative intercultural perspective-taking.

sustainability competencies with content knowledge in the context of values conflicts that emerge at the FEW Nexus:

- Box 5: Values-thinking Competency Connections to Food Justice in the FEW Nexus
- Box 6: Values-thinking in FEW Nexus Trade-offs in Water Use
- Box 7: Teaching Values-thinking Competency using Structured Decision-Making

Values-thinking competency: illuminating conflicting values systems. The FEW Nexus can help make contested issues and conflicting value systems visible in topics like Food Justice so that

students can be empowered to take action (Box 5). Food justice can be conceived of at varying scales of complexity, from an overly simple “feed the world” perspective to one that is more inclusive of other elements of justice, including “trauma/inequity, exchange, land, and labor” (Cadieux and Slocum, 2015, p1), or social movement activism (strategic thinking competency), the development of alternative food practices (values-thinking and strategic thinking competencies), and analyses of inequalities (systems thinking and values-thinking competency) (Holt-Giménez, 2010). FEW can help connect justice theories with other considerations related to food production, and help students consider justice alongside more traditional considerations of technological advancements in irrigation, chemical inputs, and

plant breeding, which have had clear economic and societal benefits but have come at a great cost to planetary systems and perhaps an overstepping of planetary boundaries entirely (Rockström et al. 2023; Steffen et al. 2015; Whitmee et al. 2015).

Values-thinking competency: illuminating trade-offs. As discussed above the FEW Nexus needs complex management and consideration of **trade-offs**, especially as the world is flattening and the scale and urgency of problems increases (Friedman, 2005). For example, there may be perceived trade-offs between efficiency and resilience, where efficiency focuses on maximizing production during (rarely achieved) normal conditions, and resilience focuses on guaranteeing production over a wide range of conditions, at the cost of some efficiency (Inouye et al. 2022). Trade-offs also occur across ecosystem services, for example, when water is used to produce exported alfalfa rather than locally used crops or when trees are used for energy rather than for building. Trade-offs also occur across time and space, for example when windbreaks are planted in global grassland biomes to provide wind protection for cattle: There is a local and short-term service provided in terms of wind protection, but over longer time frames most of the trees used for this service invade and degrade forage productivity over time—and trees invasions spread in space, negatively affecting neighbors and agricultural landscapes. The case study in Box 6 is an example of how the FEW Nexus allows students to evaluate trade-offs using real-world topics. By viewing issues through the perspectives of stakeholders, students are able to consider outcomes that aim to minimize the impacts of trade-offs and, ideally, as in the words of Gibson, are multiple reinforcing gains (Box 6; Pappo et al. in prep).

Values thinking: illuminating structured decision-making. Considering trade-offs among multiple objectives or priorities requires students to be reflective, deliberate and to consider multiple perspectives. Structured decision-making processes allow students to deal with the complexity of value trade-offs, while also synthesizing and applying evidence to understand the FEW

Nexus system (Box 7). Structured decision-making frameworks based on normative models are useful in real-life contexts, including building trust and transparency in community processes (Runge et al. 2020). However, they should not necessarily be taken as prescriptive for how we would expect students to make a decision in every context. In a classroom, structured decision-making provides a framework for thinking about a FEW's nexus decision and provides a list of steps to avoid overlooking important aspects, such as reflecting on values and trade-offs among potential solutions. As a result, students may have a greater capacity for collaboratively solving complex FEW nexus issues.

Developing skills to integrate multiple disciplines across the curriculum. In this section, we illustrate how the educational examples presented here can be combined and sequenced within a course or even an entire degree program. The FEW Nexus can be used to guide students in developing the skills to *integrate multiple disciplines*. Interdisciplinary work requires disciplinary understanding as well as disciplinary humility and collaborative skills to allow for a capacity to bridge disciplines and understand different research methods towards discovering new insights or ideas ((Tripp and Shortlidge, 2019; Angerer et al. 2021). The act of boundary crossing allows for making new connections, learning from the perspectives of the “other” and co-creating new practices (Akkerman and Bakker, 2011). These characteristics could be used to evaluate whether our curriculum and courses support students in developing these skills and mindsets.

- Box 8: Teaching Climate Change Across Disciplines with the FEW Nexus
- Box 9: Teaching Integrative Food and Water Systems with the FEW Nexus
- Box 10: Interdisciplinary Strategic Thinking with the FEW Nexus for Rural Development

Box 8 | Teaching climate change across disciplines with the FEW Nexus

Coupled Course: “Climate Responses and Response-Ability”—Appalachian State University

Institution Type: Public, 4-year, Carnegie Classification: Master's College and University (larger programs)

Level: Undergraduate major and non-major interdisciplinary general elective course

Scale: Semester-long courses taught simultaneously in a transdisciplinary format

Case Location(s): Various (multiple courses and instructors)

Description: Since the spring of 2022, faculty from 17 different academic units representing 6 colleges at Appalachian State University have taught a “Climate Responses and Response-Ability” coupled course to 739 students across campus. FEW concepts and competencies are threaded throughout these courses which are based on the UC Berkeley “Bending the Curve” curriculum (Ramanathan et al. 2016). The course objectives for all iterations include: Explaining the causes and consequences of the climate crisis and identifying strategies for climate change mitigation and adaptation that involve ecosystems, society, science, economies, and policy; analyzing climate change mitigation strategies in terms of their effectiveness and potential to provide co-benefits that increase justice and well-being at the local and global levels; explain the value of recruiting broad participation in climate conversations and develop a statement of personal commitment to climate solutions. While course activities vary across instructors, most sections include a small group project focused on a climate solution which includes a FEW Nexus component.

Competencies and the FEW Nexus: Students are exposed to data predicting various future climate scenarios depending on changes made in the current FEW Nexus systems (2-Futures Thinking Competency). The final project of this course requires students to work in transdisciplinary teams to develop solutions based on the FEW Nexus (6-Interpersonal Competency). In response to the student feedback, faculty are working with the on-campus student counseling center to develop modules for use in the classroom. These modules are in progress and will benefit a wide range of courses on-campus within and beyond this series that threaten student's mental health (7- Intrapersonal Competency).

Insights gained by the instructor: A critical element to the success of these courses is a dedicated and passionate faculty leader, originally funded by a university-level grant. This person establishes the framework for the courses and coordinates monthly meetings to establish a teaching community among the faculty fellows. Perhaps as impactful as the education to the students is the exchange of ideas and expertise among these faculty fellows, who share diverse teaching and evaluation pedagogies. These experiences continue to infiltrate these faculty's courses beyond their participation in this coupled course. Appalachian State University's Quality Enhancement Plan (QEP) linked to SACS accreditation starting in 2024 will be “Climate Literacy and Response-Ability: Cultivating Resilient and Just Communities.” This broad-reaching coupled course helped provide the proof-of-concept for this successful QEP topic and this course has now been approved as a formal general education course offering.

Box 9 | Teaching integrative food and water systems with the FEW Nexus**Sustainability semester program/learning connection—Goshen College**

Institution Type: Private, 4-year, Carnegie Classification: Baccalaureate-Arts & Sciences college

Level: Undergraduate major and minor courses in Sustainability

Scale: 5 courses taught simultaneously in a transdisciplinary format

Case Location(s): Northeastern Indiana, United States

Description: Majors and minors in the Sustainability BA degree program at Goshen College are required to complete the fall “Sustainability Semester,” which is an immersive, place-based, experiential semester, to fulfill their degree requirements. Students are housed at Goshen’s field campus, Merry Lea Environmental Learning Center, about 40 min away from the main campus. The Sustainability Semester includes five courses explicitly designed to work together to develop FEW Nexus thinking: (i) Spirituality, Sustainability, & Ethics, (ii) Freshwater Resources, (iii) Agroecology, (iv) Regenerative Agricultural Practices, (v) and Organizing Communities for Change. The program combines courses with high-impact activities, including field trips, participation in external conferences and workshops, a 10-day canoe trip to instill a watershed perspective, raising and processing their own vegetables, eggs, and meat, and hosting a farm-to-table meal. Common experiences inform discussions across courses and students are supported to make connections across courses to more fully understand concepts. Enrollment is limited to 12 students because of the intensive nature of instruction. Taking all 5 courses concurrently facilitates instructors sharing course content and referencing it across courses to fully develop FEW Nexus ideas. For example, when students visit a large-scale confinement dairy, there is much more content to cover (both in volume and in areas of expertise) than any one course could conceivably handle. The instructor of Regenerative Agriculture provides tactile experiences (hand milking goats) as well as in-depth instruction on feed rations, livestock care, the basics of enteric fermentation, and management and environmental trade-offs between confinement and pasture-based systems. The Agroecology instructor focuses on labor availability, environmental regulation & policy, subsidies, input costs, and net income, incentives for biogas generation from manure, and yield per unit of energy. The Organizing Communities Instructor explores recent changes in farm size and local communities, competition for farmland by multinational solar farm companies, community groups concerned about air and water quality around confinement farms, and the development of a local economy. The Freshwater Resources instructor ties in direct observations from the canoe trip and a water quality sampling campaign conducted in conjunction with a local non-profit to help define water quality issues and solutions as they relate to agriculture. The Sustainability Ethics instructor adds various ethical lenses and schools of thought. Throughout this process students are repeatedly brought back to the FEW Nexus as a way of scaffolding this wide range of interconnected ideas.

Competencies and the FEW Nexus: Students understand FEW issues from multiple lenses using knowledge earned both via common experiences and course content (1-Systems Thinking Competency). Students interrogate both their own values & ethical frameworks as well as those of organizations they visit on field trips (3-Values Thinking Competency). Students practice communication and cooperation through the living/learning community co-constructed by the students and facilitated by faculty and staff; everyday decisions like what to cook or what cleaning products to purchase become opportunities to develop interpersonal competence (6-Interpersonal Competency). Intentional networking with field trip hosts and guest speakers further develops this competency. Students engaged in weekly reflective writing, intentional centering activities (i.e. meditation, nature walks, garden work), and specific work to determine what types of roles students are best suited for within a movement (i.e., leader, caregiver, etc.; 7-Intrapersonal Competency).

Insights gained by the instructor: FEW approaches to education can be very powerful but also resources intensive. Various support staff are required to run an integrated residential semester like this, including a residential life coordinator, program director, farm manager, and several faculty. We have a dedicated housing facility and a campus farm for hands-on embodied instruction. The place-based nature of this work requires strong and continued relationships with local businesses and organizations. Support staff also coordinate field trips and the canoe trip. A dedicated semester can be difficult for students to fit into their schedules.

Although considerable institutional support is needed to center a semester around the FEW Nexus, impacts on student learning can be dramatic. Students develop a strong understanding of socio-environmental systems-based thinking. Students tend to enter the semester with a simplistic view of FEW Nexus concepts and often do not recognize the significance of the connections between food, water, and energy. Following the semester students are able to recognize the utility of the FEW Nexus in visualizing environmental problems and articulating solutions. They learn how to work at coalition building using a “big tent” approach by understanding multiple ethical frameworks and finding leverage points within FEW systems. Students apply these lessons in their personal lives, in their role as advocates, and in their chosen vocations. Demystifying the complexity of these systems and exploring iterative solutions ameliorates the ever-present climate anxiety of modern students.

In addition it should not be understated how teaching within the FEW Nexus is beneficial for faculty. As faculty within this semester work together to deliver FEW Nexus teaching—each instructor comes to better understand the disciplinary perspective of the others. This provides opportunities for cross-collaboration on research projects and publications and furthers the cross-training of faculty to provide further FEW Nexus instruction.

Within a major, the FEW Nexus can be integrated into many different individual courses to support the application of discipline-based concepts, so students connect their discipline to a “real-world” context as well supporting and application of the identified skills. Additionally, FEW Nexus topics are very accessible to learners in the sense that everyone encounters food, energy, and water in their daily lives, potentially making course topics more relevant to students. This may be especially important for non-majors as topics might be more “visible” to novice learners beginning to understand resource systems and engaging in sustainability work as global citizens and may help combat issues with climate anxiety, as solutions-oriented science and collective action work have been shown to moderate the demotivation cause by climate anxiety (Bowser et al. 2020; Schwartz et al. 2023).

Across the curriculum: climate change. The FEW Nexus can focus efforts on exploring a larger topic, such as climate change.

Climate change can be a particularly challenging topic to connect across disciplines, as it is exceptionally complex and potentially overwhelming, both technically and emotionally (Coelho and Dana, 2008; Verlie, 2019). Bounding climate change within FEW allows more direct comparison using other frameworks from multiple disciplines and can serve as a touchstone as faculty explore a new topic with which they may not be overly familiar (Box 8). In addition, solution-based climate education opens the opportunity for a stronger inclusion of the energy component which can be the lesser-discussed component of the FEW Nexus in courses based solely on environmental sciences.

Across disciplines: complex food and water systems. Teaching within a FEW context helps to manifest complex topics that are emergent properties of systems (Liu et al. 2015). These emergent topics often require interdisciplinary or transdisciplinary approaches in order to understand problems, formulate solutions,

Box 10 | Interdisciplinary strategic thinking with the FEW Nexus for rural development

Title: strategic thinking in postgraduate training—Institute for Rural Development (IRD), University of Venda, South Africa

Institution Type: Public, 4-year South African comprehensive rural-based institution

Level: Ph.D. in Rural Development

Scale: Whole graduate program

Case Location(s): Limpopo province, South Africa

Description: As part of the Ph.D. in Rural Development program, the students acquaint themselves with research ethics and integrity, engage communities, and understand the research process from proposal to thesis development and finally viva voce. The students develop a research proposal in the first six months of the program by working closely with their supervisors and attending regular research workshops. The remaining time is dedicated towards community entry, data collection and analysis, thesis write up, information dissemination and oral defense. They apply Kappel and Holmen's (2019) conceptual framework in their research as a guide to broadly understand research and promote public acceptance and trust that are essential for disseminating findings through science communication. The scaffolding through workshops and seminars enables students to understand the research processes, tap into other disciplines, appreciate collaborative learning, and progress with their studies. Students critically engage in social preparation and community-entry processes, other community engagement activities, and oral defense sessions (Vermeulen et al. 2015) because their research is embedded in rural communities with the intention to improve livelihoods and communicate findings in the manner understood by the communities. Likewise, practical implications and policy influence are highly anticipated and promoted. Students learn about the FEW Nexus through a rural development lens, including projects on renewable energy and adoption of rural household solar systems, indigenous ways of water sustenance for humans and livestock, adaptation strategies to climate change and variability, and water footprint for crop value chains. Through these activities, students engage with communities and apply mixed methods techniques and participatory research methods. The student products (water footprint along the crop value chains, analysis of adoption of solar systems in rural households, livestock production sustenance strategies in water-constrained communities, and adaptation strategies within water-constrained and drought-prone regions) demonstrate the importance of drawing expertise from various disciplines. Engaging communities, close supervision, brown bag sessions, and workshops assist IRD in achieving student success and well-being per the university's strategic plan.

Competencies and the FEW Nexus: Students gain community engagement skills (6-Interpersonal Competency) by learning about research ethics and integrity, and community entry with recognition and respect for multicultural and multisectoral diversities (3-Values Thinking Competency). Through their research, the students devise various rural development strategies and frameworks that help enhance the living standards of rural communities (4-Strategic Thinking Competency; 5-Implementation Competency).

Insights gained by the instructor: The students contribute to the scholarship of discovery, application, engagement, and integration within the rural development space. In that way, the SAQA (The South African Qualification Authority) expected graduation attributes for the U.S. National Qualification Level 10 (SAQA, 2012) are met. The students apply acquired knowledge to solve problems in rural communities (Barge and Shockley-Zalabak, 2008). Working with local governments highlights the importance of FEW Nexus and can help improve development plans for improved livelihoods and local economic development. FEW enhances the program as it provides a holistic approach to solving complex challenges of food and water insecurity, energy poverty, malnutrition, poverty, and underdevelopment that rural communities face and are further exacerbated by climate change and variability.

and implement solutions appropriately within the given context (Bailey et al. 2015). Preparing students for this type of work is daunting and necessitates students to make connections across multiple courses, often taken during different semesters and housed within different disciplinary departments. Fully immersive experiential residential learning experiences (i.e., geologic field camps, research experiences including fieldwork, etc.) allow students to fully focus on topics with a group of peers who are equally engaged in the topic. Students have reported an enhanced feeling of belonging within the profession (O'Brien, 2022) when participating in these types of experiences. The strengths of teaching/learning within the FEW Nexus context should similarly be enhanced within the dedicated semester context.

Across disciplines: strategic thinking for community-engaged learning. The FEW Nexus is fundamentally entwined with community-engaged research that seeks to address the challenges that predominantly rural communities face. For example, limited access and resource availability in rural communities coupled with climate change and variability impacts human and livestock well-being, and the majority of the rural populace has limited access to essential services and facilities such as clean and safe water, affordable and clean energy, and balanced and nutritious diets (Adom et al. 2022; Mabhaudhi et al. 2019). Using integrative approaches such as the FEW Nexus could help promote inclusive and equitable development as well as resource planning and management coordination (Nhamo et al. 2018). Rural development is achieved through advancing a broad spectrum of research foci such as food security and nutrition, water for agriculture, water and sanitation, governance for sustainability, resilience, social cohesion, crop, and livestock

productivity, and service delivery (infrastructure development, health, education, and water included).

To better support, engage, and co-create knowledge with rural communities, researchers and practitioners must practice the key sustainability competencies (Baker, 2006; Braxton et al. 2002). Students can demonstrate the scholarship of integration by connecting various disciplines to increase the knowledge and usability of their research outputs (Box 10). The scholarship of integration, synthesis, interpreting, and connecting various disciplines enlightens the student and research participants and educates professionals (Tobin et al. 2010). In this instance, scholars conduct research at the boundaries where fields converge, and scholars overlap (Boyer, 1990), viewing broader intellectual patterns through the lens.

Conclusion

We need students with the knowledge, skills, values, and attitudes empowering them to contribute to sustainable development. A critical first step is for academic institutions to establish robust IES programs. Within the growing number of IES programs, faculty and administrators can use the key sustainability competencies to ensure that these programs are educating students to become sustainability change makers. We argue that while identifying key sustainability competencies is important, we also need to help students apply these competencies and content-based knowledge through concrete issues so students can see the relevance of what they are learning in the world around them. The FEW Nexus can help students see the relevance of their studies to the real-world and acquire the skills and content knowledge they need to become sustainability change makers

who will transform global society by meeting the ambitious targets set by the SDGs. Using the FEW Nexus approach allows for a more holistic approach to tackling FEW-related issues and centers the crucial need to recognize and understand the interdependency of these systems.

We have presented a range of curricular examples that demonstrate in practice how the authors have applied the FEW Nexus framework to intentionally integrate key sustainability competencies and content knowledge and draw from real-world context and examples for students to see the relevance of their education into practice. In these examples, the FEW Nexus anchors abstract concepts oft-discussed in sustainability education and how the FEW Nexus approach requires students to consider trade-offs as ways to engage with issues of justice and equity. Finally, the FEW Nexus also provides a rich, contextual approach to connect across disciplines and curricula so that students can recognize the importance of cross-disciplinary work and collaborations in addressing 21st-century challenges in ways that support sustainable development.

We hope that these examples can initiate the discussion on how IES programs, courses, and activities can be organized around the FEW Nexus, but these examples are certainly not a fully representative sample. These cases were assembled based on the authors' experiences, but future work should a) collect more systematic data on how and when the FEW Nexus is embedded into current IES programs, and b) ensure a more global representation of both institutions and cases, so that FEW challenges can be considered in diverse cultural and environmental contexts.

While this paper focuses on the integration of multiple disciplines in sustainability education, the FEW Nexus can also help contextualize disciplinary-based courses and concepts. Disciplinary approaches to environmental courses provide depth to learning when compared to a breadth approach often seen in interdisciplinary environmental programs (Cooke and Vermaire, 2015). While a deep dive into a particular disciplinary focus is valuable, students struggle to see the relevance of what they are learning to real-world, complex issues. FEW topics are typically discussed in the physical and life sciences, but a uniting framework, such as the FEW Nexus, can provide a tool to link discipline-focused courses with broader, cross-cutting problems. Addressing FEW Nexus issues requires connections across geographic scales (local, national, global), and students must recognize the importance of multi-, inter-, trans-disciplinary collaborations. Importantly, FEW Nexus thinking requires IES programs that embed the key sustainability competencies in the education of change-makers and embrace humility, perspective-taking, communication, science literacy, and concern for social justice. Students need to practice reasoning through decision-making, navigating social dynamics, and co-constructing knowledge in the context of authentic struggles (Duschl, 2020), and the FEW Nexus provides an ideal setting in which to practice these skills.

Data availability

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

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Author contributions

N.D.S., C.L.R., C.R.A., J.D., M.M., and B.V. conceived the original project; all authors contributed to conceptual design and provided background perspectives; S.C., S.A., E.E.P., B.B., C.R.A., C.S.R., J.M., N.S.P., C.C., and M.M. contributed descriptions of activities, courses, and programs at their institutions, for example, boxes in Part 3; L.H., E.B., E.F.G., N.S.P., C.B.A., K.B. contributed to sections 1, 2, and 4. All authors discussed results and interpretation, as well as reviewed and edited the manuscript at all stages. The first three authors (C.L.R., B.V., and S.C.) led the overall paper development and writing. Starting with the 4th author, all remaining authors are listed in alphabetical order and are considered equal contributors to each other.

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Ethical approval does not apply as this article does not contain any studies with human participants performed by any of the authors.

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