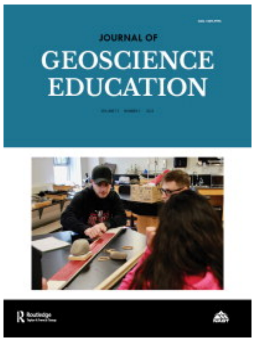

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Alignment among environmental programs in higher education: What Food-Energy-Water Nexus concepts are covered in introductory courses?

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ABSTRACT

Interdisciplinary environmental and sustainability (IES) programs are different from other fields because they focus on a complex integration of humanities, social, and natural sciences concepts centered on the interactions of coupled human and natural systems. The interdisciplinary nature of IES programs does not lend itself to traditional discipline-specific concept inventory frameworks for critically evaluating preconceptions and learning. We discuss the results of the first phase of a research project to develop a next generation concept inventory for evaluating interdisciplinary concepts important for introductory IES courses. Using the Food-Energy-Water (FEW) Nexus (the intersections/interdependencies of food, energy, and water sectors) as our focus, we conducted a content analysis of eight representative college-level introductory environmental course syllabi and course materials (e.g., textbooks, journal articles, print media) to identify common interdisciplinary FEW Nexus concepts taught in introductory IES courses. Results demonstrate that all IES introductory course materials reference the FEW Nexus. Food, energy, and/or water resources as individual elements of the FEW Nexus are frequently described, but connections between these resource systems are included less often. Biology, energy systems, waste and pollution in the natural environment, agriculture, earth sciences and geology, climate change, behavioral social sciences, and economics concepts are most associated with FEW concepts, hinting at commonalities across IES topics that anchor systems thinking. Despite differences in IES programs, there appears to be some alignment between core concepts being taught at the FEW Nexus in introductory courses.

List of abbreviations: AESS: Association for Environmental Studies and Sciences; FEW: Food-Energy-Water; IES: Interdisciplinary environmental and sustainability; NCSE: National Council for Science and Environment

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Introduction

Mechanisms to identify and assess interdisciplinary environmental and sustainability (IES) core concepts and academic learning outcomes are of intense community interest, but the rapid pace of evolution and the inherent diversity of programs has inhibited consensus among U.S. program leaders. Here we describe how a complex environmental concept—the Food-Energy-Water (FEW) Nexus (Albrecht et al., 2018)—can serve to identify core interdisciplinary concepts commonly taught in higher education IES introductory course curricula. Specifically, we ask, what environmental and FEW Nexus concepts are commonly taught in introductory IES courses? Our analysis considers how the FEW Nexus can provide a common model for foundational course content and evaluates how FEW Nexus concepts are covered in introductory IES courses.

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Growth and development of interdisciplinary environmental programs and curriculum

The proliferation of interdisciplinary higher education environmental programs, begun in the United States in the late 1960s in response to rapidly growing public concerns about environmental degradation, continues today. As of 2016, there are more than 870 institutions offering over 2,360 IES degree programs with a diversity of degree names and focus areas (Vincent et al., 2017). Prevalent degree program names include environmental science(s) (33%), environmental studies (20%), natural resources/management (18%), sustainability (11%), and environmental policy and management (7%) (Vincent et al., 2017). Other IES degrees focus on specific themes, such as coastal systems, energy policy, or water resources; others combine environmental science(s), environmental studies, natural resources, or sustainability and another disciplinary area, such as business and environmental studies or engineering and environmental science. The fastest rates of growth are in degree programs focused on sustainability (89% increase from 2012-2016), energy (62% increase), coastal and marine systems (33% increase), and water resources/water management (16% increase). There are over 2,200 disciplinary degrees with formal specializations in environment, natural resources, or sustainability (e.g., a degree in Public Administration with specialization in environmental policy; Vincent et al., 2017).

The then National (now Global) Council for Science and the Environment (NCSE; Vincent et al., 2013) conducted foundational work describing existing IES program curricula, and learning standards. Such standards have been developed outside the U.S., including the Australian Learning and Teaching Academic Standards Statement for Environment and Sustainability (Phelan et al., 2015) and the United Kingdom's Quality Code for Education Subject Benchmark Statement for Earth Sciences, Environmental Sciences and Studies (United Kingdom Quality Code for Higher Education, 2014). The Australian Statement was developed through the support of the Australian Government Office for Learning and Teaching and The UK Quality Assurance Agency is an independent body that monitors and advises on standards and quality in UK higher education. Additionally, frameworks exist that elucidate IES content (e.g., Cooke & Vermaire, 2015), provide core competencies (e.g., Brundiers et al., 2021; Redman & Wiek, 2021), and guide curriculum development (e.g., Clark & Wallace, 2015).

Two large NCSE national studies found that program administrators' curriculum preferences for undergraduate and graduate IES degree programs aligned statistically with one of three broad approaches: social systems emphasis, natural systems emphasis, or sustainability solutions emphasis (Vincent et al., 2013; Vincent & Focht, 2011). NCSE studies also discovered broad agreement on the four primary characteristics of the field (Vincent & Focht, 2009, 2011):

1. the focus of study is on interactions between human and natural systems (coupled human-nature systems);
2. the educational approach is holistic rather than reductionist—using systems thinking to integrate knowledge and insights from the natural sciences, social sciences, engineering and applied sciences, and the humanities;
3. diverse epistemological viewpoints are used to understand environmental problems and devise solutions; and,
4. the normative goal of IES programs is to prepare graduates to be sustainability-oriented problem solvers through scholarship, research, practice, and informed citizenship.

NCSE surveyed 242 IES program administrators in 2012 who ranked the importance of 41 knowledge areas in ideal curricula for each of the degree programs offered (Vincent et al., 2013). These data were analyzed using exploratory factor analysis to determine dimensions of interdisciplinary knowledge. A factor analysis revealed seven interdisciplinary knowledge dimensions in ideal IES curricula that are characterized by significant correlations within a subset of 41 knowledge areas (Vincent et al., 2013). Furthermore, five of these dimensions—Systems, Humanities, Built Environment, Social Sciences, and Sustainability—are highly correlated with each other, forming a knowledge group called Sustainability Systems. Physical Sciences and Life Sciences are moderately correlated with each other, forming a knowledge group called Natural Sciences. Together these findings support the idea that common core IES concepts and knowledge areas can be determined to support U.S. program assessment.

Despite the existence of standards in other countries and progress toward a consensus on IES core competencies, the environmental higher education community in the U.S. has not adopted a similar set of standards. Resistance to potential accreditation standards which could constrain flexibility and innovation is a primary concern for IES program leaders (personal communication). The lack of widely accepted core concepts and topics for U.S. programs has stymied development of widely used, reliable, and valid assessment tools. IES programs employ diverse methods for program assessment and most (67%) have defined learning outcomes for their programs (unpublished data from the 2012 NCSE program survey), but many struggle to effectively assess these outcomes. For example, interdisciplinary concepts are difficult to assess as they require students to integrate and transfer knowledge across disciplines and contexts (Shen, Liu, & Sung, 2014). Additionally, it can be challenging for instructors to develop questions that specifically target deep conceptual understanding, especially using a multiple-choice approach where students can memorize or guess the correct answer rather than use interdisciplinary, systems-thinking skills (Madsen, McKagan, Sayre, 2014). There remains an urgent need to develop validated tools to assess student learning and IES pedagogical practices, especially around the teaching and learning of complex synthesis concepts in foundational courses. The work presented here also provides an initial step for development of a FEW Nexus Concept Inventory, which is a type of validated and reliable assessment tool that evaluates student knowledge on given concepts. Concept inventories traditionally support assessment of teaching and learning within a discipline and are common in other STEM disciplines.

The FEW Nexus as a tool to assess student learning of environmental systems concepts

Population growth, climate change, and resource consumption place increasing pressure on food, energy, and water resources, resulting in global scarcities and inequities. In response to these pressures, the FEW Nexus gained popularity in 2011 as an interdisciplinary research and development paradigm for integrated, cross-sectoral resource management to better account for the synergies, interlinkages, and tradeoffs between food, energy, and water resources (Leck et al., 2015). Whereas previous management approaches focused on a single sector, a FEW Nexus paradigm is a holistic approach to food, energy, and water management that seeks to alleviate unintended side-effects and negative tradeoffs across resource sectors that have often occurred using a sectoral focus (Al-Saidi & Elagib, 2017; Smajgl et al., 2016). The FEW Nexus represents a coupled human and natural systems approach and is studied and understood using an interdisciplinary systems approach (Platts et al., 2022). While definitions are varied and debated, we define the FEW Nexus as the interdependencies between food, energy, and water systems and sectors including the synergies, conflicts, and tradeoffs of FEW resource management (Lally & Forbes, 2019, 2020; Lofti et al., 2020; Simpson & Jewitt, 2019). The FEW Nexus connects many environmental and social systems as biogeochemical processes provide natural resources for humans that are influenced by complex issues of access, power, inequity, and socio-cultural interactions. Although there is no single definition of "systems thinking," constructs and principles commonly applied among different disciplines include consideration of the interconnectedness of parts of a system and how those parts behave within the system (Grohs et al., 2018). The National Academies of Sciences, Engineering, and Medicine identified simulating "wicked problems" (a systems thinking situation) from real-world settings as a promising pedagogical practice to incorporate into sustainability education (National Academies of Sciences et al., 2020). For teaching and learning contexts, the FEW Nexus could provide content and scaffolding for incorporating systems thinking and sustainability concepts into courses and curricula. With global resource consumption outpacing supply, the FEW Nexus is a global priority area for research (Katz et al., 2020). Understanding the FEW Nexus and the global focus on FEW research and decision-making makes it an ideal concept for exploring complex systems content in introductory IES courses. The FEW Nexus is also a critical target for education research and collaboration, as evidenced by the recently funded National Collaborative for Research on Food, Energy, and Water Education (NC-FEW, n.d.), of which coauthor Romulo is the lead for the higher education working group.

FEW Nexus topics span natural and social sciences and have broad application across different approaches to IES curriculum design. Most IES programs do not incorporate evaluation and assessment at the program level, especially non-summative evaluations, with a main challenge to developing evaluation being the diversity of the field (Carleton-Hug & Hug, 2010). There have been several calls to synthesize and integrate disciplines that comprise the IES field for more rigorous curriculum development and evaluation (e.g., Cooke & Vermaire, 2015; Wallace & Clark, 2018). Valid (measuring the intended variable) and reliable (consistency of a measure) measures are important for evaluating learning in classrooms, institutions, and places of instruction. Additionally, students commonly develop alternative ideas about certain topics that can impede learning. A concept inventory is a test that can classify an examinee as either someone who thinks in accordance with accepted conceptions on a body of knowledge or in accordance with common alternative conceptions (Adams & Wieman, 2011). Concept inventories are not a comprehensive test of everything a student should know about a topic but rather selectively test certain critical concepts of a topic (Rowe & Smaill, 2007). No concept inventory currently exists for interdisciplinary IES content and there is a need for rigorous evaluation of IES educational practices (Carleton-Hug & Hug, 2010). Without a concept inventory or similar assessment instrument, we are not able to formally evaluate how students' understanding of basic IES concepts impacts their ability to understand complex IES concepts. Previous concept inventory work indicates that students come to a course with preconceptions about basic concepts. Other interesting findings from the Geosciences Concept Inventory (GCI) (Libarkin & Anderson, 2005) are that (1) the perceived knowledge state of students by professors is very different than the actual knowledge state of students, and (2) advanced students within geosciences programs scored highly on the GCI even though students showed no significant learning after a single introductory course (Anderson & Libarkin, 2016; Libarkin & Anderson, 2005). The implications are that professors who are unaware of the knowledge state of their students may not prepare or provide material in an accessible or optimal learning format, while it is also possible that a selection bias is occurring where only students with deeper understanding proceed into upper division courses. There is also evidence in the literature that a sound science foundation is crucial for learning of advanced topics (Libarkin & Anderson, 2016). The work presented here is the first step of an NSF funded project to develop a concept inventory for the FEW Nexus (NSF Award # 2013373)

To better inform those who teach, make curricular decisions, and manage college-level IES courses, and to establish a basis for comparison between IES introductory courses across the country, our work gathers information on introductory course materials taught in U.S. colleges and universities with a focus on FEW Nexus topics. Specifically, we ask the following research questions:

1. What environmental concepts are commonly taught within introductory IES courses in the U.S.?
2. Which elements of the FEW Nexus are commonly taught within introductory IES courses in the U.S.?
3. Where do elements of the FEW Nexus intersect with environmental concepts within introductory IES courses in the U.S.?

Methods

Sample

Introductory courses serve as foundational courses for IES majors, but they also often serve non-majors as options for institutional learning requirements and as electives for disciplinary degrees with environmental foci (Vincent et al., 2017), extending the value of understanding key IES concepts and their assessment across many higher education degree programs. To identify and understand FEW concepts covered in IES introductory courses, we coded "artifacts," text-based course learning materials including syllabi, textbook chapters, other book chapters, reports, research articles, and news articles. Websites, in-class activities, and audio-visuals were excluded for several reasons. Websites were excluded as they often contained too many pages to code with instructions to "explore" the website and were subject to frequent changes (i.e., difficult to reproduce). This lack of direction in the instructions combined with the size of many of the websites, led us to believe these were supplemental course materials that students should be aware of as resources but whose content they were not expected to know thoroughly. We did not have access to recorded lectures or assessments; in-class activities were inconsistently included by our participating samples and often did not contain enough directions to interpret their relationship to environmental concepts without the in-class context. Similarly, audio-visuals were primarily used as short video clips in class. Since we did not have recordings of class, the context was missing to interpret the short audio-visual content. We therefore constrained our coding to materials that were assigned outside of class that would "stand alone" without in-class explanation to direct student interpretation of content.

A volunteer and purposive strategy was used to select courses at higher education institutions for the study. Initially, participants were recruited by personal contacts and an emailed invitation to the Association of Environmental Studies and Sciences (AESS) listserv. During a second round of recruitment, specific programs were purposefully selected from the NCSE census of IES programs to ensure that the sample would be representative of the population of U.S. IES programs (Vincent et al., 2017). A total of 30 higher education institutions' IES programs were included. This particular project focuses on 4-year colleges and universities, so findings should only be extrapolated to 2-year colleges with careful consideration. Of note was the lack of community college responses among the environmental program networks and conferences attended by the authors. Outreach and support for those 2-year college programs would be greatly beneficial to the IES networks.

Figure 1 illustrates the thirty institutions' locations and Carnegie Classifications. We have condensed the Carnegie Classifications in Figure 1 to baccalaureate colleges granting either science or arts degrees (B), larger institutions that grant master's degrees (M1), and doctoral granting research institutions at various levels of activity (R1-3). The sample includes programs at eight baccalaureate colleges, eight master's colleges and universities, 13 doctoral universities, and one special focus institution. We compared four defining program attributes of this sample with the target population (all U.S. IES programs from the NCSE 2016 census; Vincent et al., 2017) to assess the sample's level of representativeness. Using $\alpha = 0.05$, we compared proportions of institution basic Carnegie class, institution control (public or private not-for-profit), institution census region, and degree types (name/degree level). The sample of 30 institutions/programs is representative for all four parameters, except for a small overrepresentation of environmental studies degree programs.

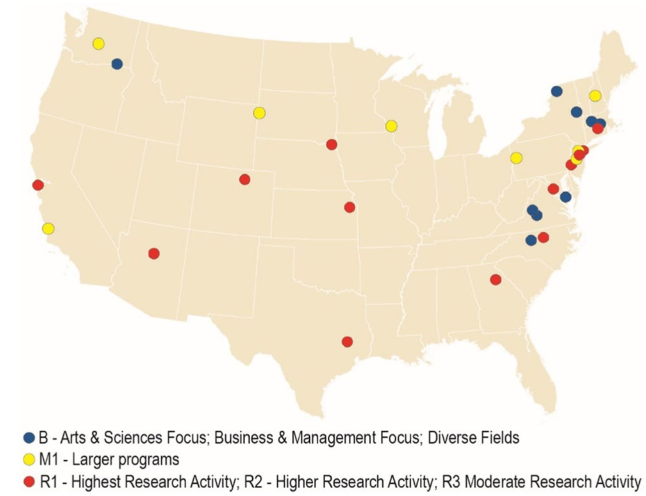

Figure 1. Distribution and Carnegie Classification of participating universities.

Due to the large number of material artifacts (831) obtained from the 30 participating colleges and universities and the time required for paragraph-level coding, a subset of materials from eight colleges and universities was selected for intensive coding. We selected a subset of eight colleges and universities based on the results of extensive previous studies of IES program curriculum conducted by the NCSE that found statistical alignment of all undergraduate degree programs with one of three broad approaches to curriculum design—natural systems emphasis, social systems emphasis, or sustainability solutions emphasis (Vincent et al., 2013). By selecting our 30 programs that represent the three empirically determined curriculum design approaches we ensured inclusion of course materials representative of the diversity of IES curriculum design approaches. Our sample of 30 colleges and universities included eight that had participated in the NCSE study and therefore had curriculum design designations. We compared defining program attributes for our subsample and the target population (all U.S. IES programs from the NCSE 2016 census; Vincent et al., 2017) to assess our subsample's level of representativeness. Using $\alpha = 0.05$ we compared proportions of institution basic Carnegie Classification, institution control (public or private not-for-profit), institution census region, and degree types (name/degree level).

The sample is inclusive and mostly representative for all four parameters. Several categories are overrepresented including baccalaureate colleges, colleges located in the Northeast census region, programs located in IES

Table 1. A total of 831 artifacts were submitted by 30 participating institutions.

	Level of coding analysis	Number of institutions in sample	Total number of artifacts per sample	Number of artifacts without FEW nexus references (excluded from analysis)	Number of audiovisual artifacts (excluded from analysis)	Number of artifacts coded per round	Number of coders	Minimum inter-coder agreement
First Round	Artifact	30	831	108	95	628	2	89%
Second Round	Paragraph	8	189	4	46	139	4	90%

After excluding 95 audio-visual artifacts, two coders analyzed the remaining 736 artifacts. Of these 736, 108 did not include references to the FEW Nexus, resulting in a total of 628 artifacts included for first round analysis. We began our second-round coding of course materials from eight institutions with 189 artifacts, 46 of which were excluded for being audio-visual artifacts and four of which did not contain FEW Nexus concepts, resulting in a total of 139 artifacts being analyzed at the paragraph level.

departments or programs versus those located in disciplinary departments, and degree programs named environmental studies, sustainability and policy and management versus environmental science(s) and natural resources. Two types of programs were underrepresented: colleges and universities from the South census division and IES degree programs located in disciplinary departments. Despite these differences, the sample of eight programs provide a good representation of the original 30 and thus IES programs at 4 year colleges nationally. The coding results from the eight programs were cross-checked against coding results for materials randomly selected from additional programs from the larger sample to ensure important concepts were not missed. The eight programs include four located at baccalaureate colleges, two at master's colleges and universities, and two at doctoral institutions. Degree types offered by these programs include environmental sciences (29%), environmental studies (43%) natural resources (7%), sustainability (21%), and policy and management (14%) evenly split between Bachelor of Science and Bachelor of Arts degrees. Supplement Table 1 provides detailed representativeness data for these two samples. Our samples did not include any Historically Black Colleges and Universities; very few of these types of institutions have IES programs (Vincent et al., 2013). We only had one Minority Serving Institution (MSI) in our larger sample and zero in the coding sample; however, our larger sample included five institutions that have significant minority enrollments (but not categorized as MSIs), and our coding sample included one of these institutions with significant minority enrollment.

Coding framework

Two rounds of coding were conducted, first at the artifact level and second at the paragraph level (Table 1). Both rounds of coding were conducted using a list of IES content knowledge areas developed by the NCSE for its curriculum design studies (Table 2; Vincent et al., 2013). This list of knowledge items was created based on an extensive literature review and subjected to multiple rounds of review by numerous individuals representing the leadership of the NCSE Council of Environmental Deans and Directors, the Association of Environmental Studies and Sciences, the Association for the Advancement of Sustainability in Higher Education, the American Association for the Advancement of Science's Forum on Science and Innovation for Sustainable Development, and the National Association of Environmental Professionals (Vincent et al., 2017). The choices made to group items or list individually—such as separating oceanography and atmospheric sciences from geosciences/earth sciences or listing political science as a single item and behavioral social sciences as a group item—were based on the perceived likelihood of the knowledge area's importance in distinguishing differences in IES curricula. Several changes were made to the original coding protocol for ease of coder interpretation and coder agreement in the present study, which is the number of agreements between coders divided by the total number of coding decisions as a means of determining reliability (the final coding protocol is presented in Supplemental Table 2; Lacy et al., 2015). For example, "chemistry" was divided into organic and inorganic codes, and "waste and pollution" was split into "waste and pollution in the natural environment" and "waste and pollution in the built environment."

FEW coding

A coding framework for the FEW Nexus was developed and pre-tested during an initial pilot phase. Two researchers discussed and independently tested the coding frame on the same sample of IES content to refine coding categories until interpretations of FEW Nexus codes across researchers were consistent (Elo et al., 2014). From this pilot coding phase, we revised the coding frame to ensure a shared understanding of coding definitions, unidimensionality (code covers one idea at a time), mutual exclusiveness of codes (meaning unit coded under only one code), and exhaustiveness (all text can be coded within the coding framework; Schreier, 2014). IES courses focus on coupled natural and human systems; therefore, we took an anthropogenic approach to defining FEW Nexus codes, whereby food, energy, and water were systems that provide resources to humans, as opposed to provisioning resources to wildlife (Table 3). Additionally, the FEW Nexus arose in response to concerns about food, energy, and water security for humans, further justifying our anthropogenic interpretation to coding. Food, energy, and water must have human uses for our coding purposes. For example, discussing food webs in an ecosystem would not qualify as "food;" however, if the food web included human consumption of plants or animals, it would be coded under "food." A "non-applicable" code was used for artifacts and paragraphs that made no explicit connection to the FEW Nexus (Table 4).

Table 2. IES curriculum knowledge areas (from Vincent et al., 2013) used as coding guide.

Natural Sciences	***Social Sciences***
Biology	*Behavioral Social Sciences* (e.g., sociology, anthropology, psychology, organization development, cultural studies)
Ecology	*Economics* (e.g., microeconomics, macroeconomics, ecological)
Chemistry (split into inorganic and organic for coding)	*Policy and Public Administration* (e.g., law & regulation, policy analysis, program evaluation, organizational theory)
Geosciences (Earth sciences/geology)	*Political Science* (e.g., government, voter behavior, international agreements, conflict studies)
Other Life Sciences (e.g., zoology, botany, microbiology)	***Applied/Professional***
Other Physical Sciences (e.g., oceanography, atmospheric sciences)	*Agriculture* (e.g., soils, range management, organic, sustainable)
Physics	*Architecture* (e.g., LEED, green design)
Humanities	*Business* (e.g. management, marketing, organizational theory)
Arts and Esthetics (e.g., expression of ideas through the arts and design)	*Education* (e.g., pedagogy, curriculum design, outreach)
History (e.g., environmental, natural, political, cultural)	*Engineering and Technology* (e.g., principles, methodologies, design)
Language Arts (e.g., structure, meaning, metaphor)	*Green Materials Design* (e.g., green chemistry, molecular toxicology, life cycle analysis)
Literature (e.g., classic environmental, expression of ideas through literature)	*Human Health* (e.g., toxicology, epidemiology, risk, nutrition)
Philosophy and Ethics (e.g., ontology, epistemology, logic, values, culture, diversity)	*Planning and Built Environment* (e.g., urban planning, land use planning)
Religion (e.g., theology, philosophy)	*Research Design and Ethics* (e.g., approaches, methods, ethical considerations)
Interdisciplinary	*Waste (split into waste/pollution in ecosystems and waste in built environments for coding)*
Climate Change/Disruption (e.g., causes, adaptation, solutions)	***Sustainability***
Energy Systems (e g. sources & supplies, impacts)	*Business/Economic Sustainability* (economic development and business practices for sustainability)
Environmental Justice (e.g., history, etiology)	*Environmental Sustainability* (ecosystems and natural resources sustainability)
Food Systems (e.g., security, distribution, production)	*Social Sustainability* (social aspects of sustainable development/sustainability
Geography (e.g., physical, economic, cultural)	*Sustainability General Concepts* (e.g., characteristics, indicators, values)
Natural Resources Management (e.g., conservation, forestry, fisheries)	*Sustainability Governance* (standards, protocols, reporting, organizations)
Systems Analysis (e.g., complexity, modeling, structure)	*Sustainability Science* (scientific and technological solutions)
*Water Systems (*e.g., scarcity, allocation, hydrology)	

Table 3. Coding protocol with definitions and examples of FEW Nexus coding approach.

FEW Concept	Definition	Example
Food	A substance consisting essentially of protein, carbohydrate, fat, and other nutrients used in the human body to sustain growth and vital processes, and to furnish energy.	Modern agriculture and global food commodity chains have pointed us in the other direction, toward a *shrinking* biodiversity, cultural diversity, knowledge diversity and even taste diversity.
Energy	Refers to renewable and nonrenewable energy used by humans for power (e.g., electricity). Does not include kinetic, potential, or caloric energy.	In 2008, the member-owned electricity cooperative set an ambitious goal to run the entire island on 50 percent renewable energy by 2023.
Water	Water in liquid forms that humans use in some manner, including for purposes such as drinking water, agricultural irrigation, and hydro-electric power.	By the end of the 1980, public health specialists were publicly stating the city would have to substantially increase the treatment of it drinking water source.
Food-Energy	A system that includes both food and energy components.	Transportation related emissions vary according to how food is transported; for example, rail and water transport are much more energy efficient than air or truck transport.
Food-Water	A system that includes both food and water components.	The culprit would be washed-out animal waste lagoons (from hog farms) that would pollute the waterway, an important source of fish for Indigenous people.
Water-Energy	A system that includes both water and energy components.	Worldwide, there are more than 45,000 large hydroelectric dams, plus countless smaller dams built for navigation, flood control, and other uses.
Food-Energy-Water	A system that includes food, energy, and water components.	Pumping, moving, treating, and distributing water for agriculture takes energy at every stage.
N/A	Does not reference food, energy, or water.	Lions hunt in groups.

Table 4. Not all course content explicitly describes explicitly describe connections to food, energy, or water systems.

Examples of text lacking explicitly described FEW Nexus connection (coded n/a)
• The desire to study and make sense of nature is most apparent in the many taxonomies and natural histories that were produced during this time period.
• Finally, the emergence of sustainability is intrinsically tied to the creation of and reaction to classical capitalist economics in the eighteenth century.
• Moreover, industrialization created deep and long-lasting social inequities between Western Europe (and a few poorer European settler societies) and the colonized world, which became poorer and more urbanized after 1800.

Codes were created for FEW Nexus resource systems described independently of other FEW Nexus resource systems (i.e., Food, Water, Energy) and to capture connections between systems (i.e., Food-Energy, Food-Water, Water-Energy, Food-Energy-Water) (Figure 2). When coding, an explicit reference to food, energy, or water was needed to be included under the FEW Nexus. For example, the following sentence focusing on climate change does not

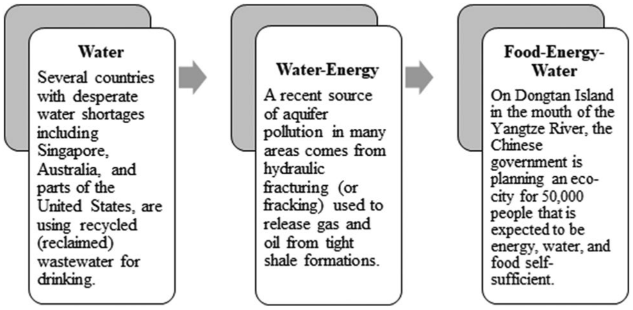

Figure 2. Example of FEW Nexus codes indicating different levels of connections between systems.

directly refer to the FEW Nexus, "To achieve this long-term temperature goal, countries aim to reach global peaking of greenhouse gas emissions as soon as possible to achieve a climate neutral world by mid-century" and would be coded under "N/A." In contrast, the following sentence provides a clear connection between climate change and the FEW Nexus, "climate change is projected to further adversely affect key development challenges, including providing clean water, energy services, and food" and was therefore coded under "Food-Energy-Water." While some students may be able to make implicit connections between FEW Nexus systems and other IES knowledge areas, here we measure direct and explicit connections so we do not overestimate student experience and comprehension.

First round artifact level coding

First round coding included 628 course learning material artifacts submitted by the faculty of the 30 participating colleges and universities and the second round of a subset of 139 artifacts from eight colleges and universities (Table 1). The first round of coding was conducted at the artifact level by two coders trained in qualitative analysis (neither were instructors for classes in our sample) using the concept coding process of Saldaña (2016) determining "macro levels of meaning" (p. 119) to identify the top three knowledge topics covered in each artifact and to identify whether the content of each artifact included content relevant to the FEW Nexus (Tables 3 and 4, Figure 2). Artifacts that made no reference to food, energy, water, or the interactions between these systems were excluded from the second round of coding. This round of coding had two purposes: 1) to identify the prevalence of the main knowledge topic areas included and 2) to identify artifacts that covered FEW topics for more in-depth coding.

Second round paragraph level coding

Second round coding included 139 course learning material artifacts from eight institutions that included FEW Nexus references. Four coders assigned knowledge areas and FEW Nexus codes to all paragraphs. Only one of these coders was an instructor whose content was part of the sample; all coders were trained in qualitative data analysis. One knowledge area (e.g., climate change, water systems, sustainability science, etc.) and one FEW Nexus (e.g., food, food-water, food-energy-water, etc.) code were assigned to each paragraph. This round of coding sought to identify the prevalence of main knowledge areas and to identify the prevalence of FEW Nexus topics at the paragraph level.

Validation

Several validation checks were conducted during coding. To ensure agreement of first-round artifact-level FEW inclusion/exclusion coding, the two coders double coded a random 10% sample of text artifacts from the 22 institutions not included in our subsample of eight institutions (agreement at 89%). As a validation check to ensure our sample of eight IES courses represented the diversity of IES's across the U.S., two coders compared our codes to the 14 institutions who provided us with a syllabus and that we had not coded at the paragraph level. Codes for the subset of eight institutions were consistent with codes found in the syllabi from the larger sample, indicating that the subset of coding represents the diversity of IES course materials in the U.S. For the second round of paragraph level coding, coder agreement was calculated for 10% of artifacts to ensure consistent interpretation of the codes for all four team members (minimum of 90% agreement across coding team) (Schreier, 2014). These calculations were completed using NVivo 1.6 coding comparisons and Excel (number of agreements divided by the total number of codes) to ensure accurate interpretation of the coding scheme.

Analysis

The artifact data were coded into themes and subthemes using NVivo 1.6 Qualitative Data Analytic software. Coding frequencies (i.e., lists the most commonly occurring words or codes), coding queries (i.e., a way of cross tabulating connections between codes), and comparative matrices (i.e., allow comparison of codes across attributes, such as type of artifact or institution) were used to analyze the data. Frequencies were used to identify the most coded areas of knowledge and FEW Nexus elements. Coding queries and comparative matrices were used to examine where areas of knowledge and FEW Nexus codes intersected, indicating key interlinkages.

Results

First, we present percentages of artifacts that contain FEW Nexus references by artifact type from our larger sample of course content from 30 institutions. We then present the number of artifacts containing FEW Nexus references by type from our subsample of course content from eight institutions before describing the results of the second-round paragraph coding from this subsample.

Of the 736 text-based artifacts from our first-round sample, 85% (628 artifacts) contained references to FEW Nexus topics (Figure 3). Technical reports, speeches, syllabi, textbook chapters, print media, and policy documents were most likely to include FEW Nexus references, though some artifact types have a small sample size and percentages should be interpreted with caution. Within our subsample of artifacts from eight institutions, 97% of artifacts included FEW Nexus topics and were included in second-round paragraph-level coding (N = 139) (Figure 4).

Paragraph level coding of subset of program artifacts

FEW concepts most often presented individually

When FEW relevant artifacts were coded at the paragraph level, about half of the paragraphs contain references to FEW Nexus components (e.g., food, energy, food-energy, etc.). This indicates that FEW Nexus constitutes a large component of IES courses. As shown in Figure 5, when FEW is included, it is most often at the individual component level (i.e., Food, Water, Energy). Individual FEW Nexus component references are followed in frequency by references to pairwise components and least frequently by references to the full FEW Nexus.

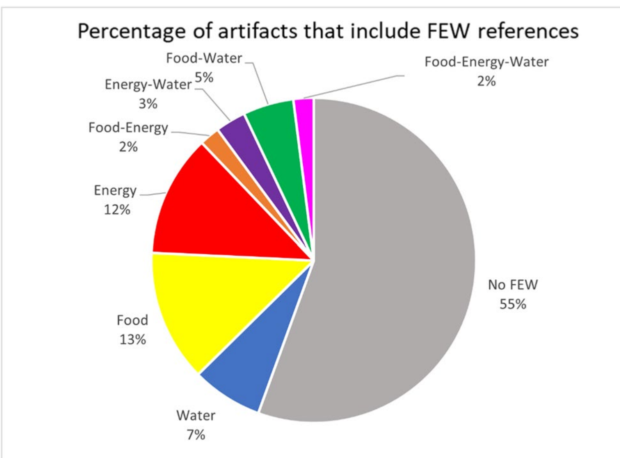

Figure 3. Percentage of artifacts by type that contain FEW Nexus topics from larger sample of 30 institutions. Audiovisual materials, websites, and in-class activities were excluded from our sample (95 artifacts excluded). A total of 736 text-based artifacts were coded for FEW Nexus connections, with 628 containing explicit references to the FEW Nexus (85%).

Knowledge areas associated with FEW

Each paragraph in our subsample of 139 artifacts was coded twice—once to identify the most prevalent knowledge area and once to identify the FEW Nexus component presented. Eight knowledge areas were found most often in course materials at the paragraph level (respectively): ecology, energy systems, waste and pollution in the natural environment, agriculture, earth sciences and geology, climate change, behavioral social sciences, and economics. This is an indication that these are somewhat common knowledge areas taught in introductory IES courses in relation to FEW Nexus materials (Tables 5 and 6); however, there was a lot of variability in what topics were most frequently included in course materials. Agriculture, conservation, behavioral and social sciences, earth science, economics, policy and publication administration, sustainability general concepts, and waste and pollution in the natural environment were all heavily referenced in a handful of courses, but ecology was the only area of knowledge coded at high frequency across the majority of courses (Table 6). A handful of course materials included religion, education, arts and esthetics, literature, and other life sciences knowledge topics, illustrating differences in how IES content may be covered in introductory courses.

Interestingly, climate change is rather lightly covered in course materials despite being a more frequently coded area of knowledge. This discrepancy can be explained by all courses including low to moderate levels of coverage, opposed to a few courses covering a topic more frequently. Similar patterns explain economics and behavioral social

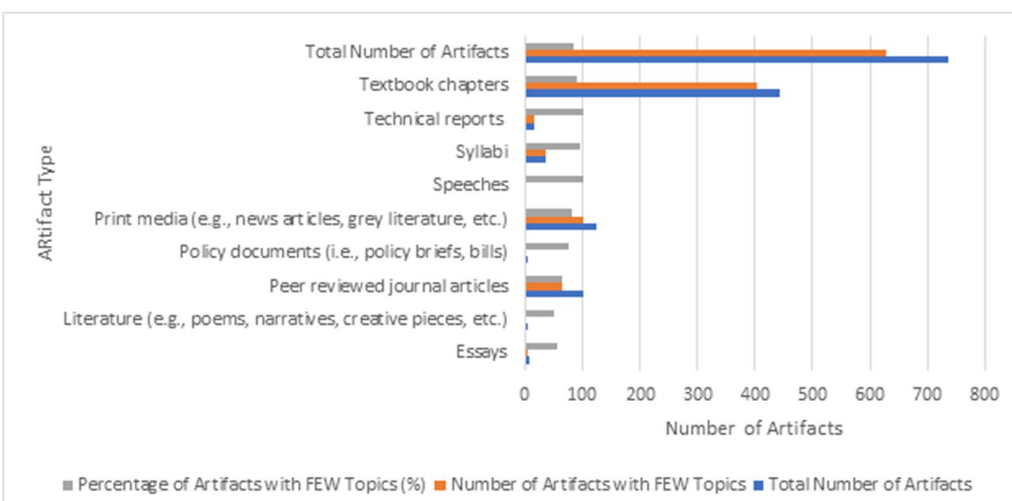

Figure 4. Percentage of artifacts by type that contain FEW Nexus topics from our subsample of eight institutions that were subsequently coded at the paragraph level to identify areas of knowledge and FEW Nexus topics. Audiovisual materials, websites, and in-class activities were excluded from our subsample (46 artifacts excluded). A total of 143 text-based artifacts were coded for FEW Nexus connections, with 139 containing explicit references to the FEW Nexus (97%).

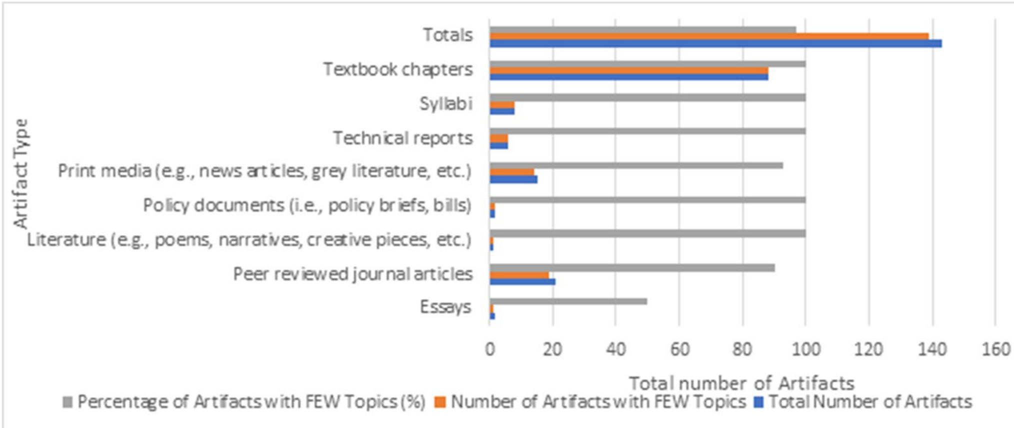

Figure 5. Percentage of FEW Nexus components referenced in sample of eight introductory IES courses.

Table 5. Most frequently coded knowledge areas from subsample of eight courses.

Knowledge Area	Number of Coded References	Knowledge Area Definition	Text Example
Agriculture	654	Process of farming/cultivating crops for food, fuel, and other products (e.g., textiles). Includes animal agriculture (raising cows, pigs, chickens, etc. for human consumption).	From experiment involving a variety of crops, researchers have learned that yields can increase by an average of 14% when windbreaks are used.
Behavioral Social Science	609	The study of humans and behavior.	When people think, they generally do not invent concepts but instead they use mental models drawn from their societies and their shared histories.
Climate Change	626	Includes naturally occurring fluctuations in climate, as well as human influenced climate change caused by fossil fuel emissions. Includes references to greenhouse gas emissions, carbon dioxide, methane, etc. Includes adaptation and mitigation behaviors, as well as description of climate change impacts (e.g., sea level rise, temperature change, flooding, etc.).	There is considerable evidence for myriad anthropogenic climate change impacts, including ice sheet and glacial melting; sea level rise; more frequent hot days and nights over land.
Ecology	1906	Ecology is focused on the interactions between organisms and their environment while Biology is focused more on the living organism's structure and function.	Abundant acorns draw deer into the woods where they browse on small plants and tree seedlings; Ticks drop off the deer and lay eggs in the leaf litter and when the eggs hatch, the larvae attach to mice, and the life cycle of Lyme disease continues.
Earth Sciences & Geology	631	Branch of science dealing with the physical constitution of the earth and its atmosphere, as well as the science that deals with the earth's physical structure and substance, its history, and the processes that act on it.	According to this principle, past geologic events can be explained by natural processes we observe operating today, such as erosion by running water, volcanism, and the gradual uplift of the Earth's crust.
Economics	603	The production, consumption, and transfer of wealth, often monetary resources. Includes macro and micro-scale economics.	For the students who received the graduation intervention (conditional cash transfer), there was a 49 percentage-point increase in enrollment in higher degree programs.
Energy Systems	974	Supplies, production, transport, and consumption of energy. May include fossil fuels and renewables. Does not refer to caloric energy needed for organisms to survive, nor does it refer to physical energy (e.g., kinetic, potential, etc.).	Recent events like the Deepwater Horizon oil spill, the death of twenty-nine West Virginia coal miners in the worst mining disaster in twenty-five years, and the crisis at Japan's Fukushima Daiichi Nuclear Power Plant are salient examples of the health and environmental costs, and economic risks, of our current energy sources.
Waste & Pollution in Natural Environments	702	Refers to waste and pollution entering the natural environment (e.g., trash, littering, point and non-point source pollution, individual and industrial pollution, etc.).	It is clear that waste ends up in marine habitats from many different sources, from inefficient industrial waste management to plastic microfibers washed out of our clothing.

sciences being top areas of knowledge despite being referenced in lower frequencies but across most courses. Table 7 illustrates the top five knowledge areas associated with the FEW Nexus. It is interesting to note that whereas earth sciences and geology is a common knowledge area in paragraphs across our subsample, it does not appear in Table 7. While geoscience topics are foundational to the FEW Nexus, course materials are not explicitly connecting earth systems

Table 6. H (high), M (medium), and L (low) areas of knowledge.

Institution in Subsample	Agriculture	Architecture	Arts	Behavioral Social Sciences	Ecology	Climate Change	Conservation	Earth Sciences	Economics	Education	Energy Systems	Engineering & Technology	Environmental Justice	Food Systems	Geography	Green Materials Design	History	Human Health	Inorganic Chemistry	Language Arts	Literature	Natural Resource Management	Organic Chemistry	Other Life Sciences	Other Physical Sciences	Philosophy & Ethics	Physics	Planning in the Built Environment	Policy & Public Administration	Political Sciences	Religion	Research Design & Ethics	Social Sustainability	Sustainability General Concepts	Sustainability Science	Sustainable Governance	Waste & Pollution in Natural Environments	Water Systems
	Knowledge Areas																																					
MidAtlantic Private Bachelor's Granting Institution	H		L	M	H	L	H	L	M	L	M	L	L	L	L	L	L	L			L	L	L			L	L		M	L	L	L	L	L	L	L	L	L
West Coast Public Master's Granting Institution	H	L		L	L	L	L		H	L	L	L	L	L	L	L	H	L			L	L			L	L		L	L	L		L	H	H	L	L	L	
Northeastern Private Doctoral Granting Institution	L	L	L	L	H	M	L	L	L	L	M	L	L	L	L	L	L	L	L		L	L	L		L	L	L	L	M	L		L	L	L	L	L	M	L
Northeastern Private Small Liberal Arts College	L		L	L	H		L	H	M		L	L	L	L	L		L	L	L		L	L	L	L	L	L	L		L	L		L	L	H			L	L
Northeastern Private Small Liberal Arts College	L	L		H		M	L	L	L	L	L	L	M	L	L		L	L		L	L	L				L		M	H	H		L	L	L	L	L	L	L
MidAtlantic Private Master's Granting Institution	L	L		L	H		L	L	L		H	L	L	L	L		L	L	L	L		L	L	L	L	L	L	L	L	L		L	L	L		L	M	L
MidAtlantic Private Bachelor's Granting Institution	L			L	H		L	L	L	L	M	L	L	L	L	L	L	L	L			L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	H	L
Midwestern Public Doctoral Granting Institution	L	H		L	L	M	L	L	L	L	H	L	L	L	L	L	L	L		L		L			L	L		M	L	L		L	L	M	L	L	L	L

Areas of knowledge that are L (low) were referenced a few times but largely absent from course materials while blank cells indicate areas of knowledge that were not coded at the paragraph level in our sample. As a reminder, we only coded the top area of knowledge for each paragraph.

Table 7. Top five knowledge areas for each FEW Nexus system and connections between systems with frequencies below.

Rank		FEW Nexus Components/Groups						
		Food-Energy-Water	*Food-Water*	*Energy-Water*	*Energy-Food*	*Food*	*Energy*	*Water*
Knowledge Areas	1	Energy Systems (42)	Agriculture (118)	Energy Systems (195)	Energy Systems (57)	Agriculture (336)	Energy Systems (666)	Water Systems (209)
	2	Agriculture (29)	Water Systems (96)	Waste and Pollution in the Natural Env. (40)	Agriculture (30)	Ecology (176)	Climate Change (131)	Waste and Pollution in the Natural Env. (156)
	3	Water Systems (23)	Waste and Pollution in the Natural Env. (48)	Water Systems (33)	Behavioral Social Sciences (29)	Food Systems (164)	Waste and Pollution in the Natural Env. (115)	Ecology (50)
	4	Waste and Pollution in the Natural Env. (21)	Natural Resource Mgmt. (42)	Architecture (22)	Food Systems (22)	Natural Resource Mgmt. (94)	Economics (96)	Planning in the Built Environment (39)
	5	Behavioral Social Sciences (18)	Behavioral Social Sciences & Climate Change (27)	Policy and Public Admin. (14)	Economics (21)	Behavioral Social Sciences (85)	Policy and Public Admin. (74)	Policy and Public Admin. (38)

to human systems at the paragraph level. Similarly, although ecology is the most frequently coded knowledge area, it only appears twice in Table 7. This is because ecology was not commonly connected to the FEW Nexus, instead focusing primarily on ecosystem interactions that were not explicitly connected to human systems.

FEW concepts connected to food, energy, and water

Course materials discuss **food** in terms of agriculture and the impacts food production systems have on ecosystems, ecosystem services, land use, and biodiversity (Table 8). Farming practices are explored in relation to impacts to ecosystems and as solutions to existing food-related problems, such as runoff and soil health. Population and consumption were presented as drivers for food systems challenges, such as food security and food equity. **Food and water** are explained in terms of the amount of water needed for agricultural production and the negative impacts from agriculture on water resources, especially impacts related to waste and pollution impacting water resources (e.g., runoff, pollution, eutrophication). **Food and energy** typically intersect around biofuels as a source of renewable energy and the resulting impacts from growing biofuel crops (e.g., economic benefits, water scarcity and pollution, and implications of growing food for fuel instead of food).

The most frequently discussed topics in relation to **energy** include sources of energy, typically differentiating fossil fuels (e.g., oil, coal, natural gas) from cleaner and/or renewable energy sources (e.g., solar, wind, nuclear). Costs of various types of energy are discussed in addition to philosophical debates regarding sustainable energy development pathways, which relate to renewable energy transition policies.

In relation to **energy and water** systems, hydroelectric is a focal area of course content. More broadly, energy systems are described as sources of waste and pollution to water systems, especially from fossil fuel externalities. Energy and water policy is considered a solution to minimize water pollution from energy production, as well as creating incentives for increasing energy efficiency through smart architectural design principles (e.g., LEED certification).

Water is commonly presented in terms of sources, flows, and importance to landscapes, soils, and ecosystems. Water intersects with both natural and human systems; however, overuse of water resources is often attributed to human behaviors. Connections between **water and energy** systems typically describe water inputs necessary for energy production (e.g., hydroelectric, solar, nuclear) and the threats to clean water from energy pollution (e.g., coal ash, acid rain). Policy and architecture design are presented as solutions for protecting water systems and encouraging efficient use of both water and energy resources.

Knowledge areas that most frequently include **food, energy, *and* water** are energy systems, agriculture, water systems, waste and pollution in the natural environment, and behavioral social sciences (respectively). Materials also discuss food, energy, and water security and threats to security from waste and pollution. Waste and pollution that affect water resources from food and energy production is a commonly discussed theme. Human consumption is described as a driver for changes to the FEW Nexus, usually at the expense of the natural environment and ecological processes.

Here we use the NCSE ideal curriculum factor analysis results to illustrate how the FEW Nexus is applied in IES course content to aid students in the systems dimension of interdisciplinary knowledge development. Knowledge areas found most often in FEW Nexus course materials are associated with the *Systems* dimension of interdisciplinary knowledge, followed by the *Social Sciences* dimension with the individual components and the energy-water pair also coded in the *Built Environment* and *Life Sciences* dimensions. Except for behavioral social sciences (found in the *Social Sciences* dimension), knowledge areas that reference food, energy, and water are associated with the *Systems* dimension. This is perhaps not surprising given that the FEW Nexus is inherently linking multiple resource systems. While geosciences

Table 8. Summary of knowledge area topics related to the FEW Nexus and example quotes to illustrate how the FEW Nexus is presented in course materials.

FEW Nexus Component	Knowledge Area Topics Related to FEW Nexus Component	Exemplar from course materials
Food	• Farming practices • Effects of agriculture on ecosystem services • Food security, distribution, and unequal access to nutritional food • Consumption of food resources	Over the past century, global food production has increased faster than human population growth, but hunger remains a chronic problem because food resources are unevenly distributed.
Energy	• Sources and supplies of energy • Pollution from energy production • Sustainable energy futures • Costs • Policies encouraging energy efficiency • Renewable energy as a climate change solution	State-level climate action is benefitting our economies and strengthening our communities: Alliance members are growing our clean energy economies and creating new jobs, while reducing air pollution, improving public health, and building more resilient communities.
Water	• Engineering, infrastructure, and architecture for managing water resources • Water pollution • Ecosystem services related to water resources • Policy mechanisms to protect water resources and prevent pollution	Many green stormwater infrastructure systems and practices utilize infiltration because it effectively filters pollutants, slows water movement, provides temporary water storage, and recharges groundwater.
Food-Water	• Farming practices and impacts to soil systems • Impacts from agriculture to water systems, such as pollution entering waterways through irrigation and runoff, and the resulting disruption of ecosystems (e.g., eutrophication) • Human consumption patterns increasing pressure on food and water resources • Food production contributing to and being affected by climate change, especially water scarcity as temperatures rise	Unsustainable land and water use, and the impacts of climate change are driving land degradation, including soil erosion, nutrient depletion, water scarcity, salinity, chemical contamination, and disruption of biological cycles.
Food-Energy	• Food as a source of energy (i.e., biofuels) • Farming practices and resulting energy inputs • Consumption of food and/or energy resources, primarily from an individual level (e.g., ecological footprint) though sometimes compared across societies (e.g., Developed vs. Developing Countries) • Financing agricultural production and energy use (e.g., subsidies)	Of course, the current allocation of crops has many economic and social benefits, and this mixed use is not likely to change completely. But even small changes in diet (for example, shifting grain-fed beef consumption to poultry, pork, or pasture-fed beef) and bioenergy policy (for example, not using food crops as biofuel feedstocks) could enhance food availability and reduce the environmental impacts of agriculture.
Energy-Water	• Water needs for energy production (e.g., hydroelectric, solar, nuclear, etc.) • Infrastructure needed to produce energy using water and to manage water resources (e.g., dams, stormwater management, green design, etc.) • Impacts to human and natural systems (e.g., energy security, water usage, pollution, etc.) resulting from energy production • Policies, laws, and regulations to encourage energy and water efficiency and reduce water pollution from energy production	Another problem with coal production was revealed in 2009 when an earthen dam broke in eastern Tennessee and released billions of gallons (3.8 billion liters) of coal ash sludge into a tributary of the Tennessee River.
Food-Energy-Water	• Sources and supplies of energy and resulting impacts to human and environmental systems (e.g., food availability from energy production, impacts on flood safety, and energy security from dams, etc.) • Farming practices and their use of food, energy, and water resources • Uses of water for food and energy production and water scarcity for these uses considering increased consumption and climate change • Waste entering the environment, especially water systems, from production processes, especially from energy and food production • Human consumption of food, energy, and water resources as a driver for changes to the FEW Nexus, usually at the expense of ecological processes and the natural environment	One of the main reasons some countries, social groups, or individuals—especially the disadvantaged—are more severely affected by biodiversity loss and ecosystem changes is limited access to substitutes or alternatives. When the quality of water deteriorates, the rich have the resources to buy personal water filters or imported bottled water that the poor can ill afford. Similarly, urban populations in developing countries have easier access to clean energy sources because of easy access to the electrical grid, while rural communities have fewer choices. Poor farmers often do not have the option of substituting modern methods for services provided by biodiversity because they cannot afford the alternatives.

and ecology were top areas of knowledge in our subsample, they infrequently (or not at all in the case of geosciences) intersected with our anthropocentric interpretation of the FEW Nexus. The *Humanities*, *Sustainability*, and *Physical Sciences* knowledge areas were infrequently coded in our sample and rarely intersected with the FEW Nexus.

Discussion

IES course artifacts contained many references to the FEW Nexus, indicating that the FEW Nexus is an important foundational concept in introductory courses. A paragraph level analysis of 139 artifacts from our subsample of eight institutions revealed that ecology, energy systems, waste and pollution in the natural environment, agriculture, earth sciences and geology, climate change, behavioral social sciences, and economics areas of knowledge were most described in IES course content in FEW Nexus artifacts. Energy systems, agriculture, water systems, waste and pollution in the natural environment, behavioral social sciences, climate change, natural resource management, architecture, policy and public administration, ecology, food systems, economics, and planning in the built environment were the knowledge areas most likely to intersect with components of the FEW Nexus (coded together at the paragraph level). Individual components of the FEW Nexus were more commonly presented in IES introductory course materials, while pairwise components were less frequently described. Knowledge areas most used to describe the connections between food, energy, and water were present in the *Systems* interdisciplinary knowledge areas of the NCSE report (Vincent et al., 2013). Areas of knowledge that intersect with any components of the FEW Nexus fell within the *Systems* knowledge area, followed by the *Social Sciences*, *Built Environment*, and *Life Sciences* areas. These findings are representative of IES curricula across the U.S., giving instructors a sense of important areas of knowledge and the utility of using the FEW Nexus to present interdisciplinary course content while facilitating systems thinking skills in students.

In the NCSE study of ideal curricula, environmental sustainability, sustainability general concepts (e.g., characteristics, indicators, values), ecology, climate change, and biology were all ranked of highest importance by IES program administrators (Vincent et al., 2013); however, only ecology and climate change appear to be important knowledge areas related to the FEW Nexus. We suspect that the lack of sustainability concepts at the FEW Nexus is explained by sustainability being a more abstract concept that did not emerge from our paragraph level coding approach. This finding indicates that instructors may need to explicitly facilitate student ability to connect course materials and environmental concepts with higher level sustainability concepts. Despite being present as top areas of knowledge in course materials and ranked highly by administrators in terms of importance (Vincent et al., 2013), ecology, biology, and geosciences infrequently intersected with FEW Nexus concepts. While ecological, biological, and geoscience concepts were commonly described in IES course materials, these knowledge areas were presented in a biophysical manner with infrequent connection to FEW Nexus resource systems that impact human systems. While important to IES programs, ecology, biology, and geosciences are not knowledge areas typically used to anchor the FEW Nexus concepts. Past research in the geosciences shows the importance of supporting science underpinnings in developing an understanding of advanced interdisciplinary thinking (Anderson & Libarkin, 2016).

Overall, we found that IES introductory courses in our sample displayed some level of alignment in the course content and FEW Nexus topics taught, indicating that the non-standardized approach of IES curricula might still lend itself to unified sets of ideas. Discrepancies across programs exist as some areas of knowledge were relegated to a handful of courses rather than found more broadly across programs. There was overlap between common areas of knowledge and FEW Nexus topics demonstrating which knowledge areas are often used to illustrate FEW Nexus topics and connections. Significantly, our content analysis results are the first to identify congruities and divergences across IES introductory courses, a field that does not have standardized accreditation and therefore covers a wide variety of topics. The FEW Nexus may be a useful tool to help emerging IES programs, or those undergoing restructuring, to cohere around a set of core topics that provide a framework upon which students can build systems thinking capacity in introductory courses (Cooke & Vermaire, 2015; Wiek et al., 2011).

Developing a better understanding of the concepts and topics covered in IES curricula is crucial for the advancement of the field for several reasons. First, our analysis of course content provides insight into the key areas that are considered most crucial for introductory learning and which topics are emphasized across institutions and programs. Decisions about what material students encounter will influence their conceptions of what is important, especially if the concepts covered in these materials are foundational knowledge for participation in more advanced courses. Secondly, topics that are less frequently covered, such as green design and sustainable governance, suggest that these areas are less central for shaping student understanding of the field in current programs. In some cases, these issues may be covered in more specialized courses, and in other cases, students may only encounter these topics peripherally or not at all. Given that this project is the first step in developing a concept inventory for environmental topics, we feel that it is important to focus our assessment tool on what is being taught, rather than focusing on what should be taught.

The eight courses in our sample are representative of environmental programs and identify a certain level of consensus or alignment in what topics are important in environmental programs; however, we also include student and faculty interviews to identify additional potential topics that are important (i.e., environmental justice) but not as frequently covered. Topics such as environmental justice may be experiencing a lag effect whereby environmental programs are increasingly incorporating ideas that are increasing in popularity but the time needed to include such topics may mean they are not as prominent in our representative sample.

Finally, student interests may include issues that are currently less covered than would be preferred. For example, according to interviews with students in IES degree programs (Authors, *in prep*), environmental justice is one of the topics of most concern to undergraduates, but we found that it is covered in less than 20% of IES introductory course content analyzed. Even in research, scholars find that insufficient attention is paid to environmental injustices as associated with various ecosystem services (Dawson et al., 2017). Gaps between student interests and materials used for instruction can lead to dissatisfaction and reduced enrollment, particularly among students who come from communities that have been underrepresented in STEM fields (Rainey et al., 2018; Sexton et al., 2018). Earlier integration of environmental justice topics could serve as a building block for future student professional pathways and general awareness of such issues.

The role of introductory IES courses may be to expose students to foundational concepts, but if advanced courses are not addressing gaps in knowledge areas and skill development, students may be unprepared for entering professional careers. Employers and organizations across the employment spectrum increasingly demand IES-specific skill outcomes, including interdisciplinary and non-cognitive skills not predicted by IQ or standardized tests (Deming, 2017; Stubbs & Cocklin, 2008). From 2000 to 2012, jobs that required non-cognitive skills (i.e., service positions that tend to be manual, such as maintenance) grew faster than jobs that required cognitive skill sets (i.e., those that require high levels of abstract thinking, such as IT) (Beaudry et al., 2014). Next generation FEW Nexus scholars must employ systems thinking, thrive in interdisciplinary teams, effectively translate and communicate scientific concepts to nonscientific audiences using evidence-based practices, demonstrate skills in facilitation, research ethics, and cross-cultural work to engage diverse communities, and connect with science to innovate and create actionable solutions (Wade et al., 2020).

IES degree programs typically focus on either natural and physical sciences or social science concepts. It is unclear to what extent IES degree programs have embraced synthesis over the teaching of the key concepts in isolation, with social science and qualitative methods underrepresented in FEW research (Albrecht et al., 2018; Newell et al., 2019; Platts et al., 2022). Issues of equity are not yet fully addressed or studied, and FEW Nexus frameworks do not adequately incorporate economic activities (Newell et al., 2019; Simpson & Jewitt, 2019). Moreover, few universities offer specific training programs related to the FEW Nexus, and published literature of examples, evidence, and best practice for teaching FEW concepts is limited (Wade et al., 2020). Research streams for FEW Nexus studies still reflect disciplinary silos and topical foci and have emerged in isolation from one another (Newell et al., 2019). We see this reflected in the lack of overlap between FEW Nexus concepts and ecology, biology, and geoscience areas of knowledge. It appears that some disciplines are more explicitly linked to the FEW Nexus than others. Instructors will have to consider how best to integrate systems connections between the FEW Nexus and important natural science topics in their classes as students are not necessarily being presented with these connections in course content.

Implications for the importance of systems thinking

Interdisciplinary systems thinking is the ability to perceive the "wholeness of a 'thing,' to perceive the connections between the 'thing' and other things with which it causally interacts, and to perceive the internal composition of sub-things, themselves interconnected and interacting to produce the thing itself" (Mobus, 2018). In other words, systems thinking is the ability to see the whole system and its parts and how these parts relate to the whole (Cloud, 2005). IES programs often emphasize the importance of integrated socio-ecological systems and the ability of students to think in terms of interlinkages, rather than discrete disciplinary concepts; however, our study suggests that students are more often presented with individual system components in their introductory course materials. While students need strong foundational disciplinary knowledge, they also need opportunities to apply this knowledge in interdisciplinary contexts to understand socio-ecological systems. It may be the role of introductory IES courses is to present the individual components of socio-ecological systems, so that upper-level courses can cultivate systems thinking competency in undergraduate students; however, even at the higher undergraduate level, understanding complex natural and social systems and cultivating systems thinking remains elusive for undergraduate students despite being a key competency identified by educators in describing their ideal curriculum (Vincent et al., 2013). For example, a geoscience study found that while a primary goal of earth science programs is for K-12 students to understand closely coupled systems (i.e., solar and earth), college students demonstrated a lack of systems thinking, referring the individual systems components rather than the processes that connect them during interviews (Libarkin et al., 2005).

Perhaps introductory courses should begin to present students with both IES and FEW Nexus core concepts and systems thinking skills in preparation for mastery in higher level IES courses (Habron et al., 2012). Introductory IES courses can prepare students by creating opportunities for students to identify recurring patterns across systems and disciplines, resulting in a more holistic understanding of human-environment interactions (Ben-Zvi-Assarf & Orion, 2005; Sadler et al., 2017). Scaffolding to build student competency in systems thinking can be a challenge, especially with multiple IES programs within the same institution. It may be the intention of IES programs to train students to think in terms of systems, but the lack of coordination across classes, instructors, and programs and lack of instructor training can create barriers to students realizing these skills.

Study limitations

Due to the substantial time investment needed to code artifacts at the paragraph level, we elected to code a sub-sample of IES course content. Our goal was therefore not to achieve statistical representativeness of IES curriculum design approaches (there are thousands of programs in the U.S.) but rather to represent the diversity of IES curricular diversity across the U.S. in our analysis. Our sample of eight IES degree programs-offering institutions was mostly representative across four criteria (e.g., Carnegie class, institution control, census region, and degree type); however, institutions from the South census region were slightly underrepresented while some categories were overrepresented.

Our decision to analyze text-based artifacts central to introductory IES course content provided a window through which to view courses in detail. Future studies could incorporate supplemental course materials beyond the scope of our analysis (e.g., documentaries, podcasts, activities, lectures, etc.) to gain a deeper understanding of how course materials can support student learning of knowledge areas and FEW Nexus systems. While we focused on extra-course materials, primarily readings assigned as homework, focusing on in-class materials would provide a greater understanding of how instructors are facilitating connections between materials that may not be present while just reading the text. Such an approach would identify whether instructors were making connections between FEW Nexus components and knowledge areas in the classroom in a way that was not captured in our analysis.

Next steps

Our content analysis was the first step in understanding alignment between knowledge areas and FEW Nexus concepts across IES introductory course content. Future research should examine what concepts are being taught to gain an understanding of long-term trends, identify emerging concepts, and highlight areas where expertise may be developing across programs. For example, green materials design was infrequently coded in our sample but may become increasingly important within IES programs as sustainable infrastructure becomes more widespread. By identifying and responding to these trends, IES programs can continue to adapt to student interests and professional pathway development post-secondary education. Universities may find this information useful in creating new programs or courses that align with broad topics being covered in IES programs. Conversely, universities may also use the results of this content analysis to identify niches that they can fill to develop particular expertise, such as green materials design. Similarly to our review of concepts, a review of core IES skill development (e.g., systems thinking, quantitative reasoning, spatial analysis) could yield similar insight into trends and reveal areas where emerging skills can be incorporated into IES programs to support professional skill development or where gaps between higher education and professional pathways exist.

We found that linkages between FEW Nexus systems were occurring less frequently than describing individual FEW Nexus components. This may be a barrier to fostering students' systems thinking abilities; however, many additional obstacles to systems thinking exist, including pervasive student alternative conceptions. Alternative conceptions can inhibit learning of early environmental concepts, creating a shaky foundation upon which students try to add more complex systems knowledge. Future research should identify commonly held student alternative conceptions related to IES and FEW Nexus content through in-depth student interviews and other classroom experiments (e.g., drawings, reflections). Specifically, probing the edges of student systems thinking capabilities would unveil areas of confusion, misconception, and knowledge. Once identified, these alternative conceptions can guide IES curriculum and course design and teaching strategies to align student ideas with scientifically accepted ideas.

Student interviews can also reveal concepts that may be important but that are less frequently covered explicitly in course readings. For example, the authors draw attention to environmental justice, a concept that was not frequent in the content analysis (appearing in less than 20% of paragraphs) but that was identified as critical in student interviews that were a separate component of a larger project (Authors, *in prep*). When environmental justice appeared in artifacts, it was largely in the context of polluting facilities being located in Black people, Indigenous people, and people of color (BIPOC) communities, the human health risks faced by BIPOC and low-income areas as a result of elevated disease risk and natural disaster preparedness (or lack thereof), and the disproportionate impacts to poor, BIPOC communities from the loss of ecosystem services and biodiversity (e.g., Ferrante & Fearnside, 2020; Wright & Boorse, 2016). Within the U.S., water and pollution inequities faced by BIPOC communities and food deserts/food sovereignty were also presented in grey literature and book chapters (e.g., Cunningham & Cunningham, 2020; Plumer & Popovich, 2020).

We currently have no systematic way to assess the efficacy of teaching interventions or curriculum design on student learning in IES programs. Assessment tools to evaluate student learning, teaching efficacy, and curriculum and course design across the breadth of IES curricula are needed but currently there is not a widely used, interdisciplinary tool. The future development of such an assessment tool could determine teaching strategies and course designs that are more effective and equitable. For example, this assessment tool can help identify and address student alternative conceptions, which can decrease persistence in IES degree programs. This study brings us one step closer to creating one such possible assessment tool, a concept inventory, by identifying common concepts to anchor assessment questions. A concept inventory will identify knowledge barriers students face that can result from inequities inherent to the United State education system (Miriti, 2020). By identifying these barriers to learning and creating a tool to evaluate teaching approaches, we can create a more diverse, equitable, and inclusive education system that enables students with minority identities to complete training in IES introductory courses.

The advantage of a concept inventory is its broadly applicable use across a discipline, or in this case, across an interdisciplinary field (i.e., environmental programs). One difficulty in assessing learning is the use of close-ended questions (e.g., multiple choice) as opposed to open-ended questions (e.g., short answer). Short answers can elucidate student understanding of systems; however, short answers can be challenging to grade. To address this issue, our concept inventory will rely on short answer questions and use machine learning to grade student responses to evaluate learning. Identifying alternative conceptions also has broader implications on student understanding of complex environmental justice issues. For example, understanding the connection between water and energy is key for confronting issues faced by poor, rural communities (Harper-Dorton & Harper, 2015). This has implications for students entering a variety of career fields by enhancing their understanding of the inextricable link between environmental and social issues.

Importantly, a concept inventory is one means of assessing learning; many other assessments could be used to identify learning. In identifying areas where systems linkages are not directly explained in course materials, we identify areas where instructors may want to use qualitative assessment methods to better understand student learning. For example, observational or reflective assessments could be targeted to uncover missing connections between particularly common but infrequently connected topics, such as ecology or geology and food systems.

Conclusions & further implications

Environmental degrees in the U.S. are rapidly increasing in popularity, covering a breadth of interdisciplinary topics, and taking various curricular approaches to program development. This diversity and breadth can present challenges in understanding the state of environmental fields, including assessing student learning of environmental topics and skill development. As the first step in developing a concept inventory assessment tool, we identified core concepts used to anchor FEW Nexus systems learning in IES introductory courses. Our content analysis revealed that the FEW Nexus is often covered in introductory IES courses, constituting about half of course content; however, individual elements of the FEW Nexus were more commonly described than were the discussions of linkages between these resource systems. Additionally, core areas of knowledge are identified that anchor FEW Nexus systems concepts.

Our findings indicate areas where instructors may need to make explicit connections between the FEW Nexus elements and environmental phenomena to facilitate systems thinking skills among students. Explicit connections between food, energy, and water were least likely to be included in course content. Instructors could use commonly covered knowledge areas, such as agriculture, energy systems, or climate change, as anchoring phenomena to help students understand connections between resource systems that they might not immediately make through reading course materials. Once introduced to individual systems (i.e., food, energy, water), students will need practice integrating knowledge about FEW Nexus systems to better understand the interlinkages, tradeoffs, and be able to develop resource management solutions.

This study is also useful for providing guidance for developing IES degree programs. The lack of accreditation in IES programs can pose a challenge for program development. By identifying common concepts and exploring the range of topics covered in IES programs, we provide a foundation upon which to understand the state of IES programs across the U.S. The breadth of topics covered and differences across courses also suggests that there is room for programs to specialize and build upon their own expertise when creating their own programs. We suggest that new programs or those undergoing revision consider emerging topics that may be under-represented in our sample, such as environmental justice, that are gaining in popularity but that might only recently have been included as core ideas.

Finally, our content analysis will eventually inform the development of the first interdisciplinary IES concept inventory to better understand student learning of complex, systems concepts. The implication of such a tool will allow for widespread assessment of student learning in IES programs. The concept inventory will be useful in assessing student learning, evaluating teaching interventions, and potentially uncovering system-wide inequities in IES programs.

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CR, SA, SV—Developed study idea and acquired funding. LH, AM, ER, LA, NB, SV, CR, SA—Designed approach to analysis and analyzed data. LH, AM, CR, SA, SV—Writing and editing with contributions from NB, LA, EB, LD, DD, EF, MJ, BM, PP, DP, RT, AT, BT, CWO.

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Human subjects

This study was approved by the IRBs of all participating institutions.

Availability of data and material

There is no dataset available for this paper.

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