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Evaluating core competencies and learning outcomes for training the next generation of sustainability researchers

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Abstract

The need to train sustainability scientists and engineers to address the complex problems of our world has never been more apparent. We organized an interdisciplinary team of instructors from universities in the states of Maine, New Hampshire, and Rhode Island who designed, taught, and assessed a multi-university course to develop the core competencies necessary for advancing sustainability solutions. Lessons from the course translate across sustainability contexts, but our specific focus was on the issues and trade-offs associated with dams. Dams provide numerous water, energy, and cultural services to society while exacting an ecological toll that disrupts the flow of water, fish, and sediment in rivers. Like many natural resource management challenges, effective dam decisions require collaboration among diverse stakeholders and disciplines. We linked key sustainability principles and practices related to interdisciplinarity, stakeholder engagement, and problem-solving to student learning outcomes that are generalizable beyond our dam-specific context. Students and instructors co-created class activities to build capacity for interdisciplinary collaboration and encourage student leadership and creativity. Assessment results show that students responded positively to activities related to stakeholder engagement and interdisciplinary collaboration, particularly when practicing nested discussion and intrapersonal reflection. These activities helped broaden students' perspectives on sustainability problems and built greater capacity for constructive communication and student leadership.

Introduction

Society faces many pressing sustainability problems, each characterized by its own social-ecological context. Developing viable solutions relies on the abilities of diverse researchers, stakeholders, and policymakers across multiple institutions to craft usable knowledge together (Whitmer et al. 2010; Clark et al. 2016). Developing training pedagogies linked to sustainability problems themselves—and the people involved in them—is one clear way to facilitate these collaborations (Wiek et al. 2011; Yarime et al. 2012; Hart et al. 2016). As a source of diverse knowledge and technical capacity, academic institutions are well-suited to train students to craft usable knowledge through interdisciplinary collaborations, build partnerships with stakeholders, and shape their research efforts for solutions. This focus on solutions, interdisciplinary approaches, and stakeholder engagement (SIS) are critical for converting knowledge into actions that can enhance the well-being of nature and society (Clark et al. 2016). Such problems engage researchers to study problems by emphasizing solutions, and doing this requires substantial stakeholder and cross-discipline expertise (Lang et al. 2012; Wiek et al. 2012; Hart et al. 2016). Significant progress has been made in identifying the need for introducing SIS principles of sustainability science into the academic realm (Sprain and Timpson 2012; Tamura and Uegaki 2012; van der Leeuw et al. 2012), with a particular focus on empirical pedagogical approaches that emphasize competence development (Wiek et al. 2011), knowledge application (Barth and Michelsen 2013), mindfulness (Wamsler et al. 2018), interdisciplinary communication among academics and stakeholders (Woods 2007), useful case studies (Stauffacher et al. 2006), and collaboration-building across multiple organizations (Tamura et al. 2018; Trott et al. 2018).

Though sustainability science training models have grown since the landmark paper by Kates et al. (2001), there is still much to learn about the benefits of using sustainability problems as a focal point for student training. Training in sustainability science remains difficult to fit into many discipline-based academic structures that prioritize deepening expertise without also integrating multiple forms of knowledge and engaging with stakeholders to work toward real solutions (Brewer 1999; Cash et al. 2003; Zarin et al. 2003; Whitmer et al. 2010; Yarime et al. 2012). These academic structures do not account for the significant additional challenges and rewards encountered in SIS research (Clark et al. 2016). Academic institutions can accelerate this change by creating incentives that emphasize progress towards solutions and training the next generation of researchers and practitioners (Hart et al. 2016). This solutions-emphasis prepares students to mobilize the capacity of diverse teams through new pedagogical models emphasizing SIS capacities (Jasanoff 2004; Meyer et al. 2016). Engagement with diverse stakeholders helps students recognize unique social-ecological contexts and perceptions of both problems and solutions (Cash et al. 2003; Stauffacher et al. 2006; Clark et al. 2016). Effective stakeholder collaborations can also foster long-term partnerships critical for progress towards solutions, demonstrate the responsiveness of academic institutions to societal concerns, and develop broader community support for higher education practices (Lang et al. 2012; Clark et al. 2016).

To address the need for training models that can be adapted to diverse sustainability problems, we explore a multi-institution, interdisciplinary curriculum co-developed and taught by instructors from universities in Maine, New Hampshire, and Rhode Island. The goals of this collaborative effort were to strengthen core SIS competencies in students, prepare them for advancing solutions to real-world sustainability problems, and begin constructing a general training model based on SIS practices. Here we describe learning themes related to strengthening core competencies, tailored activities, and robust assessment techniques used to design and implement the course (Wiggins and McTighe 2005; Barth et al. 2007). Our course design was inspired by concepts from interdisciplinary and sustainability science pedagogy literature (Cash et al. 2003; Stauffacher et al. 2006; Woods 2007; Dewulf et al. 2007; Morse et al. 2007; Thompson 2009; Westberg et al. 2010; Winowiecki et al. 2011; Daniels and Walker 2012; Clark et al. 2016; McGreavy et al. 2016). We then detail the experiences of students and instructors based on course surveys, focusing on the challenges and outcomes of a co-created educational process for sustainability. Our assessments focus on improving our understanding of students' core competencies, confidence with class topics, and the relative effectiveness of activities. Drawing from existing literature and the results of our original research, we provide a generalized training model for undergraduate and graduate students in sustainability science that could be applied in related science, engineering, and communication courses. We emphasize an iterative, co-creation training model in which instructors and students collaborate to connect learning outcomes, competencies, and class activities (Figure 1).

Course synopsis

Five instructors led the cross-campus, shared course "Learning from dams: Theory and practice of sustainability science." Instructors received valuable guidance regarding the design of the course from other faculty with expertise in sustainability science pedagogy. Faculty first convened in fall 2016 to design the basic class framework. Twenty-four students, including eight undergraduate, seven Master's, and nine doctoral students were enrolled in the course across four universities in three New England states (seven from University of Rhode Island, seven from University of Maine, nine from University of New Hampshire, one from University of Southern Maine). Cross-university recruitment was necessary to expand the academic diversity of students and to encourage greater interdisciplinarity. No single university had sufficient breadth of expertise to tackle sustainability problems alone. Class consisted of a three-hour session every week during the 2017 fourteen-week spring semester, with students and faculty meeting at each institution and then connecting to other universities via videoconference. These sessions consisted of multiple combined activities and student-instructor co-creation meetings used to adapt the course syllabus to the needs and interests of students.

Dams were the central focus for the course, as we were collaborating across universities on a four-year National Science Foundation EPSCoR-funded research project "The Future of Dams" (https://www.newenglandsustainabilityconsortium.org/dams), composed of more than forty researchers whose skills and expertise spanned over twenty disciplines. One goal of the project was to equip students with team-building and engagement competencies to contribute to solutions development. As a result, our student cohort was highly interdisciplinary and reflected the multiple forms of knowledge necessary to understand dam and related natural resource management controversies. At the start of the course, students indicated academic backgrounds in wildlife ecology, communication, social sciences, environmental science, civil and environmental engineering, Earth and climate sciences, biology, watershed management, natural resource economics, hydrology, fisheries science, and systems dynamics. Dams are a useful model system because they require interdisciplinary approaches to understand a range of considerations and decision impacts on freshwater ecosystems, societal connections to rivers and lakes, and the economics of fisheries and power/water utilities (e.g. Roy et al. 2018). While there is a growing number of local and global dam decision case studies highlighting their impact on the food-energy-water nexus within different contexts (World Commission on Dams 2000; Scodanibbio and Mañez 2005; Opperman et al. 2011), we intentionally developed a generalized training model that can be modified for other sustainability science and natural resource topics beyond dams. This reflects our intention to create a course that taught sustainability science concepts, but used a specific case study to develop critical core competencies in the discipline.

Drawing from an extensive literature review, we designed the syllabus to provide students with clear learning outcomes for sustainability science theory and practice. Course learning outcomes, core competencies, and activities were framed around the challenges and benefits of SIS principles. We focus on three general learning themes for SIS training (Figure 1) that include solutions, interdisciplinarity, and stakeholders. For the solutions learning theme, students were provided opportunities to explore how there is rarely one perfect solution to sustainability problems, but by working together they better understood problem contexts and how to contribute to a suite of solutions. The pursuit of solutions contrasted with a traditional academic focus on the pursuit of knowledge (Yarime et al. 2012; Hart et al. 2016). The interdisciplinary learning theme encouraged students to exchange and co-create ideas across academic boundaries. The stakeholder learning theme connected the class with members of communities and organizations to help students understand sustainability problems and potential solutions from multiple perspectives.

Students worked within these learning themes by developing three core competencies recognized as foundational in sustainability science pedagogy: critical reflection (Woods 2007, Knowlton 2014), communication (Stauffacher et al. 2006; McGreavy et al. 2016), and systems thinking (Heemskerk et al. 2003; Daniels and Walker 2012; Habron et al. 2013). These core competencies encompass several nested components, each connected to distinct learning outcomes developed for our rubric and drawn from existing literature (Cash et al. 2003; Stauffacher et al. 2006; Woods 2007; Dewulf et al. 2007; Morse et al. 2007; Thompson 2009; Westberg et al. 2010; Winowiecki et al. 2011; Daniels and Walker 2012; Clark et al. 2016; McGreavy et al. 2016), and our collective experiences with sustainability science pedagogy (Supplemental Table 1). Critical reflection represents a student's ability to describe thoughtfully their knowledge growth sparked by course activities. Systems thinking represents a student's ability to move beyond collective content knowledge to provide critical assessments of system components and dynamics that relate to a sustainability problem (Daniels and Walker 2012). Communication represents a student's capacity to recognize and pursue opportunities for and challenges in collaboration and engagement. We chose to focus on interdisciplinary collaboration and stakeholder engagement as two sub-components of communication to reflect their importance in the learning themes. Our course rubric reflected these core competencies, aligning student work with learning themes, coursework evaluation, and assessments (Supplemental Table 1).

The course syllabus provided enough pedagogical structure to support student learning themes, yet it was also flexible to encourage student creativity and leadership. Regular student-instructor co-creation meetings (sensu Voorberg et al. 2015) encouraged student reflections on course direction, suggestions for effective activities, and learning theme adaptations to better tailor the course to student needs and aspirations. Student-led course changes were more frequent in the second half of the semester, after students had developed a stronger understanding of SIS principles. Instructors were more likely to act upon student suggestions to create new activities and amend learning themes if they advanced the core competencies.

Instructors connected students across campuses using video conferencing software (Zoom) to foster small group and class-wide discussions regardless of geographic distance (Tamura et al. 2018). We used an online platform (Google Drive) to organize course materials and student work and to co-create "live group notes" in real time to reflect dynamically on new knowledge and questions for larger course-based discussions and interviews with stakeholders that took place through the course. The benefits were at least twofold: students could refer to group notes during later activities, and notes served as critical artifacts for post-course assessment and future course refinement.

Activities

We selected activities from sustainability science pedagogy to align with intended learning themes (Kagan 1989; Dewulf et al. 2007; Sprain and Timpson 2012; McGreavy et al. 2016). We also adapted and created new activities based on student-instructor co-creation meetings. Each activity was meant to move students towards the learning themes by combining core competencies in different ways. Instructors often combined multiple activities in a class session or series of sessions to ensure that students explored a diversity of core competencies. This approach kept students working towards learning themes and thinking adaptively about sustainability problems, thereby ensuring continued sharing and co-creation of usable knowledge. Students completed several short-term projects and one final project based on their work completed in the activities. These projects emerged from course activities, with topics based on student collaboratives in and out of class. We do not include short-term and final projects in our assessment of the course. Students presented their work through the following activities to emphasize its connection to learning themes.

Icebreakers: We used two activities, the jargon game and mind mapping, as icebreakers to introduce concepts of interdisciplinary collaboration. For the jargon game, students independently wrote one-page descriptions of research interests for an audience familiar with terms and concepts in their discipline. Students then joined randomly assigned groups to collect jargon terms not understood by a general audience. Students merged jargon terms into group statements, as prose, poetry, lyrics, or another verbal form of expression. These presentations served teambuilding purposes, breaking down the barriers between disciplines and stimulating student partnerships, but they also helped reveal needs to overcome language barriers (Jasanoff 2004). Mind mapping was used to help students describe various social-ecological influences of dams and the dynamic links among them, identifying how their own content knowledge contributes to understanding a complex system, and how they planned to work with other students to broaden this understanding and co-create innovative science (Daniels and Walker 2012).

Nested discussions: A weekly framework for nested discussion was based on the think-pair-share model (Lyman 1987). Nested discussions combined intrapersonal reflection, loosely organized discussion in assigned groups crossing disciplines and institutions, and organized class-wide discussions to synthesize important concepts and ways of thinking provided by groups and individuals that may otherwise be left unmentioned (Kagan 1989; Wiesendanger and Bader 1992; Addor et al. 2015). Students completed a weekly one-page reflective writing assignment related to upcoming class activities, current reading assignments, or class discussions. Instructors selected student leaders to develop compelling discussion questions and oversee small group organization. Students were split into small groups of about three, represented by multiple academic backgrounds, to discuss perspectives offered by each member. Groups elected a lead note-taker as they proceeded with reflections and activities. Group discussions continued for approximately one quarter to three quarters of class time, depending on activity length and availability of time. Students convened as one class-wide group before, after, and occasionally in between small group sessions, in which case participants changed groups halfway through. Groups and individuals took advantage of class-wide meetings to reflect on activities and contribute to a larger synthesis of the discussion material through presentations, conversations, and live group notes. Student leaders and instructors provided concluding remarks at the end of class.

Local/global case studies: Case studies provided a comprehensive reference of real sustainability problems gathered from a diverse set of academic and professional knowledge

(Stauffacher et al. 2006; Sprain and Timpson 2012). Case studies spanned large dam construction projects in developing countries (e.g., Scodanibbio and Mañez 2005) to local river restoration debates in New England (e.g., Opperman et al. 2011). Case studies typically consisted of a collection of published articles, reports, and public comments. These materials were required reading/listening by students prior to the next class session, at which time instructors used nested discussions for a deeper analysis. Each case study revealed sustainability issues shaped by a system with deeply rooted complexities, incomplete social-ecological information, and context-dependent conditions with no clear path to a single, scalable solution (Stauffacher et al. 2006).

Stakeholder interviews: Students and instructors invited stakeholders to class for informal interviews, including town/state officials and residents, often in conjunction with case studies. Interview agendas and questions were entirely designed and led by students. In addition to prepared questions, students also crafted and organized follow-up questions using live group notes.

Negotiation simulations: Instructors organized negotiation simulations to explore the complexities of how stakeholders interpret sustainability problems. Students divided into groups and embodied different stakeholder roles (Ashcraft and Susskind 2008). Students roleplayed stakeholders involved with freshwater use for irrigation, municipal storage, recreation, and other concerns about river health and water quality. Negotiation simulations require significant coordination to ensure participants understand specific roles and that the negotiation forum is conducted smoothly. There was an incentive to reach consensus on a decision, but multiple decisions were possible, allowing students to be more flexible with their negotiations. Students engaged in class-wide discussions afterwards to reflect on these negotiations.

Writing retreat: Students across campuses convened in person for a two-day writing retreat halfway through the semester. Prior to the retreat, students outlined collaborative plans for group term papers. The retreat consisted of self-organized group writing sessions, punctuated by class-wide progress updates. Students were asked to complete a one-page reflection and short answer essay on their retreat experiences. In our experience, writing retreats may be especially beneficial if they link to ongoing research partnerships, as retreats can help build relationships among collaborators. This was a rare opportunity for students to meet one another for the first time in person. Though not an essential component of our course, we describe below how this in-person meeting provided significant additional benefits on top of our remote course structure.

Fact sheets: Student groups produced disciplinary and interdisciplinary fact sheets to report case study findings. Groups of students with similar content knowledge produced and presented disciplinary fact sheets, focusing on case study components most relevant to their knowledge. Groups that consisted of students with diverse content knowledge produced interdisciplinary fact sheets, and were challenged to overcome significant communication barriers while designing a broad case analysis and present their work to a diverse audience.

Data collection and analysis methods

Our data collection relied on a pre and post-course survey design and we extended and supported our analysis of survey data with observations from the course and review of course documents and student projects (Creswell 2014). The pre- and post-course surveys included both quantitative, closed-ended questions (i.e. Likert scale) as well as open-ended essay responses (Supplemental Tables 2-3). Survey questions aimed to operationalize the identified core competencies related to solutions, interdisciplinarity, and stakeholder engagement and also asked students to reflect on their own learning experiences in and out of the course. To explore the effectiveness of activities, we combined our literature review of course activities, instructors' qualitative class observations, and students' survey responses. Effective activities are those that deeply engage the student in multiple core competencies simultaneously, or are able to connect to other activities to increase the practice of core competencies in students (McGreavy et al. 2016, 2017).

We measured students' perceptions of the effectiveness of each course activity with Likert scales. Likert scales were also used to measure changes in confidence in sustainability science knowledge, testing differences using two-way t-tests and paired, one-way multivariate analysis of variance (MANOVA) (Anderson 1958), each with means grouped by pre- and post-assessment results, to compare means in self-reported confidence before and after the course (e.g., Tamura et al. 2018).

We also conducted content analysis on the open-ended essay responses on the pre- and post-surveys to assess the extent to which students demonstrated changes in core competencies (Neuendorf 2017). The content analysis relied on the course rubric (Supplemental Table 1) as a codebook and the lead author led this analysis and assessed the reliability of the interpretations through in-depth discussions with co-authors and qualitative observations of course materials (Corbin and Strauss 2008). Combining quantitative and qualitative forms of analysis and supporting interpretations with informal observations and review of course materials provided a rich understanding of students' conceptualization of SIS principles.

Results and discussion

What core competencies do students find most valuable?

Overall, students indicated that communication, especially in the context of stakeholder engagement and interdisciplinary collaboration, was critical for their training in sustainability science, followed by developing content knowledge in their own disciplines, and systems thinking (Figure 2). For example, students reflected on the need for "Communication … and the ability to work at problems from various perspectives" and "an awareness of both the related science and social constructs." The course, they said, helped them to "work with other people across disciplines and geographies." Students answered the following survey questions: "What areas (topics, skills, activities, etc.) have most strengthened your capacity for conducting sustainability research?", "What do you still need to do to improve your sustainability research skills?", and "What combination of skills and knowledge do you see as most important for your work in sustainability research?" (supplemental Table 3).

Responses that referenced the systems thinking core competency included wanting to understand the ecological-social-economic connections drawn by dams, like the motivation to better understand relations between "knowledge about the natural system and the socio-economic context in which the research is being conducted." Other students showed interest in learning more about the social structure surrounding dams, including "Identifying what needs an organization may have, and then being able to work together with others to address those needs in a way that empowers." Still others tended to emphasize content knowledge in their own disciplines, like a freshwater ecology student who wanted to develop "a solid understanding of ecology and dams."

These results suggest that students recognized the need for greater training opportunities in stakeholder engagement and facilitation in academic institutions, where the primary emphasis is often on strengthening disciplinary content knowledge. Though content knowledge is centrally important in academia (Brewer 1999; Zarin et al. 2003; Whitmer et al. 2010; Yarime et al. 2012), it was not seen as a primary or singular need in the eyes of students. This finding provides empirical support for other studies (Woods 2007; Thompson 2009; Lindenfeld et al. 2012) that call for stronger emphasis of communication capacities. Content knowledge is obviously important, but these results suggest that if academic institutions are to advance student training in sustainability science, content training must be paired with training to help students engage with stakeholders and participate in cross-disciplinary collaboration and systems thinking. Below we describe specific activities that encourage this pairing.

How do core competencies influence student learning?

The content analysis sought to identify how students may be using different modes of thinking and therefore emphasizing different core competencies when they reflect on or write about SIS concepts (Figure 3). More specifically, we tracked the frequency with which students explicitly referenced core competencies to answer a series of pre- and post-course survey essay questions. Overall, students demonstrated a general increase in the use of core competencies, with communication exhibiting the greatest increase. Below we identify how students combine different core competencies when answering essay questions that relate specifically to each learning theme (Figure 1).

Solutions-driven: For the solutions-driven learning theme, when students were asked "Which steps could you or others take to identify a dam-related sustainability problem and possible solutions?" most students relied on systems thinking competencies with less emphasis for reflection on personal experiences and discussion of communication needs. However, student use of communication competencies grew more than others by the end of the course (Figure 3). One student suggested "possible solutions can be found by the meticulous study of the underlying causes of each issue," while another student mentioned that "solutions should be focused on the specific cause of the problem and vetted to ensure they do not produce unintended consequences." However, by the end of the course students demonstrated significantly greater use of communication competencies, particularly stakeholder engagement, to describe solutions. Use of critical reflection also increased by the end of the course, but to a lesser degree.

Virtually all students called for comprehensive environmental/ecological assessments in some form. Student responses point to the need to understand the many ecological components and feedbacks of a sustainability problem through observation and data collection before trying a solution. Many students also recognized the significance of stakeholders as diverse and influential members in a broader social-ecological system impacted by dam decisions. One student stated they would like an "open dialogue with stakeholders" to "study the system from multiple perspectives to identify problems and solutions," and then provided example perspectives based on their stakeholder interview experiences. However, there were some cases where students incorporated the concept of stakeholders in limited and general terms, suggesting that stakeholder concerns "should be incorporated" in decision making but focusing primarily on ecological study needs. Students also tended to emphasize stakeholder engagement more than interdisciplinary collaboration as an important form of communication, suggesting that they more often associate "solutions" with the interest of stakeholders in mind, rather than just research findings from interdisciplinary collaborators.

Based on these results, student responses tended to emphasize the need to understand and characterize the complex system surrounding a sustainability problem before developing solutions. Students who expand upon this and recognize the need to be mindful and inclusive of potential stakeholder roles exhibit a broader understanding of the requirements for solutions to sustainability problems (Clark et al. 2016; Wamsler et al. 2018). We found the use of case studies and stakeholder interviews to be helpful in encouraging this broader social-ecological perspective in students, as we discuss below.

Interdisciplinarity: Students were asked to offer their definitions of and experiences with interdisciplinary work. We then compared these to published definitions for interdisciplinary and multidisciplinary work to identify what type of collaboration is most familiar to students (Choi and Pak 2006; Stauffacher et al. 2006; Woods 2007). These two forms of collaboration are distinguished by the level of co-creation between research partners with different content knowledge:

1. Multidisciplinary: Sharing knowledge and perspectives with peers to pursue common research interests.
2. Interdisciplinary: Co-creating new knowledge with peers and contributing to a broadened group perspective.

Though we did not define "transdisciplinary" explicitly in the course, students frequently participated in stakeholder engagement and collaborative activities that would be largely defined as "transdisciplinary" (Thoren and Persson 2013).

At the start of class, 65% of students provided a multidisciplinary definition, while 35% of responses were interdisciplinary. This trend was reversed by the end of class. Numerous early responses emphasized "including multiple disciplines," or "multiple people in different fields of study" who "bring their individual expertise to the table." A few went beyond this to include the importance of "working across different fields," describing "work among disciplines, not simply to draw from the knowledge of another discipline, but rather to integrate different disciplines into a cohesive whole," and how "interdisciplinary work can address problems more fully than isolating aspects of the problem by academic departments." Students most frequently used communication core competencies and this trend grew by the end of class (Figure 3). Responses rich with critical reflection (Figure 3) suggest that prior to this course, most students experienced multidisciplinary collaborations, or they did not identify differences between sharing and co-creating knowledge (Choi and Pak 2006). Most students' past collaborative experiences occurred in undergraduate courses in their discipline, generally matching the traditional academic model that often limits the exposure of students to other forms of expertise and opportunities to practice more integrative forms of collaboration (Hart et al. 2016).

In addition to academic collaborative experiences, students also shared their interpretations of stakeholder engagement in their definition of interdisciplinary work. Students suggested that interdisciplinary work can help place stakeholders "in an influential position" to define sustainability problems, and this can help build "a structured framework to help stakeholders make decisions." By the end of class, students tended to reflect upon their experiences during the course to exemplify interdisciplinary collaboration. One student suggested, "we drew from our various areas of expertise to co-create something new and adapt it into something useful/meaningful for the class." Other students contrasted their previous experiences with that in the course: "I do have some previous experience with interdisciplinary work from past courses, but nothing like what the Learning from Dams class involved. It was a valuable experience to work on assignments with friends from so many different backgrounds that I would not normally interact with."

We suggest that instructors should be explicit about the different definitions and expected objectives/outcomes between multidisciplinary and interdisciplinary methods. Instructors must provide recurring opportunities to practice interdisciplinarity and demonstrate its benefits. Pre-existing interdisciplinary partnerships help facilitate new partnerships between students who are new to the concept. We found that it is preferable for students, rather than instructors, to share this expertise, (Kagan 1989; Wiesendanger and Bader 1992), though both approaches are effective at demonstrating the benefits of interdisciplinarity.

Stakeholder engagement: When asked the question "What, for you, is a stakeholder? What role can stakeholders play in sustainability science?" students relied largely on a combination of stakeholder engagement and systems thinking core competencies to emphasize the role of stakeholders in the coupled social-ecological aspects of sustainability problems (Figure 3). The use of these core competencies uniformly increased by the end of class. Typically, students defined stakeholders as "anyone who is directly or indirectly impacted by or involved in a decision." Many students emphasized the broad network of stakeholders impacted specifically by decisions relating to dams, for example, "property owners, dam owners, consulting firms, construction workers, people who engage in recreational activities, …people who make a living from [dams], tribes, …tax payers, policy makers, local government, activist groups…" Most students identified the value of partnerships with stakeholders (e.g. Senecah 2004; Walker et al. 2006; Daniels and Walker 2012): "stakeholders in sustainability science can help bridge the gap between science and people."

Students relied on the critical reflection core competency only when they had personal experiences to share, and the use of reflection became more prominent by the end of class primarily because of stakeholder interviews, strengthening students' narratives in support of engagement (Figure 3). Some students expressed how it was "incredibly valuable to hear first-hand how [sustainability] problems are actually tackled and how people respond to presented solutions", after meeting with a local dam removal advisory committee. Drawing from their reflections, some students acknowledged conflict as a common element of stakeholder engagement, between different stakeholder groups or between stakeholders and researchers. Students often defined conflict as resulting from "the differing interests of two parties." Of the students that acknowledged the presence of conflicts, several of them emphasized the difficulties they pose for decision makers: "it is almost always true that [a decision] will make one or more groups of stakeholders unhappy." A few others extended this thought positively, identifying how divergences can be important for conflict resolution (e.g. Daniels and Walker 2012; Gardner 2013) vetting potential decisions: "stakeholders can hold researchers and policymakers accountable for producing sustainable solutions and shape those solutions through their involvement."

Interdisciplinary collaboration was not emphasized in many of these student responses, both in the pre- and post-assessment. This suggests that students tended to reserve its definition for collaborations between researchers in this context. This result contrasts with the interdisciplinary question above where there was greater stakeholder emphasis. Our framing of these questions may have contributed to the different responses and the pattern may also indicate a need to emphasize multiple forms of knowledge within and outside of academia.

What activities were most effective for student learning?

We measured activity effectiveness for each of our three core competencies based on class observations and student survey responses (Figure 4), and activities were chosen to ensure that students experienced thorough training in each core competency. Results suggest that the effectiveness of each activity varied within the context of the course. Some activities placed greater emphasis on specific core competencies over others. Combining activities is critical to ensure that students are provided opportunities to connect ideas using all core competencies (e.g. McGreavy et al. 2016, 2017). Instructors frequently combined case studies with stakeholder interviews and nested discussions to ensure that students had solid experiences in reflection, systems thinking, and communication. Negotiation simulations were also combined with nested discussions to incorporate a stronger emphasis on students' personal reflections of the experience. Nested discussions dramatically improved the resonance of this and many other activities. Other combinations, such as among case studies, negotiation simulation, and stakeholder interviews, helped students to improve in one core competency, such as communication, by practicing multiple approaches.

We note that some activities provided significant benefits that may not translate directly to core competencies but were critical for team building (e.g. Thompson 2009). For example, icebreakers were important in the early stages of the course but were later overshadowed by other activities. These encouraged early-stage communication and teambuilding, but they were followed by other details-oriented group work after the first few class sessions. Other later activities such as the writing retreat were also important for teambuilding. The writing retreat stands out as the time when the interdisciplinary collaboration concepts coalesced for many students. Students indicated that "[the writing retreat] gave us the opportunity to get to know one another on a personal level and build trust," "I found that I care about the work more when others are also involved compared to the time when I am working individually," and "I got to know my classmates, and I now would like to stay in contact and collaborate with them in the future." Other activities such as the stakeholder interviews were useful for understanding the context of sustainability problems. Students mentioned that "[stakeholder interviews] made me realize that science isn't necessarily enough to get the job done on its own," and "It 'humanized' some of the perspectives I couldn't quite wrap my head around."

How confident are students with sustainability science concepts?

On average, student self-reported confidence increased 7.6% for content knowledge that relates to SIS principles (Figure 5). The largest improvements in student confidence came in "using common terms to explain complex research" (16.2% avg.), "stakeholder engagement" (13.3% avg.), "communication" (6.3% avg.), and "interdisciplinary work" (+5.9% avg.), suggesting that students gained confidence in communication skills required for interdisciplinary collaboration and stakeholder engagement. Results for each category follow a normal distribution with equal variance. However, only one of the changes in self-reported student confidence from start to end of class was statistically significant based on t-tests ($p=0.03$ Figure 5). MANOVA results suggest the cross-category unanimous trend of improved confidence is also not statistically significant ($p=0.12$). Most students indicated that they had previously taken courses in sustainability science, and these students tended to rate themselves with moderate to high confidence at the start of class. These previous courses were predominantly hosted within students' primary concentrations. Based on the limitations of our Likert scale results, we strongly suggest a combined qualitative and quantitative approach including additional student materials for a more holistic assessment of if, why, and how students benefit from sustainability science courses (Creswell 2014). We also suggest careful design of the Likert scale questions and consideration of alternatives, such as slider scales (Cook et al. 2001).

Building a general model for SIS training

We recommend that academic institutions strengthen sustainability science courses by creating opportunities for nested, interdisciplinary discussion that facilitate cohort-building among students with disparate academic backgrounds and different experience levels. Students identified communication core competencies as the most important component of their future training in sustainability science. These findings agree with previous pedagogy literature (Woods 2007; Lang et al. 2012; McGreavy et al. 2016). Nested discussions emerged as a particularly effective method for translating and co-creating knowledge across disciplinary boundaries to address real-world challenges. For our course, the "scale" of communication and opportunities for co-creation were as important as the content. Students found nested discussion to be a particularly useful communication method when combined with other activities, such as case studies, stakeholder interviews, negotiation simulations, writing retreats, and fact sheets. The interpersonal reflection component of nested discussions provided an important opportunity for students to "make sense" of complex group conversations with other students and broaden their own perspectives on course topics. Scaling up our conversations, from personal observations to group sharing and class-wide synthesis, revealed important insights from a broader collection of students who otherwise might not have participated.

The usefulness of nested discussions depended on student participation representing a broad diversity of expertise. Most students enrolled in our class to learn from fellow students and broaden their own knowledge of sustainability problems, rather than to deepen their own disciplinary content knowledge. Unless students' disciplinary expertise and interests are sufficiently diverse, the goal of interdisciplinary collaboration will be harder to achieve, and students will not develop as broad an understanding of the sustainability problem or the motivations behind SIS principles. Though we were able to assemble a class with the requisite disciplinary diversity across multiple universities, many of the activities we designed remain applicable for courses with less interdisciplinary diversity.

We discovered three major benefits of student-instructor co-creation. First, we modeled an important commitment in sustainability science to knowledge co-creation processes that can support the use of knowledge in decision making (Cash et al. 2003). Second, taking on the responsibility of course co-creation improved students' commitment to the success of the activities that they developed and allowed them to better recognize the functions of different activities. Third, this process encouraged greater trust between students and instructors, allowing students to build interpersonal capacities within interdisciplinary activities (e.g. Jackson 1993; Senecah 2004). Students gained important capacities in leadership, negotiation, and trust when course responsibilities extended beyond scholarship to include the direction of the course itself. Students gained additional pedagogical skills by openly questioning, negotiating, and shaping course activities and learning themes. Students justified their pedagogical decisions, empowering them to think critically not just about designing a successful course but about charting their own emerging careers. The co-creation process produced some uncertainty in the direction and outcomes of some course activities, but instructors and students ultimately found that the benefits of exercising student leadership and flexible goals were indispensable (e.g. Komives 2011; Seemiller 2013).

Students indicated that stakeholder engagement was the most crucial core competency gained in the class, suggesting that sustainability-related courses must involve some form of discussion and/or collaboration between students and stakeholders. Approaches to student stakeholder engagement should reflect best practices developed by SIS researchers (e.g. Senecah 2004; Walker et al. 2006; Lang et al. 2012; Wiek et al. 2012; Yarime et al. 2012; Daniels and

Walker 2012; Druschke and Hychka 2015). This requires that students learn about the diverse perspectives that stakeholders have about sustainability problems, including the challenges in finding viable solutions (Clark et al. 2016). Our student-led approach provided four main benefits. First, students gained important experiences in coordinating and hosting interviews with non-academic participants, a first-time experience for many students. Second, participating stakeholders seemed to feel comfortable with the opportunity to share their knowledge of the sustainability problem directly with students. Third, these conversations provided a space in which students could hear and consider others' diverse perspectives about dams (e.g. Wamsler et al. 2018). Finally, this activity helped students respect stakeholder partnerships and provide a supportive opportunity to discuss how to build these partnerships in mutually beneficial ways (e.g. Senecah 2004). Several students also favored negotiation simulations, though these rely on role-play by the students and do not include participation by actual stakeholders. However, negotiation simulations provide alternative benefits as a model system with an accelerated approach to reaching consensus on decisions among diverse stakeholders within a single class period. Conversely, stakeholder interviews provided snapshots of ongoing issues that might take years to resolve.

A major goal was to cultivate longevity in student partnerships and build their capacity to pursue new interdisciplinary collaborations and maintain previous fruitful partnerships with long-lasting outcomes (e.g. Voorberg et al. 2015). These student partnerships crossed disciplinary and institutional boundaries. Sustainability science needs a broad network of passionate collaborators if it is to take hold and flourish in academic institutions. Training the next generation of sustainability scientists holds promise to bring about this change.

Conclusions and future work

We designed a generalizable sustainability science training model to advance learning themes encouraging SIS principles. We used dams as a model system to expand and refine this approach, recognizing that dams as a system share features and challenges seen in other coupled social-ecological systems (e.g. food systems, urbanization, forest management) requiring multiple forms of expertise and engagement to solve. Our class brought students together virtually from four New England universities to develop sustainability-related competencies. The course was designed to encourage student leadership through co-creation of the course and multiple leadership roles. Nested discussion techniques were used to ensure that students were prepared for discussions and co-creation of ideas that crossed disciplinary boundaries. Assessment suggests that student confidence remained high throughout the course, and by the end, students reflected that communication competencies are most important for their future development as sustainability scientists, with a strong emphasis on stakeholder engagement. Students used different combinations of core competencies in their discourse when asked about different SIS principles in sustainability science. We expect these results apply to a broad range of settings and that our model can be used to help train the next generation of sustainability scientists and incrementally transform academic institutions in the process. Future work should focus on testing general training approaches on different course topics outside of dams, emphasizing communication competencies for interdisciplinary teams and stakeholder engagement, improving procedures for student-instructor co-production, and further development of concise and recurrent course assessments to span the diversity of student coursework.

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Figures

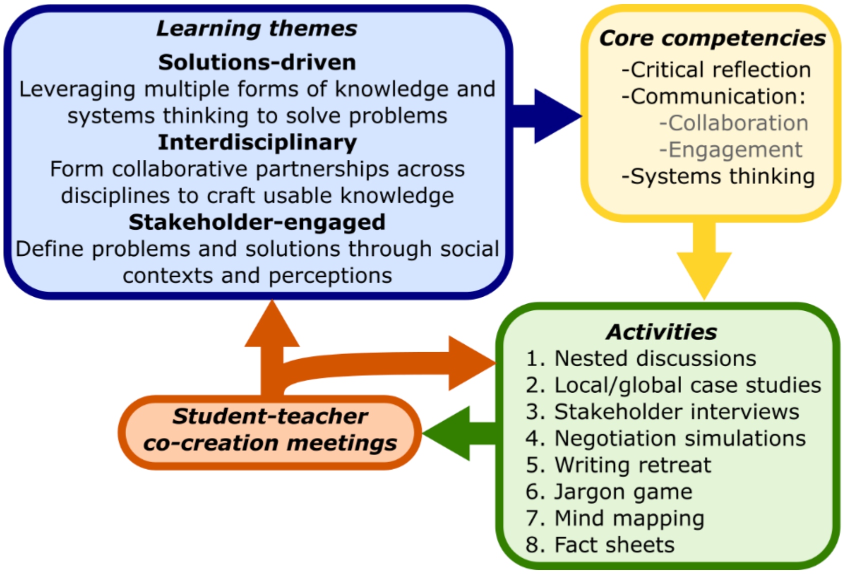

Figure 1: Our iterative training model. Key sustainability science learning themes (blue) influence the selection of activities (green). Each activity incorporates three core competencies that are common in sustainability science (yellow). Students reflected upon the effectiveness of training activities and learning themes and suggested future changes to both through co-creation meetings (orange).

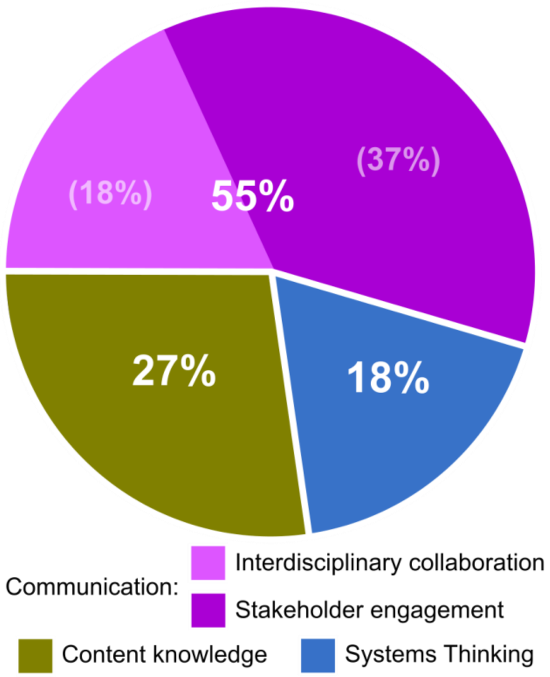

Figure 2: General types of core competencies and content knowledge that are important for future training, as indicated by student survey responses.

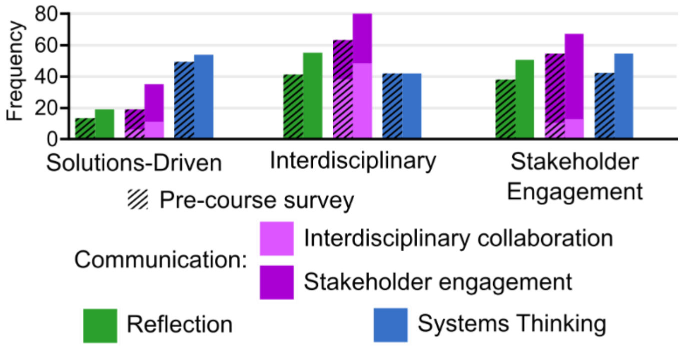

Figure 3: Frequency of independent instances of core competencies used by students when answering questions that relate to course learning themes; summed for all students. Hatched bars: pre-course survey, solid: post-course survey.

Core competencies	Icebreakers	Nested discussions	Case studies	Stakeholder interviews	Negotiation simulation	Writing retreat	Fact sheets
% Effective	33	85	89	89	93	91	54
Communication: Interdisciplinary Collaboration	X	X	X	X	X	X	X
Communication: Stakeholder Engagement				X	X		
Reflection	X	X	X			X	X
Systems thinking	X	X	X		X	X	X

Figure 4: Course activities and relevant core competencies for learning. X symbols: use of core competencies in activities as indicated in literature. % Effective: average level of effectiveness based on student survey data. demonstration.

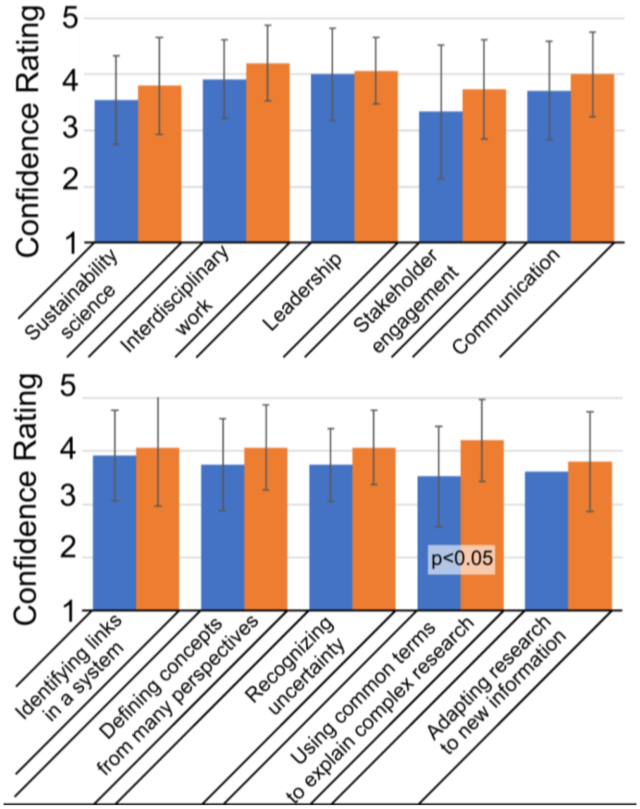

Figure 5: Mean student confidence ratings based on pre-course (blue) and post-course (orange) surveys. We identify statistically significant results where $p<0.05$. Error bars denote one standard

deviation. Confidence ratings: 1 = “not at all confident”, 2 = “somewhat unconfident”, 3 = “neither confident nor unconfident”, 4 = “somewhat confident”, 5 = “highly confident”.

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