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Sustainability science graduate students as boundary spanners

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Abstract

Purpose

Becoming a sustainability scientist requires specialized training beyond interdisciplinarity: it requires training in boundary spanning, interdisciplinary collaboration, and stakeholder engagement—all of which are often absent in the kind of science education programs that have been the hallmark of modern specialization-driven science.

Approach

Using boundary spanning as a framework for understanding graduate education training needs, we share results from our autoethnographic research on graduate education by focusing on one graduate program in particular, the Sustainability Solutions Initiative (SSI) at the University of Maine. We used a mixed-methods approach, including a quantitative survey and an autoethnographic reflection, to analyze our experiences as PhD students in sustainability science.

Findings

We identified four essential sustainability science boundaries that need to be incorporated into graduate programs: disciplines within academia, students and their advisors, researchers and stakeholders, and place based and generalizable research. We present the implications of each of these boundaries for future sustainability science training programs and offer seven guiding points to provide a basis for the development of a sustainability science education framework.

Originality

Our reflections are intended for academic leaders in sustainability science who are training new interdisciplinary scientists to solve complex sustainability challenges. Our experiences as a cohort of doctoral students with diverse academic and professional backgrounds provide a unique opportunity to reflect not only on the challenges of sustainability science itself, but also on the specific needs of students and programs striving to provide solutions.

Keywords

Sustainability, graduate education, interdisciplinary research, boundary spanning, organizational innovation

Article Classification Research Paper

Sustainability Science Graduate Students as Boundary Spanners

Introduction

Global citizens today live in a world rife with complex, or 'wicked' problems. Wicked problems are often characterized by competing value systems, unpredictable cause-effect relationships, high degrees of uncertainty, and multiple levels of government regulations (Rittel and Webber, 1973; Weber and Khademian, 2008). More than ever, scientists across disciplines are called upon to solve wicked problems, which tend to defy traditional scientific and disciplinary approaches. These problems require scientists to hold a more comprehensive, collaborative, and interdisciplinary skill set than is traditionally developed during single-discipline training programs.

Sustainability science is a fledgling branch of science that focuses on addressing wicked problems in social-ecological systems (SES), and demands scientific rigor across disciplines and institutions (Clark, 2007; Kajikawa, 2008). Leaders in sustainability science have established a guiding research agenda that calls for, among other things, an increase in the capacity to conduct this emerging scientific approach (Kates et al., 2001). To truly respond to society's most pressing and complex problems, academic institutions need to rethink how they train future scientists in ways to identify, analyze, and provide solutions to the challenges of SES. With prominent scientific organizations, such as the National Science Foundation (NSF), embracing sustainability science, numerous sustainability science research and education programs have emerged at universities across the United States (Clark, 2007). If we consider newly trained PhDs as central to the advancement and promotion of sustainability science, understanding their education pathways becomes particularly important.

Interdisciplinary graduate training has received attention in the literature (Borrego and Newswander, 2010; Graybill et al., 2006; Moslemi et al., 2009; Schmidt et al., 2012; Tress et al., 2009; Wagner et al., 2012), but we argue that becoming sustainability scientists requires specialized training beyond interdisciplinarity. In particular, the call for sustainability science brings refined academic training needs in boundary spanning, interdisciplinary collaboration, and stakeholder engagement within problem-based research —all of which are often absent in the kind of science education programs that have been the hallmark of modern specialization-driven science (Kueffer et al., 2012). Sustainability science research requires researchers to manage and span boundaries between academic departments to develop interdisciplinary expertise. Integrated research requires scientists to critically question boundaries that favor scientific framing and analysis of problems (Gieryn, 1983; Jasanoff, 1987) over non-expert or traditional ecological knowledge approaches. Sustainability science also requires researchers to reach out to non-academic audiences, including policy makers and other stakeholders to develop a "new contract" in which knowledge generation and problem-solving actions are inextricably linked (Bäckstrand, 2003). As an emerging field, sustainability science has few faculty researchers trained in all of the skills mentioned above (Kueffer et al., 2012), and yet the faculty is charged with educating and mentoring new scientists to carry the sustainability torch while working through the emergence of the new field themselves. As such, the time is ripe for a focused examination of graduate student education in sustainability science.

The question we address in this paper is: What aspects of graduate education are necessary to adequately prepare new researchers to successfully engage in sustainability science? To begin, we reflect on and assess our graduate training in a large, sustainability science initiative to provide insights and recommendations for future students, faculty mentors, and leaders of

sustainability science research programs. We argue that although sustainability science requires mastery in a larger suite of skills than "traditional" interdisciplinary studies, and with the right institutional support, faculty participation, and graduate student backgrounds, sustainability graduate programs can produce scientists fully capable of contributing solutions to wicked problems. We assert that our training has moved forward in producing a different kind of researcher: one that sees, through an interdisciplinary lens, the complex world and is able to develop and evaluate solutions for its wicked problems.

We begin with a brief discussion of sustainability science and describe the University of Maine's Sustainability Solutions Initiative (SSI) as a case study of research and education in sustainability science. We then use boundary spanning as a framework for understanding graduate education training needs. We share results from mixed methods research on graduate education in SSI and conclude with a discussion of the implications of these experiences for future sustainability science training programs.

Building Blocks of Sustainability Science

Sustainability itself has been defined in many ways, most commonly as meeting the needs of the current generation without compromising the ability of future generations to meet their needs (Bruntland Commission, 1987). Sustainability science distinguishes itself from other fields not only by focusing on the applied problem of understanding and promoting sustainability, but also by the several dimensions of how sustainability science is conducted (Clark and Dickson, 2003; Kates, 2011). It is problem-based, geared towards understanding and helping solve issues that arise from interactions of the natural and social systems. The ever-evolving interactions between people and their environments are at the heart of these issues, suggesting no clear start or end to

the problem (Kates et al., 2001). Given this, sustainability science is based on the belief that to address such problems, relevant stakeholders must be engaged in multiple aspects of the research initiative from problem identification, through data collection, to problem solving. Furthermore, sustainability science does not end with publication in a scientific journal, but must contribute to developing solutions for the target SES, through implementing policy, educating citizens, developing technological fixes, or other means (Kajikawa, 2008). Therefore, while sustainability science demands interdisciplinary and inter-organizational approaches to understanding and solving problems, it is distinct from other interdisciplinary contexts that may lack the complex, solutions-based, stakeholder-driven SES aspects described here.

Based on these definitions, there are three distinguishing characteristics of sustainability science that classify areas for training: (1) interdisciplinary research; (2) stakeholder-researcher partnerships; and (3) creating solutions from knowledge. The demands of interdisciplinary education shift from making students knowledgeable in one discipline to requiring them to "gain fluency in the ideas and language of *various disciplines* and also the behaviors expected in various disciplinary communities" (italics added, Holley, 2009). Similarly, training in stakeholder engaged research requires students to learn how to identify and manage researcher-stakeholder relationships. Sustainability science argues that knowledge derived from both researchers and stakeholders is key to understanding and solving sustainability issues, but there is not yet consensus on how to best integrate these bottom-up and top-down approaches to research (Reed et al., 2006). Finally, conducting science with solutions-oriented goals often demands a flexible approach to research and places dual pressures on scientists to both contribute to one's field *and* contribute to the development of solutions. Interdisciplinary, collaborative, solutions-oriented work requires a high degree of self-evaluation, cultural sensitivity, and

adaptability to working with others (Reich and Reich, 2006), yet many graduate students and scholars never receive training in these areas. In the following section, we turn to a case study to examine how these characteristics have been integrated into one training program.

Sustainability Solutions Initiative (SSI)

SSI is a five-year, NSF funded, $20 million research initiative at the University of Maine that seeks to "connect knowledge with action in ways that promote strong economies, vibrant communities, and healthy ecosystems in and beyond Maine." SSI uses both place-based and stakeholder-driven research at local and regional scales to develop science-based solutions across three core research areas: (1) SES; (2) the linkage between knowledge and action; and (3) organizational innovation that supports sustainability science. SSI utilizes a portfolio approach characterized by multiple projects that cross-cut numerous disciplines, including ecology, natural resources, economics, education, communication, engineering, and others. The portfolio is intended to diversify approaches, attacking wicked problems from multiple angles and across scales. In addition to several new faculty and post-docs, SSI recruited and funded 28 doctoral students, each of whom is affiliated with one or more projects within the portfolio. This group of sustainability science doctoral students, of which we, the authors, are all a part, has served as an incubator for innovation in graduate education, and provides an opportunity to reflect on the specific aspects of training necessary to fledge the next generation of sustainability scientists.

Boundary Spanning: A framework for training needs

Schmidt et al. (2012) used the "boundary spanning" concept, both figuratively and literally, to make recommendations for improving interdisciplinary and international graduate research training. Similarly, within SSI, the concept of boundaries and boundary spanning is used to

frame the disconnect—particularly in environmental science—between the scientists conducting academic research and the policy-makers and citizens facing real-world challenges.

This metaphor is useful to understand the typical distinctions, and sometimes barriers, that occur between diverse types of institutions, expertise, audiences, and even geographic scales. Several theorists have developed strategies to build common languages and coordinated approaches to cross such boundaries, yet few of these approaches are cited as core to the training of sustainability scientists (Clark et al., 2011; Weerts and Sandmann, 2010). Whitmer et al. (2010) identified a critical need for academic training to, "provide mentoring, leadership training, networking, technical support, and innovative curriculum development to foster successful engagement" (p. 314). It is in this spirit that we use the boundary spanning framework to identify areas for future training in sustainability science. Specifically, we examine the formal and informal education that guides graduate students' ability to span four specific boundaries: (1) disciplines within academia; (2) students and their advisors; (3) academic researchers and stakeholder partners; and (4) place-based and generalizable research. The next section presents data from SSI graduate students that highlight the need for training in these four areas of training.

Introspection from a Graduate Student Cohort

We used a mixed-methods approach, including a quantitative survey and an autoethnographic reflection, to analyze our experiences as PhD students in sustainability science (Creswell, 2003). Researchers working in similar interdisciplinary contexts have demonstrated the value of an autoethnographic approach (Armstrong et al., 2012; Graybill et al., 2006). In this vein, seven of the 14 doctoral students who began their programs in 2010 (referred to as Cohort 1) gathered

approximately once a month for a year starting in early 2012 to discuss and record individual and shared experiences. The four training themes discussed in this article were derived from a collaborative thematic analysis of meeting records from these gatherings.

To represent the entire SSI doctoral student population rather than only the members of Cohort 1 (n=14), we supplemented our autoethnographic approach with a web-based Qualtrics survey, sent in January 2013 to all SSI doctoral students remaining enrolled in the program (n=22). This group included first-, second-, third-, and fourth-year students. The survey included a combination of multiple choice, Likert-scale, and open-ended questions, to elicit both comparisons across individuals and specific contextual details of individuals. Respondents were asked to identify their perceived level of interdisciplinarity. To achieve a consistent measure of disciplinarity, we used the definitions of multi-, trans-, and interdisciplinarity set forth by Miller et al. (2008). The survey also assessed the following: expectations of and motivations for joining SSI, the development of hard and soft skills relevant to researchers and professionals students' perceptions of the adequacy of their training as sustainability scientists, and basic background and demographic information. Master's students conducting SSI research were excluded from the survey because of the shorter duration of their programs and to focus this research on doctoral student training. Hereafter, we will simply refer to the respondents as *students* rather than *PhD students*. Of the 22 recipients, we received responses from 18, yielding a response rate of 86%, which is exceptionally high for internet surveys although this was to be expected from the personal/professional relationships amongst SSI students. All seven authors of this paper are included among the 18 responses. We used evidence from the results of the survey to confirm or counter the themes of our experiences that emerged from our autoethnographic assessment.

Who we are

SSI is a research center rather than an academic department; therefore, SSI students each have a home department, such as biology and ecology, communication and journalism, economics, forest resources, psychology, or wildlife ecology. There is no formal, unified training among all students, although a core sustainability science readings course was offered each year. Survey results indicated that the most common (N=7, or 37%) degree sought was an interdisciplinary PhD, with another six (32%) PhDs in Ecology and Environmental Science—an interdisciplinary degree granted among multiple academic departments—and the remainder (41%) being PhDs in the subject of the home department. Age is an interesting characteristic of SSI students as results indicated they are older (the mode was the 31-35 category, and 5 respondents were over 35) than typical doctoral students in STEM disciplines who graduate at a median age of 30 years (National Science Foundation, 2012). Participants also reported having significant professional experience prior to enrolling in SSI. Five students had 5-10 years of experience, with four students having more than ten years of professional experience. Only two had less than one year professional experience.

SSI student motivations for pursuing PhDs are diverse. A common theme discovered during informal discussions is that a high number of students were not interested in academic careers. There is evidence, however, that during the SSI program, some individual preferences for post-PhD career paths shifted towards academic paths (Susan Gardner, personal communication, February 13, 2013). Survey results indicate that 65% of SSI students have interest in government, NGO, or private sector careers; 18% indicated interest in research and/or teaching at the university level, and 18% indicated they were equally interested in both. When asked what type of work they wanted to pursue after their degrees, regardless of type of institution, 53%

reported an interest in pursuing research, indicating an affinity for conducting research, but not necessarily in a university setting.

Learning to Span the Boundaries

Based on our autoethnographic reflections and survey results, and using our boundary spanning framework, we now highlight the four areas of training we believe are essential for sustainability scientists.

Disciplines within Academia

Sustainability science aims to simultaneously and collaboratively address how ecological, social and economic systems interact and is often more interdisciplinary than other scientific fields (Schoolman et al., 2012). While traditionally PhD research largely focused on deep and solitary examination within a single discipline, the training of graduate students in multiple disciplines is of growing interest (Evans and Randalls, 2008; Gardner et al., 2012; Schmidt et al., 2012). More specifically, sustainability science is unique in that it specifically calls for truly integrating social, ecological, and economic disciplines as opposed to interdisciplinary research that relies primarily on one discipline that is augmented by another (Miller et al., 2008).

SSI students each must satisfy the requirements of their home departments. In addition, SSI students are also required to take a one-credit sustainability science readings course. The readings course is the only formal curriculum requirement for SSI. Occasionally, relevant elective courses were offered that brought SSI students together for coursework and provided some degree of interdisciplinary research training, such as conservation planning and university-stakeholder partnerships. However, these courses were neither required nor broadly taken by SSI

students. In contrast, SSI regularly provided informal interdisciplinary learning opportunities that were highly valuable to graduate student training. There were numerous informal fora for discussions across disciplines including "brown bag lunches" focused on sustainability science problems and monthly SSI-wide meetings that included research updates from teams. In addition, there were informal ad hoc workshops, such as those on science communication and SES modeling.

Our survey results demonstrate that graduate students often faced the paradox of being trained as interdisciplinary researchers from within existing disciplines. Many students stated that they wanted to gain in-depth knowledge within their home discipline, but also wanted to collaborate with other disciplines, possibly through the larger research teams to which they belonged. One student's statement exemplified these dual goals: "I expected to work with individuals from a variety of different disciplines, and gain a better understanding of alternative research methods and epistemologies." Given the disparate curriculum requirements, each SSI student, in collaboration with advisors, individually navigated the extent to which his or her research was discipline-specific or interdisciplinary and how interdisciplinary future career paths will be. The students held in common the challenge of negotiating the boundary between depth in one field and breadth across many fields, and shared an understanding of the importance of gaining both disciplinary and interdisciplinary research skills.

It is not evident, however, that SSI students received the dual training that they desired and expected. Most students expressed dissatisfaction with the level of formal and informal training they received. Several students suggested that "core coursework in sustainability science has been lacking." Others were satisfied with taking formal courses primarily in specific disciplines, but desired more informal training opportunities in interdisciplinary research:

> I expected some focused discussions or workshops in how different types of data are brought together, how different ways of examining issues are combined, etc. I'm not sure if I thought that would happen at the [project] team level or at the whole SSI level, but regardless, it hasn't happened at all. I'm on my own to figure out how to do this.

Thus, while most students agreed that they are getting the discipline specific training they needed from their home departments, there was a range of expectations about what type of training students should receive in interdisciplinary research, and a general lack of satisfaction in the degree of interdisciplinary training received to date. While we cannot comment on the degree of interdisciplinary training provided in other sustainability programs, we suggest each such graduate training program should make a conscious effort to evaluate and define its expectations for interdisciplinarity.

These results suggest several opportunities for building on the strengths of the existing program and improving areas of weakness. For example, while there are also downsides of having students scattered across university departments, the benefit is that most (but not all) students feel that they gained the deep knowledge in their individual disciplines required of PhD students. This suggests that connecting sustainability science graduate students with specific departments is a key aspect of their training. However, our results also suggest that programs must specifically address student training in interdisciplinary research. Placing students on interdisciplinary research teams and offering ad-hoc classes over a few years does not adequately prepare graduate students for interdisciplinary research in sustainability science. **We recommend a short but required core curriculum (e.g. one course per semester for two years) that explores the complexities of conducting disciplinary and interdisciplinary**

research in the context of sustainability science. Schmidt et al. (2012) provide an example of the role that a common curriculum can play in graduate interdisciplinary training. This curriculum should bridge theory and practice, and include at a minimum, formal courses in sustainability science concepts, interdisciplinary research design and methodology, stakeholder-university partnerships, and science communication.

The Students and their Advisors

Faculty advisors, whose mentoring style is often informed by their own graduate training experiences, are typically responsible for ensuring their PhD students are appropriately trained in their subjects, conduct valid and worthwhile research, and are socialized in their disciplines (Weidman et al., 2001). While sustainability science PhD students require this disciplinary and institutional mentoring, they also require advisors who can provide guidance on other aspects of sustainability science, such as engaging with stakeholders, conducting interdisciplinary research, and contributing to real-world solutions. Advisors may or may not be aware of the need, or have the ability, to train students in these non-traditional skills. In addition, students themselves may come into a sustainability science program with professional knowledge and experience related to solutions-driven research, stakeholder relationships, and interdisciplinary projects, altering the traditional faculty-student dynamic of mentor-mentee. In this situation, advisor and advisee are both able to benefit through mutual learning. Literature on interdisciplinary graduate education often points to the need to have graduate advisors who are supportive of interdisciplinary research (Graybill et al., 2006; Schmidt et al., 2012; Tress et al., 2009), but does not explicitly address the gaps or the mutual learning that can occur during graduate education in non-traditional skills required of sustainability scientists.

Our experience sheds some light on the relationships between PhD students and their advisors, and suggests that mutual learning was acknowledged in only a fraction of student-advisor relationships. The strong support from many SSI advisors is clear in some student responses: "My advisors embrace interdisciplinary research and have worked to make the interdisciplinary approach seamless in my comprehensive exam and dissertation processes." This support may be expected, since faculty advisors all applied for funding to conduct projects under the umbrella of SSI. However, a handful of students felt their advisors neither understood nor supported interdisciplinary research, as expressed by this student: "My advisor has a fairly conventional and strict view of the role of depth in the doctoral program, bounded by fairly well-defined disciplinary boundaries and grounded in my field of specialization." This suggests that even though faculty applied for funding for interdisciplinary projects, some did not necessarily believe that PhD students themselves should conduct this type of research during their training. Given the recommendation in previous literature for supportive faculty, specific and deliberate effort must be made to ensure faculty advisors share a common understanding of graduate student research roles in sustainability science programs.

While many students reported advisor support for their interdisciplinary research, fewer reported having advisors able to provide guidance in how to conduct such research. For many advisors, SSI represents the first time they have treaded the waters of interdisciplinarity, stakeholder research, or connecting knowledge with solutions. Yet several SSI students reported bringing with them extensive experience in interdisciplinary work through previous academic training and professional work experience, reversing the traditional academic hierarchy between advisors and students. One student who has two advisors in different disciplines reported that "they brought me on to be the 'bridge' between their two disciplines." This dynamic of mutual learning can

foster added collegiality and respect between team members, with less of the intellectual hierarchy often present in advisor/advisee relationships. However, other students expressed more frustration with guidance from their advisors:

> "My research is pretty different from what [my advisor] does, so even though [my advisor] gets the big picture really well, and is excited about it, there is little guidance in terms of how to form research questions (or, even, what are appropriate research questions), how to develop methods, what types of journals to use as models, etc."

These comments suggest that some students believe they have specific sustainability science skills they can contribute to the team, but they may not feel empowered to do so.

Conversely, some students desired mentoring in specific sustainability science skills they lack but which simply could not be provided by faculty who may themselves lack these skills. Many of the SSI faculty experienced significant demands because of their involvement in a cross-cutting program. Some were not only ill-equipped themselves to conduct sustainability science, but perhaps were not given guidance from their leadership in how to mentor students in non-traditional skills. **Future sustainability science programs should consider providing specialized training to the advisors, and to facilitate discussions that institutionalize expectations for sustainability science mentoring.** In addition, faculty advisors of sustainability science graduate students should have open dialogue with their students about the skills each brings to the project, and their expectations for mutual learning, interdisciplinary, and stakeholder-driven and solutions-based research.

Academic researchers and stakeholder partners

Stakeholder-researcher partnerships are an integral aspect of sustainability science. Numerous sustainability science scholars argue that a collaborative approach to problem identification, research, analysis and interpretation may be instrumental in connecting knowledge to action (Cash et al., 2003; Clark and Dickson, 2003; van Kerkhoff and Lebel, 2006; Whitmer et al., 2010). SSI has embraced the significance of stakeholder-researcher partnerships at both institutional and team levels, and this aspect of sustainability is clearly communicated as important to both student and programmatic success. However, forming and cultivating these partnerships is very challenging and is not an implicit skill for PhD students or academics (Kueffer et al., 2012). For many there is a significant knowledge gap in both the theory and practice of working with stakeholders. The former can be addressed with formal teaching, but the latter requires practice and experiential learning (Silka, 1999). Within SSI, such training has been primarily experiential, augmented with a limited number of formal training opportunities, which may not be directly applicable. For example, an optional NSF-sponsored workshop on science communication was offered, which while important for general science communications, was not designed to focus on the complexities of partnerships themselves. In addition, an elective course on university-stakeholder partnerships was offered by a leading expert on such partnerships in SSI. With those exceptions, most of our training in developing and leveraging university-stakeholder partnerships has come from participation in our individual team's research.

Teams approached stakeholder engagement in widely different ways, and thus the culture and frequency of engagement have developed at the project team level, rather than across SSI. Therefore, SSI student experiences vary significantly in terms of 1) the types of stakeholders with whom they interact, 2) the level of stakeholder participation in research projects, and 3) the

level of empowerment students have to initiate and manage the partnerships. Teams may collaborate with local citizens, state and federal regulatory agency representatives, or industry partners and NGOs. While some students work closely with project partners designing the research study, collecting data, and analyzing results, other interactions are more cursory, often restricted to brief communication or surveys. For some students, interactions with stakeholders were completely absent. Even with SSI's broad collective experience in developing and managing partnerships, there was minimal formal reflection on the constraints, ethical questions, and lessons learned through these experiences. Despite the lack of formal training opportunities, 67% of student respondents believe they are getting better at the key skills needed for stakeholder engagement, especially with group facilitation and creative problem solving. Yet some students felt they could complete their degrees with only a slightly greater knowledge of partnerships than when they arrived.

Due to the timeline of pre-identifying research teams and questions for the application for the large NSF grant that funds SSI, many of our teams did not truly co-identify with stakeholders' specific research questions during the proposal phase. At a minimum, this meant that PhD students did not have the opportunity to experience and learn about this aspect of partnerships and, at its worst, risked producing research that is not adequately calibrated to the needs of stakeholders. As indicated by one student, this disconnect between the research and stakeholders at a critical phase was not apparent to everyone at the beginning of our programs:

> I didn't realize that the already established project teams were not necessarily planned with community partners. I have found this to be a struggle because it feels like we're playing catch-up, without a lot of flexibility.

We also found that faculty expertise in conducting stakeholder research was varied, with some having extensive experience and others having none at all. There appeared to be a mismatch in the desire of SSI to conduct (and teach about) stakeholder partnerships, and its capacity to actually do so. Since the majority of SSI students had prior professional experience, their ability to actively engage in, and in some cases manage, these partnerships was vital to the success of cultivating partnership for several teams.

With such great variation in partnership capacity between and within teams, we suggest that research teams should have members with some training in stakeholder engagement, but that individual students seeking to become sustainability scientists should be trained to have a thorough understanding of stakeholder partnerships. **Thus, we believe that sustainability science training should emphasize formal training in both the theoretical and practical aspects of research partnerships.** One solution would be to require a course that combines learning the theory of partnerships with a guided stakeholder partnership practicum that encourages students to reflect, discuss and learn from their experiences on research teams. Additionally, each team should have at least one member with substantial experience in partnership development and facilitation. This person would lead the team's partnerships and would engage other team members in development of these skills vital for sustainability science.

Place-based and generalizable research

Maine is the most rural state in the United States (USCB, 2010) and consequently SSI's place-based sustainability science focused on problems in rural and urbanizing areas. Thus SSI was uniquely positioned to address a different suite of sustainability issues compared with other sustainability science programs, which tend to focus on urban areas. The rural nature of Maine

along with the New England tradition of home-rule in policy arenas make the local level of stakeholder engagement that much more important. By emphasizing the creation of solutions to local challenges, SSI has provided excellent training at this scale through SSI-wide informal discussions and on-the-ground stakeholder-based research. While the SSI emphasis on place-based research has many advantages, we questioned if it adequately prepares scientists to develop generalizable theories that advance sustainability science as a field.

The need for science to generalize case-study specific knowledge to broad problems epitomizes the difficulty of adequately addressing scale in research projects. Kates et al. (2001) note, "The regional character of much of what sustainability science is trying to explain means that relevant research will have to integrate the effects of key processes across the full range of scales, from local to global" (Kates et al., 2001). The drive to move across scales also comes from major funding organizations, such as NSF, who seek to make insights from these questions applicable in other contexts for the sake of scientific knowledge production and fiscal efficiency. Therefore adequate training in extrapolating and generalizing research from place-based context to the broader scientific realm is vital for the training of PhD students.

The process of developing dissertation research questions based on stakeholder-based research has enabled many SSI students to walk the line between working with stakeholders on applied questions and contributing to the broader, generalized scientific debate. In the relatively short window of opportunity that PhD students have, it is difficult to both focus on place-based problems and to develop generalizable sustainability science theories. SSI, with its portfolio model, provided a unique opportunity to study multiple manifestations of sustainability challenges. Though as students we were immersed in project-based challenges, we were rarely engaged in discussions across the portfolio. **We suggest students should be involved in**

discussions that synthesize common challenges and themes across multiple sustainability science projects, which would further their training in identifying cross-cutting sustainability theories.

Conclusions

We believe a commitment to improve graduate education in sustainability science is a critical component of crossing the boundary from an emergent field to an established one upon which society can rely to address wicked problems. Graduate education should help students master core competencies in theory and practice by not only providing a methodological foundation from which to conduct research, but also by cultivating a universal language that allows researchers and stakeholders jointly to take lessons from the laboratory to the real world. Such common ground is especially important for new generations of sustainability scientists, who may call a wide range of departments and institutions home.

Based on our experiences and analysis, we recommend that the sustainability science community develop a common framework to inform and guide future sustainability science graduate education at universities. Universities establishing such programs should use the framework to deliberately and rigorously identify their own goals, evaluate their institutional abilities to deliver the program, and design the necessary components of their sustainability science research and education programs. We believe a framework should foster a culture of mutual learning across three domains: student experience, faculty capacity, and institutional support. It is essential that this be a deliberate effort; simply adapting traditional models of disciplinary graduate education may leave future sustainability scientists ill-equipped to produce new relevant knowledge and develop significant solutions.

As graduate students nearing the end of our own education, we humbly offer the following as a basis for the development of a sustainability science education framework:

- Provide opportunities for graduate students to be active members of interdisciplinary research teams;
- Develop a core curriculum to ground graduate students in the theory and methodologies of sustainability science, both by drawing from existing course offerings as well as designing new, sustainability science-specific courses;
- If graduate students have a home department outside of the sustainability science training program, clearly articulate the dual expectations placed on the students by the program and their home departments;
- Ensure formal and informal, and theoretical and experiential educational opportunities are part of the students' training;
- Assemble faculty members who have the expertise necessary to mentor advisees in sustainability science, or provide necessary training for engaged faculty who lack such expertise;
- Pre-determine and communicate the expected role of the graduate student in the stakeholder engagement process, and provide the necessary training to do so; and
- Provide opportunities for, and engage students in, cross-team and program-wide dialogues to develop cross-cutting research questions and knowledge synthesis.

We believe addressing all these components of training programs in a common framework will better prepare the next generation of sustainability scientists. Furthermore, a program that has critically considered these issues during the program development phase will have greater transparency and will offer clear expectations for all participants. Administrators and faculty will

benefit by having strong students who are able to make meaningful contributions to the program. Stakeholders will benefit by having strong relationships with scientists that will yield salient, credible, and relevant information to solve problems. Most importantly for our discussion, graduate students will benefit by gaining a comprehensive sustainability science education, which they can then apply throughout their careers.

Sustainability science, with its focus on integrating multiple disciplinary perspectives to develop solutions for on-the-ground problems, provides educational challenges not experienced in traditional disciplinary doctoral programs. However, as graduate students navigate their formal training programs and begin to develop their own research programs, regardless of their disciplinary lens or professional sector, a rigorous grounding in the theory and methods of this field will result in highly skilled scientists producing valuable research outcomes.

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