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A community-engaged approach to transdisciplinary doctoral training in urban ecosystem
services

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Abstract: Community-based projects with inclusive stakeholder engagement are increasingly important to achieve robust outcomes in the science and management of ‘wicked’ urban ecosystem service challenges. We summarize lessons learned from a transdisciplinary, team-based doctoral education program that engaged students in research on such multi-stakeholder, complex problems. The key lessons are (a) problem-based components foster active student engagement and accelerate transdisciplinary analysis, (b) problems addressing more acute interventions by public or private organizations enable learning by clearly delineating the issues and revealing the goals and perspectives of varied stakeholders, (c) successful projects that address wicked problems require that transdisciplinary teams begin from inception to robustly frame research questions with multiple lenses and choose appropriate theories and methods to implement projects, (d) regular stakeholder engagement leads to mutually meaningful project outcomes that advance scholarly frontiers for university researchers and provide relevant solutions for community partners, and (e) university administrative investment in program faculty, students and staff and flexibility to reward innovative collaborations across disciplinary boundaries are keys to facilitate success in transdisciplinary education. Our lessons provide guidance both for addressing wicked problems through research projects in general and for formulating transdisciplinary training approaches for graduate education.

Keywords: community engagement, problem-based research, transdisciplinary doctoral education, urban ecosystem services, wicked problems

1. Introduction

Humans have a profound influence on the earth's biosphere and climatic systems, leading to grand challenges involving earth's modified climate system, exploited ecosystems, and fragmented social systems that govern their use. No longer is any place on earth considered pristine. Contaminants and invasive species can be found in remote locations from Antarctica to the ocean depths (e.g., Taylor et al. 2016). To solve today's complex socio-ecological problems, complicated by cross-jurisdictional and geographic boundaries, traditional reductionist disciplinary approaches are insufficient. These challenges have led scholars to recognize a class of complex problems that cannot be solved with standard disciplinary approaches. Rittel and Webber (1973), in their seminal paper, conceptualized this class of "wicked" problems in the context of urban planning (see Box 1), and their ideas have been extended into environmental management (Sayer et al. 2013; Jussaume and Ervin 2016). Such complex challenges stand in contrast to "tame" problems, such as eliminating specific sources of food contamination or engineering better stormwater retention basin geometries, which could be solved with single disciplinary approaches. As a result, interdisciplinary, or preferably transdisciplinary approaches that engage diverse stakeholders (Lang et al. 2012; Bracken et al. 2015), are required to understand the nature of such complex socio-ecological problems and develop actionable approaches to manage them (e.g., van Riper et al. 2017). These new approaches typically adopt transformational sustainability science, which departs from sustainability science that has

focused on generating descriptive-analytical knowledge of the past, present and future (Wiek et al. 2012). Thus, transformational sustainability science uses innovative models to better facilitate co-production of knowledge between academicians and practitioners through co-learning to identify feasible and practical solutions (Wiek et al., 2012; Wiek and Key 2015; Keeler et al. 2016; Matson et al. 2016; Horcea-Milcu et al. 2019). With transformational sustainability science, scientists become active participants in decision-making processes that seek fundamental societal changes (Wiek et al. 2012).

Box 1. Characteristics of a wicked problem (after Rittel and Webber, 1973, pp. 161-167)

1. No definitive formulation.
2. No stopping rule.
3. No true or false solutions, but good or bad.
4. No immediate or ultimate test of a solution.
5. Every solution is a one-shot operation, i.e., no opportunity to learn by trial and error.
6. No enumerable set of solutions, nor is there a well described set of permissible operations.
7. Each wicked problem is essentially unique.
8. Each wicked problem is symptomatic of another problem.
9. Wicked problems have multiple potential and viable causes.
10. Those (planners) who propose solutions have no right to be wrong.

Creating interdisciplinary environments in university settings can present both opportunities and challenges (Miller et al. 2008; Shandas and Brown 2016). In this research context, using a pluralistic approach to integrating multiple epistemologies can lead to a better integration of investigations (Miller et al. 2008). The US National Science Foundation's Integrative Graduate Education and Research Traineeship (IGERT) program was developed in part to pioneer change in graduate education to achieve interdisciplinary research and education in U.S. Ph.D. programs that transcend traditional disciplinary boundaries (IGERT 2018). With support from the NSF IGERT program, faculty at Portland State University (PSU) developed a transdisciplinary curriculum based on team learning with active community partner engagement (Walter et al. 2007, Gethmann et al. 2015) to train doctoral students to understand and manage ecosystem services that support urbanizing regions (hereafter ESUR-IGERT). Our program shares some common characteristics with other IGERT programs with a sustainability focus in terms of an interdisciplinary team of scientists and practitioners and using experiential learning about critical environmental issues (Graybill et al., 2006). The nexus of ecosystem services and urbanizing regions generates many wicked problems that require the integration of multiple disciplines to understand their roots and boundaries (e.g., balancing environmental quality and social equity; providing for outdoor recreation opportunities while minimizing public health risks; maintaining biological diversity and wildlife habitat in areas of dense human habitation or suburban sprawl) (Ervin et al. 2012, Haase et al. 2014, Shandas et al. 2014). Restoring ecosystem services in urban areas could offer multiple benefits for society and the environment (Elmqvist et al. 2015). Therefore, our curriculum was designed to train ESUR-IGERT students to serve in professional roles in which they would diagnose wicked problems

and design productive approaches, rather than specific solutions, through transdisciplinary methods.

A fundamental challenge of addressing wicked problems is developing approaches that accommodate the needs of all parties. Being able to identify and articulate power dynamics can facilitate design processes and strategies to address power imbalances (Ostrom et al. 1994; Cook and Kothari 2001, Barnaud and Van Paassen 2013, Horcea-Milcu et al. 2016, Martinez-Harms et al. 2018). Projects that directly address power differentials provide opportunities to engage in philosophical and sociological underpinnings of decision-making. Student training included an introduction to a social equity lens that encompasses broader environmental and social justice concerns to effectively address wicked environmental problems embedded in a broader societal context as well as the cultural aspect of ecosystem services (Daniel et al. 2012). Our IGERT was designed to achieve such a “knowledge democracy” to form actionable, collaborative approaches for progress on wicked problems (Bunders et al. 2010).

Several weaknesses of U.S. graduate education have been identified by national studies (Altbach and Knight 2007; Crozier et al 2008; Altbach et al. 2016) and serve as the motivation for a number of national initiatives to expand interdisciplinary, project-based graduate education (e.g., Woodrow Wilson Foundation; Carnegie Initiative on the Doctorate; American Council on Education’s Commission on Internationalization and Global Engagement). While most traditional doctoral programs are well suited to prepare future professors for new knowledge generation, they are less effective in preparing students for jobs in industry, the public sector, the non-profit sector, and other professional venues that require designing approaches to wicked socio-ecological problems (Persha et al. 2011; Bruggemann et al., 2012).

Missing from most graduate training programs are opportunities and appropriate professional preparation that match the full spectrum of career pathways doctoral students might pursue, including non-academic posts (Ciannelli et al. 2014; Lang et al. 2017).

Additionally, U.S. graduate education is generally not designed to prepare students for the challenges of participating in an increasingly interdependent global scientific community (Choudaha and Chang 2012; Pain 2016). Traditionally, the introduction of an explicitly interdisciplinary or transdisciplinary component can run counter to the expectations of a typical doctoral committee in terms of individual versus shared effort. Exposure to transdisciplinary dimensions of research can provide opportunities to make scientific contributions that benefit local communities and have global consequences (e.g., Wilbanks and Kates, 1999; Schinler et al., 2012), while contributing to global scientific understanding of critical issues such as urban ecosystem services (Costanza et al. 2011, Ervin et al. 2012). Our program builds upon recent efforts in transdisciplinary environmental education (Wiek et al. 2011) at some pioneering institutes (e.g., ETH Zurich's Transdisciplinarity Lab, Arizona State University's School of Sustainability). We posit that involving students in transdisciplinary research and education enriches their experiential knowledge, provides opportunities to engage in problem-based scholarship, and offers exposure to different approaches for addressing solutions to practical problems, many that embody wicked challenges facing our communities. University researchers are uniquely positioned to conduct community-engaged research because they can leverage the most current accumulated knowledge and apply it to emerging problems in their region (Evans et al. 2015; Wiek and Kay 2015; Crow-Miller et al. 2016). This combination of conceptual capacity, research skill, and the geographic proximity of the problem can engender the

goodwill, investment, and collaboration of public and private partners interested in structuring solutions.

We report how we developed the community-engaged transdisciplinary doctoral program, worked with stakeholders to tackle their wicked problems, and addressed opportunities and challenges. By doing so, we share a process for identifying and conducting appropriate projects to engage students in experiential and collaborative learning and scholarship with explicit stakeholder engagement. First, we introduce an innovative conceptual model for transdisciplinary graduate education and research and summarize the history and process of developing this model through curriculum creation and refinement. Second, we share the selection process and overview of community-engaged class project topics and student learning experiences in the transdisciplinary curriculum. Finally, we conclude with lessons for future community-engaged problem-based transdisciplinary scholarship for other doctoral programs that may face similar issues.

2. ESUR-IGERT courses

2.1 Organizing principle of the ESUR-IGERT curriculum

The guiding principle of our curriculum design was that we engaged community partners closely, actively, and continuously with our pedagogy, emphasizing the role of the community partners in helping to foster transdisciplinary graduate education and research from problem identification to possible solution generation. We drew upon theories from the engagement literature on participatory action research (Rahman 1991; Kindon et al. 2007; Ruckelshaus et al.

2015), asset-based community development (Kretzmann and McKnight 1993; Green and Haines 2016), and participatory planning (Fisher 2001). We chose these theories to frame our approach to our projects that explicitly addressed how urban-suburban communities directly take on challenging sustainability problems. We developed possible solutions to those problems with close collaboration between university researchers and community partners.

With this community-engaged participatory approach, we propose that academic institutions can expand upon traditional disciplinarily-focused doctoral degrees that are inherently singular and somewhat lonely enterprises to train transdisciplinary practitioners, teachers, and researchers (Benbasat and Gass 2002; Dryden et al. 2012). As summarized in the NSF dear colleague letter (NSF 2016), discoveries and scientific advancement are often made at the frontier – which frequently coincides with the intersections of disciplinary boundaries – and necessitate additional resources to promote interdisciplinary research and education.

Specifically:

- *Scientific advances often lie outside the scope of a single program or discipline, such that substantial funding support from more than one program or discipline is necessary.*
- *Transdisciplinary lines of research promise transformational advances.*
- *Prospective discoveries reside at the interfaces of disciplinary boundaries that may not be recognized through traditional review or co-review*

As illustrated in Figure 1, our community-engaged transdisciplinary (CET) model enables a stronger relationship among community partners, students, and faculty. In the CET model, community partners are part of the core team, actively and regularly engaging with a university

learning environment in which student-faculty interactions are also strong. In the traditional educational model, community partners are loosely connected, if at all, to students and faculty, and the connection between students and faculty is also variable. Additional university resources and investment are frequently needed to strengthen and tighten the interactions among the three actors.

2.2 ESUR-IGERT courses

To implement the CET model, with internal university support, the authors team-taught an experimental course titled *“Ecosystem Services and Sustainability: Field Projects”* focused on outcomes of the historic removal of Marmot Dam from the Sandy River, Oregon, in winter 2009, prior to NSF IGERT funding. A pair of faculty (comprising one social and one biophysical scientist) supervised each student group project assessing environmental, economic, and socio-cultural impacts of the shift in ecosystem services resulting from dam removal (Yeakley et al. 2016). Student - faculty interactions included multiple site visits, attendance at community meetings, and engagement with several community partners to integrate community perspectives and knowledge into design and implementation of community-based research projects (Kindon et al. 2007). For example, one group conducted resident surveys of perceptions and values of the lake lost after dam removal, revealing that a key stakeholder group was neglected in the dam removal decision process. This course laid a fundamental foundation for the future ESUR-IGERT doctoral program.

With funding from NSF, we admitted five cohorts with student numbers in parenthesis, 2011 (6), 2012 (7), 2013 (7), 2014 (7) and 2015 (7). Although we started planning in the fall of

2010, the program was formally launched in August, 2011 and ended in August, 2017. Students sought degrees in several academic programs, encompassing anthropology, environmental and material engineering, environmental science, geography, public policy, sociology, and urban studies and planning. ESUR-IGERT faculty initially offered four core courses, each taught by a pair of subject specialists: ecological, social, methodological, and economic aspects of ecosystem service analysis and valuation, respectively. Constructive feedback from the first cohort of ESUR-IGERT students, reported by an external evaluator at the end of the cohort's first academic year, pointed out that faculty members instructing each class presented the material through their disciplinary frameworks with little integration across different lenses, highlighting the need to integrate across disciplines in each course. Moreover, our first cohort of doctoral students failed to achieve the degree of interdisciplinarity sought by the ESUR-IGERT program as most of the students ended up focusing on their disciplinary journey with only one pair co-presenting and co-publishing interdisciplinary work.

2.3 Revision of the ESUR-IGERT curriculum

From the cohort one feedback, we recognized that implementation of the three-way interaction illustrated in Figure 1 required development of a transdisciplinary curriculum integrating theory and practice of multiple disciplines, including ecology, economics, geography, sociology, and urban planning. Through engagement with and learning from an external evaluator, the IGERT faculty team restructured the course series to create three integrated, transdisciplinary courses taught as a series within a single academic year (Table 1). After Year 2, the ESUR-IGERT courses were co-taught by two instructors, each from different

disciplinary backgrounds. This approach represented an effective step toward making transdisciplinarity an integral part of the ESUR-IGERT program. The 1st course focused on relevant *theories* from sociology, anthropology, ecology, economics, physical geography, spatial analysis, and urban studies and planning that together contributed to the analysis of ecosystem services and provided adequate exposure and depth across fields. In the 2nd course, subject specialists (including community partners) presented *methods and tools* applied to ecosystem service assessment in the context of their research, and students completed in-depth lab assignments to practice these methods and tools using local examples. In the third course, student teams synthesized the theoretical concepts, approaches, and tools learned from the first two courses to conduct a *place-based, stakeholder-engaged, socio-ecological project*. Students individually (second cohort) or in teams (third through fifth cohort) were presented with a local, timely, multi-faceted (i.e., involving many stakeholders with contrasting viewpoints), “wicked problem” concerning ecosystem management. Additionally, four supplementary courses were designed to support students’ team-building approaches, methodological skills, and writing competencies (Figure 2). Incoming students were introduced to the concept of wicked problems in an intensive Summer Institute that invited stakeholder parties engaged in a contested sustainability issue. Supplemental courses framed student research questions via ethics (see Box 2), writing, and in-depth reading and group discussion.

In addition to required ESUR-IGERT core courses, each student took additional courses required or recommended in her/his discipline. By taking both interdisciplinary and disciplinary courses (in terms of both theories and methods), we aimed to train our students to be a general specialist, i.e. a T-shaped researcher (Brown et al. 2015). As sustainability science

pushes the disciplinary boundaries, our aim was to train our students to become versatile in navigating different theories and methods in various disciplines, which has been termed epistemological agility (Haider et al. 2018).

BOX 2: Worldviews and ethical considerations - Individuals from different disciplines bring diverse world views to an interdisciplinary team. Interdisciplinary work requires acknowledgement of the various ways of knowing the world and how each person's 'way of knowing' affects their perspective in the work they do. When working on problem-based research, consideration of diverse users and their perspectives is essential to effective and just problem-solving. As such, we integrated discussion of disciplinary perspectives and ontologies into the core course series, including scientific ethics, and taught a dedicated course on *Science, Values and Politics* during the year two curriculum to train our students to navigate different worldviews or theories of knowledge (Eigenbrode et al. 2007; McWilliam and Tan 2010; Haider et al.2018).

3. Cohort project topics and learning outcomes

3.1 Project topic selection

The ESUR-IGERT faculty selected project topics based on three parameters. First, the topics addressed the fundamental principle of incorporating experiential knowledge and stakeholder engagement into the pedagogical approach. Second, any prospective project had strong and broad ESUR-IGERT faculty interest or was connected to an ongoing faculty research program. Third, we considered community partners' interest and willingness to support

students' projects, which typically focused on contentious sustainability issues. For cohort years 2 and 3, the class project topics were chosen by the faculty team teaching the third course. In response to the students' feedback and the need to introduce class project topics earlier to better integrate across the three courses, in years 4 and 5, the ESUR-IGERT core faculty discussed project ideas during the summer. This revised approach was highly effective in terms of selecting a viable class project topic and engaging relevant stakeholders in advance.

For the fourth year's cohort project, the ESUR-IGERT faculty selected the Willamette Falls Legacy project because it addressed an upcoming community level decision about the existence and nature of a massive development project (i.e., a sharp intervention point loomed in the near future). The topic was chosen because it had the most favorable attributes to enhance transdisciplinarity and could successfully address equity and diversity issues, including those of local tribal access to important traditional salmon and lamprey fishing sites. The regional Native American community has a long tradition of salmon and lamprey fishing as part of their culture and nutrition and relies on fisheries at the site (Close et al. 2002) while their harvest rights have been challenged with evolving river management and treaty rights (Galbreath et al. 2014). The fifth year's cohort project, the Clackamas watershed ecosystem services project, was selected in large part because two ESUR-IGERT faculty had active ongoing research with community partners and it similarly involved upcoming large-scale decision making about water and land management. Each cohort's projects represented a diverse set of objectives, methods, stakeholder involvement, and pedagogical outcomes (Table 2).

3.2 Main characteristics of projects

The scale of each cohort project varied in terms of space, time, stakeholder engagement, and land use characteristics (Table 3). All projects are positioned along a spectrum of wicked problems, yet smaller scale, timely projects typically had stronger stakeholder buy-in than larger scale, forward-looking projects that exhibited greater diversity of engaged stakeholders. Unifying characteristics of student course projects included: active engagement with salient stakeholders in formulating and executing their studies; integration of experiential knowledge, which included stakeholder input as well as personal contact and field experience by the students; creation of transdisciplinary student teams; and flexibility around pedagogical approaches (Eigenbrode et al., 2007; Wiek et al. 2011). Students identified these characteristics as the elements that led to their transdisciplinary learning. For example, stakeholder outreach and engagement occurred from project development to completion, spanned multiple agency levels, from local to federal, and exposed students to diverse social, economic and environmental interests of stakeholders, their ability to influence the direction of solutions, and the challenges of decision making agencies being attentive to outcomes that promote social justice. Interdisciplinary student teams were able to address a suite of ecosystem service aspects, facilitated by diverse pedagogical approaches, both in methods used and outcomes realized.

The faculty provided the boundary conditions, describing a specific wicked problem with a defined spatiotemporal domain (e.g., a riverine island to be developed, a watershed in which a dam was recently removed). Within that domain, a student team selected a specific topic of their interest then narrowed the project scope through discussion with, and feedback from faculty and community partners. This exercise in problem identification and framing led to a

refined research question(s) and selection of appropriate methods. Student teams then carried out the project with constant feedback from multiple parties and presented findings to the public (i.e., other students, the faculty, and external stakeholders). By doing so, students indicated that they appreciated the “wickedness” of the problem that they were investigating and learned to work with both diverse stakeholders and peers who view the world with different lenses.

In all cases, the involvement of diverse community partners facilitated salient problem identification and refinement of the conceptual framework to align with the issue at hand (Bosque-Perez et al. 2016). Students were willing to modify the scope of their work to offer potentially useable information to relevant stakeholders. According to an ESUR-IGERT student survey conducted in Spring 2016, the majority of the student respondents enjoyed regular engagement with willing community partners and greatly valued the role of practitioners, who helped ground their projects in the “real world” from problem definition to conceptual framework development, to career impact (see Table 4). Similar satisfactory responses were found in other IGERT programs when students were actively engaged with community partners and co-produced knowledge and potential solutions together (Eigenbrode et al., 2007; Wiek et al., 2015; Bosque-Pérez et al. 2016).

While the first and second year’s projects did not result in any actionable outcomes because most projects had already been completed before students’ involvement, later years’ cohort projects yielded some decision-relevant outcomes. In particular, the fifth year’s cohort project, the Clackamas watershed project, led to a fruitful resilience outcome with the explicit involvement of stakeholders (citation). A couple of ESUR-IGERT faculty (one social scientist and

one physical scientist) continued to work with the community partners who were interested in exploring watershed resilience in the face of climate change and population growth. The two-year follow-up project, co-sponsored by PSU-ISS (Institute for Sustainable Solutions) and the community partners, hosted two stakeholder workshops to identify resilience pathways of the watershed. The research group shared their findings, obtained feedback, and modified their assumptions and analyses throughout the project period. Two IGERT students were continuously involved in the project, with one student completing a dissertation on a related topic (Larson 2019).

4. Discussion

4.1 Lessons for engaging community partners

While engaging with stakeholders presents abundant opportunities for improving policy options to address wicked environmental problems (Sayer et al. 2013, Frantzeskaki and Kabisch 2016, Liqueste et al. 2016, Antognelli and Vizzari 2017), few research-based graduate programs offer a structured opportunity for graduate students to directly engage stakeholders through curricular efforts. Our program was similar in several respects to other IGERT sustainability-related programs. For example, in our survey of such programs (see Appendix Table A), most addressed large-scale, wicked problems and all had three or more disciplines working together. A smaller subset, however, had non-academic partners, and only a few had a supporting home center that was not a specific academic department. In our case, the ESUR-IGERT curriculum deliberately integrated graduate student training with regional stakeholders on questions of

ecosystem services. By involving stakeholders early in the process, our graduate students were able to identify the immediate and pressing needs of their community partners, while the faculty actively coached students in research design, scholarly contribution, and transdisciplinary pedagogy. IGERT faculty engaged community stakeholders in classroom presentations and extensively in group projects. This overt strategy assured stakeholder experiential knowledge entered the curriculum and became essential intelligence in crafting approaches to address the wicked problems under study. IGERT fellows rated the collaborations with community stakeholders very highly in terms of delivering educational value to their training program. By and large, the stakeholders also expressed positive evaluations of IGERT student contributions to their ecosystem service management issues affecting urban populations.

Through this process and congruous with the literature on ecosystem services (Costanza et al. 2011), several lessons emerged. Active and comprehensive stakeholder engagement: (1) helped frame the context and tailor inputs to local needs and data availability (Ruckelshaus et al., 2015); (2) assured output metrics and knowledge production processes were credible, relevant, and legitimate (Cash et al., 2003; Cowling et al., 2008), and (3) constructed a comprehensive picture of the values in play and the tradeoffs including ecological and cultural perspectives (Iniesta-Arandia et al. 2014). In addition, faculty engagement reminded students that they were not consultants (helping them navigate through occasional pressure from stakeholders to serve in that role), but instead were available to co-produce knowledge with community stakeholders. Co-producing knowledge in this context consisted of numerous meetings that helped each research team identify tractable challenges facing the

stakeholder(s), methods that showed promise, and outputs (and outcomes) that offered insights on the specific topic including potential solutions (Miller et al. 2014), while balancing a need for scholarly contribution (Kaczorowska et al. 2016). The effectiveness of our program in this regard was confirmed by the survey findings that the ESUR-IGERT students were more interested than non-IGERT students in working with collaborators outside academia and cultivating broader perspectives through working with a diverse group ($p < 0.05$). However, community partners could consider such collaborative learning as a time sink if they perceive that the desired outcomes are not being facilitated by the university partners. It is thus crucial to have a facilitating agent or organization either through an graduate program or an institute (e.g., the Institute for Sustainable Solutions (ISS) at PSU) that promotes such engagement, as evidenced by some IGERT programs shown in Appendix Table A.

4.2 Lessons for training students

Community-engaged transdisciplinary education present both opportunities and challenges, which are viewed differently by faculty, student, community partner, and university administrator perspectives (see Table 5). As revealed by the student survey, informal conversations, and monthly ESUR-IGERT student-faculty meetings, successful implementation of transdisciplinary research via our core curriculum was one of the most important tools for training our students. While the earlier cohort (2nd cohort), that worked as individuals, rather than in teams, had mixed opinions about the success of the core curriculum in fostering transdisciplinary research, later cohorts (4th and 5th cohorts), all of which conducted group projects, unanimously agreed that the core course sequence was critical to their

transdisciplinary education and ongoing research (as reflected in student feedback; Table 6). This outcome as our program matured reflects the ESUR-IGERT faculty team revisions of the transdisciplinary curriculum and continued refinement of our community-based model (Figures 1 and 2).

By working with peers from other disciplinary backgrounds, students were able to extend their base of training to incorporate peer learning that expanded upon their disciplinary background. Additionally, by framing projects to address wicked problems that transcend particular disciplinary approaches, no one student had an authoritative prerogative over topics and it served to initiate transformative learning that went beyond traditional disciplinary boundaries (Hawkey et al. 2019). Such student socialization (Lovitts 2001) is a critical part of intellectual and professional growth in inter- and trans-disciplinary education (Boden et al. 2011). By engaging community partners as an essential part of their course projects, students were able to acquire experiential knowledge to address emergent research questions. The community partner buy-in at the onset of the project is the key ingredient for the successful implementation of students' projects. Students' training via the ethics course also provided a foundation for students to understand and respect the different lenses that stakeholders, other professionals, and their peers brought to the table and assured that students considered issues of equity and social/environmental justice.

However, there were some challenges in completing group projects by the ESUR-IGERT students. While we originally had a requirement that students would co-author a chapter of their dissertations, we soon realized that this was both impractical and did not conform to the individual-based approach that is expected of any doctoral student in the academy. Thus, we

modified the requirement so that students instead were required to coauthor integrative presentations at professional conferences and/or articles in both the peer-reviewed literature and the popular press.

Additional challenges to transdisciplinary education and learning included strict degree requirements in certain departments, a perceived distraction from their dissertation work that can increase degree completion time, challenges of funding such work, and potential anxiety of ‘interdisciplinary’ about employment post completion. This problem of disciplinary norms and practices has been identified in other IGERT programs and graduate programs in general (Boden et al. 2011, Link et al. 2013, Pinter et al. 2013; Shandas and Brown, 2016). These challenges were partially alleviated through careful mentoring and some community partner contributions to students’ stipends. Finally, we offered research funding incentives for students who voluntarily initiated additional interdisciplinary projects beyond their coursework.

4.3 Lessons for faculty

U.S. academic faculty frequently stay within disciplinary silos with ongoing professional learning derived from interactions with peers of similar training. Our ESUR-IGERT program provided a unique professional development opportunity whereby core faculty experienced intellectual and professional growth through exposure to the work of other team faculty via collaboration teaching core courses, co-mentoring students on class projects, co-advising IGERT students on dissertation research, active engagement with community partners, and co-writing manuscripts and research proposals (e.g., Ervin et al. 2012, Shandas et al. 2014, Yeakley et al. 2016). This close collaboration by faculty and students from diverse disciplines led not only to

broader thinking among faculty but also to a number of transdisciplinary projects that included explicit stakeholder engagement (e.g., Goodling et al. 2015; Denham 2017; Grabowski et al. 2017; Chiapella et al. 2019). Additionally, the process of co-teaching courses that spanned socio-ecological issues with students from diverse backgrounds and previous professional experiences led to learning not only by other students but also by the faculty. These professional development opportunities were significant for core faculty members, whereby such experiences were noted in promotions with tenure and to administrative positions. In addition, some faculty used the ESUR-IGERT transdisciplinary ecosystem service experience to assume local, regional, and national leadership roles in municipal, state, and federal government initiatives and advisory panels.

Even as IGERT faculty experienced the intellectual benefits of interdisciplinary collaborations that advanced the science and practice of urban ecosystem service management, there were substantial costs within the constraints of current institutional and professional structures. The time investment required to be attentive in a meaningful way to other disciplinary perspectives and approaches encroaches upon time available for disciplinary and departmental responsibilities, such as teaching loads. When departments, and more significantly, higher levels of administration were able to accommodate faculty needs for time and recognize accomplishments derived from transdisciplinary work, the net benefits to faculty, students, and research partners were elevated. If such a reward system was not in place, transdisciplinary education and research can be perceived as an additional work burden (Robinson and Hawthorne 2018). To alleviate faculty burden, some departments committed

resources to buy-out faculty time so that affected faculty could devote the time needed to transdisciplinary education and research.

The ESUR-IGERT program received varied support from university administration, including IGERT-funded Ph.D. students, stipends for IGERT associates, tuition remissions for IGERT fellows, dedicated office and classroom space, and partial funding of the program administrator. These were largely negotiated by the IGERT PI and co-PIs at the time of application submission. All teaching assignments were decided by the core team to achieve high-quality interdisciplinary instruction. Several faculty counted IGERT teaching responsibilities toward departmental requirements, e.g., credit hours per year, by negotiation with departmental chairs and sharing course credit hours with their teaching partners. However, other faculty were unable to count IGERT courses towards departmental requirements, which caused an excessive teaching load for some. In effect, they subsidized the ESUR-IGERT program to meet interdisciplinary educational goals. This unevenness in support of IGERT faculty remained a problem until the program's end.

4.4 Recommendations for university administrators and institutions

During the development of our project, we ran into a number of institutional challenges, many of which were barriers that arose from the rigidity of academic structure within a public university. Prior to submission of the NSF proposal, the PSU provost agreed to provide graduate research assistantship support and dedicated classroom and student office space, which was, in part, realized as a result of a \$25M family foundation award to the university to support sustainability initiatives. Despite that valuable high-level institutional support, our

faculty found that their departments were not always amenable to allowing ESUR-IGERT courses to be taught within their standard teaching assignments (i.e., “in-load”). As such, some of the project teaching was above load, and thus essentially pro bono work. Such issues have been identified in other IGERT programs (e.g., Pinter et al. 2013). Given these challenges, we suggest that academic administrators wishing to foster a transdisciplinary program consider providing funding to participating departments to offset the costs of participation. If these funds were transferred from the central administration budget to the departments, then department chairs would see transdisciplinary curriculum participation as a benefit rather than a cost to their department. This outcome likely hinges on the argument that building such transdisciplinary capacity will eventually lead to more effective student and faculty recruitment and broader research opportunities. These suggestions corroborate others who have echoed similar sentiments (e.g., Shandas and Brown, 2016).

To optimize opportunities and overcome barriers in future graduate training initiatives, we suggest the following. First, *clearly identify the complex issues at an appropriate scale and of mutual interest between university researchers and community partners*. Second, *create an environment that allows for participating community partners, students, and faculty to support diverse perspectives and methods*. Third, *identify team members with a combination of needed expertise and good interpersonal chemistry*. Fourth, *assure active rather than passive interactions among the engaged actors, via regular engagement of relevant stakeholders and creation of space for students to be well aware of the critical issues and viable pathways*. Fifth, *create a university-based reward system whereby the administration promotes rather than stifles transdisciplinary, community-based graduate education*. While most NSF-funded IGERT

programs are now completed, the legacy effects of such transdisciplinary education programs could be long-lasting, as long as universities maintain a structure and institutional values that facilitate such transdisciplinary endeavors. As shown in Appendix Table A, some IGERT programs were established within an existing institute or a managing organization, which were turned into a standalone program after the respective IGERT program ended. Nevertheless, even without external funding, the design of transdisciplinary teams of students and faculty provide learning opportunities currently unavailable through traditional academic structures.

5. Conclusions

In summary, wicked socio-ecological challenges to sustainable development abound, and adequate solutions to these challenges exceed the capacity of narrow, single discipline approaches to address them (Lang et al. 2017). If academe and students trained therein are to make useful contributions to managing these complex problems, more transdisciplinary curricula are essential to prepare students for effective service to society. We propose a model of such training that embeds active engagement with community partners to integrate experiential learning and to generate frontier intellectual knowledge. Feedback from doctoral students with diverse disciplinary backgrounds who were trained in our ESUR-IGERT program supports this departure from the traditional disciplinary approach. However, like any other inter-/trans-disciplinary program, ESUR-IGERT experienced challenges, and our recommendations for successful implementation of future transdisciplinary education are based on our experiences. Having a dedicated organization within a university can enhance community engagement and transdisciplinary research. Indeed, without more

transdisciplinarily-trained doctoral students, the next generation of ecosystem science and management will struggle to discover the novel approaches needed to address dominant and emerging challenges that confront societies and their environments around the globe.

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Table 1: Final ESUR-IGERT curriculum

Term	Fall	Winter	Spring
Course title	Foundations of Ecosystem Services	Models and Methods in Ecosystem Services	Ecosystem Services Applications
Focus	Theory	Methods and tools	Applications
Primary instructors' disciplines	Sociology; Ecology	Geography and Spatial Science; Economics, Business	Environmental Science; Urban Studies and Planning
Student learning goals and outcomes	<ol style="list-style-type: none"> 1. Understand the discourse of Coupled Natural and Human Systems (CNHS) and describe the foundational concepts in the conceptual model applied 2. Understand basic theories and application of ecological concepts and valuation 3. Understand the basic theories and application of social valuation, including equity and justice dimensions 4. Understand basic theories & assumptions of economic valuation and applications 5. Understand the basic theories of cultural valuation and their relevance to ecosystem service management; explore applications 6. Understand interdependences between biophysical systems and urbanizing areas 7. Understand how social constructions and governance structure impact how society manages ecosystem services 	<ol style="list-style-type: none"> 1. Learn the basic elements of common economic valuation methodologies and how they apply to ecosystem service issues, especially as related to urbanizing regions 2. Understand basic models and methods of ecological valuation, including biocentrism and apply them to community partner issues 3. Understand the methods of social valuation, including equity and justice dimensions 4. Understand the theories of geospatial analysis and their applications to ecosystem service valuation 5. Understand the issue of scale in ecosystem service science 6. Evaluate the pros and cons of each valuation methods and models 	<ol style="list-style-type: none"> 1. Identify and characterize a real world wicked problem in ecosystem services management for an urbanizing region. 2. Conceptualize the underlying analytical frameworks of dominant biophysical, spatial and valuation models and methods for ecosystem service analysis for the selected wicked problem. 3. Apply major biophysical, spatial and valuation models and methods to example ecosystem service issues for the selected wicked problem. 4. Understand how to frame ecosystem services analyses for tractable research models and methods that yield salient findings for all relevant stakeholder groups. 5. Identify primary and secondary data sources needed to apply the relevant models and methods to the group problem and approaches for obtaining those data. 6. Apply relevant models and methods with currently available data or proxies to examine the relationships of interest and draw tentative conclusions or implications. 7. Present the findings of the modeling and methods applications to peer students, faculty and interested community partners.

Table 2: Main characteristics of representative ESUR-IGERT class projects

Project topic/theme	Project objectives	Students composition/ disciplinarity, term	Community partners	Potential impacts on stakeholder?	Pedagogical outcomes; tools learned and implemented
Marmot dam knowledge and attitudes	Assess the socio-ecological consequences of dam removal	Interdisciplinary (ecology, geography, socio-economic) team of students for 12 weeks	PGE, Community of Sandy,	Identified a miscommunication between PGE and the community	Social survey Non-parametric statistics
Hayden Island Community attitudes	Analyze biophysical and socio-economic impacts of marine port development	Largely disciplinary studies conducted by separate students in one term	Port of Portland, Portland BPS, Nature Conservancy, and local residents	Identified health and environmental impacts on local residents that had been neglected in the planning process	Social survey, environmental assessment model
Columbia River Restoration	Analyze tradeoffs between hydropower and recreation/restoration	Three interdisciplinary teams	Government agencies, tribes, non-profit groups, and for-profit firms	Identified the emergence of a “restoration economy” that augmented the local recreation/ tourist economy	Snowball sampling and semi-structured interviews
Willamette Fall Pacific Lamprey	Investigate social equity concerns of both local stakeholders and Tribal stakeholders	Two teams, each composed of both social and natural science students	Native Indian Oregon City PGE, USGS	Social equity, human health and sustainability	Choice experiment; exploration of how to interview Tribal members.
Clackamas and road ecology	Examine land development and water-related ecosystem services	Environmental social science, Systems science for two terms	Metro, Clackamas County Residents	Land development, quality of life, environmental health	GIS, spatial statistical analysis

Table 3: Characteristics of each year's class project

Topic	Scale*	Community engagement	Time horizon	Level of stakeholder consensus**	Length of student project	Land use
Marmot	focal/local	Private, local, state, federal	Past, current	Medium/high	Spring	Mixed (urban to rural)
Hayden	focal/local	Local private and public partners	Current	High	Mid-winter to spring	Urban
Columbia	regional/international	Regional/federal	Ongoing forward	Low	Spring	Mixed (urban-rural)
Willamette Falls	focal/local	Private, local, tribe	Current	Medium/high	Year long	Urban
Clackamas	local/regional	Local, regional, private	Current Forward	Medium/high	Year long	Mixed (urban-rural)

**focal/local = The main interest or affected area is confined to either a specific point in place or small geographical area (e.g., City of Portland or neighborhood); regional = The issue crosses over two different jurisdictional boundaries (e.g., County or State)

**scoring criteria for stakeholder consensus is based on 1) Low = very contentious, lack of common vision and approaches to tackle the problem among different stakeholders, 2) Medium = Different stakeholders share some common viewpoints to achieve the same goal, but may not agree with the ways to achieve the goal, 3) High = Different stakeholders share common vision and generally appreciates the different approaches to tackle the issue.

Table 4. Student responses regarding engaging community partners in their research projects

Question	Student responses
<p>a. If this engagement affect the problem definition of your research? If so in what way?</p>	<p><i>Yes, because I am studying the community partners that I worked with (cohort #1)</i> <i>My work with a community partner has completely shaped my dissertation research (cohort #2)</i> <i>My experience with community partners has been mainly in agency with partnerships. I was involved in facilitating. Were both very productive. (cohort #3)</i> <i>Absolutely, engaging with stakeholders meant that we were constantly molding our research question (cohort #4)</i> <i>Yes, hearing from the community partners at the beginning of the year did help us come up with a project idea that was interesting to us (cohort #5)</i></p>
<p>b. Did this engagement affect the conceptual framework of the issue, i.e. beyond a traditional disciplinary approach</p>	<p><i>Yes, not simply public involvement but about science and technological choices (cohort #1)</i> <i>Yes. I'm bringing urban political ecology, community organizing, and popular education/learning frameworks together for my research. The issue on the ground dictated this framing (cohort #2)</i> <i>Also, in our own class - one of the most exciting interdisciplinary undergraduate projects I have been involved in - community partners in Portland and Seattle have played a wonderful role (cohort #3)</i> <i>I think that our community engagement shifted our work to be much more humanistic (cohort #4)</i> <i>Engaging with community partners helped us frame our research questions and methods to be feasible and relevant (cohort #5)</i></p>
<p>c. Did this engagement had any impact on preparing for your career? If so, how</p>	<p><i>Yes, built connections for doing ... applied and academic research (cohort #1)</i> <i>Yes. I am now even more suited to become either an academic or agency person who will resist preliminary problem definition/epistemological closure (cohort #2)</i> <i>Yes, specially this course/experience interdisciplinary teaching + in doing applied research and international work (cohort #3)</i> <i>It has and will continue to, provide me with an excellent professional network (cohort #4)</i></p>

Table 5: Summary of opportunities and challenges in community-based participatory interdisciplinary education

Party	Opportunities	Challenges
Community partners	<ul style="list-style-type: none"> - Answer their questions - Acquire new perspectives (e.g., social justice), knowledge and skills - Obtain assistance and potential solutions without financial commitment 	<ul style="list-style-type: none"> - Require additional time commitment (data retrieval, orientation, consulting) - May not receive useable information
Students	<ul style="list-style-type: none"> - Collaborate with students across different disciplines - Obtain experiential knowledge - Diversify portfolio - Enhance high demand future job markets outside of academia 	<ul style="list-style-type: none"> - Potentially increase completion time - Conflict with meeting department requirements - Concern about academic jobs
Faculty	<ul style="list-style-type: none"> - Enhance intellectual stimuli - Co-advise students beyond one's discipline - Advance career (broadening conceptual understanding beyond one's discipline, publications) - Enable successful interdisciplinary grant applications 	<ul style="list-style-type: none"> - Require additional time and resource investment, e.g., may detract from P&T for young faculty - Institutional inertia and resource constraint - Tension with disciplinary norms and practices
University administrators	<ul style="list-style-type: none"> - Demonstrate an exemplary case for frontier research and education - Help potential fundraising - Enhance contemporary student recruitments 	<ul style="list-style-type: none"> - Require additional resource investment - Convince other administrators to buy-in interdisciplinary education

Table 6: Sample student responses regarding the usefulness of interdisciplinary curriculum

Cohort Year 2	Cohorts Year 4 and 5
<ul style="list-style-type: none"> - <i>“The subject matter is essentially interdisciplinary research”.</i> - <i>“Though heavily encouraged as a positive thing. The link to interdisciplinary research, while loud and vigorous, was often unclear. Many “interdisciplinary” articles tend to skew more heavily towards one field over another due to the disciplinary leaning of particular publications and the question of overall synthesis remains uneasy. The program did not necessarily make it easier to do interdisciplinary work and I have not really done so since the end of my core courses”.</i> - <i>“Somewhat useful, but to be honest, IGERT’s take on “interdisciplinary” often feels very stilted/superficial, and the point is belabored to the point of not really just delving in and doing what’s necessary to address a particular problem/project. Working w/ real groups working in real life is where I’ve mostly encountered actual interdisciplinary issues/work in a streamlined way”.</i> 	<ul style="list-style-type: none"> - <i>“The core classes were certainly interdisciplinary in the sense that we worked with other students and faculty from across the campus. It seems that participants in this program are almost self-selecting in this regard, and I felt an implicit support of interdisciplinary study right from the start”.</i> - <i>“The core courses were also a good introduction to interdisciplinary research, bringing together both students and faculty from a diverse range of disciplines and offering a variety of perspectives on Ecosystem Services”.</i> - <i>“This was one of the most useful parts of these core courses. The discourse and dialogue around interdisciplinary research, as well as the opportunity to conduct projects as interdisciplinary teams”.</i> - <i>“The courses were very useful in providing interdisciplinary approaches and encouraging multiple viewpoints during discussion”.</i> - <i>“The courses did promote the inception of interdisciplinary research ideas and the beginnings of great collaboration”.</i>

Appendix Table A: Summary of IGERT-sustainability related programs that involve/d community engagement

University	Topic	Disciplines	Partners	Program home or supporting center
University of Alaska	Resilience and Adaption of Social-Ecological Systems	ecology, economics, anthropology, climate dynamics, and philosophy	Alaskan Native American community and with managers, businesses, and conservation groups.	NA
University of California at San Diego	Public Policy and Nuclear Threats	science, social science, and humanities departments	Lawrence Livermore, Los Alamos National Laboratories, a governmental or non-governmental organization	The Institute on Global Conflict and Cooperation
University of North Carolina at Chapel Hill	Land cover change and population and environment	social, natural, and spatial science in research on population-environment interactions	International organizations in three developing countries	Carolina Population Center
University of Washington	Five environmentally-related themes (Water, eco-materials, biodiversity, forest ecosystem, environmental social sciences)	Education, social work, engineering, computer science, biology, forest science, geology, anthropology	Pacific Northwest National Laboratory, six international universities	NA
Columbia University	Globalization and International Development	economics, political science, sociology, development studies, urban planning	International partners	NA
University of Rhode Island	Change in Coastal Ecosystems	ecology, biology, fisheries, natural resources science, economics, governance, planning, coastal policy	non-academic partner institutions	NA
Arizona State University	Urban ecology	Chemical and Environmental Engineering, Mathematical	Non-academic and International partners	NA

		Computational and Modeling Science, Earth and Space Sciences, Geography and Urban Planning, History, Philosophy, Religious Studies, Sociology, Life Science, Sustainability		
University of Illinois at Chicago	Landscape, Ecological and Anthropogenic Processes	Ecology, remediation and restoration, planning and policy, environmental economics	Chicago Botanic Garden, USDA Forest Service, The Field Museum, Midewin National Tallgrass Prairie, the Army Corp of Engineers	NA
University of Wisconsin at Madison	Vulnerability and Sustainability in Coupled Human-Natural Systems	Sociology, Health Science, Economics, agronomy, Electrical and Computer Engineering, URBAN AND REGIONAL PLANNING, geography, public affairs, forest ecology and management, biological system engineering, soil science,	Nature Conservancy , other international partners, Wisconsin Department of Natural Resources, Open Source Seed Initiative	Nelson Institute for Environmental Studies
University of Texas at Austin	Indoor Environmental Science and Engineering	Material engineering, environmental engineering, economics, biology, architectural engineering, advertising, community and regional planning	Local practitioners, federal agencies (e.g., US Department of Energy, US Environmental Protection Agency)	NA
University of Maryland Baltimore County	Water in the Urban Environment	Chemical, Biochemical, and Environmental Engineering; Economics; Public Policy; Geography and Environmental Systems; Marine, Estuarine, and Environmental Science; Mathematics; Chemistry	US Geological Survey, USDA Forest Service, City of Baltimore, Patuxent Wildlife Research Center, D.C. Water and Sewer Authority, Maryland Dept. of Public Safety and Correctional Services, Baltimore County, Parks and People Foundation,	Center for Urban Environmental Research and Education

			Resources for the Future, Exponent, Pittsburgh Parks Conservancy, Chesapeake and Coastal Bays	
University of Hawaii	emerging infectious diseases	evolutionary ecology, biomedical science, parasitology	National and international partner universities	NA
University at Buffalo	Ecosystem restoration	Ecology, geology, environmental engineering, geography, biology, hydrology, philosophy, mechanical engineering, chemistry	Two regional universities and Native American community	NA
University of Idaho	Ecosystem Management in Tropical and Temperate Regions	agricultural ecology, forest ecology and management, conservation biology and biodiversity assessment, ecological genetics, soil science, watershed sciences, ethics, rural sociology, policy, social impact assessment, environmental economics	International partners	NA
Portland State University	Urban ecosystem services	Anthropology, Business, ecology, environmental economics, environmental engineering, geography, mechanical engineering, sociology, systems science, public health, urban planning	US Forest Service, US Geological Survey, PGE, City of Portland, Metro, non-governmental organization, other regional universities that serve underrepresentative population	Institute for Sustainable Solutions (ISS)

IGERT programs that focus on “sustainability” theme were selected for creating this table. Information extracted from <http://www.igert.org/projects>. Additional information was obtained from NSF final project reports provided by some PIs.

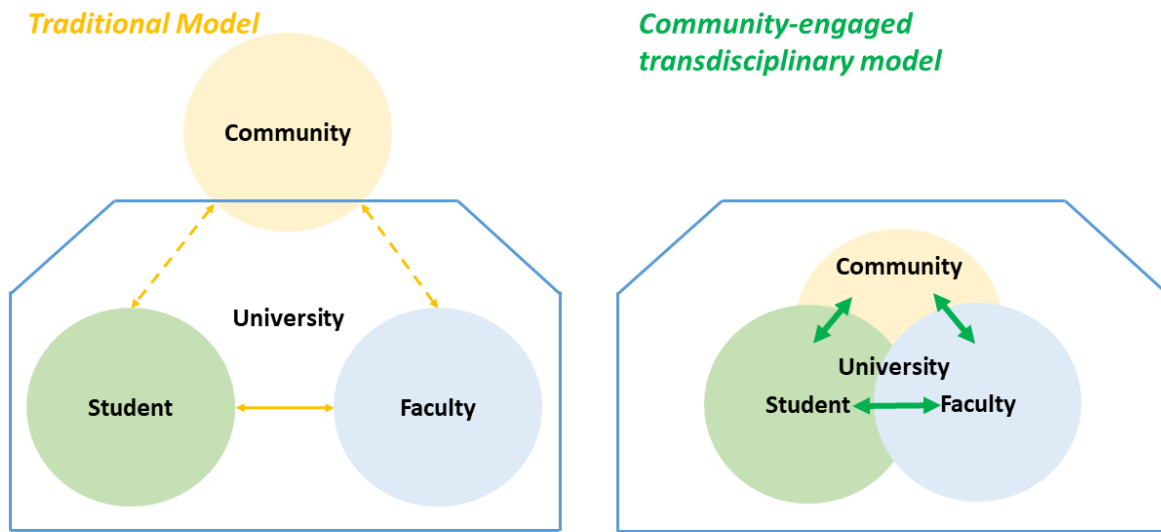


Figure 1. Relationship among community partner(s), faculty, and students in a traditional model (left) and a university supported community-engaged transdisciplinary model (right). In the community-engaged transdisciplinary model, community values and inputs are fully incorporated into student and faculty scholarship while allowing student and faculty role to be exchangeable.

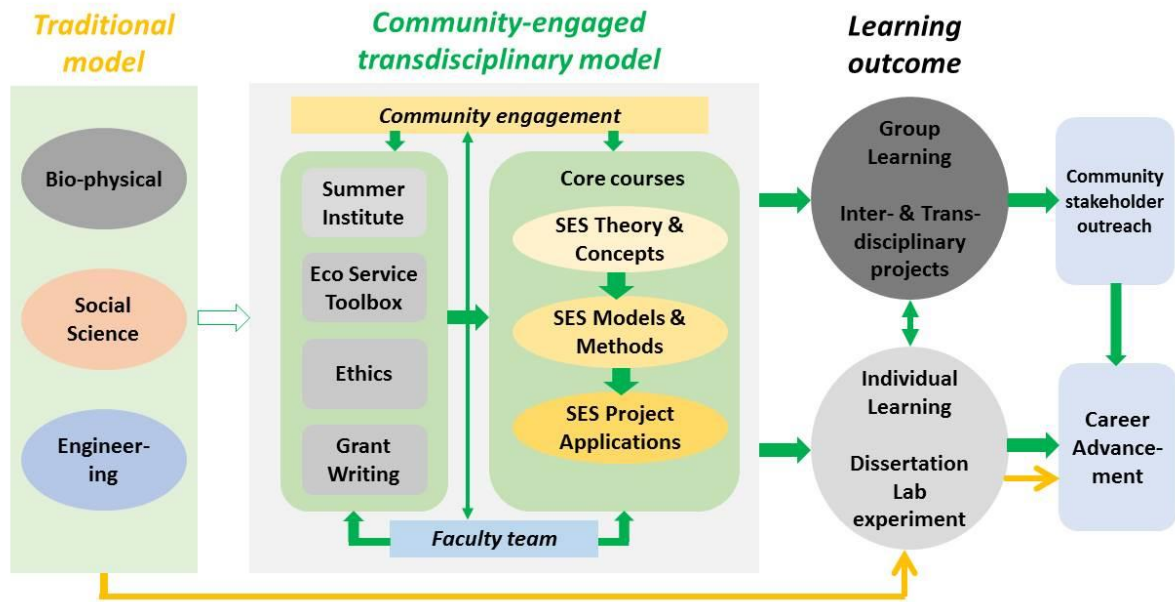


Figure 2. Comparison of traditional disciplinary versus university supported community-engaged transdisciplinary curricula and learning outcomes in ecosystem services. The light green box and the associated orange arrows indicate a traditional disciplinary oriented model of graduate education, while dark green box and the associated green arrows show our community-engaged transdisciplinary model of graduate education.