A Pedagogical Model for Team-Based, Problem-Focused Interdisciplinary Doctoral Education

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Interdisciplinarity is crucial for addressing the complex problems society faces. We present a model for educating doctoral students for careers involving interdisciplinary, team-based research to address problem-focused questions. The educational model is theoretically based and evaluated in light of the literature, faculty perspectives, and an assessment by students of educational successes and challenges they experienced. The educational model involves (a) the identification of integrated research questions combining team members' disciplines, (b) course work to review theoretical underpinnings of interdisciplinarity and to develop integrated research proposals to address the questions, (c) meetings and workshops to enhance team cohesiveness, (d) engagement with stakeholders, and (e) interdisciplinary team research that yields joint dissertation chapters and publications. The model achieved a high level of integration among students. This model addresses the widely acknowledged need to impart interdisciplinary research and team membership skills as part of graduate education.

Keywords: integrated research, collaboration, social–ecological, "shield-shaped" competency, Integrative Graduate Education and Research Traineeship (IGERT)

Complex problems such as climate and land-use change, habitat destruction, and water scarcity threaten coupled human and natural systems globally. The ability to understand and address such problems requires integrated forms of inquiry that include the biophysical and social sciences and the perspectives and knowledge of human communities experiencing these problems. Integrated frameworks for investigating complex problems fall within the conceptual domain of interdisciplinary research (Klein 1990) and are growing in their use within the research community (Sayer and Campbell 2001, Hicks et al. 2010, Lang et al. 2012, Manfredo et al. 2014, Brown et al. 2015). The expansion of problem-focused interdisciplinary research often simultaneously involves team-based research, because both are essential to our collective ability to understand and provide solutions for complex problems (Khagram et al. 2010, Cheruvelil et al. 2014). Effective interdisciplinary research teams comprise individuals with the disciplinary depth needed to understand the specialized components of complex systems, the interdisciplinary breadth required to communicate and integrate effectively across disciplinary boundaries, and the ability and commitment to work with stakeholders to address problem-focused research questions (Eigenbrode et al. 2007, Morse et al. 2007, Cooke and Hilton 2015). Given the magnitude of societal problems, there is an urgent need to educate early-career scientists in interdisciplinary team-based research and equipping them with the ability to tackle problem-focused questions.

Most models to train students for interdisciplinary research focus on cultivating an interdisciplinary individual who can integrate concepts and learn from the multiple disciplines needed to address a question (Klein 1990, Graybill et al. 2006, Manathunga et al. 2007, Tress et al. 2009, Jones and Merritt 2010, Cosens et al. 2011, Repko 2012, Vinhateiro et al. 2012). Many such models seek to create individuals with "T competency" (August et al. 2010, Uhlenbrook and de Jong 2012). The T concept reflects an individual's interdisciplinary breadth in the horizontal bar of the T and the disciplinary depth as the T's vertical bar. Although this individual-based approach works for some situations, many complex problems can only be effectively addressed by experts working together in inter- or transdisciplinary teams (Hackett and Rhoten 2009, Khagram et al. 2010, Cooke and Hilton 2015). Successful interdisciplinary collaborations

BioScience 66: 477–488.
doi:10.1093/biosci/biw042
Advance Access publication 10 March 2016

typically confront multiple challenges (Morse et al. 2007, Castán Broto et al. 2009, Broadbent and Vaughter 2014), which often stem from ineffective communication and a lack of mutual understanding of epistemological frameworks among team members (Eigenbrode et al. 2007, Miller et al. 2008). Therefore, educational models are needed that emphasize team-based, interdisciplinary inquiry to hone critical collaborative skills (Moslemi et al. 2009, Pennington et al. 2013, Stokols 2013).

To fill this need, a novel model for team-based interdisciplinary doctoral education was created and implemented via an international partnership between the University of Idaho (UI) and the Tropical Agricultural Research and Higher Education Center (CATIE) in Costa Rica. The educational model involves (a) the identification of integrated research questions combining team members' disciplines, (b) course work to review theoretical underpinnings of interdisciplinarity and develop integrated research proposals to address the questions, (c) meetings and workshops to enhance team cohesiveness, (d) engagement with stakeholders, and (e) interdisciplinary team research that yields joint dissertation chapters and publications. The UI-CATIE educational model (hereafter referred to as *the educational model*) was grounded in the inter- and transdisciplinary literature and faculty perspectives and has been improved on the basis of successes and challenges experienced by participating students and faculty. In this article, the model is described, assessed through a survey, and discussed using examples of its application to demonstrate how it functions and how it influenced participants. This article serves as a resource for academics seeking to build similar doctoral programs with the goal of fostering the next generation of researchers possessing the skills necessary to evaluate and provide solutions for the increasingly complex problems society faces.

Fundamental elements of the educational model

Figure 1 outlines the educational model of team-based interdisciplinary research and juxtaposes it with the model of problem-focused interdisciplinary research that is common in the literature (e.g., Klein 1990, Jahn 2008, Repko 2012). The common model required modifications for implementation within a doctoral program in which the students are expected to define and develop their research plans.

Model design. Team formation in the educational model precedes the identification of a specific research problem, altering the impetus and timing of reflexive iterations in the process. In the common model (left column, figure 1), multiple adjustments to team composition might be needed to approach a problem. By contrast, in the educational model (right column, figure 1), the team of students is recruited by advising faculty for a general problem area and must subsequently delineate the specific research. Adjustments that may be required by educational, research, and stakeholder goals must be met by redefining the problem rather than the team's composition. After iteratively redefining the problem, the initial stage of the interdisciplinary process is complete. From that point, the common model and this educational model proceed in similar fashion to apply and communicate findings with the people and communities that helped define the research (figure 1).

To advance the collaborative skills required for effective interdisciplinary research and to address problem-based questions, the educational model seeks to develop individuals that have "shield-shaped" competency (figure 2) rather than T competency. These *shield-shaped* individuals have depth of knowledge in their own discipline and the practical and epistemological understanding required to work with teammates in other disciplines. The combination of shield-shaped individuals creates synergy within the team and greater potential to effectively address complex, interdisciplinary problems.

Model application. UI and CATIE implemented two graduate educational projects from 2001 to 2016 with the goal of producing individuals who possess the disciplinary depth and interdisciplinary breadth to be effective members of interdisciplinary research teams and who can work with stakeholders to address complex societal problems. The first project focused on biodiversity conservation and sustainable production in human-dominated landscapes, and the second focused on the resilience of ecological and social systems. The educational model evolved and was improved from the first to the second project. These improvements included redesigning the recruitment strategy to better diversify the scientific disciplines in each team, expanding the involvement of stakeholders, and emphasizing philosophical issues as components of interdisciplinary training. This article focuses on the second project, with some examples from the first.

Faculty involvement. We found that commitment, engagement, and mentoring of students by multiple faculty members were important for the students to develop the skills needed to engage in rigorous interdisciplinary teamwork. The faculty participants were selected on the basis of their expertise and commitment to mentor students in an interdisciplinary team setting. Over two-thirds of the students had two faculty co-advisors. The project faculty team-taught program-required courses and developed learning objectives and assessment protocols. The faculty mentored individual students and teams, participated in team meetings, and helped identify research questions. They assisted the students in developing grant proposals, conducting fieldwork, engaging with stakeholders, providing feedback on research results, and writing publications.

Team-forming and recruitment process. In the first project, the students self-selected into geographically focused teams on the basis of their research interests and subsequently defined interdisciplinary research questions. Some of the students switched teams, causing instability and increasing

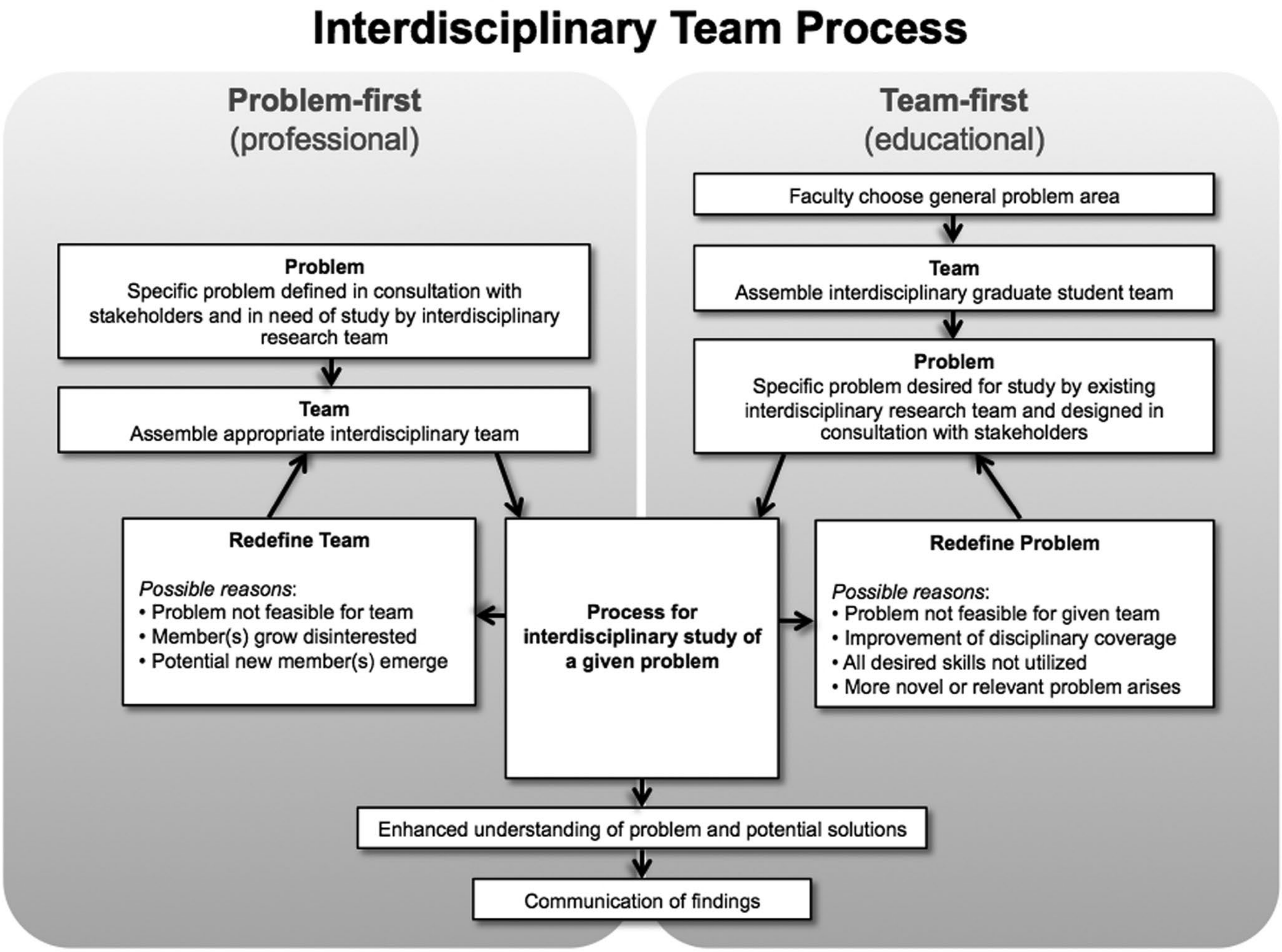

Figure 1. A comparison of the common "problem-first" model and the educational "team-first" model for interdisciplinary research. Both are built on the same core processes of interdisciplinary study previously defined in the literature (e.g., Klein 1990, Jahn 2008, Repko 2012), but the educational model highlighted in this article emphasizes collaborative teamwork by doctoral students. The educational flow path highlights the cyclic nature of this model in practice and how the processes of team-based problem-finding—not just those of problem-solving—are also an integral part of a team-based interdisciplinary doctoral education.

the time required to initiate research. In the second project, the process was modified. The faculty teams first developed overarching interdisciplinary research questions for six geographic locations and defined the disciplines needed for each team. Prospective students were recruited across the United States for the disciplines within each team. Efforts were made to recruit students from underrepresented groups. The recruitment of Hispanic students was facilitated by the opportunity to conduct research in Costa Rica.

For both projects, the applicants submitted statements of disciplinary and interdisciplinary research interests. The faculty evaluated these applications, and outstanding candidates were interviewed simultaneously over a 4-day period at UI. Interviews included oral presentations by the candidates, highlighting their disciplinary and interdisciplinary expertise and interests. A key element of the interviews was a team-building exercise that required the candidates to work in teams over a 2-day period on a hypothetical case study, culminating in team oral presentations. Interviews and peer evaluations of interviewees proved crucial for identifying the candidates likely to succeed in a demanding, team-based interdisciplinary program.

Project structure. In both projects, the student teams were required to plan and conduct integrated research, culminating in "dissertation sets" comprising coordinated dissertations related to an overarching research theme. These dissertations contained disciplinary chapters and interdisciplinary co-authored chapters. The students were required to produce at least one interdisciplinary peer-reviewed publication with their team members.

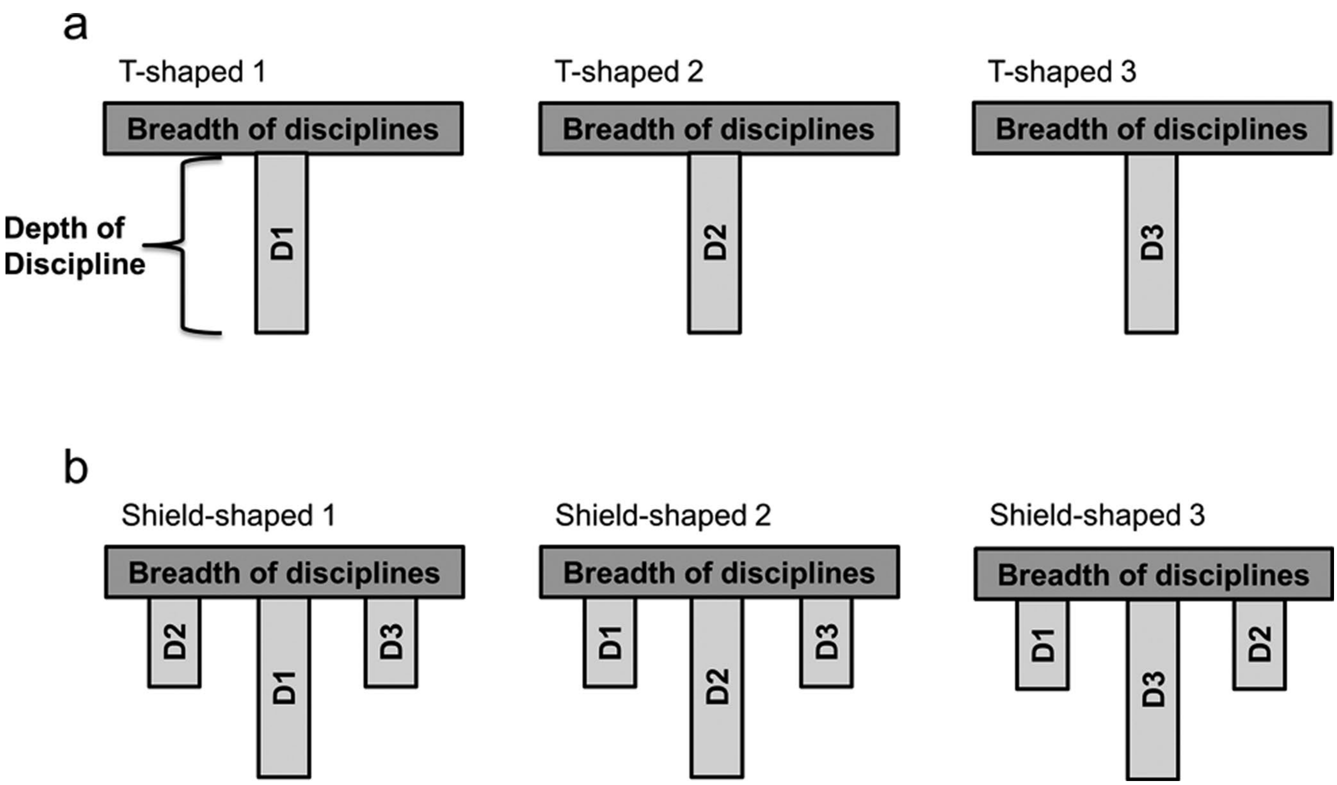

Figure 2. Examples of the (a) T-shaped competency model and (b) shield-shaped competency model, in which D1 to D3 represent different disciplines. The educational model described in this article sought to create individuals with shield-shaped competency. Assuming the combination of breadth and depth equals research or problem-solving potential, then the benefits of a shield-shaped individual occur at both the individual and team levels. The individual gains the understanding and training necessary to proficiently address problems across multiple disciplines (given reasonable depth in such disciplines). Combining multiple shield-shaped individuals within a team environment creates a synergistic effect that generates greater potential to tackle complex interdisciplinary problems, compared with the team of T-shaped individuals.

For the second project, a three-week immersion course taught at the beginning of the program fostered team building and exposed the students to the social–ecological systems of their study areas. The first week of the course involved on-campus orientations, social events, and an off-campus retreat for the students and faculty that focused on team-building exercises. During the remaining two weeks, the group divided into geographically based teams of students and faculty and visited their respective regions to learn about the local ecology and social context and meet with stakeholders to refine research topics of broad interest (figure 1). The students and faculty then began the process of delineating focused research questions that integrated team member disciplines.

The students in both projects took the team-taught courses Interdisciplinary Research Methods I and II (see supplemental materials) in the first year of the program. In these courses, the students examined the literature, language, and paradigms used by biophysical and social scientists, as well as literature on team science and interdisciplinary research models. They also reviewed successful interdisciplinary grant proposals. By the end of the second course, each team produced a draft proposal for their interdisciplinary research project.

During the first project, the students took a seminar titled Philosophical Issues in Interdisciplinary Research. This resulted in the development of a collaborative science Toolbox exercise (Eigenbrode et al. 2007) that was implemented in the second project (see box 1).

In both projects, the students fulfilled disciplinary requirements in their academic units to acquire knowledge depth and took at least one course outside of their discipline. The students conducting research in Costa Rica were enrolled in the UI-CATIE Joint Doctoral Program. In general, the first 18 months were devoted to course work and proposal writing, followed by interdisciplinary and disciplinary research. Toward the end of a student's tenure in the program, one semester of funding was dedicated to ensure active involvement in interdisciplinary data interpretation and manuscript writing.

The teams engaged in diverse interdisciplinary research projects (table 1). The teams used multiple integration catalysts to facilitate their interdisciplinary endeavors, including

Box 1. The Toolbox.

Toolbox workshops are designed to enhance communication and collaboration in cross-disciplinary research teams by increasing the degree of mutual understanding among collaborators about their research worldviews (Eigenbrode et al. 2007, O'Rourke and Crowley 2013). Facilitated by members of the Toolbox Project (*http://toolbox-project.org*), each workshop consists of a dialogue among collaborators about tacit research assumptions that guide their scientific practice. Dialogues last 60 to 90 minutes and are structured by a survey instrument that articulates research assumptions in the form of Likert-scale items with which participants can agree or disagree. Assumptions are organized into modules that correspond to key philosophical dimensions of scientific research practice. The Toolbox survey used with the participants of the second project comprises six modules: motivation, methodology, confirmation, reality, values, and reductionism. The first three pertain to the *epistemic*, or knowledge-related, aspects of scientific research, whereas the remaining modules are associated with the *metaphysical*, or world-related, aspects. Sample prompts include "scientific research must be hypothesis driven" and "value-neutral scientific research is possible." Dialogues illuminate fundamental differences in how participants conduct research, enabling them to coordinate their research practices, avoid potentially divisive disagreements, and improve communication about their collaborative research projects.

Table 1. Interdisciplinary teams in second project, integration catalysts and research topics.

Team name	Institution, country	Number of students	Number of faculty members	Disciplines	Integration catalysts	Research topic[a]
Hojancha	Idaho-CATIE, Costa Rica	4	6	Entomology Ecohydrology Economics Ecology	Grant proposals Manuscripts	Assessment of ecosystem services from ecological, economic, and social perspectives
San Juan-La Selva	Idaho-CATIE, Costa Rica	4	5	Political ecology Rural sociology Conservation genetics Forest ecology	Joint field work Grant proposals Stakeholder workshops Manuscripts	Evaluation of effects of agricultural intensification on social-ecological systems
Turrialba	Idaho-CATIE, Costa Rica	4	5	Rural sociology Ecohydrology Ecology	Joint field work Stakeholder workshops Manuscript	Matching scales of drinking water provisioning and management
Sagebrush	Idaho, USA	4	5	Rural sociology Wildlife ecology Plant ecology Ecohydrology	Grant proposals Stakeholder workshops Manuscripts	A framework for the assessment of social-ecological impacts within public lands
Northern Rockies	Idaho, USA	3	6	Social psychology Forest ecology Ecohydrology Climatology	Grant proposal Stakeholder workshops Online material for stakeholders Manuscripts	Evaluation and advancement of climate change communication
Palouse	Idaho, USA	4	6	Entomology Soil Science Plant Ecology Economics	Joint field work Manuscripts	Evaluation of ecosystem services from prairie remnants

[a]See Supplemental Materials for additional information on research topics, approach and activities of teams.

the development of joint manuscripts and grant proposals, joint fieldwork, and stakeholder workshops (table 1, supplemental materials).

Annual meetings were a key educational element of both projects. The 4- to 5-day meetings were held in Idaho or Costa Rica, and all of the students and many of the faculty members participated. During the meetings, the students made interdisciplinary team and disciplinary presentations and interacted with fellow students, faculty, and members of the project's external advisory panel (EAP). The students organized interdisciplinary workshops to collect data and/or identify cross-team collaborations that resulted in three publications. The attendants conducted field visits and engaged in events with stakeholders. Social events to promote project cohesiveness and a sense of belonging were an important element of meetings.

During both projects, spending unstructured social time as a team allowed the students to build interpersonal relationships and learn more about each other's background, motivations, and goals. Personal connections between the team members helped foster mutually respectful communication when challenges arose in interdisciplinary teamwork. To facilitate these interactions, time for informal team activities was scheduled during

Table 2. Constructive alignment of educational model with paired assessment.

Learning objective	Learning experience	Learning assessment
Well-grounded knowledge (breadth and depth)	Courses, seminars, literature review, individual proposals, team proposals	Graduation requirements: coursework, presentations, preliminary exam, team-based dissertation chapter, publications
Skills in interdisciplinary teamwork	Team research projects, Toolbox exercise, summer immersion, fieldwork	Team-based dissertation chapter, publications
Skills in interdisciplinary communication	Annual meeting, Toolbox exercise, team meetings, proposals, presentations, elevator-speeches, and manuscripts	Team-based dissertation chapter, professional and academic presentations
Ability to solve problem-based questions	Research design, team publications, problem-finding workshops/coursework, engagement with stakeholders	Public feedback, team-based dissertation chapter, publications
Ability to engage stakeholders	Immersion course, outreach workshops, public presentations, extension publications	Annual assessment survey, public feedback, academic presentation feedback
Strong philosophical understanding (epistemological and ontological)	Toolbox exercise, introductory philosophical coursework	Preliminary exam (interdisciplinary component)

the interview sessions, immersion course, and annual meetings.

Project management. A steering committee (SC), which included the project director, five UI faculty members, and two CATIE faculty members, managed the project. The SC faculty members served as leaders for the interdisciplinary teams and were selected on the basis of their research expertise, leadership credentials, and experience with and commitment to interdisciplinary graduate education. Two student representatives, elected by their fellow trainees for 1-year terms, joined the SC. Having student representatives improved communication between the students and faculty, created a sense of ownership in the project, and enhanced the students' leadership skills. The EAP, composed of three scientists with diverse disciplinary and interdisciplinary backgrounds, worked closely with the SC to ensure goals and objectives were met. During annual meetings, the EAP conducted reviews and made recommendations for improvement.

Funding. Funding was obtained through a combination of faculty- and student-developed grants to diverse programs and agencies. All students obtained experience in grant-proposal writing. The development of team proposals for funding interdisciplinary work served as a catalyst for the integration for several teams (table 1). Many of the students also served as teaching assistants or instructors to generate funding and gain teaching experience.

Methods and analytical framework

A constructive alignment (Borrego and Cutler 2010) of the educational model was developed that included six student learning objectives, learning experiences designed to achieve each objective, and assessment metrics for each objective (table 2). The intentional alignment of objectives, experiences, and tasks established an active learning environment, as well as the structure for the assessment of success and challenge outcomes.

Data collection. A survey was used to obtain student feedback on the components of the educational model and allowed students to describe their perceptions of their learning experiences. The online survey (supplemental materials) was conducted anonymously in 2014 with second-project students, because they participated in the final version of the educational model. The survey metrics included both Likert-scale and open-ended questions. The Likert-scale metrics included a self-assessment of student interdisciplinary communication skills prior to and three to four years after joining the program and asked the participants to rate the importance of the elements of the educational model in fostering their development as interdisciplinary scientists. The Likert scales ranged from 1 to 7, in which 7 represented the highest score and 1 the lowest. The open-ended questions solicited student views concerning interdisciplinary communication across the project lifespan, the utility of coursework, the benefits and tradeoffs of formal and informal meetings, the advantages and disadvantages of interdisciplinary research, the most challenging and rewarding aspects of team research, and the ability of team-based interdisciplinary research to prepare them for their careers. As per approval by the UI Institutional Review Board (#08-270), the project followed ethical guidelines for working with human subjects and procedures to protect data confidentiality.

Data analysis. Quantitative and qualitative analytical approaches were used. The Likert-scale survey questions were analyzed by calculating the mean and standard error of all responses. The constructive alignment provided an analytical framework for a deductive analysis of the responses to

Table 3. Student perceptions of successes and challenges associated with the educational model.

Learning Objective		Student perceptions of successes (S) and challenges (C) related to the learning experience and assessment
Well-grounded knowledge (breadth and depth)	S	"Courses offered a wide view of interdisciplinary methods, started getting familiar with terminology and concepts. Also you get to know how your peers think during different situations."
	C	"I think that the IGERT coursework was sufficient in laying the ground work for the idea of interdisciplinary science, but interdisciplinary science is not something that can necessarily be taught… the material covered in the IGERT classes...would have been much more effective in the 2nd or 3rd year of our program."
Skills in interdisciplinary teamwork	S	"The required interdisciplinary chapter was the constant that made us continue working together to achieve interdisciplinarity."
	C	"My team had very different research interests, goals, ideas about what meaningful research is, and simple differences in personality that made teamwork very difficult at times."
Skills in interdisciplinary communication	S	"Annual meetings are critical for a large IDR group or program. I always came away from the annual meetings with new information and new ways of approaching problems. And I feel like I contributed to helping others with difficulties they had encountered."
	C	"It is very time consuming, and therefore takes away from the time and energy the student/researcher has to spend on becoming an expert in their own discipline. It also sometimes forces changes in the study design of projects that ultimately lead to weaker inference in the disciplinary projects."
Ability to address problem-focused questions	S	"Interdisciplinary research allows for a more holistic understanding of a problem. There is a greater likelihood that the researcher will appreciate the complexity of the problem at hand. [It] also allows for more creativity in each step of the research process, as there are fewer established frameworks for approaching a problem."
	C	"Establishing a common language between disciplines, identifying an interdisciplinary question, and accepting other disciplines' methods of testing a hypothesis are all barriers towards making progress in interdisciplinary research."
Ability to engage stakeholders	S	"The field trip we took in August of our first year was seminal in our experience. It helped us understand the issues of people and managers in the system. Continued contact with these and other stakeholders helped us get out of theory and get into how interdisciplinarity in science matters on the ground to real world problems."
	C	*No students made statements related to challenges of incorporating stakeholder views*
Strong philosophical understanding (epistemological and ontological)	S	"Interdisciplinary research creates a mindset that there is no right answer and the answer depends on whose interests are at stake. Therefore, the way an interdisciplinary scientist approaches a problem is also going to be multifaceted and require different methods and epistemologies."
	C	"It was helpful to learn about the methods of other disciplines, although I think we could have covered a lot of that on our own team time and focused more on team-based approaches in class."

the open-ended questions in the survey (Patton 2015). The open-ended responses were analyzed for students' perceptions of the relationships between their learning experiences and assessments and their teams' successes or challenges in achieving the six learning objectives. Data were summarized to illustrate the successes and challenges experienced by students (table 3).

Results

The responses from all 22 students in the second project were obtained and included in the survey analysis. The students had generally positive experiences with both faculty and student teams, with mean ratings of 4.8/7 and 5.5/7, respectively (figure 3). The student survey responses indicated that their perceived ability for interdisciplinary communication improved through the duration of the project, as was illustrated by an increase in the mean rating from 3.2/7 to 5.8/7 (figure 3). The students showed high confidence that their interdisciplinary work would yield at least one team publication (figure 3). Most of the students agreed that the co-authored interdisciplinary team chapter or paper is an important component of the educational model. All components were perceived as at least "somewhat important" in the students' development as interdisciplinary scientists (figure 4).

The open-ended responses to the survey illustrated the alignments students identified between their learning experiences and their individual and team achievements, as well as a diversity of perspectives among the participants (table 3). For example, although many of the students commented on the value of interdisciplinary science as an approach to answer complex questions, some also noted the challenge of the increased time commitment required. The students described successful and challenging aspects of all the learning experiences except for one: No challenge to working with stakeholders was mentioned in the open-ended responses (table 3). This suggests that challenges to working with stakeholders were not directly related to the educational model and were likely associated with team rapport with stakeholders or stakeholders' logistical constraints to working with teams.

To highlight the success of the educational model in achieving learning objectives, each is summarized below.

Well-grounded knowledge. The educational model promoted collaborative skills and interdisciplinary breadth of individuals whose shield-shaped profile is distinct from the T-shaped profile by having substantive familiarity with the epistemologies and research methods of several disciplines beyond

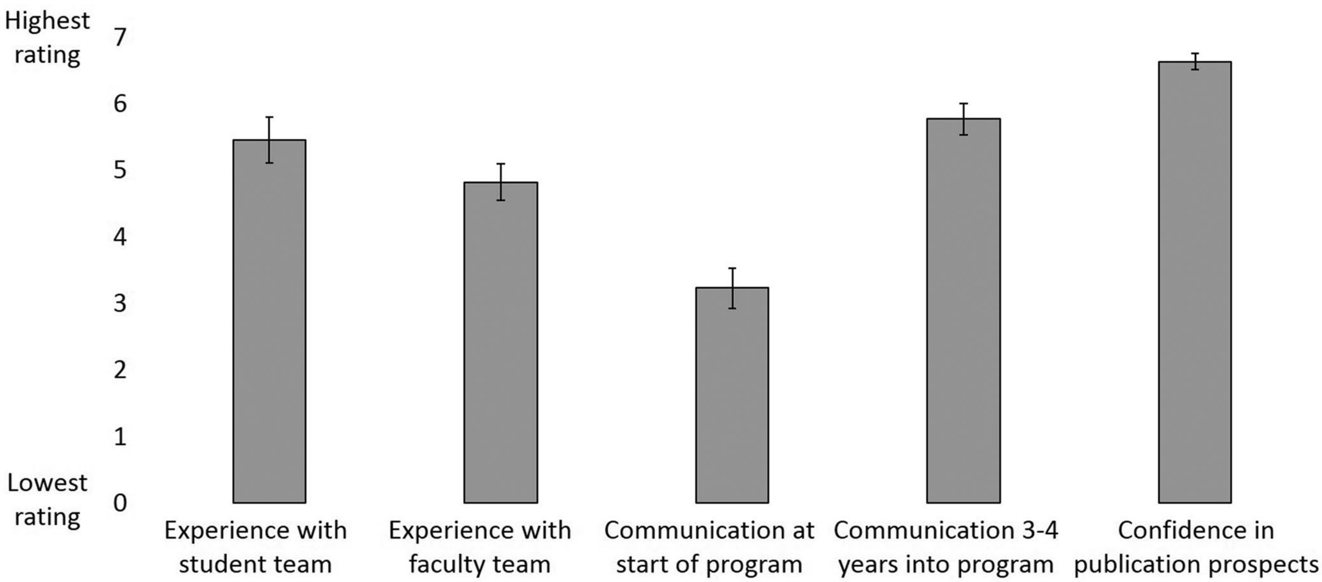

Figure 3. The average ratings of students' experiences with the educational model on a scale of 1–7 (1, lowest rating; 7, highest rating). The elements were as follows: (a) experience with the student team, (b) experience with the faculty team, (c) team ability to communicate across disciplines at the start of the project, (d) team ability to communicate across disciplines 3 to 4 years after joining the project, and (e) confidence that interdisciplinary work will yield at least one publication. Each bar represents the average rating and standard errors. N=22.

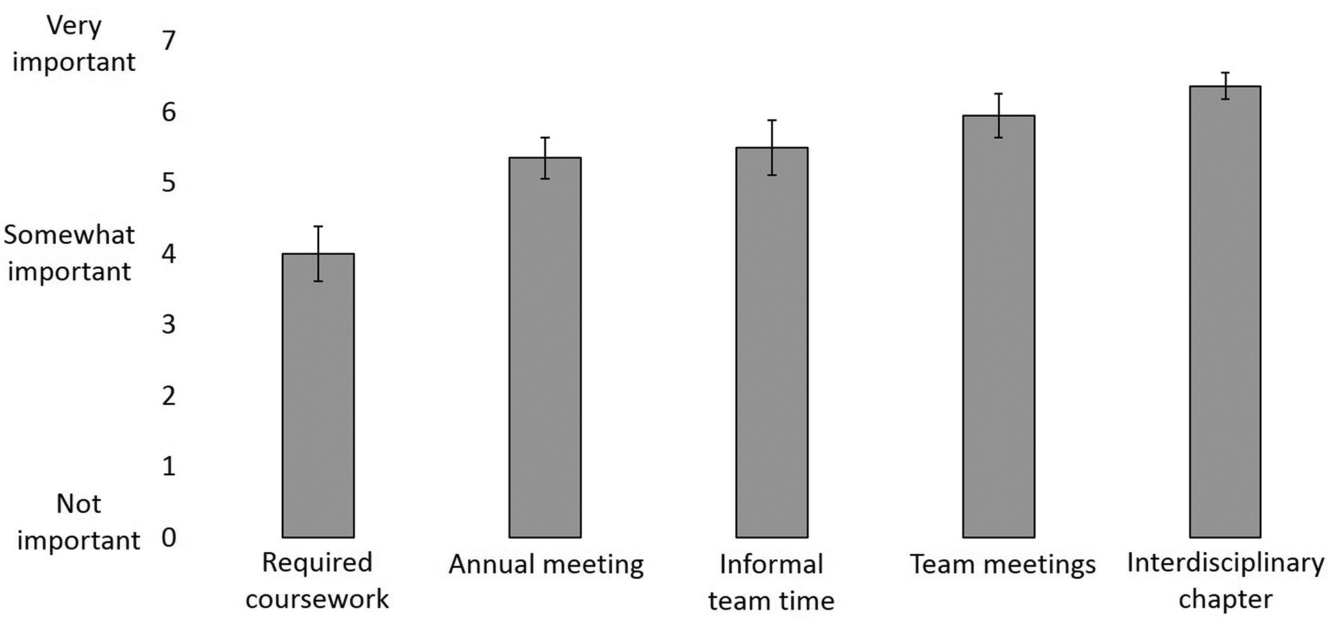

Figure 4. Student assessment of the importance of components of the educational model for their development as interdisciplinary scientists. Students were asked to rate each component of the program on a scale of 1–7 (1, not important; 4, somewhat important; 7, very important). Each bar represents the average rating and standard errors. N=22.

their primary one (figure 2). We believe this familiarity with other disciplines allows shield-shaped individuals to function more effectively in interdisciplinary teams (figure 2), in which integration involving disparate research paradigms is required. Shield-shaped individuals were produced through interdisciplinary coursework, the effort spent developing interdisciplinary team proposals, and the collaboration of the students as team members throughout their tenure in the program. Some students perceived that the time required for this integration limited their ability to develop extensive disciplinary depth. Nonetheless, according to the survey results, most of the students recognized the benefits of investing in the experience of applying for interdisciplinary team grants, developing interdisciplinary publications, and acquiring the proven ability to conduct interdisciplinary team research at the doctoral level.

Skills in interdisciplinary teamwork. The students reported positive experiences with their interdisciplinary teams (figure 3). The immersion course and informal team time allowed the students to develop strong interpersonal relationships, which were key to the teams' long-term success. After initial funding ended, commitment by some of the team members to interdisciplinary research diminished, presenting a challenge to the affected teams. In these cases, the requirement of a co-authored interdisciplinary dissertation chapter or paper and funding specifically allocated to support it helped motivate the students and keep the teams together (tables 1 and 3). This is supported by the students' ranking of the interdisciplinary chapter or paper as one of the most important elements of the educational model (figure 4).

Skills in interdisciplinary communication. The educational model was successful in developing interdisciplinary communication skills, as was indicated by the increase in the students' perceived ability to communicate from the point when they joined the program to the time when the survey was conducted (figure 3). The students listed interdisciplinary communication as one of the greatest challenges and most rewarding skills obtained through the program (table 3), sentiments similar to those expressed by the participants in past IGERT projects (Roy et al. 2013). Variation in responses (figure 3) reflects the time and effort required to learn these skills through participating in team meetings, writing proposals, developing oral presentations for a wide variety of audiences, and writing individual and co-authored manuscripts (tables 1 and 3).

The ability to address problem-focused questions. The educational model allows for a more holistic view of complex problems (table 3), because shield-shaped students work in teams (figure 2) to address problems that bridge disparate disciplines. Although coursework and workshops helped teams develop problem-focused research questions, there were challenges in communication across disciplines, particularly at the start of the project (figure 3). These challenges, combined with differing epistemic frameworks, conceptual scales, and focal themes, created difficulties for the teams in defining a problem and determining the feasibility of addressing it. These challenges are likely to arise in any interdisciplinary project. Participation in interdisciplinary coursework, in courses outside of their primary discipline, and in interdisciplinary seminars and workshops helped the students and teams develop problem-focused research questions and effective approaches to answering them. In addition, presenting research plans and results of team projects to stakeholders and at professional conferences and listening openly to colleagues assisted the teams in navigating communication challenges and understanding the broader value of their work. All teams required mentoring from their faculty advisors to achieve effective integration. Successfully working through communication challenges to identify a shared vision for each team's research was crucial for students' development and prepared them for similar challenges that they will face in their careers as interdisciplinary scientists.

The ability to engage stakeholders. The educational model facilitated interaction between the students and people who live and work in the areas where research was conducted. Four of the six teams structured some of their research around stakeholder workshops (table 1), and all the teams delivered presentations to the public. Most of the students highlighted the immersion course at the beginning of the program as the foundation for building rapport with local communities. The relationships with stakeholders that began during the immersion course facilitated collaboration, information exchange, and the delivery of results to stakeholders.

Strong philosophical understanding. The educational model facilitated appreciation for the various epistemological approaches used in science. Conducting the Toolbox exercise facilitated student reflection on their disciplinary epistemologies and helped identify the conversations required to reconcile epistemologies among disciplines and achieve integration. The continual conversations within and among teams conducted in light of the insights gained in the Toolbox exercise generated an understanding of different philosophical approaches to science and encouraged the teams and individuals to arrive at their own more integrated philosophies of science.

Discussion

The educational model prepared the students for interdisciplinary, collaborative team-based research to address problem-based questions by engaging stakeholders. It helped create individuals with shield-shaped competency with the understanding and training necessary to work in a team environment to address complex interdisciplinary problems. This resulted in a high level of integration among the students. The students were exposed to theoretical and empirical literature on disciplinary and interdisciplinary research and contributed to this growing literature as part of their doctoral educations. The graduates from both projects asserted that the interdisciplinary experience and professional development opportunities provided by the educational model were instrumental in their ability to secure and succeed in their current positions. Of the 20 students enrolled in the first project, 18 completed their doctoral degrees (table 4); 11 were female, including two Hispanics. Many are currently engaged in interdisciplinary research and education projects. Half are in academia, and the remainder work with government agencies or nongovernmental organizations. The students and faculty published over 50 journal papers, including 10 interdisciplinary ones. They made over 100 disciplinary and 30 interdisciplinary

Table 4. Project outcomes and student placement.

Project years	2001–2008	2009–2016
Number of students enrolled	20	23
Number of students graduated[a]	18	12 by Dec 2015
Graduate placement	9 in academia; 9 in other positions including international, state, and tribal agencies, and non-governmental organizations (NGOs)	3 in academia; 9 in other positions including post docs, tribal agencies and NGOs; 10 scheduled to graduate in 2016
Range in time to graduation	3.5–6 years	3.5–5.5 years
Number of interdisciplinary publications	10	5
Number of disciplinary publications	45	8

[a]The retention rates for the program were 90% and 96% for the first and second project, respectively. The graduation rate for the first project was 90%.

presentations at professional meetings and numerous presentations to stakeholders. Of the 23 students enrolled in the second project, 12 have completed their doctoral degrees, 10 are scheduled to graduate in 2016, and one left the program (table 4). Seven of the students are female, and six are Hispanic or Native American. Three of the second-project graduates currently hold academic positions. All the teams developed interdisciplinary dissertation chapters or papers. Five interdisciplinary papers (Fremier et al. 2013, Blades et al. 2015, Kemp et al. 2015, Klos et al. 2015, Shaver et al. 2015) have been published, and several others have been submitted or are being developed. The students and faculty made over 80 disciplinary and 70 interdisciplinary presentations at meetings and over 60 presentations to stakeholders.

The program retained students at a very high rate (90% and 96% for the first and second project, respectively; table 4). The graduation rate for the first project (90%; table 4) surpasses the graduation rates for comparable doctoral programs in the United States (54%; Carney et al. 2011). Similar to other IGERT projects (Carney et al. 2011), the students in both projects completed their degrees (table 4) within times comparable to those of other doctoral students or sooner. These figures indicate that the educational model enhanced the ability to retain and graduate students in a timely fashion. This success in retention and graduation was a function of many of the project elements, including the rigorous trainee identification and recruitment process, the strong sense of belonging created by the projects, and the team-based nature of the graduate experience that is the hallmark of the educational model. According to the experiences and perspectives of the project participants, the educational model fulfilled the call to better prepare future scientists to address complex problems in coupled social–ecological systems.

Effects on faculty. Over the course of the two projects, the educational model also transformed many of the faculty participants. For these faculty members, the concentration on a team-based approach opened new collaborative relationships and initiated unique professional development opportunities, such as (a) participation in the Toolbox exercise, (b) experience with interdisciplinary advising, and (c) co-mentoring one another in the challenges and approaches to interdisciplinarity as co-advisors and team participants. For many, the educational model also helped cultivate interinstitutional and international collaborations and experience, substantively promoting career development. The faculty also led the development of courses that enhanced offerings at both institutions and enabled a more diverse and dynamic range of contemporary curricula open to program and nonprogram participants. These courses constitute a legacy of source material for future pedagogy in team-based interdisciplinary research skills.

Effects on institutions. The educational model resulted in significant changes in the culture of graduate education at UI and CATIE by (a) promoting better integration of research and educational activities among academic units; (b) enhancing interdisciplinary collaboration between faculty and graduate students; (c) providing a unique, team-based interdisciplinary education combined with strong disciplinary training for participating students; (d) providing students with a practical and theoretical understanding of interacting ecological and social processes and helping them think across disciplinary boundaries; (e) developing new methods, tools, and theory for team-based research; and (f) helping students and faculty gain international and crosscultural experience and improve their ability to work with stakeholders.

The importance of promoting innovative graduate education in US universities has been highlighted previously (Van Hartesveldt and Giordan 2008, Borrego et al. 2014, Gould 2015). This was achieved at UI by the educational model in several ways: (a) UI allows graduate students across the university to pursue team-based interdisciplinary projects in the form of the educational model; (b) a co-authored interdisciplinary chapter is allowed in UI dissertations, and students outside the projects have used this approach; (c) other groups at UI, including another IGERT project, use diverse components from the educational model.

CATIE adapted elements of the educational model, resulting in changes in MS-level teaching. The course Economic, Ecological and Social Considerations in Sustainable Human Development: An Interdisciplinary Approach was developed. It adopts concepts from the educational model to promote the integration and application of knowledge from the social, economic, and ecological sciences to sustainable human development in the tropics. It promotes the adoption of skills and tools for interdisciplinary analysis by using interdisciplinary papers (Morse et al. 2008, Shaver et al. 2015) published by project teams as case studies.

Use and modification of the educational model. An extension of the educational model to other institutions could include the development of a best-practices manual to document and elaborate on the opportunities and challenges with a team-based interdisciplinary program attempting to blend research and educational goals. Recruiting students to a team-based interdisciplinary graduate program needs to be a conscious, well-designed activity. The students attracted to such programs have a wide variety of backgrounds across the biophysical and social sciences and hold diverse philosophies of science. Introductory coursework on the philosophies of science during the start of a project, and in conjunction with the Toolbox exercise, could help students gain the right vocabulary to share and understand their epistemic differences. A faculty-training program for all mentors early in a project could increase knowledge about project goals and the required faculty commitment to succeed in interdisciplinary team-based research. Institutions interested in promoting interdisciplinary team-based doctoral work also could benefit by adopting policies that allow team papers as part of doctoral dissertations.

Conclusions

We submit that the educational model described here is widely applicable. It could strengthen doctoral education by preparing scientists to work collaboratively on complex problems that affect coupled social–ecological systems globally. The need for such an approach and many of its elements are well recognized (e.g., Repko 2012, Borrego et al. 2014, Brown et al. 2015, Record et al. 2016), but their integration into a comprehensive, theoretically grounded, deeply integrated approach like the one described here has been lacking. Our hope is that the adoption of this educational model in whole or in part will improve doctoral-level interdisciplinary education. The educational model evolved as we employed it, and we expect others who adopt it will continue to innovate and share these innovations as part of the transition from single investigators to collaborative teams for the production and application of knowledge. Success with this transition is imperative to ensure that science remains effective in the face of the rapidly accelerating complexity of the problems it must address.

Acknowledgments

We are grateful to the students and faculty involved in the projects and the members of the external advisory panels who made invaluable contributions during the development and implementation of the educational model described. We are also grateful to our anonymous reviewers for useful comments that helped improved the manuscript. Survey data are deposited at *www.northwestknowledge.net/doi?doi=10.7923/G4KW5CXT*

Funding statement

Development and implementation of the educational model were financially supported by NSF–IGERT, UI and CATIE. Other funding for the projects was obtained from NSF–Coupled Natural Human Systems, NSF Graduate Research Fellowship, US Agency for International Development Borlaug Fellows in Food Security, National Atmospheric and Space Administration, Fulbright Scholars, Bureau of Land Management, US Geological Service, Idaho Governor's Office of Species Conservation, and UI Stillinger and McIntire-Stennis funds.

Supplemental material

The supplemental material is available online at *http://bioscience.oxfordjournals.org/lookup/suppl/doi:10.1093/biosci/biw042/-/DC1*.

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