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Strengthening the role of universities in addressing sustainability challenges: the Mitchell Center for Sustainability Solutions as an institutional experiment

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Synthesis

Strengthening the role of universities in addressing sustainability challenges: the Mitchell Center for Sustainability Solutions as an institutional experiment

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ABSTRACT. As the magnitude, complexity, and urgency of many sustainability problems increase, there is a growing need for universities to contribute more effectively to problem solving. Drawing upon prior research on social-ecological systems, knowledge-action connections, and organizational innovation, we developed an integrated conceptual framework for strengthening the capacity of universities to help society understand and respond to a wide range of sustainability challenges. Based on experiences gained in creating the Senator George J. Mitchell Center for Sustainability Solutions (Mitchell Center), we tested this framework by evaluating the experiences of interdisciplinary research teams involved in place-based, solutions-oriented research projects at the scale of a single region (i.e., the state of Maine, USA). We employed a multiple-case-study approach examining the experiences of three interdisciplinary research teams working on tidal energy development, adaptation to climate change, and forest vulnerability to an invasive insect. Drawing upon documents, observations, interviews, and other data sources, three common patterns emerged across these cases that were associated with more effective problem-solving strategies. First, an emphasis on local places and short-term dynamics in social-ecological systems research provides more frequent opportunities for learning while doing. Second, iterative stakeholder engagement and inclusive forms of knowledge co-production can generate substantial returns on investment, especially when researchers are dedicated to a shared process of problem identification and they avoid framing solutions too narrowly. Although these practices are time consuming, they can be accelerated by leveraging existing stakeholder relationships. Third, efforts to mobilize interdisciplinary expertise and link knowledge with action are facilitated by an organizational culture that emphasizes mutual respect, adaptability, and solutions. Participation of faculty associated with interdisciplinary academic programs, solutions-oriented fields, and units with partnership-oriented missions hastens collaboration within teams and between teams and stakeholders. The Mitchell Center also created a risk-tolerant culture that encouraged organizational learning. Solutions-focused programs at other universities can potentially benefit from the lessons we learned.

Key Words: *emerald ash borer (Agrilus planipennis); interdisciplinary research; knowledge-action connections: organizational innovation; place-based solutions; Senator George J. Mitchell Center for Sustainability Solutions; social-ecological systems; solutions-oriented research; stormwater infrastructure; sustainability science; sustainability solutions; tidal energy development; universities*

INTRODUCTION

One of the greatest challenges facing society is to link the production of knowledge with actions that both meet human needs and preserve the planet's life-support systems (Kates et al. 2001, Chapin et al. 2009). Sustainability science and related approaches call for innovative interdisciplinary research that is both problem-focused and use-inspired to advance the theory and practice of sustainable development. Concurrently, sustainability science demands unprecedented levels of collaboration and interaction across diverse organizations and institutions that are critical to knowledge exchange, cooperative research, and new forms of engagement (Cash et al. 2003, Clark et al. 2010, 2011). There is a growing consensus that fields like sustainability science can help create more effective strategies for knowledge production and use that will accelerate the transition to sustainability (van Kerkhoff and Lebel 2006, Matson 2009). Accordingly, investments in developing the capacity of universities to help understand and solve pressing sustainability problems represent major opportunities for transformative institutional change.

Universities have the potential to help manage and span the complex boundaries that are often encountered in efforts to address sustainability challenges (Cash et al. 2003, Clark et al. 2011). Research universities, in particular, contain an extraordinary breadth of expertise—in the natural and social sciences, engineering, business, and the arts and humanities—that is needed to examine the causes and consequences of sustainability problems that are by definition multifaceted. Moreover, they have an organizational ability to generate and share new knowledge, tools, and practices that can be used to help solve pressing societal problems. Researchers in the fields of community engagement and higher education have increasingly conceptualized universities as "anchor organizations" that enjoy stability within a community and can broadly catalyze change by providing wide-reaching frameworks for education, workforce development, and engagement (CEOs for Cities 2010, Kingma 2011).

In reality, however, universities often struggle to mobilize their unique capacities in ways that effectively link knowledge with

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action (Renaud 2004, Matson 2009, Rood 2009, Whitmer et al. 2010, Crow and Dabars 2015). One important factor contributing to this incomplete linkage is the lack of alignment between the research-generated supply of and societal demand for scientific information (McNie 2007, Sarewitz and Pielke 2007). This problem is often exacerbated by disciplinary silos within universities, and by challenges involved in combining science with other forms of knowledge in ways that contribute more effectively to decision-making (Kueffer et al. 2012). To advance and benefit from crucial knowledge exchange aimed at achieving sustainable development, universities need to identify and implement new strategies for both organizational and institutional change that overcome these alignment issues (Tilbury 2012). For the purposes of this paper, we define organizational change as change that typically occurs via management systems (e.g., strategies, processes, procedures, and relationships). In contrast, institutional change "transcends organizational change to focus on entire classes of organizations serving different societal functions" and is concerned with "the underlying social rules and norms that define how these societal functions are structured and governed" (Halal 2001).

Our goal here is to develop an integrative conceptual framework for how university research can help solve real-world sustainability problems, and to identify core strategies linked to this framework that can aid in the creation of more effective programs. We draw upon our experiences designing and implementing an institutional-scale, sustainability science experiment in conjunction with the creation of the Senator George J. Mitchell Center for Sustainability Solutions (Mitchell Center). We use the term *experiment* not in the methodological sense of replication, controls, and randomization, but as a metaphor denoting a strategic intervention to transform a complex system that is accompanied by high uncertainty and requires considerable social learning. Using cases from the Mitchell Center's portfolio of stakeholder-engaged, interdisciplinary, and place-based projects, we compare the context and experiences of three research teams. We identify three core strategies that contributed to the success of these projects, and suggest that the growing community of universities engaged in sustainability science research can benefit from the lessons we learned.

MITCHELL CENTER FOR SUSTAINABILITY SOLUTIONS

Design

The vision guiding the design of the Mitchell Center was to grow the capacity of universities to collaborate effectively with society in solving pressing sustainability problems. We view sustainability science as a use-inspired field that aims to help solve problems with intersecting economic, socio-cultural, and ecological dimensions (Clark and Dickson 2003, Hart and Bell 2013, Miller 2015). Our approach to sustainability science is based on iterative cycles of stakeholder engagement, research, and implementation, and aims to facilitate multiple forms of individual and institutional change.

Our conceptual framework for solutions-oriented sustainability research builds upon and integrates three major conceptual themes that we consider fundamental to the growth of institutional capacity: 1) evaluating the dynamics of coupled social–ecological systems and determining how their resilience can be increased; (2) understanding and strengthening connections between social–ecological systems knowledge and societal actions (denoted as K↔A, where the double arrow emphasizes the reflexive nature of these connections); and (3) identifying and implementing strategies for organizational innovation that lead to improved interdisciplinary collaboration and robust university–stakeholder partnerships. Rather than viewing social–ecological systems, K↔A, and organizational innovation as independent research efforts, we believe they represent key components of a coordinated strategy for supporting integrative, solutions-focused research in sustainability science.

In the following paragraphs, we briefly summarize how the Mitchell Center's design is linked to, and continues to build synergies among, these three conceptual themes.

Evaluating social–ecological systems contexts

The Mitchell Center's social–ecological systems research is stakeholder driven and maintains a solutions-oriented focus. While the role of thresholds and feedbacks in understanding the dynamics and resilience of social–ecological systems cannot be overstated (Walker et al. 2004, Folke et al. 2005, Anderies et al. 2006, Groffman et al. 2006, Liu et al. 2007, Collins et al. 2011, Vervoort et al. 2012, Garmestani and Benson 2013), it is not yet clear how this extensive body of work might best support the development of more effective pathways to inform decision-making and facilitate social change (Ostrom 2009). Numerous universities have grown their capacity for social–ecological systems analysis, but more research is needed to ascertain how such social–ecological systems knowledge can be aligned with societal needs for generating real-world solutions (Miller 2015).

Understanding how knowledge↔action connections can improve societal outcomes

Our K↔A research aims to advance understanding of knowledge systems processes and to create stronger linkages between scientific information and societal needs (Sarewitz and Pielke 2007). Solutions-driven sustainability science focuses on how different stakeholders interact with the research process and how they use the scientific information it generates in decision-making (Kates et al. 2001, van Kerkhoff and Lebel 2006, Clark et al. 2010, van Kerkhoff and Szlezák 2010). Thus, K↔A research is central to tackling sustainability challenges because it is explicitly focused on the processes that facilitate and hinder individual and institutional change. This necessitates reciprocal analyses of interactions between research and decision-making (Cash et al. 2003, Sarewitz and Pielke 2007), with a particular emphasis on how this can be facilitated by more effective boundary work (Clark et al. 2011).

Fostering organizational innovation for the enhancement of internal and external collaboration

Organizational innovation research can play a central role in facilitating organizational and institutional change because it helps identify, implement, and evaluate strategies and tactics for enhancing the contributions of universities to the solution of sustainability problems. Efforts to strengthen the role of universities in addressing such challenges must overcome a variety of barriers that often limit the success of interdisciplinary teams and stakeholder engagement. There is an extensive literature

documenting the difficulties of surmounting disciplinary differences in ontologies and epistemologies (Amey and Brown 2004, Gardner et al. 2012, McCoy and Gardner 2012); creating institutional reward systems that promote interdisciplinary collaboration (Lattuca 2001, Kueffer et al. 2012); and developing durable, solutions-driven partnerships with stakeholders (Brown et al. 2010). Our organizational innovation research strategy also addressed key barriers to interdisciplinary collaboration at the level of the university (Gardner et al. 2012, McCoy and Gardner 2012), including barriers to promoting effective interdisciplinary doctoral education, faculty collaboration, stakeholder engagement, and institutional collaboration with state and federal agencies, nongovernmental organizations, and K-12 educational institutions.

In summary, our conceptual framework for the design of solutions-focused research programs asserts that social–ecological systems, K↔A, and organizational innovation themes represent core and interlinked building blocks for expanding organizational and institutional capacities to address a wide variety of sustainability problems.

IMPLEMENTATION

We implemented these design concepts within the context of a network of higher education institutions located in a single U.S. state, Maine. This network was led by the University of Maine, a public research university that has a land-grant mission of linking research with societal needs (Kellogg Commission on the Future of State and Land-Grant Universities 1999). Our work was supported in part by a five-year, US$20 million grant from the National Science Foundation, which facilitated the launch in 2009 of an experimental program called the Sustainability Solutions Initiative. The successful completion of this grant in 2014 was marked by the creation of a permanent university research center, the Senator George J. Mitchell Center for Sustainability Solutions, to underscore Maine's long-term commitment to solutions-focused sustainability science.

The Mitchell Center's initial emphasis was broadly organized around sustainability problems linked with the research theme of landscape change (Committee on Grand Challenges in Environmental Sciences, and Oversight Commission for the Committee on Grand Challenges in Environmental Sciences 2001), which is a central element in efforts to address sustainability challenges in Maine (The Metropolitan Policy Program 2006). Landscape change is also an important nexus for sustainability science research (Turner et al. 2007), including the development of multiscale complex systems models of urban, semi-urban, and rural regions (Liu et al. 2007, Alberti 2008). Our research approach examined interactions among several landscape change arenas (i.e., urbanization, forest ecosystem management, climate, and energy). We sought to identify the differing spatial, temporal, and institutional scales at which these landscape processes affect, and are influenced by, various interacting ecological, socio-cultural, and economic changes.

At the outset of our 5-year National Science Foundation grant we created a portfolio of research projects to address specific sustainability problems and solutions opportunities. We purposely focused our work within Maine, which provides a more homogeneous biophysical and socio-cultural setting than study systems incorporating larger geographic regions. By allowing for comparisons across different stakeholder and problem contexts, this portfolio represented an innovative response to one of sustainability science's foremost challenges: determining how research efforts being conducted in different places and on different problems can be used to develop general principles and best practices in the pursuit of real-world solutions (Ostrom 2005, Liu et al. 2007, Clark et al. 2011, Matson 2012).

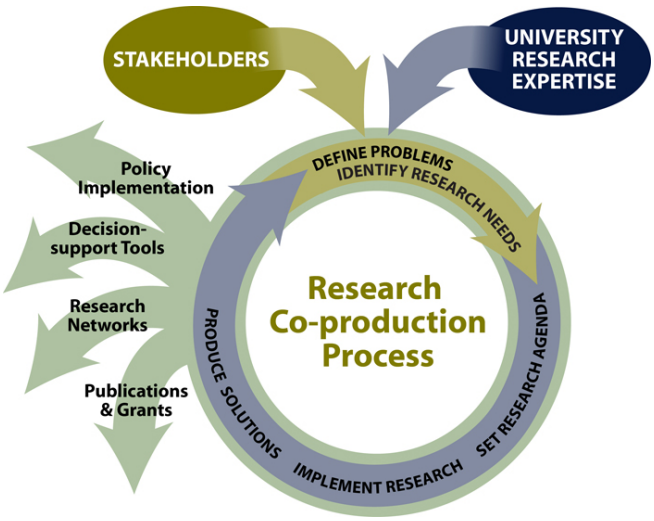
The process by which specific projects were initiated was strongly guided by research on developing stronger connections between knowledge and action (Jacobs 2002, Cash et al. 2003, Clark and Holliday 2006, van Kerkhoff and Lebel 2006, van Kerkhoff and Szlezák 2010, Clark et al. 2011). We operationalized this guidance by issuing a request for proposals that offered potential funding to teams of faculty who were interested in developing a research project. The criteria for evaluating proposals included an emphasis on initial and on-going stakeholder engagement, the formation and integration of interdisciplinary teams focused on both social–ecological systems and K↔A research, and an emphasis on solutions. Following an evaluation process that included both internal and external peer reviews, some of the research proposals were awarded funding. Throughout the project, we received valuable guidance from a distinguished and engaged advisory board that was chaired by Robert W. Kates and included both researchers and stakeholders.

The research portfolio was comprised of twenty interdisciplinary teams from eleven Maine universities and colleges (Appendix 1). More than 100 faculty representing 20+ disciplines (with social scientists somewhat more numerous than natural scientists and engineers, and female and male faculty roughly equal in number) and several hundred students constituted the total number of university participants. These teams partnered with more than 300 stakeholder organizations representing all levels of government, the private sector, and nongovernmental organizations. Many facets of our strategy, tactics, projects, and partnerships were introduced in a special issue of the *Maine Policy Review* that focused on the Sustainability Solutions Initiative (Volume 21, Issue 1, 2012, http://digitalcommons.library.umaine.edu/mpr/vol21/iss1/).

Researchers generally engaged with stakeholders at the outset of each project, to understand stakeholder concerns, needs, assets, and organizational and institutional contexts. This process also provided greater clarity about the kinds of expertise that might be needed to develop solutions. Interdisciplinary teams of faculty and students were formed to work in partnership with stakeholders via a process of problem co-definition, research co-design, and knowledge co-production (Fig. 1). For the purposes of this paper, we view interdisciplinarity as an intellectual enterprise that is issue driven, collaborative, integrative, and reflexive (Robinson 2008).

We used a variety of approaches to expand the ability of these research teams to engage in stakeholder partnerships, build interdisciplinary capacity, and solve problems. For example, we held monthly meetings of the project teams to provide faculty and students with training in social–ecological systems research. We also hosted numerous workshops and events to share stakeholder perspectives and K↔A research strategies.

Fig. 1. The Mitchell Center's research co-production process.



Our social–ecological systems and K↔A research was augmented by organizational innovation research conducted by multiple social scientists. These researchers represented a wide range of fields, including higher education, social psychology, communication, and economics. They employed multiple methods, including qualitative research, survey research, and experimental games. The results of this research were often used to inform and improve our organizational policies and practices.

AN ANALYSIS OF THREE CASES

Methods

We employed a multiple-case study method (Creswell 2007, Yin 2014) to evaluate how social–ecological systems, K↔A, and organizational innovation approaches influenced the progress of solutions-focused sustainability science projects. The unit of analysis for this research was the research team and stakeholder partners involved in tackling a particular, place-based sustainability challenge in Maine. Our research sought to answer two core questions: What features of social–ecological systems, K↔A, and organizational innovation mattered for the solutions-development process? And, how did they matter?

We selected three cases from the research portfolio using two major criteria: (1) Projects identified as making significant progress in developing solutions, based on an annual, external evaluation led by The University of Maine's Vice President for Research—this evaluation focused particular attention on progress in stakeholder engagement, interdisciplinary teamwork, and the development of tangible solutions; (2) projects that spanned a wide variety of team expertise, stakeholder composition and engagement strategies, and sustainability problems (i.e., forests, energy, and climate adaptation)—our replication strategy was literal rather than theoretical (sensu Yin 2014), because we anticipated that similar patterns might emerge across the three cases.

Guided by our conceptual framework and research questions, we developed a common data collection protocol for describing key characteristics of each case study (e.g., the problem, place, stakeholders, disciplines, solutions, etc.) and asked leaders of the three case studies to provide this information in narrative form. We then compared these summaries with other information about the cases, including documents (e.g., project reports and peer-reviewed papers by research team members about the cases), interviews, and observations of the research teams (e.g., during internal meetings, as well as meetings with stakeholders) to inform refinements of the individual cases. Cross-case insights emerged from comparative, iterative analyses of patterns across the individual case studies. Background information about these cases is provided in Appendix 2.

The authors of this paper played a range of roles in the organization of the project as well as the case study research. The overall project was led by Hart, and was guided by a leadership team (the Stewardship Council) that included Bell, Jain, Lindenfeld, and McGill. The Stewardship Council developed the research design and led the cross-case analysis process. They also organized and led the all-team meetings and workshops at which social–ecological systems and K↔A trainings occurred. The three projects included in the study were led or co-led by Jain (climate adaptation), Johnson (tidal energy), and Ranco (forest pests). Our expertise spanned a broad range of natural science, social science, and engineering disciplines, including anthropology (Ranco), civil engineering and climate change (Jain), communication (Lindenfeld), ecology (Hart, McGill), economics (Bell), and human ecology (Johnson).

Assessing the potential for tidal energy development

Social–ecological system

This research team evaluated the interacting technological, economic, social, and environmental issues affecting the potential for tidal power development, focusing on locations within the Bay of Fundy, where some of the world's largest tides occur (Table 1). Because tidally driven hydrokinetic turbines are a relatively new technology, the project team worked with a variety of stakeholders (e.g., tidal power developers, federal and state resource and regulatory agencies, tribal communities, commercial fishermen, municipal officials, and nongovernmental organizations) to understand their perspectives. While some stakeholders were interested in the economic development and climate-mitigation potential of tidal power, others were concerned about the potential adverse effects of turbines on commercial fishing, and how this would vary with the project's future size. Given the limited experience of industry, regulators, and other stakeholders with tidal energy, a multiyear process is required for the potential development and permitting of such projects.

Knowledge↔action

Both the project team and the tidal-power developer were committed to broad-based stakeholder engagement and participation and to building trust with the community through frequent interactions; some team members were local residents. Community members also sought reassurance that the developer would not be able to influence the research outcomes of the team. Co-production processes were strengthened in part by incorporating the knowledge of local fisherman into the research plans for fish sampling in the bay. Central to the success of the project was the team's ability to adapt its research, collaboration, and communication strategies to overcome a variety of institutional barriers.

Table 1. Major characteristics of three solutions-focused research projects: tidal energy.

Social–ecological systems attributes		K↔A processes and results		Organizational innovation challenges and opportunities	
System components	Scales and dynamics	Coproduction strategies	Contributions to solutions development	Mobilizing interdisciplinary expertise	Building organizational capacity
Issue Technological, economic, ecological, and social factors involved in tidal energy development	*Spatial scale* Local estuaries (Cobscook Bay and Western Passage)	*Engagement processes* Discussions with community members and regulators to encourage broad-based participation Innovative tidal-power developer supportive of collaboration and engagement Maintaining independence between university research and project developers	*Specific outcomes* First tidal turbine in U. S.A. to generate power to the grid New models for turbine design and placement New models for engagement in renewable energy development New methods for assessing fish–turbine interactions	*Team expertise* Mechanical engineering, physical oceanography, marine biology, social science	*Support for faculty involvement* Pretenure faculty benefited from location in interdisciplinary school
Stakeholders Tidal-power developers, municipalities, federal and state regulatory and permitting agencies, commercial fishermen, local and tribal communities	*Temporal scale* Multiyear development and permitting process	*Knowledge integration* Expertise of both local fishermen and researchers used to guide fish sampling	*Knowledge system processes* Improved permitting and regulatory processes	*Interdisciplinary collaboration strategies* Biweekly team meetings of faculty, graduate students, postdoc, and stakeholders Some faculty from different disciplines occupy shared space Blending the strengths of science and engineering	*Aligning with organizational goals* Energy identified as key organizational strength
Ecological context Unique estuary with important fisheries	*Key feedbacks* Potential negative interactions between turbines and fishing/ navigation	*Flexible research agenda* Increased focus on providing permitting-relevant data	*Transferability* Japanese researchers interested in using similar stakeholder engagement and environmental assessment strategies for tidal power development in Japan>		*Organizational learning* Coproduction process increased level of interest and engagement by fishermen and communities Intentional efforts towards early, ongoing engagement of stakeholders and transparency helped improve collaborations and reduce conflict
Social context Interest in economic and community development Concerns regarding environmental impacts Limited experience with tidal power projects	*Key thresholds* How do profitability and fisheries impacts vary with scale of tidal energy development?				

One key indicator of the project's progress was that knowledge produced jointly by the interdisciplinary research team and stakeholders contributed significantly to the first U.S. commercial project in which tidal turbines generated electricity to the grid (Groening 2012). Moreover, the team made important contributions to the design and evaluation of similar projects in other regions via multiple research strategies (e.g., producing new models for turbine design, evaluating fish–turbine interactions, and identifying more effective stakeholder-engagement methods). In fact, Japanese researchers visited Maine several times to learn how the team's results could be applied to the development of tidal power in Japan.

Organizational innovation
To address the diverse issues involved in tidal power development, the team included experts in mechanical engineering, physical oceanography, marine biology, and social science. The result was a blending of the discovery orientation of science with engineering's focus on solutions. Biweekly meetings of the team helped maintain communication, increase integration, and respond to new challenges. Some biophysical and social science faculty had adjacent offices, which facilitated increased collaboration. Although two faculty members were pre-tenure, the interdisciplinary program in which they were housed emphasized the importance of problem-focused, interdisciplinary research. This project's focus also aligned closely with a university-wide emphasis on renewable energy research.

Adapting to a changing climate in coastal communities

Social–ecological system
This research team sought to understand and strengthen community resilience in the face of an increased frequency and volume of extreme precipitation, which is magnifying stormwater runoff and damaging transportation infrastructure (e.g., culverts and roads) (Table 2). As the team worked with citizens and officials representing local, state, and federal agencies, a range of concerns emerged, including risks to public safety, traffic, and local economies. Using towns as a central unit of analysis, the project considered the annual process of municipal budget decisions as well as the multi-decadal scale of culvert life span and climate change. These concerns were affirmed by the devastation from Hurricane Irene in 2012, which left the nearby state of Vermont with failed culverts and bridges, and damages totaling US$733 million (The Associated Press 2012). One striking challenge faced by communities is the cross-cutting nature of infrastructure and resource management problems, together with fragmented decision-making.

Knowledge↔action
Drawing upon established community networks developed by faculty from Cooperative Extension and Sea Grant programs that support engagement with and outreach to diverse stakeholders, this project encouraged broad-based participation of local officials. The multifaceted nature of the problem required the integration of knowledge regarding hydro-climatic change; community-level planning; and governance systems that influence stormwater infrastructure design, permitting, and financing. The research team began their work expecting that sea-level rise was a primary concern, but quickly adjusted their strategy when results of surveys and focus groups highlighted more immediate concerns with stormwater management. This research facilitated the development of a variety of decision-support tools (e.g., mapping culvert locations, scheduling maintenance, and estimating the culvert size needed to carry greater amounts of runoff). This work also helped create revised ordinances that account for a changing climate, as well as education materials to improve citizen-level stewardship. Although these tools were developed for a single model town, they should be transferable to other municipalities that are faced with similar challenges but are embedded in their own municipal social networks.

Organizational innovation
The research team developed expertise to examine relationships between climate and hydrology, use hydraulic models in culvert design, and analyze institutional arrangements. By combining the solutions-oriented culture of civil engineering and the community engagement culture of the Sea Grant and Cooperative Extension programs, the project was able to create a unified strategy for thinking about infrastructure adaptation in the context of community resilience. Although the team included pre-tenure faculty, this did not prevent them from working in an interdisciplinary, solutions-focused manner.

Organizational learning occurred as the team identified more effective ways to tailor their research design and products to the scales at which municipal decision-making and planning take place. For example, one key factor that influenced the salience of research products is their synchronization with the decision calendars used by different institutions.

Reducing vulnerability to an invasive forest pest, the emerald ash borer

Social–ecological system
This research team worked to strengthen the capacity for detecting and responding to an invasive forest pest, the emerald ash borer (*Agrilus planipennis*) (Table 3). There is currently little prospect of eradicating this pest (Government Accountability Office 2006), which could arrive in Maine from the adjacent state of New Hampshire or from the Canadian province of Quebec in a few years (Kovacs et al. 2010). Vulnerability to the emerald ash borer's impact differs across Maine communities and stakeholders. The emerald ash borer is of limited significance to the forest products industry, because ash is not a commercially important species. But the emerald ash borer represents an enormous threat to the identity, traditions, and economy of the Wabanaki (translated as people of the dawn), an indigenous cultural and political confederacy that includes the Penobscot, Passamaquoddy, Maliseet, and Micmac tribes. Tribal culture and livelihoods are intimately tied to the basket tree, or brown ash, *Fraxinus nigra*, which has been used in the basket making that has been an integral part of Wabanaki culture for centuries. Accordingly, this project provided an opportunity for the university to work with diverse partners, including basket makers, brown ash harvesters, and resource managers from Maine's four Indian tribes, along with federal and state resource agencies, to develop shared plans for detecting and responding to the emerald ash borer.

Knowledge↔action
Because tribal knowledge and concerns have often been underrepresented in planning processes for invasive species (Ranco et al. 2012), this project sought to ensure that tribal members were active participants. Representatives of multiple

Table 2. Major characteristics of three solutions-focused research projects: coastal adaptation.

Social–ecological systems attributes		K↔A processes and results		Organizational innovation challenges and opportunities	
System components	Scales and dynamics	Coproduction strategies	Contributions to solutions development	Mobilizing interdisciplinary expertise	Building organizational capacity
Issue Damage to stormwater and transportation infrastructure from increased frequency of extreme precipitation	*Spatial scale* Towns as unit of analysis	*Engagement processes* Encouraged broad-based participation of officials using Sea Grant Extension faculty expertise and community networks	*Specific outcomes* Decision-support tools to: Map culvert locations Schedule maintenance Estimate needed culvert size, analyze replacement needs and costs, etc.	*Team expertise* Hydro-climate analysis and modeling, civil engineering, decision analysis, and community engagement	*Support for faculty involvement* Team included pre-tenure faculty, and close integration with Sea Grant and Cooperative Extension programs
Stakeholders Municipalities, state and federal transportation departments and emergency-management agencies	*Temporal scale* Annual infrastructure decisions, multi-decadal-scale life expectancy of culverts, and changes in extreme events	*Knowledge integration* Hydro-climatic change research Scales of community level planning Governance linked to stormwater infrastructure design, permitting, and financing	*Knowledge system processes* Revised ordinance that reflects changing frequency of extreme rain events Educational material development to improve citizen-level stewardship of stormwater infrastructure	*Interdisciplinary collaboration strategies* Collaborative efforts between civil engineering and Sea Grant faculty to use hydro-climatic information Mobilizing respective expertise in coastal community resilience and climate-related infrastructure adaptation	*Aligning with organizational goals* Solutions-oriented engineering unit as home base
Ecological context Nexus of water and land resources	*Key feedbacks* Strong impacts of extreme events on municipal budgets, tourism, and public safety	*Flexible research agenda* Shifted focus from coastal erosion to culverts in response to coast-wide municipal official survey	*Transferability* Model coproduction process for other towns and climate-adaptation challenges		*Organizational learning* Research was aimed at improving uptake of scientific information at scales of decision-making and planning Early, ongoing engagement of select decision-makers helped delineate decision calendars and processes Integrating and tailoring biophysical and engineering research to fit knowledge gaps and information needs
Social context Socially and economically important infrastructure Public safety	*Key thresholds* Devastation caused by Hurricane Irene, a potential focusing event and tipping point with respect to community resilience Cross-cutting infrastructure and resource management problems with fragmented decision-making				

Table 3. Major characteristics of three solutions-focused research projects: the emerald ash borer.

Social–ecological systems attributes		K↔A processes and results		Organizational innovation challenges and opportunities	
System components	Scales and dynamics	coproduction strategies	Contributions to solutions development	Mobilizing interdisciplinary expertise	Building organizational capacity
Issue	*Spatial scale*	*Engagement processes*	*Specific outcomes*	*Team expertise*	*Support for faculty involvement*
Reducing vulnerability to the likely arrival of the emerald ash borer	Statewide, but patchy, distribution of basket-quality trees	Process valued indigenous knowledge and tribal sovereignty Strong emphasis on power-sharing, including financial support of tribal partners Interdisciplinary team emerged as key boundary organization	Legislation banning the importation of firewood to Maine from other regions Creation of monitoring network for the emerald ash borer, linking state and federal agencies with landowners Education program for Native American youth, to collect seeds for future replanting	Indigenous knowledge, tribal sovereignty, social science, forest ecosystem science	Joint appointment and identity of team leader facilitated more flexible roles
Stakeholders	*Temporal scale*	*Knowledge integration*	*Knowledge system processes*	*Interdisciplinary collaboration strategies*	*Aligning with organizational goals*
Tribal communities, including ash harvesters, basket makers, Maine Indian Basketmakers Alliance, tribal, state, and federal resource agencies	Rapid spread of the emerald ash borer towards Maine, with decadal-scale consequences	Indigenous knowledge and statistical modeling combined to evaluate tree distributions	One of first U.S. collaborations in which tribes worked with state and federal governments prior to arrival of invasive species, including development of memorandum of understanding among the parties	Tribally affiliated faculty shared and promoted common vision to ensure that tribal knowledge and concerns were represented Project led by Native American Research Center, involving diverse schools and departments	Organizational commitment to diversity and engagement, including the education of tribal students via tribal partnerships
Ecological context	*Key feedbacks*	*Flexible research agenda*	*Transferability*		*Organizational learning*
Small but important fraction of forest tree species vulnerable to the emerald ash borer	Impact of the emerald ash borer on tribal identity, local economies, sovereignty	Shifted from focus on availability of basket-quality trees to the emerald ash borer threat in response to concerns raised by tribal communities	Model collaborative process for other sustainability challenges facing tribal communities		Increased university capacity to convene key parties, build trust, identify research needs, and search for improved policies and practices
Social context	*Key thresholds*				
Emerald ash borer threat experienced differently by tribes than other stakeholders	Established agreements about emerald ash borer response plans				

tribes regularly participated in the planning meetings, and two representatives of the Maine Indian Basketmakers Alliance were supported by the grant as members of the project's leadership team. This team also served as a boundary organization (Guston 2001) that helped facilitate connections between science and policy and between researchers and communities, with particular attention focused on how the group interacted in a context where power and knowledge were unevenly shared. For instance, they combined tribal knowledge with statistical models of tree distributions to identify stands of basket-quality trees that could potentially be protected. By shifting the initial focus of this research from an emphasis on the availability of basket-quality trees to the imminent emerald ash borer threat, the team demonstrated their responsiveness to tribal concerns.

To help reduce the region's vulnerability to the emerald ash borer, team members provided expert testimony that contributed to the passage of legislation banning the importation of firewood to Maine from other regions. Other solutions-oriented strategies that were implemented include: an education program for Native

American youth, for collecting seeds for cryopreservation and future replanting of brown ash; the creation of a monitoring network for emerald ash borers that links state and federal agencies with landowners; and the initiation of a process by which tribal governments in Maine and the U.S. Department of Agriculture Animal and Plant Health Inspection Service (USDA-APHIS) can develop a memorandum of understanding to ensure quick and collaborative responses to infestations.

Organizational innovation
A key element of this project was the expertise in indigenous knowledge, tribal sovereignty, social science, and forest ecosystem science represented by the team. Moreover, two faculty are also tribal members. Because of the project's connections to The University of Maine's Native American center, it was able to leverage an established network of university and tribal relationships. The project also aligned with an institutional commitment to engage Native students in tribally focused research and education projects. Perhaps most importantly, the team helped develop the university's capacity to fill important co-production roles as a boundary organization that convenes key parties, builds trust, identifies research needs, and searches for policies and practices to cope with the potential impacts of an emerald ash borer invasion and other challenges.

LESSONS LEARNED

Taken together, these three projects offer important insights regarding the characteristics that strengthen efforts to understand coupled systems, link knowledge with action, and increase the problem-solving capacity of universities. Despite important differences in the projects, we identified several common themes that can help universities contribute more effectively to the development of sustainability solutions.

Solutions-oriented social–ecological systems research is aided by a focus on small scales

Social–ecological systems attributes are an intrinsic feature of the problems tackled by solutions-oriented sustainability science, and, in turn, these attributes markedly shape the strategy for conducting on-the-ground collaborative research. For example, the problem context is strongly connected to the system's dominant space and time scales, dynamic behavior, and stakeholders. Despite the wide range of space and time scales associated with the three different projects, each focused considerable attention on fine scale dynamics (i.e., the literal "here and now" that is inherent in the pursuit of many place-based solutions). The projects not only emphasized local systems (e.g., a single town or bay), they also sought to understand and influence near-term dynamics (e.g., a town's annual infrastructure planning cycle or the first-of-its-kind planning process for deploying and evaluating tidal energy). By concentrating on these finer scales, teams not only created a more manageable scope for their initial analyses, they shortened the time required to formulate and answer key research questions. These systems cannot be fully understood without attention to a range of scales, however, so all the projects included research elements focused on larger scales (e.g., decadal-scale changes in extreme precipitation or generational-scale resilience of tribal cultural traditions) and cross-scale interactions.

Although each team examined social–ecological systems dynamics as part of its strategy for understanding and potentially changing system behavior, it seems unlikely that this research strategy will always generate the kinds of knowledge needed for near-term decision-making. For instance, biophysical research conducted by the tidal energy team did not find major adverse effects of single turbines on fish, but much more research is needed to assess the potential adverse effects of the many turbines that would be required for commercial-scale energy production. Similarly, when the emerald ash borer team began developing its research plans in 2010, many experts suggested that the beetle might not reach Maine for a decade or more, which seemed to provide adequate time to develop systems models for informing management decisions. But the beetle spread more rapidly than expected (e.g., it was detected <60 km from Maine's border in May 2013). So it is now much less likely that social–ecological systems knowledge will be sufficient to meet potentially urgent decision-making needs.

Knowledge↔action strategies benefit from established collaborative networks and a co-production ethos

Iterative stakeholder engagement and inclusive forms of knowledge co-production can yield major dividends (van Kerkoff and Lebel 2006), but they are often very time consuming. All three Mitchell Center projects sought to balance these conflicting demands by building on existing university–stakeholder networks to accelerate the collaborative process. For example, the coastal adaptation and tidal energy projects included Cooperative Extension and Sea Grant staff members who had a long history of working closely with diverse stakeholders. Similarly, the researcher who led the emerald ash borer project was also a widely respected member of the Penobscot Indian Nation, which greatly facilitated the team's ability to collaborate with tribal communities and other partners.

One of the clearest signs of a genuine commitment by researchers to collaborative knowledge production is a willingness to adjust research questions and strategies based on stakeholder input. Each team demonstrated this flexibility by embracing stakeholders' suggestions that new or different research questions be addressed, which also increased the level of mutual respect and trust within the partnership. In the case of the emerald ash borer and coastal adaptation projects, the process of defining the problem and developing a research plan was dramatically changed because of stakeholder input. Similarly, the tidal energy team's strategy for establishing an ecological baseline regarding fish abundance and diversity benefited greatly from suggestions by local fishers about suitable sampling sites and methods. In our experience, this ability to modify research plans based on diverse forms of knowledge and know-how greatly increased the prospects for co-creating useful solutions.

Organizational innovation is enhanced by mutual respect, adaptability, and a commitment to solutions

Although universities have many valuable characteristics that can help society address sustainability challenges, the capacity for organizational innovation is key to universities achieving their full potential. The complexity and growing urgency of many sustainability problems need to be matched by an increased ability of universities to: respond to changing societal concerns and needs, promote systems thinking that spans disciplinary boundaries, and place a greater emphasis on linking such systems knowledge with societal action.

These three projects contributed to, and benefited from, an innovative organizational culture that emphasized respect, adaptability, and solutions. A collective regard for the knowledge and research skills of different team members helped overcome the inherent ontological and epistemological differences that exist among disciplines, and it helped develop the systems-level understanding that depends upon the power of interdisciplinarity. Common strategies that enabled successful interdisciplinary collaboration included the development of sustained, mutually respectful communication among team members, including graduate students and post-doctoral researchers, which is a framework that has proven essential to effective interdisciplinarity (Thompson 2009). All three teams blended the strengths of natural and social science, and two of them included faculty from engineering programs, which generally have more experience in developing solutions to real-world problems. This ability to assimilate and value diverse forms of knowledge also facilitated the process by which researchers and stakeholders integrated their respective expertise to co-produce a common understanding of sustainability challenges and opportunities.

For individual researchers, interdisciplinary teams, and the university as a whole, dedication to problem solving was a major factor contributing to the Mitchell Center's progress. For instance, the Mitchell Center is based at a land-grant university whose mission emphasizes the importance of research that addresses the state's needs. Moreover, all three projects benefitted from participation by faculty who represented units with strong interdisciplinary and problem-solving cultures, including the School of Marine Sciences and the School of Forest Resources, and who had robust ties to The University of Maine's Cooperative Extension program and to its Agricultural and Forest Experiment Station. Although faculty promotion and tenure criteria and processes varied among units and did not consistently prioritize engaged, interdisciplinary research, the challenges created by such variation in professional rewards did not prevent these projects or participants from making significant progress. Indeed, many team members expressed a strong desire for their research to "make a difference", and exhibited a willingness to take professional risks (e.g., during promotion and tenure processes) in pursuit of this goal.

The Mitchell Center's work was enhanced by individual and organizational flexibility. All three project teams had to adjust their research expertise and strategies to respond more effectively to the concerns and needs of stakeholders. This also meant that the teams had to become more proficient at mediating complex boundaries between science and society. This process of organizational learning was facilitated by the support of a major 5-year grant that allowed more time to learn from mistakes and overcome setbacks.

CONCLUSION

We believe that universities are uniquely positioned to help accelerate the transition to sustainability. Few other societal institutions have the breadth and depth of relevant expertise, the core commitment to the advancement of understanding, or the potential for engaging in the multi-decadal partnerships required to identify, analyze, and solve sustainability problems. Our experiences with the design and implementation of the Mitchell Center for Sustainability Solutions have demonstrated that it is possible to leverage these foundational strengths in ways that also surmount two major organizational challenges: (1) overcoming the disciplinary fragmentation that can impede the development of an integrated understanding of sustainability problems; and (2) ensuring that research not only increases understanding, but also strengthens our collective ability to link knowledge with action. We hope these lessons have value for other university-based efforts towards tackling sustainability challenges, and look forward to additional comparative analyses that can accelerate our collective progress.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/7283

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Appendix 1

Background Information on the 20 Projects that Constituted the Mitchell Center's Initial Research Portfolio.

Protecting Natural Resources at the Community Scale
Team: University of Maine
Project range: Statewide
[online] URL: http://umaine.edu/mitchellcenter/using-vernal-pools-to-study-urbanization-climate-change-and-forest-management/

Sustainable Urban Regions Project (SURP)
Team: University of Southern Maine, University of Maine
Project range: Portland and Bangor
[online] URL: http://umaine.edu/mitchellcenter/sustainable-urban-regions-project-surp/

Safeguarding a Vulnerable Watershed
Decision tools to support water resources sustainability of managed lake systems
Team: University of Maine, University of Southern Maine
Project range: Sebago Lake Watershed
[online] URL: http://umaine.edu/mitchellcenter/safeguarding-a-vulnerable-watershed/

People, Landscape and Communities (PLACE)
Team: University of Maine
Project range: Statewide
[online] URL: http://umaine.edu/mitchellcenter/people-landscape-and-communities-place/

The Knowledge-to-Action Collaborative
Team: University of Maine
Project range: Statewide
[online] URL: http://umaine.edu/mitchellcenter/knowledge-to-action/

Mapping a Sustainable Future
Team: University of Maine, University of Maine School of Law
Project range: Lower Penobscot River Watershed and Casco Bay Watershed
[online] URL: http://umaine.edu/mitchellcenter/mapping-a-sustainable-future/

Adapting to a Changing Climate in Coastal Communities
Team: University of Maine, UMaine Cooperative Extension
Project range: Coastal Maine
[online] URL: http://umaine.edu/mitchellcenter/helping-communities-weather-the-storms/

Reducing Vulnerability to an Invasive Forest Pest, the Emerald Ash Borer
Team: University of Maine
Project range: Statewide
[online] URL: http://umaine.edu/mitchellcenter/mobilizing-to-fight-the-emerald-ash-borer/

Assessing the Potential for Tidal Energy Development
Team: University of Maine
Project range: Down East Maine
[online] URL: http://umaine.edu/mitchellcenter/renewable-energy-from-the-tides/

Effects of Climate Change on Organisms (ECCO)
Team: University of Maine
Project range: Statewide
[online] URL: http://umaine.edu/mitchellcenter/effects-of-climate-change-on-organisms/

Socio-Ecological Systems Synergy
Team: University of Maine
Range: Project wide
[online] URL: http://umaine.edu/mitchellcenter/socio-ecological-systems/

Organizational Innovation: Systems Analysis of SSI
Team: University of Maine
Range: Project wide
[online] URL: http://umaine.edu/mitchellcenter/organizational-innovation/

Restoring Maine's Rivers
Team: Bates & Bowdoin Colleges, University of Southern Maine
Project range: Androscoggin and Kennebec Rivers and Estuary
[online] URL: http://umaine.edu/mitchellcenter/restoring-maines-rivers/

Sustaining Our Lakes
Team: Colby College
Project range: Belgrade Lakes Watershed
[online] URL: http://umaine.edu/mitchellcenter/sustaining-our-lakes/

Sustaining Quality of Place in the Saco River Estuary
Team: University of New England
Project range: Saco River Estuary
[online] URL: http://umaine.edu/mitchellcenter/quality-of-place-in-the-saco-river-estuary/

Understanding An Insect Threat to Maine's Hemlock Trees
Team: Unity College
Project range: Southern & Central Maine
[online] URL: http://umaine.edu/mitchellcenter/understanding-an-insect-threat-to-hemlock-trees/

Assessing the Feasibility and Sustainability of Grass Biomass Production in Aroostook County
Team: University of Maine at Presque Isle (UMPI)
Project range: Aroostook River Watershed
[online] URL: http://umaine.edu/mitchellcenter/feasibility-of-grass-biomass-production-in-aroostook-county/

Charting the Rangeley Region's Social and Ecological Systems
Team: University of Maine at Farmington (UMF)
Project range: Belgrade & Rangeley Lakes Regions
[online] URL: http://umaine.edu/mitchellcenter/charting-the-rangeley-regions-social-ecological-systems/

Biomass Energy Resources in the St. John Valley, Aroostook County, Maine
Team: University of Maine at Fort Kent (UMFK)
Project range: St. John Valley
[online] URL: http://umaine.edu/mitchellcenter/feasibility-of-grass-biomass-production-in-aroostook-county/

Evaluating Interactions Between Wild Turkeys and Maine Agriculture
University of Maine at Augusta (UMA)
Project range: Statewide
[online] URL: http://umaine.edu/mitchellcenter/interactions-of-wild-turkeys-and-agriculture/

Appendix 2
Sources of Additional Information for the Case Studies

Assessing the potential for tidal energy development

Publications

Jansujwicz, J. S., and T. R. Johnson. 2014. The Maine Tidal Power Initiative: Transdisciplinary sustainability science research for the responsible development of tidal power. *Sustainability Science,* doi: 10.1007/s11625-014-0263-7.

Johnson, T. R., J. Jansujwicz, and G. Zydlewski. 2013. Tidal power development in Maine: Stakeholder identification and perceptions of engagement. *Estuaries and Coasts*, 38(S1):266-278.

Jansujwicz, J. S., and T. R. Johnson. 2013. Understanding and informing permitting decisions for tidal power development in Maine. *Estuaries and Coasts,* 38(S1):253-265.

Johnson, T., and G. B. Zydlewski. 2012. Research for the sustainable development of tidal power in Maine. *Maine Policy Review,* 21 (1):58-64. [online] URL: http://digitalcommons.library.umaine.edu/mpr/vol21/iss1/10/

Masters Thesis

Vieser, J. D. 2014. Collaborative research on finfish and their distribution and diversity in Cobscook Bay, Maine. Unpublished M.S. thesis. University of Maine, Orono, ME.

Conference Proceedings

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Fact Sheet

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