Collaboration Across Boundaries for Social-Ecological Systems Science

Experiences Around the World

Edited by
Stephen G. Perz

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For those about to cross
For those who salute the strangers
For those who govern for sustainability

Preface

It was my turn to talk, but this would not be straightforward. I was in the country of my second language, but not everybody in the group spoke that language, so I resorted to my third tongue, which more of the visitors seemed to grasp. I hoped people would be able to follow along, especially since many were from nonacademic organizations like governmental agencies and nongovernmental organizations. But even the academics present weren't from my discipline, sociology: they were mostly hydrologists and limnologists. My introduction thus amounted to a strange proposition for a meeting that at first glance seemed like an absurd exercise. Why was an academic talking to academics of other disciplines, people from nonacademic organizations, in another country, in a language not native to that country in the first place? What was all this for?

The participants at that meeting had come together to better understand the dynamics of a threatened watershed, especially the part passing through a series of towns with rapidly changing land use due to urbanization. The watershed thus constituted a dynamic Social-Ecological System (SES) experiencing complex changes involving human settlements with new activities closely tied to terrestrial and

aquatic ecosystems which have their own interactions. Everybody around the room had both academic as well as practical reasons to be present, since the watershed in question was not well-understood, and because it was experiencing rapid changes of political importance tied to water quality, flood control, and other concerns. What is more, everybody around the room knew that they only commanded a small portion of the issues and expertise that would be necessary to understand and then address the problems. They needed to talk to each other in order to improve their collective understanding and thereby clarify the basis for policies and other actions to better sustain the watershed and the human populations and ecosystems that depend upon it.

In other words, to adequately respond to the complex interplay of rapidly changing dynamics in the watershed as an SES, the parties present found it necessary to leave the confines of their institutional abodes and cross boundaries among academic disciplines, organizational types, and countries of origin in order to collaborate. This case is by no means unique, for SESs of many kinds around the world are experiencing rapid changes that are prompting shared concerns among diverse stakeholders, raising questions for scientists of various disciplines, governments of many countries, and businesses and communities alike. At the watersheds meeting, much as at many others with different kinds of players who seek to collaborate across boundaries, there were very good reasons to join forces, and thus ample goodwill. The shared concerns and complementary capacities among the parties present provided the incentive to reach out; the scientists could produce the data needed by other stakeholders in order to make informed decisions, notably governments with regard to policies that would affect other parties, hopefully for the better.

Be that as it may, significant challenges arise when groups reach out to each other across boundaries and try to engage to pursue joint actions. In the case described above, and in many others, stakeholders seeking to collaborate across boundaries discover that they make contrasting assumptions about the SES and its problems, so they adopt different perspectives about the nature of the issues and how they should be approached, and consequently reach divergent conclusions about what should be done. The upshot is often miscommunication,

confusion and conflict, which in turn hinder discussion and impede advances toward joint action. Adequately understanding watersheds and other social-ecological systems presents challenges, as does improving their governance and the effectiveness of their management. Beyond those tasks is the additional obstacle course involving the groundwork required to manage the travails of crossing boundaries to make the necessary collaboration possible in the first place.

This book takes up issues of engaging in effective practice when crossing boundaries for collaboration, focusing on the specific case of understanding SESs in order to improve their governance and management for sustainability and resilience. We therefore focus on the challenges to scientific practice from collaboration across boundaries in the conduct of research on SESs. Our purpose is to better respond to the problems presented by rapid change in SESs by working in teams of scientists and other collaborators who are likely to span multiple kinds of divides. This requires recognition of the challenges of collaboration across boundaries in terms of the need to learn the skills necessary to work in diverse teams. Those skills come not from the sciences involved in understanding the technical details of SESs, but rather from other disciplines. The acquisition of skills such as in social learning and teaming will be indispensable if scientists and practitioners are to rise to the challenge of collaboration across boundaries for knowledge production and application. We pursue this agenda by working from what is known about the skills and practices essential for spanning divides to work as teams, and by reflecting on concrete experiences to derive specific lessons and thereby improve future practice in SES science.

Rather than speak from the experience of one person or even one team, this book recounts the experiences of a suite of teams working on complex SESs around the world. In the process, the teams crossed not one but multiple types of boundaries simultaneously. Along the way, the teams had to learn or find practices to manage the consequent challenges. In the event, the teams identified and developed a diversity of strategies to improve their collaborative practice as they spanned divides. In many cases, teams found their way to practices established in the applied behavioral science literatures on management and collaboration. The teams also engaged in highly innovative strategies, often taking

advantage of long-standing relations of trust and happenstance to learn lessons and improve practice. If direct experience is a hard teacher, the lessons won are that much more valuable and worth sharing.

This book therefore lets those teams speak with their own voices, and often those of their partners, to report what they have learned. The teams were constituted under particular funding programs and thus had similar mandates, budgets and scientific goals, which permits comparisons among their cases. That said, the teams themselves have distinct histories, and studied a range of different SESs in a diversity of cultural and political contexts, all of which can affect the efficacy of specific strategies and practices they can implement to collaborate effectively. This permits comparative reflections on how team structure and constitution, as well as external circumstances, may affect team performance.

What stands to arise from comparisons of these many experiences are broader insights about collaboration across boundaries, in terms of challenges that are shared and those which are more context-dependent, strategic practices employed and their effectiveness across cases, and thus conclusions to be drawn from lessons learned. Our collective intent in this book is thus to detail challenges, strategies and lessons from collaboration across boundaries in SES science, in order to make recommendations and thereby improve future projects in support of sustainability and resilience initiatives. Just as the research projects reported in what follows permit in-depth understanding of SESs, as examples of team science that span divides, they also offer a deeper understanding of collaboration across boundaries that can benefit future partners in similar endeavors.

Gainesville, USA Stephen G. Perz

Contents

1 Introduction: Collaboration Across Boundaries for Social-Ecological Systems Science 1
Stephen G. Perz

2 Lessons Learned About Collaborating Across Coupled Natural-Human Systems Research on Mexico's Payments for Hydrological Services Program 35
Erin C. Pischke, Z. Carter Berry, Randall K. Kolka, Jacob Salcone, Diana Córdoba, Xoco Shinbrot, Sergio Miguel López Ramirez, Kelly W. Jones, Russell G. Congalton, Robert H. Manson, Juan José Von Thaden Ugalde, Theresa Selfa, V. Sophie Avila Foucat and Heidi Asbjornsen

3 Adapting to the Challenges of International and Interdisciplinary Research of Coupled Human and Natural Systems 79
Sarah Laborde, Sui Chian Phang and Mark Moritz

4 Collaborative Research Across Boundaries: Mangrove Ecosystem Services and Poverty Traps as a Coupled Natural-Human System 115
Emi Uchida, Victor H. Rivera-Monroy, Sara A. Ates, Edward Castañeda-Moya, Arthur J. Gold, Todd Guilfoos, Mario F. Hernandez, Razack Lokina, Mwita M. Mangora, Stephen R. Midway, Catherine McNally, Michael J. Polito, Matthew Robertson, Robert V. Rohli, Hirotsugu Uchida, Lindsey West and Xiaochen Zhao

5 Learning About Forest Futures Under Climate Change Through Transdisciplinary Collaboration Across Traditional and Western Knowledge Systems 153
Erica A. H. Smithwick, Christopher Caldwell, Alexander Klippel, Robert M. Scheller, Nancy Tuana, Rebecca Bliege Bird, Klaus Keller, Dennis Vickers, Melissa Lucash, Robert E. Nicholas, Stacey Olson, Kelsey L. Ruckert, Jared Oyler, Casey Helgeson and Jiawei Huang

6 Sustaining Interdisciplinary Collaboration Across Continents and Cultures: Lessons from the Mongolian Rangelands and Resilience Project 185
María E. Fernández-Giménez, Arren Allegretti, Jay Angerer, Batkhishig Baival, Batbuyan Batjav, Steven Fassnacht, Chantsallkham Jamsranjav, Khishigbayar Jamiyansharav, Melinda Laituri, Robin S. Reid, Jessica Thompson, Tungalag Ulambayar and Niah Venable

7 Challenges of Boundary Crossing in Graduate Training for Coupled Human-Natural Systems Research 227
Elizabeth G. King and Nathan Nibbelink

8 Understanding the Central Great Plains as a Coupled Climatic-Hydrological-Human System: Lessons Learned in Operationalizing Interdisciplinary Collaboration 265
Marcellus Caldas, Martha Mather, Jason Bergtold, Melinda Daniels, Gabriel Granco, Joseph A. Aistrup, David Haukos, Aleksey Y. Sheshukov, Matthew R. Sanderson and Jessica L. Heier Stamm

9 High-Resolution Remote Sensing Data as a Boundary Object to Facilitate Interdisciplinary Collaboration 295
T. Trevor Caughlin, Sarah J. Graves, Gregory P. Asner, Bryan C. Tarbox and Stephanie A. Bohlman

10 Scientists and Stakeholders, Data and Diagnostics: Crossing Boundaries for Modeling the Impacts of Highway Paving in a Tri-national Frontier in the Amazon 327
Stephen G. Perz, Galia Selaya, Rafael Muñoz-Carpena, Gregory Kiker, Christopher Baraloto, Matthew Marsik and Jane Southworth

11 Collaboration Across Boundaries: Reflections on Studying the Sustainability of the Mississippi River Delta as a Coupled Natural-Human System 361
Nina S.-N. Lam, Y. Jun Xu, R. Kelley Pace, Kam-biu Liu, Yi Qiang, Siddhartha Narra, Thomas A. Bianchette, Heng Cai, Lei Zou, Kenan Li, Sanjeev Joshi and Volodymyr Mihunov

12 Crossing Boundaries for Collaboration in Comparative Perspective: Key Insights, Lessons Learned, and Recommendations for Future Practice 395
Stephen G. Perz

Index 431

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List of Figures

Fig. 2.1 Map of two study microwatersheds in central Veracruz State in Mexico receiving payments for hydrological services (*Source* Map made by Jose Von Thaden Ugalde using ArcMap 10.4.1) 42

Fig. 2.2 Map of data collection sites in Veracruz, Mexico (*Source* Map made by Jose Von Thaden Ugalde using ArcMap 10.4.1) 43

Fig. 2.3 **a** Cloud forest in Veracruz; **b** Ejido in the Gavilanes watershed (*Source* Photographs by Erin Pischke) 44

Fig. 2.4 Conceptual model of PHS programs in Mexico. Blue arrows represent the expected linear relationship between Mexico's PHS program and its impacts on program participants, forest cover, and hydrologic services. Green dashed arrows indicate the more complex (often indirect and unintended) linkages and feedbacks that emerge between PHS programs and the social, economic, and biophysical systems (*Source* Figure created by the authors) (Color figure online) 45

Fig. 2.5 **a** Conducting surveys in the watershed; **b** Conducting surveys in the watershed (*Source* Photographs by Erin Pischke) 50

Fig. 2.6 **a**–**d** Biophysical data collection in the watershed (*Source* Photographs by Z. Carter Berry) 52
Fig. 3.1 Map of the Logone Floodplain in the Far North Region of Cameroon (*Source* Map created by the authors using ArcGIS software [ESRI Corp., Redlands, CA]) 82
Fig. 3.2 Fishing canals are changing the landscape of the Logone Floodplain. **A** Flooded area from three over-imposed Landsat images and field-surveyed fishing canals (pink markers). **B** Zoom of the black frame in A—pink lines are fishing canals. **C** Zoom of the black frame in B—black arrows represent flow paths of water during flood recession. **D** Photograph of fish trap located at the pin on frame C, at the end of a canal (Photograph by O. Atti). **E** Number of fishing canals in the Logone floodplain since 1915, reconstituted from the age of canals surveyed; linear fit until 1979 ($R^2 = 0.974$ for 1915–1979), then exponential fit ($R^2 = 0.993$ for 1980–2014). **F** A Chadian worker deepening a canal in the dry season (*Source* Reproduced with permission from Laborde et al. (2016); Figure created by the authors using Adobe Illustrator) (Color figure online) 86
Fig. 3.3 The initial conceptual model of coupled system and key variables (*Source* left; reproduced from *African Journal of Aquatic Science* (2016) 41(1): 99–108 with permission © NISC (Pty) Ltd) and the conceptual model at the end of the project (*Source* right; *Source* figure created by the authors) 87
Fig. 3.4 Networks showing the MORSL team organization across (**a**) geographies, (**b**) languages and (**c**) expertise as of April 2014, a few months after starting the project. Each node is a researcher in the network. The edges are weighted based on the frequency of collaborative interactions between two researchers: (1) have met, rare interactions; (2) interact regularly, e.g., weekly meetings; (3) more frequent interactions, for logistics or based on a formal relationship (e.g., supervision, or partnership on other projects). The size of nodes is proportional to their

weighted degree (number of edges, considering the weight of edges) (*Source* Figure adapted by the authors using Gephi, modified from Laborde et al. 2018a to show only 2014 networks) 95
Fig. 3.5 Weekly survey that was sent to researchers that participated in that week's MORSL meeting (*Source* Figure created by the authors using Google Forms) 98
Fig. 4.1 Mangrove ecosystem services and poverty traps framework. In this diagram, stock is represented by rectangles and flows by thick arrows and rounded rectangles indicating ecosystem services. Curved arrows represent feedback loops while thin straight arrows show conditioning factors and drivers. Dotted arrows represent nonexisting flows or feedback loops (*Source* Figure created by the authors) 120
Fig. 4.2 Research team structure (*Source* Figure created by the authors) 123
Fig. 5.1 Conceptual diagram showing feedbacks between natural and human systems in the Menominee forest sector (*Source* Figure created by the authors) 158
Fig. 5.2 Study area in northern Wisconsin, including Menominee Nation (in box) and adjacent watersheds (*Source* Map created by Melissa Lucash using ArcMap 10.5.1) 160
Fig. 5.3 Illustration of the collaborative network evolution of our project. Each node represents an individual who was connected to the project in some way. Solid lines represent formal academic linkage (funded project, co-authorship), whereas dotted lines indicate informal academic relationships (current or former colleagues or peers) (*Source* Figure created by the authors) 163
Fig. 5.4 Important phases and group processes that occurred through project development. Official collaboration did not occur until the project was funded on the second submission, almost two years after initial discussions (*Source* Figure created by the authors) 166
Fig. 6.1 MOR2 coupled natural-human systems conceptual model (*Source* Figure adapted by the authors from Reid et al. 2014) 190

Fig. 6.2 MOR2 study sites. Dark outlines are study counties (*soum*). Soums with triangles indicate counties with formal CBRM organization and those without were non-CBRM counties with traditional herder neighborhoods (*Source* Figure created by G. Allington in R, adapted from Fernández-Giménez et al. 2018) 193

Fig. 6.3 MOR2 core team composition. The core team comprised 13 individuals, including all PIs, graduate students, post-docs, and two collaborating scientists, one based in Mongolia and one in the United States (*Source* Figure created by the authors) 196

Fig. 7.1 Modes of individual engagement in interdisciplinary research. Colored shapes represent individual researchers, whose scientific approach is aligned to a particular domain (NS or HS) in CNH research, or discipline. Increasing depth of engagement in disciplinary research is represented vertically, from awareness of research topics, to epistemic appreciation, to utilization of methodologies to conduct research. **a:** Sharing and Communicating model: researchers are grounded in the epistemic perspective and methodologies of their own domain or discipline, and mostly connect with other approaches at the awareness level through planned data sharing, though some team members may have deeper appreciation for other approaches. **b:** "Standing on a Bridge" model: the discipline-bridging field has its own epistemic commitments and methodologies, and the researcher (dashed) connects with traditional disciplinary scholarship as in the Sharing and Communication model. **c:** Straddling Boundaries model: researchers have depth of knowledge in more than one discipline, and use theories and methodologies from both to conduct research (*Source* Figure created by the authors) (Color figure online) 234

Fig. 7.2 Conceptual plots of collaboration effectiveness resulting from with varying degrees of overlap in disciplinary expertise (a and b) or support for interdisciplinary training (c). **a:** Perz's argument that an intermediate degree of overlapping capacities and interests is optimal

for maximizing collaboration effectiveness. **b:** Collaboration effectiveness curves may be different for ICON students (solid) and committee members (dashed), but for both, greater dissimilarity can be effective because the ICON rep can help span communication barriers. When the goal of collaboration is knowledge synthesis (dotted), the optimum shifts toward greater similarity in expertise, and has a narrower peak because research products must fit into an overarching framework. **c:** When considering support for interdisciplinary education, a generously overlapping degree of shared commitment is always valuable (*Source* Figure created by the authors) (Color figure online) 246

Fig. 7.3 Career placement of the 13 ICON program graduates to date (*Source* Figure created by the authors) 253

Fig. 8.1 Gradients of land cover, population density, precipitation, and temperature in the Smoky Hill watershed, Kansas and Colorado (*Source* Figure created by Robert Daniels using ArcGIS) 270

Fig. 8.2 The research components (*Source* Figure created by the authors) 272

Fig. 8.3 Agent-based model applied to the Smoky Hill River Watershed in Kansas (*Source* Figure created by the authors) 278

Fig. 8.4 Recommendations for collaboration in transdisciplinary research (*Source* Figure created by the authors) 283

Fig. 9.1 Conceptual diagram of reforestation as a coupled natural-human system. This flowchart displays our initial conceptual model for forest cover increases as the outcome of social and ecological drivers in Latin American cattle pastures (*Source* Figure created by the authors) 300

Fig. 9.2 Study area of Los Santos Province, Panama. The upper map in this figure is the country of Panama, with a yellow star indicating the location of the capital city. Black lines represent provincial boundaries. The inset in the map displays our study area, the province of Los Santos. The inset displays a forest cover in 2000 using a forest/non-forest classification from Hansen et al. (2013). Green colors indicate forest, while black indicates non-forest pixels

(*Source* Figure created by the authors using QGIS and R) (Color figure online) 302
Fig. 9.3 Importance of landowner boundaries for determining patterns of tree cover. Cadastral data indicate the importance of landowner decision-making for driving heterogeneous patterns of tree cover in our study landscape. This figure shows that neighboring parcels frequently have very different amounts and types of tree cover. The black lines indicate boundaries between mapped parcels (derived from ANATI 2000). Imagery courtesy of Google Earth (2018) (*Source* Figure created by the authors using QGIS and R) (Color figure online) 306
Fig. 9.4 Medium and high-resolution remotely sensed data. This figure contrasts four different sources of remotely sensed imagery we have used to understand reforestation dynamics in Los Santos province. The location chosen for these images includes a patch of secondary forest as well as some actively grazed land with dispersed pasture trees. In a clockwise direction, **a** represents medium-resolution Landsat data (30 × 30 m; Caughlin, Rifai, et al. 2016), **b** represents a subset of the hyperspectral visible-to-shortwave infrared data (2 m; Asner et al. 2012), **c** represents a Canopy Height Model (CHM) derived from LiDAR data (1.3 m; Asner et al. 2012), and **d** represents Google Earth imagery (<0.5 m; Google Earth 2018) (*Source* Figure created by the authors using QGIS and R) 308
Fig. 9.5 Local farmers participating in land cover change research. This photo demonstrates local farmers engaging in a board game based on land cover change data. As part of this activity, farmers interpreted tree cover change in high-resolution imagery (*Source* Photo taken by T. Caughlin) 314
Fig. 10.1 Forest types in the tri-national "MAP" frontier (Madre de Dios/Peru, Acre/Brazil, and Pando/Bolivia) (*Source* Figure created by Galia Selaya using ArcGIS 10.4 with data from Wanderley Ferreira) 334

Fig. 11.1 The study area showing Lake Pontchartrain as a hypothetical boundary, with parishes to the north called the "North" whereas parishes to the south called the "South" (Lam, Xu et al. 2018). Reproduced with permission 365
Fig. 11.2 The Mississippi River Delta Coupled Natural-Human dynamics framework (Lam, Xu et al. 2018). Reproduced with permission 368
Fig. 11.3 Projected elevation map with areas below sea level shown in red (Zou et al. 2016). Reproduced with permission (Colour figure online) 376
Fig. 11.4 Continuous RIM scores map by block-group; scores ranging from 1–4, the higher the score, the more resilient (Cai et al. 2016). Reproduced with permission 377
Fig. 11.5 The MRD coupled natural-human (CNH) system dynamic model (Li and Lam 2018a). Reproduced with permission 379
Fig. 12.1 The cycle of adaptive management for collaboration across boundaries (*Source* Figure created by the author) 420

List of Tables

Table 6.1	Communication and collaboration strategies for MOR2 core team and extended team	197
Table 6.2	MOR2 sub-teams and data collected	204
Table 7.1	Summary of the seven issues identified by Perz (2016) as challenges in boundary-crossing collaborations; the manifestations of those challenges in the intra-academic context of the ICON Ph.D. program; the desired outcomes of those challenges; and the strategies and program elements that have been instrumental in addressing them	256
Table 11.1	Summary of survey responses on collaboration across boundaries	384

List of Boxes

Box 6.1 Reflection of former US Ph.D. student 200
Box 6.2 Reflection of Mongolian Ph.D. student 208
Box 6.3 Reflection of Mongolian post-doctoral fellow 209

1

Introduction: Collaboration Across Boundaries for Social-Ecological Systems Science

Stephen G. Perz

1.1 The Central Challenge

Collaboration across boundaries, such as interdisciplinarity via the formation of scientific teams, is by now widely recognized as an indispensable response to complex problems (Perz 2016). "Wicked problems" that defy established solutions within institutional and cultural silos are typically marshaled as examples of situations where crossing boundaries for collaboration is necessary (Balint et al. 2011; Brown et al. 2008). Illustrative cases of wicked problems include health care provision, environmental degradation, and immigration policy. Funders of innovative science increasingly seek projects with teams that span disciplinary and other divides (e.g., Gewin 2014). Similarly, various areas of practice, such as in environmental conservation, increasingly underscore governance approaches to management (e.g., Batterbury and Fernando 2006; Biermann and Pattberg 2008; Lemos and Agrawal 2006; Newig and

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Fritsch 2009; Young 1997), as via multi-stakeholder processes, comanagement, and other collaborative modes that feature joint action by governments and other stakeholders (e.g., Armitage et al. 2009; Brick et al. 2001; Buck et al. 2001; Carlsson and Berkes 2005; Colfer 2010; Galat and Berkly 2014; Hemmati 2002; Lauber et al. 2011; Manring 2007; Poncelet 2004; Warner 2007).

The institutions that define disciplines, organizations, countries, and other bounded domains for thought and action exist for many reasons. This carries the crucial implication that crossing boundaries among domains for collaboration is not an automatic or natural process. Bounded domains like disciplines have cultures, and those cultures rest upon assumptions and practices that support theories and methods that may or may not be commensurate across domains. Those assumptions and practices are thus not always obvious or intuitive, which bears the additional repercussion that they must be learned. Collaboration and crossing boundaries thus require the acquisition of knowledge and skills for effective practice.

It is therefore problematic that the knowledge and especially the skills for collaboration and crossing boundaries tend to be overlooked or assumed by specialists of a given domain, even among those who recognize that they need to span divides. There remains a strong tendency to focus on the wicked problem at hand, which is certainly honorable precisely because it is complicated and important. But that also often corresponds to paying insufficient attention to the practices that enable the expertise in collaboration and crossing boundaries to be effectively deployed to address said problem. Similarly, there remains an inclination to dismiss the interpersonal and managerial aspects of collaboration, and of crossing boundaries. While scientists are professional thinkers, and some are naturally sensitive and gregarious, it is incautious to assume that one's team has the requisite knowledge and skills for applying best practices for collaboration across boundaries. One does not merely collaborate; one manages to do so. Similarly, crossing boundaries is not a routine act, but rather a gesture out of the ordinary, which is subject to questioning due to suspicion. Crossing boundaries for collaboration thus implies a steep learning curve, and a lack of preparation poses significant risks to being able to advance effectively.

It is therefore heartening to note that there are sciences relevant to the effective practice of crossing boundaries for collaboration. However, these sciences differ from those typically invoked to address wicked problems. In the case of environmental problems, it is biophysical and socioeconomic sciences that are usually brought together. But those differ from the sciences required to support collaboration across boundaries per se. Those instead fall in the applied behavioral sciences, notably in psychology and management. While these sciences are not new, they have all too rarely found purchase among specialists in other sciences who would benefit from applying their insights. Hence there is something of a boundary between the sciences often brought to bear on the technical issues involved in wicked problems, and the applied sciences that support best practices in collaborating across boundaries to actually address said problems. The practice of the second is necessary to advance the first.

There are several bodies of thought and scientific literatures on collaboration. In terms of theory, perhaps the classic point of departure concerns the political science literature on the conditions under which collective action is possible. Olson's (1965) statement argued that self-interest undermines collective action in all but the smallest groups. Ostrom's (1990) reply however provided examples that identified the conditions under which collective action can occur among many social actors in a sustained fashion. More broadly, the business administration literature has a body of theory concerning management practices in bureaucratic organizations with hierarchical structures (e.g., Daft 2005; Gittel and Weiss 2004; Gittel et al. 2010; Gomez-Mejia et al. 2008; Heckscher and Adler 2006). Varied forms of hierarchical structures, chains of command, and their implications for the flow of authority and information are eminently germane to the conduct of business and other joint activity. In psychology, there are multiple literatures relevant to the enterprise of collaboration. The organizational behavior literature offers numerous insights concerning the relationship between organizational structure and behavior on various levels of scale, ranging among individuals in organizational cultures, team dynamics and productivity, and inter-organizational relationships (e.g., Hersey et al. 2007; Ott et al. 2003). As a complement, industrial psychology has highlighted various

applied aspects of behavior in formal organizations, whether in terms of hiring procedures, training and workforce development, performance evaluation, and topics related to organizational performance and consumer behavior (e.g., Cascio 1995; Landy and Conte 2016). Out of research on business management and psychology has emerged work on the "science of teams" (e.g., Fiori 2008; Jones et al. 2008; Wildman and Bedwell 2013) which has focused on issues of the formation and social processes on teams.

Research in these applied behavioral sciences has identified suites of tasks necessary to pursue collaboration, along with challenges that arise in the pursuit of those tasks, and practices to facilitate collaboration. The key summary message that stems from these literatures is twofold. First, collaboration does require effort at learning in order to practice the skills needed to make possible the effective pursuit of shared goals, so collaboration should only be done when necessary. But second, collaboration via the application of those skills makes possible the achievement of shared goals that would otherwise be beyond the reach of the collaborators if they acted independently. As work from the management literature on collaboration has noted, there is "collaborative advantage" in terms of the achievements that become possible via collaboration, if one can learn the skills and apply best practices to avoid "collaborative inertia" (Huxham and Vangen 2005; Lank 2006).

Similarly, there are scholarly literatures on crossing boundaries. Crossing boundaries can complicate collaboration, and thus requires separate recognition. While the general set of skills and practices for crossing boundaries in many ways builds on those involved in collaboration itself, spanning divides often entrains very context-specific challenges and requires some emendations of those skills and practices. Literatures on crossing boundaries thus tend to focus on spanning specific kinds of divides and focus on particular insights from direct experiences. These literatures include work on the practice of interdisciplinarity, inter-organizational collaboration, and international cooperation, all of which I discuss below.

We should respond to calls to cross boundaries for collaboration to address wicked problems. But we also need to acknowledge what others have already learned about the skills required and the practices vital

to be effective in spanning divides. In this book, we take up the case of social-environmental problems as a case of wicked problems in order to examine SES science, both in terms of knowledge production for understanding complex systems and for the application of that knowledge to better govern them. In the remainder of this chapter, I briefly review SES science and how it motivates the need for collaboration across boundaries. Then I offer a framework of the issues, tasks, challenges, and practices for effective collaboration, along with a discussion of the complications and strategies of crossing boundaries for collaboration, featuring interdisciplinarity, inter-organizational collaboration, and international cooperation, which are germane to the pursuit of SES science.

1.2 Social-Ecological Systems Science

By SES science, I refer to the integrated study of SESs by scientific teams that span various academic disciplines, and likely also organizational types, countries, and other boundaries. SESs constitute an example of complex dynamic systems (e.g., Anderies et al. 2006; Epstein et al. 2015; Folke 2006; Fischer et al. 2015; Walker et al. 2006). The focus on complexity arose in response to the inadequacies of established equilibrium approaches to the analysis of dynamic systems. Complex systems approaches have gained favor in the analysis of systems experiencing disturbances and thus far from equilibria or in the process of shifting from one state to another. Consequently, analysis of complex dynamic systems tends to feature nonlinearities in system behavior, generally observed in terms of some key indicator of system state whose dynamics either speed up or slow down, and whose observed values move in directions not seen previously. Such nonlinearities are attributed to other aspects of system complexity such as feedback processes among interacting system components wherein a change in one component affects another that feeds back to the first, whether via a positive feedback that accelerates the change or a negative feedback that dampens it. Another focus of inquiry to explain nonlinearities concerns cross-scale processes, or teleconnections, which may themselves involve

feedbacks, constituting telecouplings (Friis et al. 2016; Liu et al. 2015). Complex systems may also exhibit critical thresholds (cf. Scheffer et al. 2012) such that a system component that reaches a particular value modifies relationships elsewhere in the system, leading to cascading changes that alter how the system is organized and resulting in a new system state. Complexity science thus features uncertainty and surprise in complex dynamic systems, in recognition that disturbances to systems may yield responses beyond the bounds of that seen historically, resulting in potentially undesirable outcomes.

SES science has emerged out of complex systems science as recognition has grown that SESs exhibit many of these traits seen in complex dynamic systems. This has, in turn, resulted in work to develop conceptual frameworks on SESs. Liu et al. (2007) offer an influential rendering of SESs as linked social and ecological subsystems, each with their respective system components and relationships. They underscore however the importance of social-ecological interactions between the two subsystems, and highlight that those interactions are reciprocal, thus leading to the potential for generating nonlinearities as via feedbacks, telecouplings, and so forth. More recently, Binder et al. (2013) and Boumans et al. (2015) have provided reviews of different approaches to modeling SESs, including system flows (as of energy, materials, and information), human decision behavior, product analyses as to their ecological ramifications, resilience and adaptation approaches, and capitals-based approaches.

In these and other publications (cf. McConnell et al. 2011), groups of scientists have highlighted specific aspects of SESs for purposes of analysis. Particular attention has gone to reciprocity in social-ecological feedback loops, especially with the goal of quantifying the extent to which the dynamics in each subsystem modify those of the other. Closely related to this concern has been interest in various forms of networks and connectivity among system components, which defines the structure of relationships and feedbacks (e.g., Barnes et al. 2017). Also relevant is the growing focus on cross-scale processes as they lead to telecouplings. This takes advantage of the classic problem of defining system boundaries to instead embrace the fact that localities are linked and may thus be affected by far distant drivers which they may, in turn,

affect via feedbacks (Liu et al. 2015). SES science has featured the concern with critical thresholds as related to the issue of resilience (Lade et al. 2013; Gunderson et al. 2017). This stems in part from the ecological definition of resilience in terms of the disturbance required for an SES to shift from one state to another, which in turn relates directly to concerns about ecosystem degradation into undesirable states from both a social and ecological standpoint. Concerns about critical thresholds as "tipping points" in SESs is also tied to interest in surprise and uncertainty in SESs, especially as concerns human behavioral changes under shifting conditions. At the same time, there is interest in system trajectories and path dependency, whether based on initial conditions or later system dynamics that become self-reinforcing.

Drawing on these ideas, empirical research and dynamic modeling efforts have proliferated in recent years, as teams of scientists have taken up integrated study of SESs of various types around the world. While a full review is beyond the scope of this chapter, it is worth noting a selection of examples, especially as they feature the interactions of social and ecological subsystems in specific SESs, along with other prominent elements of SESs as complex dynamic systems.

Analyses of SESs often involve water bodies and water resources, including fisheries. Leslie et al. (2009) focus on a marine fishery in a coastal ecosystem being impacted by climate change as well as distinct groups of fishers that respond differently to regulatory mechanisms. Downing et al. (2014) similarly take up the case of a lake fishery, where multiple fish species have particular ecological relationships as well as specific economic values to different human fishing groups, all in turn affected by external economies and policies. Villamayor-Tomas et al. (2016) report on the possible impacts of a proposed hydropower plant on a watershed with fish species on which local stakeholders depend. Bury et al. (2013) evaluate the dynamics of a glacier-dependent watershed that is being modified by climate change via shifting precipitation and snowpack, leading to downstream conflicts among human user groups, which themselves are changing activities in the form of new mining and hydropower initiatives. Yu et al. (2015) evaluate the design of irrigation systems to manage the flows of ecological benefits to local species and economic benefits to agricultural user groups.

Other analyses evaluate resource use in terrestrial ecosystems. Qi et al. (2012) consider the soil dynamics in dryland agricultural systems being impacted by climate change and shifting human land use, which jointly modify both carbon and water fluxes. Oakes et al. (2015) provide analysis of forest ecosystems as they are impacted synergistically by both climate change and human activity. Carter et al. (2014) study conservation of ecosystems with large wildlife species and growing populations of human user groups, focusing especially on how external disturbances and telecouplings affect wildlife–human interactions.

There is also increasing attention to urban areas as SESs. Spies et al. (2014) take up the case of the wildland-urban interface in a fire-prone ecosystem, where there are human and natural causes of fire, and fire suppression policies lead to worse fires when they occur. Fan et al. (2014) consider the social-ecological dynamics of urban areas defined by government planners, occupied and used by other human stakeholders, but also inhabited by many other species that find ways to adapt to engineered landscapes.

In this and other research in SES science, there is agreement on the need for collaboration across boundaries. Many such discussions focus on the importance of teaming for interdisciplinary collaboration (e.g., Fischer et al. 2015; McConnell et al. 2011). Most of the references just cited involved publications of five or more coauthors, sometimes many more, and they frequently come from different disciplines, and/or different organizations or countries.

What is more, there is broad agreement that SES science can contribute to applications in environmental governance processes and management regimes for ecosystem sustainability (e.g., Armitage et al. 2009; Berkes et al. 2003; Ostrom 2009; Guerrero and Wilson 2016). To that end, Ostrom (2009) offers a framework for evaluating SESs, in which she further unpacks the system components. Her assemblage includes the resource system (biophysical processes), resource units (lands, watersheds, etc.), the governance system (government and stakeholders and decision processes) and resource users (user groups), and their interactions. Notable here is the focus on differentiating system components for purposes of applications in governance processes for SES management for sustainability.

In a related vein, there has been considerable emphasis on participatory approaches to both the study and the management of SESs (e.g., Devisscher et al. 2016; Mehryar et al. 2017). This complements the parallel recognition among scientists of the importance of local knowledge for the study and management of SESs (e.g., Berkes and Turner 2006; Ruiz-Mallén and Corbera 2013; Mantyka-Pringle et al. 2017; Winter and Lucas 2017). This work builds on the multi-stakeholder process literature noted earlier. All such work routinely highlights the importance of scientists crossing boundaries to work in a transdisciplinary mode with nonacademic stakeholders on governance and management problems. As with the science of teaming, crossing boundaries for governance and management of SESs has its own scientific literature (e.g., Berdej and Armitage 2016; Guimaraes et al. 2015).

There remains however a situation where training and thus learning about collaboration and crossing boundaries are in demand, and yet the knowledge, skills, and experiences remain in short supply. There is agreement that the study and management of SESs requires integrative approaches to span various divides, but the challenges put off those who would embark on the adventure. SES science is certainly complicated, and calls to read the literatures of one's collaborators to gain fundamental knowledge are certainly valid. But the skills required for collaboration across boundaries must also be explicitly outlined, or the practices vital to the collective enterprise cannot be acquired. Scientists have to learn these skills in order to take on the additional roles of being good brokers, communicators, managers, leaders, and so on. The next section offers a framework of the issues, tasks, challenges, and strategic practices for effective collaboration.

1.3 Collaboration: A Framework

Previous work on collaboration has offered various renditions of the many vagaries at play when forming teams and pursuing collective endeavors. Literature on collaboration includes classic statements from the management literature (e.g., Kraus 1980) and work on multi-stakeholder processes (e.g., Gray 1989). Research on collaboration

in business administration has focused on joint ventures among different firms (e.g., Austin 2000; Cropper et al. 2008) and among divisions, departments, and other entities within firms (e.g., Hansen 2009; Heckscher and Adler 2006). In addition, there is work on collaboration among nongovernmental organizations (NGOs) (e.g., Poncelet 2004; Reuer 2004; Wondolleck and Yaffee 2000). These and similar statements provide lists of issues entrained by initiating collaborative efforts. Discussions typically highlight the exigencies involved and then call attention to the skills and practices necessary to avoid the pitfalls in order to move forward jointly toward shared goals. The issues commonly noted include the importance of effective communication, the joint definition of goals, establishment of a clear management structure, and routine reporting for coordination and accountability.

Here I offer a framework for collaboration based in part on previous work, as well as my own experience on SES science and conservation and development projects (Perz 2016). The framework is organized around seven issues: (1) introductions and communication, (2) inequalities and politics, (3) common interests and complementary capacities, (4) goals and objectives, (5) leadership, governance, and management, (6) expectations and benefits, and (7) uncertainty and surprise (Perz 2016, Chapter 3). These issues allow us to unpack the labor that is collaboration. This list runs somewhat beyond those typically noted in previous work on collaboration, notably by the attention paid to inequalities and politics as well as surprise and uncertainty. This is because those issues have received somewhat less attention than the others in most previous work on collaboration, and have in my experience proven to be particularly thorny in the context of crossing boundaries.

For each issue, I identify a suite of tasks to be performed to address the issue, challenges that may arise in the pursuit of those tasks, and strategic practices that can help with the tasks so that collaboration can proceed effectively. This means of organizing the labors of collaboration provides a framework that not only sets forth the difficulties likely to arise, but also affords as basis for addressing the exigencies. By directly relating the issues, tasks, and challenges to strategic practices, one gains an operational basis for collaboration to realize collaborative advantage. The following discussion offers a brief exegesis on the seven

issues involved in the framework for collaborative practice. This is not intended to be a definitive discussion. Readers interested in a longer version of what follows can consult Perz (2016, Chapter 3) and sources cited in this section.

Introductions in particular and communication in general are well-known as vital to effective collaborative practice. Through introductions, potential collaborators begin to get to know one another, and key is learning what each knows and what each does not with regard to the shared interest at play. From the onset of introductions, communication skills play a determinant role as potential partners assess the prospects to achieve collaborative advantage. Tasks are immediately entrained, such as coming to a common understanding of the meaning of key terms and making assumptions explicit. The first is especially challenging on science teams that contain specialists with large technical vocabularies. The second bedevils collaborators in most all endeavors because assumptions are often implicitly held and thus hard to identify, or they are explicit but ideological and therefore viewed as inviolable and nonnegotiable. A useful strategic practice for introductions and communication is to understand the onset of collaboration in terms of courtships. This implies engaging in extensive side consultations to learn more about the prospective partner, and managing the emerging relationship as a measured process over time and not as a hasty decision based on a one-night stand. Both permit the social learning necessary to appraise the benefits of a prospective partner and help with comprehending new terms and dredging up assumptions for critical examination. Another strategic practice is to work through network brokers (cf. Manring 2007). These are well-connected individuals already familiar with both of the prospective partners and who can use that knowledge to facilitate introductions and communication.

If complementarities among collaborators beget collaborative advantage, the flip side of the same coin is that differences stemming from complementarities correspond to inequalities that can become political. Issues of power must be openly and immediately addressed for any collaborative effort to advance; otherwise, mistrust builds and endangers joint action. Insofar as SES science also proposes to generate findings that can be applied in policy and management, the external political

context can greatly affect the impacts of a collaborative enterprise. Collaborators must therefore honestly assess their respective capacities as well as the broader political risks to their proposed course of action. The first is easier said than done, for more influential partners often seek to assert themselves and thus reproduce inequalities, often beginning with the framing of the problem or invoking a specific theoretical approach. Even if partners begin to build ties of trust, one may be riven with internal political conflicts. The second requires some structural analysis of the collaborators vis-à-vis the relevant powers-that-be, especially with regard to whether the two have any means of directly communicating. Further, the political context is subject to change, for better or worse. Problems stemming from partner inequalities and internal and external politics are especially difficult because they are sensitive, and they tend to recur over time. The resulting conflicts thus have to be managed; they cannot be solved (cf. Burton and Drakes 1990). Strategic practices however permit management of the challenges. Among partners with past histories of conflict, venting of grievances right up-front can help clear the air, or at least permit explicit recognition of issues to be addressed. Among new partners who are unequal, network brokers can moderate the discussion, which can include nonnegotiable issues as decided by weaker partners (cf. Edmunds and Wollenberg 2002). Network brokers can also exert moral authority by calling out partners, especially stronger ones, when they try to exercise dominance. Collaborators of partners with internal conflicts can adopt "non-aligned policies" with regard to the combatants in question, which helps keep the focus of the collaboration on shared interests. Collaborators can begin to address an unsympathetic political context by proactively providing information about the proposed activities and their benefits. At least in the cases where lack of knowledge or familiarity is the problem, communication can at a minimum clarify the disposition of vested interests. An extensive discussion of inequalities and politics in collaboration is available in Perz (2016, Chapter 6).

Crucial to realizing collaborative advantage is to square up the common interests with complementary capacities among partners. In SES science, shared interests generally stem from a social-environmental problem and some opportunity for knowledge production to improve

management outcomes. Defining the approach to be taken then requires sorting out the knowledge funds, experiences and other capacities of each partner as they differ from and thus add value to those of the others. Shared interests can be defined through a process of independent free listing of interests that are then made public to identify common interests among the partners. The same procedure with the opposite logic can be pursued for identification of complementary capacities. Challenges arise when partners articulate their interests vaguely or overestimate their capacities. Interests and capacities must be clear enough to permit identification of gaps in needs to thereby afford planning of joint actions with a clear division of labor. As a strategic practice, there is a need to critically evaluate all claims about interests and capacities, especially in light of the problem at hand and in the context of previous responses and their limitations. This provides a basis for clarifying the approach to be taken, whether in terms of knowledge generation or management applications, in terms of aligning partner capacities with their proposed responsibilities. All this is not to say that partners must be entirely complementary in their capacities; some redundancy can be very useful, especially if one partner proves inadequate to meet the challenges they face.

Delineating goals and objectives is unequivocally important for collaborators, especially if SES science explicitly contemplates the application of knowledge to policy or management. In conservation and development work, goals and objectives are defined as part of the process of developing a theory of change (e.g., Breuer et al. 2016; Taplin et al. 2013) for purposes of monitoring and evaluating of performance (e.g., Hockings et al. 2005; Saterson et al. 1996). That is, defining a goal entrains identification of objectives to be achieved in order to attain the goal. In turn, identification of objectives requires definition of specific activities theorized to be necessary to achieve said objectives. That then necessitates setting of performance indicators and targets for the outputs of the activities. Underlying such logical frameworks for generating results is a theory of change, an argument as to why the actions proposed will yield the outcomes desired, along with assumptions underlying the argument as a means of risk analysis. The tasks of defining goals and objectives are thus quite extensive. Collaborators

unfamiliar with theory of change approaches and the construction of logical frameworks for results thus pose challenges to the process of defining goals and objectives. Further, partners may not agree on goals, or objectives, or activities, or indicators, or targets, or their underlying assumptions. Fortunately, development of theories of change and results frameworks requires learning, and partners can learn together. Everybody needs to go dig up arguments and supporting information to justify goals and all the details that they might imply. The design of logical frameworks can proceed specifically on the basis of identified partner capacities, which helps divide the anticipated labor, clarify responsibilities, and allow for identification of weaknesses, whether in terms of time allowed for performance of work or otherwise. Critical analysis of the proposed sequence of activities and their outputs also serves as a reality check. If some partners end up with more responsibilities, the keys are that everyone learns and everyone takes on responsibilities commensurate with their experience and capacities.

Statements on collaboration have often featured the interrelated issues of leadership, governance, and management. The first pertains to the design of a collaborative structure that establishes a chain of command, as well as the roles and styles of leaders; the second concerns how the collaborative structure will define who gets to participate in making strategic decisions governing the collective enterprise; and the third focuses on day-to-day operational practices and oversight. Beyond the leaders, collaborative structures define functional roles for various specialists, whether scientific or administrative, and how they are to divide their labor and work together. Collaborative structures are also often supported by the establishment of written agreements, which involves approval by authorities of participating organizations. These tasks are outlined in detail in the literatures on business administration and organizational behavior. The challenges nonetheless bear noting. Partners may have differing leadership styles, or prefer different governance structures and procedures. Leadership may not understand or be disinclined to listen to technical staff. Partners may resist signing agreements, or fail to deliver on the commitments made therein. Collaborative structures have both vertical (chain of command) and horizontal (network) dimensions, and combining the two

through partnering can be confusing to partners accustomed to one or the other. Strategic practices for managing these challenges include the concept of "servant leadership" (Greenleaf 2002), where leaders serve the partners by adhering to an ethic of advancing the shared interests of the collaborative endeavor, rather than the interests of an individual or organization. There must be clearly defined performance evaluation procedures based on stated goals and deadlines. At all turns, strategic practices in collaborative structures must prioritize the shared interests of the collaborative enterprise over the self-interests of particular constituencies. Beyond leadership styles and procedures, the design of collaborative structures is crucial for effective management of collaboration. "Distributed leadership" (Spillane 2006) is very useful, for it involves dividing responsibilities among managers or organizations such that they must discuss management problems and jointly take decisions in light of shared goals. Distributed leadership also helps to manage the tensions of vertical and horizontal relationships in collaborative structures. Both types of relationships are necessary for productive collaboration: vertical relationships define clear chains of command and permit efficiencies in getting work done; horizontal relationships facilitate the flow of information and thus innovation. A longer discussion of the design of collaborative structures can be found in Perz (2016, Chapter 5).

With all that is involved in collaboration, partners must devote careful attention to the issue of expectations and benefits. Expectations refer to the responsibilities to be assumed for work done and products delivered; benefits refer to who gets what if they do what is expected. Both may be monetary or nonmonetary, and short or long term. Clarifying these aspects is crucial to avoid unhappy realizations and conflicts later. Similarly, partners need to talk out how each sees their respective expectations relative to benefits, as some may be asked to bear greater burdens than others for the sake of the collaborative enterprise. One challenge is therefore to be sufficiently clear up-front, as some partners may hold back for cultural or political reasons. As work unfolds, some technical tasks may prove more difficult than expected, and partners may want to renegotiate. Then there is the problem of what happens if somebody does not fulfill the expectations to which they have agreed. An obvious

strategic practice is to hold an up-front workshop on these issues to promote dialogue and clarifications. A related practice is to be transparent about who gets what, especially in monetary terms; this includes talking about salaries in order to justify personnel budgets on funded projects. As noted above, the inequalities go on display so then they can be discussed instead of left to simmer. Especially for partners focused on short-term monetary benefits, discussion of nonmonetary and long-term benefits is a vital strategic practice. Collaboration forges network ties that can lead to downstream opportunities, including publications and future projects.

A final issue at play in collaboration concerns surprises and uncertainty. Collaborative enterprises are risky endeavors due to surprises that may stem from partners themselves as well as the broader context. Indeed, SES science projects may themselves be affected by the very environmental changes they propose to study, like extreme climatic events or systems crossing tipping points. Working with new partners necessarily entrains uncertainties, especially in larger networks. So does working in new contexts like other countries or rapidly changing regions. There are different management procedures to pursue, depending on the level of ambient uncertainty confronting collaborators. The classic default is rational planning, where partners can define future actions and outcomes with a reasonable degree of uncertainty, but that is only feasible under low levels of uncertainty. Researchers involved in environmental management have long recognized the limitations of rational planning and thus advocated adaptive management (cf. Holling 1978; Lee 1993), in which partners define plans, implement and gather data, and then adjust based on the findings. This permits a modicum of adaptation if uncertainty is somewhat greater. SES researchers have gone beyond adaptation to scenario planning (cf. Peterson et al. 2003; Shoemaker 1991) when uncertainty is yet higher. Collaborators facing significant uncertainty jointly develop several possible scenarios of future change in order to plan for each and thereby seek to pursue desirable pathways. If the level of uncertainty is so high that even a few scenarios are going to be insufficient to plan any course of action, then there is one final option: "muddling through" (cf. Lindblom 1959; Wollenberg et al. 2007). This amounts to a strategy of staying

connected with local partners and waiting for opportunities to appear, however unexpected, and simply being ready to drop everything to try and respond. A more extensive discussion of surprise and uncertainty in collaboration is available in Perz (2016, Chapter 7).

1.4 Crossing Boundaries for Collaboration

Insofar as calls for SES science entrain teams of scientists who work across disciplines in various countries and seek to convey their findings to nonacademics, the strategy underlying the pursuit of SES science is that of collaboration across boundaries. The foregoing framework provides a roadmap for recognizing and responding to the exigencies of collaboration. When crossing boundaries, the complexity of the issues in that framework increases. It is one thing to collaborate with another scientist of one's discipline, organization, and country; it is another work with a researcher of a different discipline, organization, or country.

Having said that, I hasten to emphasize that crossing boundaries can amplify collaborative advantage (Perz 2016, Chapter 4). If all the issues of collaboration are magnified when crossing boundaries, from the struggles of communication through surprises and uncertainty, so too are the potential impacts. Hence just as inequalities may be wider and politics intensified when spanning divides, so too are the complementarities among partners, and thus the collaborative advantages of joining forces. Crossing boundaries for collaboration may present additional challenges, but it also increases collaborative advantages.

This section examines domains with boundaries relevant to SES science, focusing on disciplines, organizational types and countries. There are of course other forms of boundaries, whether defined culturally, institutionally, or politically. The sociological categories delimited by race/ethnicity and gender come to mind, as do institutional designations like scientist and technical staff or faculty and student. For present purposes, I discuss how interdisciplinarity, inter-organizational collaboration and international cooperation complicate the challenges of collaboration. I then note selected strategic practices to facilitate the realization of the additional collaborative advantages from spanning divides for joint action.

As SES researchers know well, academic disciplines constitute scholarly domains with boundaries (e.g., Becher and Trowler 1989; Kagan 2009). Disciplines require command over topical content and a suite of methodological skills. Boundaries between disciplines reflect their historical differences in their bodies of thought, their traditional methods, and their key insights. Disciplines thus constitute specialties that offer complementary contributions to the broader academic enterprise; one would not confuse a cultural anthropologist with a physical chemist. That said, boundaries also demarcate frontiers between disciplines, which can be difficult to cross, not only because disciplines have differing theories, methods, and insights, but also because they have different histories and cultures. Whereas the first group is often explicit and can be acquired by some reading, the second is often implicit and harder to apprehend. Crossing disciplinary boundaries is thus more than a matter of reading up on the fundamentals of another discipline; it requires time and dialogue with the players. This motivates the literatures on multi- and interdisciplinarity (e.g., Frodeman et al. 2010; Klein 1996, 2010; Weingart and Stehr 2000).

In turn, that work has outlined specific challenges and strategic practices in interdisciplinarity (e.g., Kainer et al. 2006; Lélé and Norgaard 2005). Whereas interdisciplinarity involves a conceptual synthesis in a single collaborative effort, much previous work on interdisciplinary collaboration has featured the importance of communication, specifically the issue of arriving at shared understandings of technical terms (e.g., Monteiro and Keating 2009; Pennington 2008). But disciplines are not created equal, so arriving at shared understandings of terms and framing problems becomes a political process (MacMynowski 2007; Oughton and Bracken 2009; Schoenberger 2001). Collaborators across disciplines thus need time to engage in critically interrogating all frames proposed for an interdisciplinary project, to manage the potential for domination by some partisans, and to better ensure integration of contributions from different disciplines. Good interdisciplinary collaborators are not afraid to reveal the "dirty laundry" of the assumptions, blind spots and limitations of their disciplines. This facilitates deeper ontological and epistemological discussions that inform theoretical and methodological choices in interdisciplinary project development. There

is growing appreciation of the "cultural turn" in the social sciences by biological scientists (e.g., Moon and Blackman 2014).

SES scientists also know that applying their findings often requires partnering across the boundaries between different types of organizations (e.g., Cropper et al. 2008; Poncelet 2004; Robinson et al. 2000; Wondolleck and Yaffee 2000). This is the issue addressed in the literature on transdisciplinarity (e.g., Hirsch Hadorn et al. 2008; Pohl 2005). Such statements typically differentiate between academics and nonacademic stakeholders. It is important to go further and differentiate among organizational types, including universities, government agencies (GAs), for-profit businesses, nonprofit organizations (aka NGOs), community associations, and others. Each has their distinct mandates, strategic assets and liabilities, organizational structures, key personnel, cultural assumptions, and practical imperatives (e.g., Easterby-Smith et al. 2000; Knoben and Oerlemans 2006; Phillips et al. 2000). Contrasts in the last pair of these characteristics are illustrative, as cultural assumptions and practical imperatives present significant challenges to collaboration among different types of organizations. Universities view knowledge production and dissemination as inviolable mandates, but have countervailing imperatives between hierarchical authority from administrations to faculty and deeply felt values about faculty autonomy and freedom of inquiry. In contrast, NGOs often see themselves as filling needs left by GAs and other organizations, including for conducting applied research and providing outreach to communities on issues of concern, but NGOs rely on external funding for their activities, which also orients much of their focus. The prospect of universities collaborating with NGOs thus requires navigating the distinct cultural values on the roles of basic and applied research, the distinct imperatives that drive the timeframes of their operations, and other contrasts, such as in their organizational structures and key personnel.

The many contrasts in organizational types bear significant implications for inter-organizational collaboration. One issue is that organizations operate on different calendars, which distinct annual deadlines during which it becomes very hard to respond to requests from partners. This makes it very important to detail dates on flow charts for the timing of joint activities and submission of deliverables. Similarly, the

operational protocols of different organizations likely differ, following the principle that bureaucracies are invariably designed to ensure their continued survival, on their own specific terms (Peters 2001). Hence the procedures of a GA may not square comfortably with those of a community association. This requires administrative points of contact in order to translate specific procedures in the paperwork of one into those of another, so papers from one are interpretable and acceptable by the other. Given the contrasting structures of different organizational types, it can be challenging to identify equivalent individuals to serve as the points of contact. This often occurs as a player in one organization reaches out to the authorities of another in order to find the appropriate counterpart. University faculty may or may not neatly match up with technical personnel in a GA or NGO. The work to gain an understanding of each other's organization is richly rewarding however, for then each becomes the diplomat of their organization to the other's, which is not only necessary but facilitative of inter-institutional ties. While perpetually asking questions to clarify bureaucratic procedures and organizational cultures might seem dull, it is an investment in knowledge that is rarely shared and very valuable, for it creates the conditions for recognizing complementarities vital for inter-organizational collaborative advantage.

Working in other countries (or multiple countries at the same time) poses similar challenges, but the cultural and historical depth of the differences is greater, especially when working in far-distant places (e.g., Chasek 2000; Gaillard 1994; Keating and Jarvenpaa 2016; Young 1989). Countries of course have territorial boundaries, historically determined, often set after various forms of conflicts. Hence the challenges of crossing national boundaries can be especially complicated. Language differences are the most obvious cultural manifestation of boundaries, but other cultural dimensions of boundaries may also impede collaboration, such as understandings of time as they inform when meetings actually begin (as opposed to when they are putatively set to begin). Institutional systems generally differ among countries, such that getting visas to enter, travel, and all manner of other logistical details will likely need considerable attention before any work can be

done. And if the country of interest for collaboration has tense diplomatic relations with one's home country, then the sensitivities of working there become especially delicate, not only for oneself but especially for one's in-country collaborators. Crossing national boundaries is thus very demanding, and identification of motivated and capable collaborators is crucial.

Perhaps nowhere more than when crossing national boundaries are the travails as well as the benefits of crossing boundaries as evident. Finding partners well-disposed to serve as emissaries on behalf of their country is vital, for they can break down (or at least interpret and translate) the manifold cultural, institutional, and political barriers-that-be. This first requires careful attention to decoding one's own country's culture, institutions, and politics. If the discussion gets to the point where partners can raise concerns about each other's countries, especially the stronger of those represented, then a modicum of trust has been gained, trust to manage the potentially large inequalities at play (Stewart and Gray 2006). Sharing national beverages at a bar facilitates this process, but it is likely to be extended, for decoding cultures takes time, institutional procedures are difficult to learn, and politics can present sudden crises. Another key practice is to be ready when a partner has a locally induced crisis and makes requests of their collaborators to wait or otherwise modify their best-laid plans, with some cost to the activities and products contemplated. If the collaborators are ready to make sacrifices for the partner, productivity may drop, but political capital among the team is won. This creates the conditions for reciprocity later, reciprocity that may prove crucial to sustainable international cooperation. As with inter-organizational collaboration, forming multiple points of contact, as on the scientific and administrative fronts, can be very valuable, for this fosters broader communication and learning across national boundaries, which helps stabilize collaborative relationships. There is much more than can be said about strategic practices and crucial moments when spanning boundaries for collaboration, whether among disciplines, organizational types, or countries; a longer discussion is available in Perz (2016, Chapter 4).

1.5 Outline of the Book

The foregoing framework for collaboration and the discussion of crossing boundaries is merely a point of departure. Both stem from my experience working to collaborate across boundaries in the southwestern Amazon. A major point of this book is to draw on the experiences of other scientific teams working to improve understanding and management of SESs in other parts of the world. A key contribution of what follows is therefore to offer additional reflections from other cases of SES team science and its applications. The chapters that follow therefore draw from no less than ten different collaborative endeavors involving SES science that crossed one or more boundaries, whether those discussed above or others.

The teams share a common mandate as all but one formed to pursue SES science under the same scientific funding program. The "Dynamics of Coupled Natural and Human Systems" (CNH) program of the US National Science Foundation (NSF) has funded numerous scientific teams working around the world to improve understanding and management of SESs (NSF 2018). Like other NSF programs, CNH projects are evaluated in terms of their "intellectual merit" as well as their "broader impacts." Under the first rubric, "Research projects to be supported by CNH must include analyses of four different components: (1) the dynamics of a natural system; (2) the dynamics of a human system; (3) the processes through which the natural system affects the human system; and 4) the processes through which the human system affects the natural system" (NSF 2018). This all but necessitates interdisciplinarity teaming. Under the second, CNH teams must demonstrate the real-world relevance of their research by focusing on SESs where management outcomes will affect both human communities as well as ecosystems, which necessitates inter-organizational collaboration and frequently international cooperation. Hence CNH project teams operate under broadly similar conceptual frameworks of complex SESs, and pursue similar strategies in addressing SES management problems. These shared priorities ensure a degree of comparability among the cases that follow. Each CNH team crossed boundaries for collaboration in order to study and improve management of SESs for sustainability.

In each chapter, a CNH team provides a discussion of their project, featuring how they have managed the vagaries of collaborating across boundaries in the pursuit of SES science and management. Each chapter begins with an introduction to the CNH problem being addressed, calling attention to the organizational aspects of the approach adopted. The team then provides a discussion of their conceptual framework of the SES under study, featuring its key components and relationships. This is followed by a description of the study region, noting salient aspects of its history and recent social and ecological dynamics. Teams then focus on how they formed, the structure of their organization, the key partners and the boundaries they crossed in order to collaborate. The heart of each chapter then discusses the exigencies of their experience in collaborating across boundaries, noting the salient issues, tasks and challenges, and then discussing the key strategic practices they employed. This discussion provides the basis for reflection on what worked, what did not, and why. Chapters then conclude by featuring key lessons learned that motivate recommendations for future practice among teams seeking to collaborate across boundaries for SES science with sustainability goals.

Together, the chapters offer a broad panoply of experiences in terms of the types of SESs studied, the structures of the teams formed, the locations of the study sites around the world, the key boundaries being crossed, the challenges encountered, the strategies for managing the challenges, and the recommendations offered. In Chapter 2, Pischke and colleagues report on the case of socio-ecohydrologic systems in Mexico and focus on the issue of scaling up various datasets for integrated modeling, and feature the issues of communication necessary for integration and interpretation of findings, notably for application in public policy. In Chapter 3, Laborde and colleagues reflect on the first author's role as an embedded observer of an interdisciplinary and international science team studying regimes shifts in the Logone Floodplain in northern Cameroon, discussing perspectives on developing a quantitative model as a focus for team cohesion when crossing boundaries, as well as a product of research. In Chapter 4, Uchida and colleagues discuss their research on mangrove ecosystem services in coastal Tanzania, highlighting how the rigors of fieldwork pose challenges to

understanding of dynamics in this SES, and how the research can affect stakeholders and thereby provide a basis for management to avoid poverty traps. Smithwick and colleagues offer Chapter 5, on the integration of indigenous knowledge with virtual reality technologies for sustainable future management of forests of the Menominee Nation, featuring teaming that prominently incorporates Menominee members and use of 3-D visualizations in management decisions. Fernández-Giménez and colleagues present Chapter 6, on the Mongolian Rangelands and Resilience Project, a collaborative effort among multiple universities and NGOs seeking to integrate data from fieldwork, monitoring systems and stakeholders, in which they offer reflections on lessons from simultaneously crossing multiple boundaries. In Chapter 7, King and Nibbelink report on an innovative transdisciplinary graduate training program, which prompts their in-depth discussion of the challenges to graduate training and mentoring to prepare young scientists to collaborate across boundaries for SES science. Caldas and colleagues offer Chapter 8, on the integration of models to understand coupling between hydrosystems, ecosystems and land use in the context of climate change and varying degrees of environmental concern among stakeholders in the Central Great Plains of North America. Caughlin and colleagues provide Chapter 9, which takes up issues concerning human decisions and secondary vegetation succession in Panama, featuring a dispute over the interpretation data due to scale mismatch that led to use of high-resolution satellite imagery, followed by eliciting stakeholder via role-playing games so the science team could confirm if its new interpretation of land cover was valid. Perz and colleagues provide Chapter 10, which focuses on their modeling project to evaluate the social and ecological impacts of highway paving in the southwestern Amazon, featuring a suite of issues stemming from the development as well as evaluation of dynamic simulation models. Lam et al. outline in Chapter 11 their experience in crossing disciplinary boundaries to better understand the Mississippi River Delta as a coupled natural and human system. In Chapter 12, I conclude by offering a comparative perspective on the experiences of the teams in the projects reported in terms of their key insights, shared challenges, factors that affected the difficulty of the challenges, notable strategic practices to address the

challenges, and recommendations for future teams proposing to collaborate across boundaries.

There is a general conclusion that bears repeating from these diverse experiences. While there are additional travails of collaboration across boundaries, let us not lose sight of the point of these enterprises: they make possible what would otherwise be beyond the reach of the individuals and organizations involved if they worked separately. It is also worth reminding ourselves of the larger purpose of SES science: the understanding and sustainable management of SESs. The road via collaboration across boundaries may be winding and onerous, but the goal is not only valuable but vital. Further, if spanning divides poses additional difficulties, they are complications that can usually be managed through the application of strategic practices. May future collaborators proposing innovative SES science benefit from the hard-won lessons of the teams who took the time to reflect on their experiences in the chapters that follow. This book is for them all, and their respective partners, and the sustainability of SESs everywhere.

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2

Lessons Learned About Collaborating Across Coupled Natural-Human Systems Research on Mexico's Payments for Hydrological Services Program

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2.1 Introduction

Of the many ecosystem services, hydrologic services are arguably one of the most critical for sustaining human societies and yet one of the most threatened. With growing global dangers of water scarcity and declining water quality (Liu et al. 2017), payment for hydrologic service (PHS) programs have surged over the past two decades (Goldman-Benner et al. 2012; Kaplowitz et al. 2012; Leimona et al. 2015; Postel and

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Thompson 2005; Porras et al. 2008; Stanton et al. 2010). By connecting ecosystem service "suppliers" and "consumers" in ways that explicitly incorporate a market value for such services, PHS programs seek to eliminate the externalities distorting traditional markets and create incentives for conservation that are equal to or greater than the opportunity costs foregone by limiting land use options. If successful, such approaches could vastly improve the supply, quality, and regulation of water resources within individual countries and globally.

PHS policies inherently operate within coupled social-ecohydrological systems. PHS policies are designed to enhance hydrological services provided by *biophysical systems* by eliciting certain desirable behaviors from *social systems* through incentives that target the associated *economic systems*. PHS programs generally seek to forge linkages between upstream and downstream natural and human communities. These linkages result from hydrologic flows through watersheds as well

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as from the relationships between producers and consumers of water resources. Interactions and feedbacks within payments for hydrological services-social-ecohydrological systems may be intensified by intended or unintended effects on the social system, for example, poverty alleviation or the equitable distribution of resources (Wunder 2015), or the biophysical system, particularly carbon sequestration and biodiversity (Wendland et al. 2010). Such effects may interact either synergistically or antagonistically with hydrologic services, resulting in complex feedbacks, interactions, and tradeoffs that may lead to unexpected and often surprising outcomes within coupled social-ecohydrological systems (Jenerette et al. 2006; Lebel and Daniel 2009; Porras et al. 2008).

An academic debate around the effectiveness of PHS in social-ecohydrological systems has emerged in recent years due to the limitations in assessment of environmental and socioeconomic outcomes. This is in part because of the complexity of PHS schemes, combined with an overall lack of systematic monitoring and evaluation.

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For example, a global meta-analysis performed by Brouwer et al. (2011) found that only 47% of PHS programs actually monitor impacts on service provisioning. In Mexico, a study contracted by USAID found that 40% of 45 local matching programs do no monitoring whatsoever, with the rest monitoring forest cover rather than water resources per se (Saldaña-Herrera 2013). Consequently, PHS programs have come under increasing scrutiny worldwide (Börner et al. 2017; Muradian et al. 2013), and the potential for PHS programs to enhance watershed sustainability has been questioned (Asbjornsen et al. 2015). Thus, substantial uncertainty remains about the ability of PHS programs to directly influence peoples' decisions related to water resources, especially over longer time periods or in response to different PHS program structures (Brouwer et al. 2011; Hayes 2012). Accurately quantifying and predicting the effects of coupled PHS and social-ecohydrological systems interactions is therefore critical to establishing a sound theoretical framework for policy decisions that links scientific knowledge with practical solutions for protecting hydrological services, while maximizing benefits to society (Grima et al. 2016).

One of the first and longest-running PHS programs worldwide was established in Mexico by the national government in 2003. The program, referred to as *Programa de Pago por Servicios Ambientales Hydrologicos*, was created in response to a presidential decree that the protection of water resources—and the forests considered essential to providing those resources—is a matter of national security. The program expanded from US$17.9 million in payments to 272 landowners of 127,000 ha in 2003 to a total of US$628 million paid to 9521 landowner groups with holdings of 5.83 million ha by 2017. This program was financed through payment of water concessions made by the National Water Commission (CONAGUA) to the National Forest Commission (CONAFOR), as well as from funds directly allocated by Mexico's Congress. The PHS program was envisioned as a mechanism for providing financial incentives to landowners to conserve their forest cover in key watersheds identified on the basis of the presence of priority ecosystems, proximity to national parks and downstream cities, the degree of aquifer overexploitation, and overlap with poverty alleviation programs (Alix-Garcia et al. 2015; McAfee and Shapiro 2010;

Muñoz-Piña et al. 2008; Perevochtchikova et al. 2012). In 2008, an additional local matching program was created by CONAFOR aimed at promoting greater participation by local stakeholders and financing for the PHS program by local governments and other partners that contribute at least 50% of operating funds (Nava-López et al. 2018). Recent trends throughout much of Mexico (including our study region) suggest a transition from the nationally supported program to matching fund programs cofinanced by both local sources and CONAFOR under diverse administrative structures. More recently, PHS programs throughout much of Mexico (including our study region) are managed under diverse institutional arrangements, including municipal government agencies and non-governmental organization (Nava-López et al. 2018). Mexico's PHS program typifies common approaches globally (e.g., Grima et al. 2016; Salzman et al. 2018; Sanchez 2015) and thus provides a model system for assessing interactions between PHS programs and complex dynamics occurring within coupled social-ecohydrological systems, as well as the associated constraints and opportunities for enhancing watershed sustainability. Due to the long history and diverse institutional arrangements, PHS programs in Mexico are representative of PHS programs throughout Latin America (Ingram et al. 2014; Grima et al. 2016; Hayes et al. 2015) and thus provide a model system for assessing interactions between PHS programs and complex dynamics occurring within coupled social-ecohydrological systems, as well as the associated constraints and opportunities for enhancing watershed sustainability.

Another emerging tool within watershed management among diverse actors is involving the public in scientific research, or citizen science (Bonney et al. 2009). Citizen science is increasingly recognized worldwide as an effective, low-cost means to collect large amounts of data for natural resource monitoring and management. Not only can citizen science provide data at spatial scales and resolutions never before attainable (Wright et al. 2015), but many argue that it can directly impact participants' perceptions, decisions, and behaviors in ways that are aligned with resource management goals (Crall et al. 2012). However, the success of these projects rests on the assumption that citizen science volunteers are easily recruited and valid data easily collected, despite a dearth

of evidence on best practices for securing such participation (Bruyere and Rappe 2007). Moreover, few studies have examined the effect of citizen science interventions on stewardship behaviors and perceptions (Follett and Strezov 2015). Therefore, developing an approach to designing citizen science programs that explicitly allow for assessment of program impacts on volunteers can provide valuable data for determining the potential complementary role of citizen science in enhancing the effectiveness of PHS programs.

With this in mind, the overarching goal of our research was to advance the fundamental understanding of linkages, interactions, and feedbacks between Mexico's PHS program and coupled social-ecohydrological systems. Of particular interest was to conduct an interdisciplinary evaluation of the capacity of PHS in Mexico to achieve stated outcomes (e.g., enhanced forest conservation and water quality and quantity), as well as larger goals related to watershed sustainability, defined here as the ability to maintain the well-being of human societies without undermining the integrity of the hydrological cycle or the ecological systems that depend on it (Gleick 1998) and as measured through key indicators (Asbjornsen et al. 2015). Finally, a broader long-term goal is to facilitate improvements in PHS policy development and implementation by utilizing a transdisciplinary approach to understanding the relationship between PHS programs and the coupled natural-human systems (CNH) in which they operate. We focused our work on two contrasting PHS programs in Veracruz State, Mexico: one overseen by a local government trust (FIDECOAGUA) in the Gavilanes Watershed, and one managed by a non-governmental organization (PROSAPIX) in the Pixquiac Watershed. Our specific research objectives were to:

1. Examine the motivations underlying people's decisions to participate in the PHS program and the subsequent effects on their social and economic well-being, as well as their perceptions and planned behaviors in relation to watershed sustainability.
2. Assess the impacts of the major land use/land cover types on hydrologic services (i.e., water supply and quality) and the potential trade-offs with other ecosystem services (e.g., carbon sequestration, biodiversity).

3. Assess the potential for citizen science water monitoring programs to enhance PHS program effectiveness through the effects of participation on environmental knowledge, perceptions, and stewardship behaviors over time, and by providing scientifically validated water flow measurements to improve capacity to monitor changes in watershed services over time.
4. Integrate the socioeconomic and biophysical data into a CNH modeling framework to simulate the impact of different land use scenarios on hydrological services and tradeoffs and apply this model to understanding impacts on stakeholder decision-making processes within the context of participatory workshops.

In this chapter, we present our experiences with this interdisciplinary project in Mexico, including the challenges and boundaries we faced while conducting research, while also highlighting our achievements. We present key lessons learned so that others can benefit from our experience. In the remainder of this chapter, we discuss our study area (Sect. 2.2), the CNH system we studied (Sect. 2.3), how we organized our team (Sect. 2.4), the challenges we encountered (Sect. 2.5), the successes we achieved (Sect. 2.6), and conclude with a summary of the key lessons learned and recommendations for other teams (Sect. 2.7).

2.2 Study Area

We conducted our research within two adjacent watersheds in central Veracruz with PHS programs (Figs. 2.1 and 2.2): Gavilanes (~4000 ha) and Pixquiac (~10,000 ha). These watersheds have similar biophysical and climatic characteristics, yet they differ in key socioeconomic and land use characteristics (Fig. 2.3). One difference is that the Gavilanes watershed is entirely within the municipality that uses its water, whereas the Pixquiac watershed covers several municipalities and the city of Xalapa. This means that Xalapa's government must negotiate among landowners in various municipalities to make payments related to the PHS program, which can be politically sensitive since these groups do not vote or pay taxes in Xalapa. A second key difference concerns

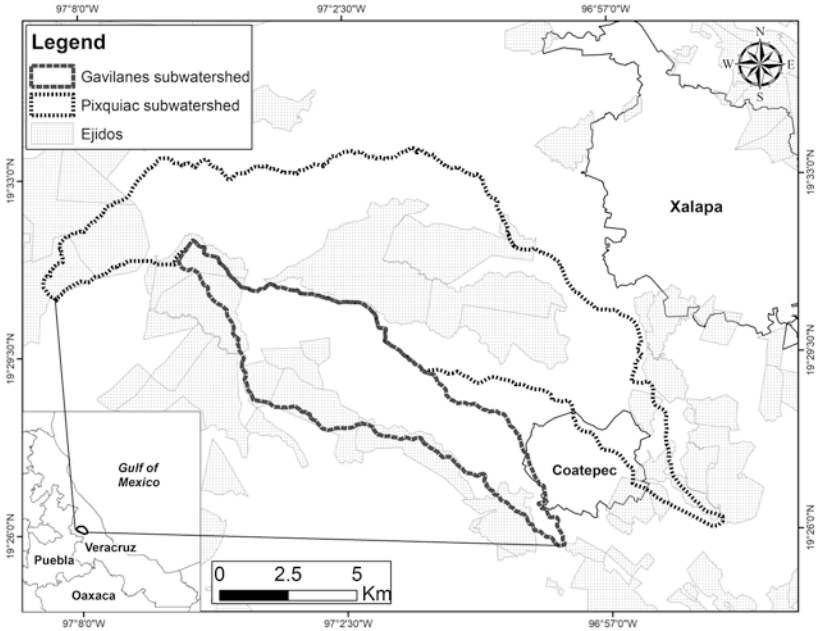

Fig. 2.1 Map of two study microwatersheds in central Veracruz State in Mexico receiving payments for hydrological services (*Source* Map made by Jose Von Thaden Ugalde using ArcMap 10.4.1)

higher population densities in the Pixquiac, since it includes Xalapa, Veracruz's second largest city (pop. 388,000), while Gavilanes supports the smaller city of Coatepec (pop. 50,000) and therefore experiences lower demands on water resources.

2.3 Coupled Natural-Human System: PHS Programs and Social-Ecohydrological Systems

The CNH system in Veracruz, Mexico, involves multiple linkages between ecosystem services and social and economic outcomes within human systems, as depicted in the conceptual model guiding this study

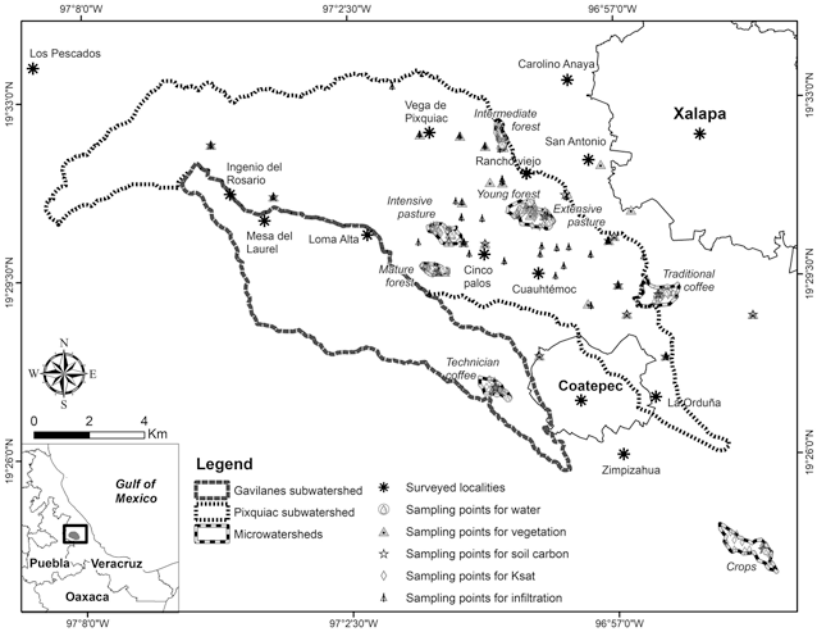

Fig. 2.2 Map of data collection sites in Veracruz, Mexico (*Source* Map made by Jose Von Thaden Ugalde using ArcMap 10.4.1)

(Fig. 2.4). This model highlights how the PHS program was originally designed as a linear construct, wherein participation of upstream landowners (e.g., water providers) would result in greater protection of forest cover and more sustainable land use practices, which ultimately would lead to improved provisioning of hydrologic services for downstream water users (e.g., blue solid arrows). However, due to the inherent complexities of CNH system dynamics, PHS policies typically lead to interactions and feedbacks between the socioeconomic and biophysical systems that were not intended by the program administrators or by the program participants (e.g., dashed green lines). To improve the design of PHS programs to better achieve watershed sustainability goals, knowledge about the underlying mechanisms that determine these complex relationships and the trade-offs between ecosystem service provisioning and socioeconomic costs and benefits is critical.

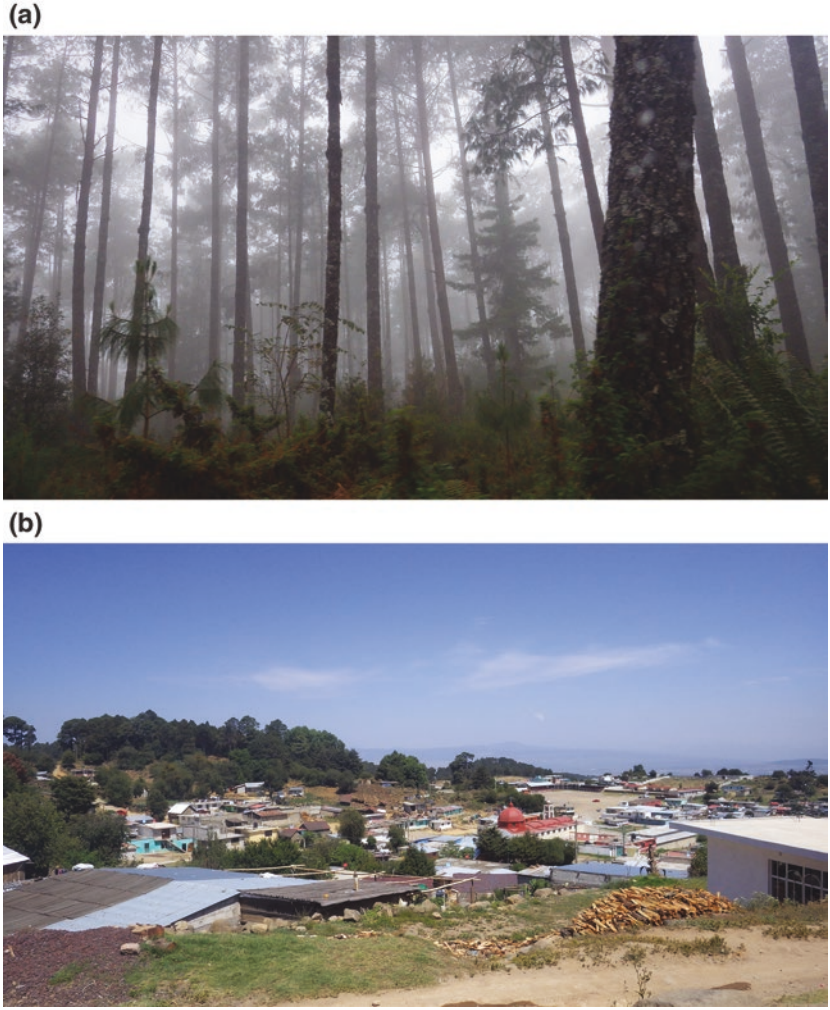

Fig. 2.3 **a** Cloud forest in Veracruz; **b** Ejido in the Gavilanes watershed (*Source* Photographs by Erin Pischke)

The focus of Mexico's PHS program on conserving (or restoring) forest cover is due to the perceived role of forests in enhancing watershed sustainability through increased water supply, erosion control, nutrient regulation, water purification, and flood protection (Burkhard et al.

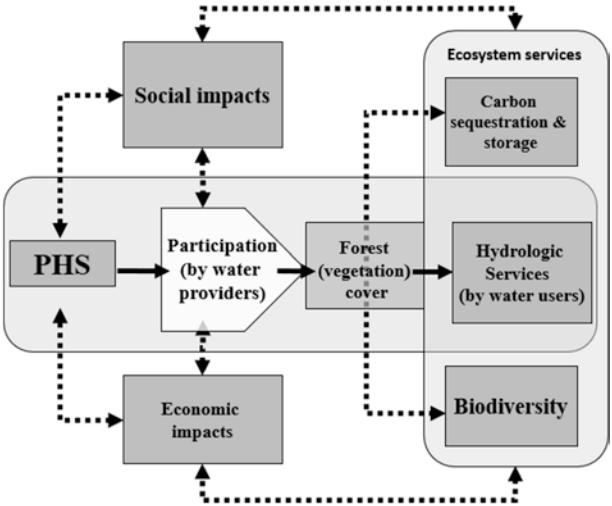

Fig. 2.4 Conceptual model of PHS programs in Mexico. Blue arrows represent the expected linear relationship between Mexico's PHS program and its impacts on program participants, forest cover, and hydrologic services. Green dashed arrows indicate the more complex (often indirect and unintended) linkages and feedbacks that emerge between PHS programs and the social, economic, and biophysical systems (*Source* Figure created by the authors) (Color figure online)

2012; Walker et al. 2009). Due to the steep topography and high rainfall in the Veracruz study region, flood and erosion mitigation as well as accessible, reliable, and clean drinking water are specifically targeted in the PHS program. While using forest cover as a proxy can be effective in providing general information about the quality and abundance of hydrological services, it does not capture the complex, often non-linear, relationships between vegetative cover, land use, and their impacts on hydrology and diverse hydrological services (Bruijnzeel 2004; Muñoz-Piña et al. 2008). For example, in this CNH system it has been shown that less forest cover leads to greater peak flow and lower seasonal base flows, reducing the total annual water availability (Asbjornsen et al. 2017; Bruijnzeel 2004; Muñoz-Villers et al. 2012; Muñoz-Villers and McDonnell 2013; Wilcox et al. 2008). In cloud forests, these effects are amplified because these environments are typically found in foggy, wet,

and often windy conditions where ecological and hydrological functioning implies high rainfall, cloud water interception, and low evaporative losses (Bruijnzeel et al. 2011; Holwerda et al. 2010; Jarvis and Mulligan 2011). However, these relationships are not always linear and some are unexpected. For example, many young secondary forests can provide hydrological benefits similar to mature forests (Muñoz-Villers et al. 2012). In addition, reforestation can reduce water availability to lower-lying regions (Trabucco et al. 2008). Finally, not all cloud forests exhibit higher water production than non-cloud forests (Munoz-Villers et al. 2015). Capturing these intricate trade-offs between hydrological services and land cover is thus critical for accurate quantification of the net effects of land cover on watershed sustainability, which is instrumental for improving PHS program targeting and performance (Mokondoko et al. 2018).

In addition to the hydrological services that forests provide, there are other ecosystem services that are affected by changes in land cover. In the national PHS program, additional focus was placed on carbon sequestration[1] and biodiversity preservation including natural forest cover and agroforestry systems like shade coffee. Forests generally capture and store more carbon than non-forest ecosystems, while clearing of forests for agricultural conversion releases large amounts of carbon (Pan et al. 2011). Biodiversity is a critical, albeit less tangible and quantifiable ecosystem service provided by different land use/land cover types. High levels of biodiversity have been shown to enhance ecosystem resilience and stability (Tilman et al. 1997), while species diversity influences both carbon sequestration and storage (Bunker et al. 2005), nutrient cycling, and vegetation water use (Asbjornsen et al. 2011). Nevertheless, trade-offs exist between ecosystem services and local knowledge of ecosystem function and service provisioning is often lacking. There is consequently growing interest in the policy arena for strategies that combine or "bundle" ecosystem services in some contexts while disaggregating or "stacking" them in others, with the goal of

[1]Carbon was only included in the PHS program from 2004 to 2006 but then eliminated in preparation for a separate payment for ecosystem services program through REDD+.

balancing ecosystem service trade-offs and the willingness of user groups to pay for them (Mokondoko et al. 2016; Raudsepp-Hearne et al. 2010; Robertson et al. 2014).

The preservation of this suite of ecosystem services is intended to have positive effects on several human components of the CNH system. In theory, payment for ecosystem services programs should improve economic status through poverty alleviation (McAfee and Shapiro 2010; Muñoz-Piña et al. 2008; Perevochtchikova et al. 2012). This could occur directly, through large payments, or indirectly, through improved ecosystems that incentivize the poor to undertake new livelihood strategies that generate additional or increased income streams (Wunder 2008). However, combining socioeconomic goals with efforts to ensure ecosystem provisioning has been challenging in practice and may negatively impact program effectiveness (Alix-Garcia et al. 2015; Börner et al. 2017; Calvet-Mir et al. 2015). The type and quantity of the compensation utilized as well as perceptions of the program will likely dictate the ability of a PHS program to generate net socioeconomic benefits.

Changes in socioeconomic conditions should in theory feedback to influence an individual's or a community's perceptions and behaviors in ways that promote greater forest conservation (Alix-Garcia et al. 2012; Grieg-Gran et al. 2005). However, benefits from PHS programs may be somewhat limited in Mexico due to inadequate payment amounts based on opportunity costs calculated from national averages. There is also the longstanding culture of subsidies used by policymakers to periodically redirect land use decisions in rural areas, which landowners may assume will occur again in the future (Manson et al. 2013; Muñoz-Piña et al. 2008). Further, the social contexts within the communities may affect the success of the program. Within our study region, much of the land is under ejido (i.e., collective) ownership (Bray et al. 2006), and thus, PHS programs must be approved and managed by the entire community. This creates added complexity, as decisions about precisely how, where, and to whom payments are made must involve some degree of collective process, potentially compromising the influence of the PHS program.

Another important consideration that adds complexity and is often overlooked in PHS design is that participation in payment for ecosystem services programs may have indirect effects on stewardship behavior. For example, fostering greater environmental awareness and the adoption of best management practices may have long-lasting effects on ecosystem service provisioning (Deng et al. 2016; Grillos 2017; Moros et al. 2019). Such non-economic motivations can impact participant retention as well as the continuation of stewardship behaviors after the cessation of payments.

All of these complexities must be addressed when designing the structure and implementation of PHS programs and are reflected in the multiple feedback arrows in the conceptual model (Fig. 2.4). When functioning effectively, PHS programs should incentivize individuals or communities to preserve forests, improving the ecosystem services provisioned by those forests, which feed back to improve socioeconomic livelihoods for those individuals or communities. Ultimately, these positive feedbacks increase motivation by upstream and downstream watershed residents to contribute to the PHS program via enrollment or payments, respectively, indicating the potential for positive reinforcement among the different CNH system components.

2.4 Approach to Collaboration Across Boundaries

Our research team employed a transdisciplinary collaborative approach with an interdisciplinary research team to elucidate the complex linkages between Mexico's PHS program, and the dynamics of coupled social-ecohydrological systems. Our interdisciplinary research team consisted of approximately 35 people, including 20 research scientists and 12 university students and post-doctoral researchers from universities in Mexico and the United States, as well as several community and NGO representatives from Veracruz. This number has fluctuated over the years. Our team was interdisciplinary because we intended to integrate the theories and methods of multiple scientific disciplines. Our research

was transdisciplinary in that it was premised on crossing geographic, disciplinary and social group boundaries in order to incorporate a wider range of scientific, professional and cultural voices into the research process (Bernstein 2015).

To meet our objectives, we developed and implemented an interdisciplinary approach via sub-teams. Although the project PI is an ecologist, the sub-teams were led by researchers having expertise in different disciplines related to the overall project. Specifically, we organized our team into six sub-teams, each of which was led by a co-PI: socioeconomic, landscape analysis, biophysical, community-based watershed monitoring, model integration, and participatory workshops.

Although originally the plan was to identify a single study system for data collection, over time, it became evident that the scales needed to address different social and biophysical science questions were inherently and fundamentally different. Thus, compromises were needed to allow for each of the sub-teams to meet its specific objectives through disciplinary research focused on key indicators. These indicators were identified by the entire team at an early stage of project implementation (see Asbjornsen et al. 2011 for details) and provided a guiding framework for obtaining the data needed to develop the integrated model of PHS-CNH dynamics. The indicators were selected based on our hypotheses about which attributes with the social and biophysical systems should be most sensitive to the PHS program and thus best capture the interactions and feedbacks within our coupled natural-human system conceptual model (Fig. 2.4). Below, we briefly describe the methods used by each sub-team.

2.4.1 Socioeconomic Methods

To conduct the socioeconomic components of the research, we used qualitative interviewing and quantitative survey methods. The scale of this component was at the community (ejido) level, with interview and survey data collected at the household level in the two micro watersheds, as well as in "downstream" communities (e.g., in the cities of Coatepec and Xalapa; see Fig. 2.5).

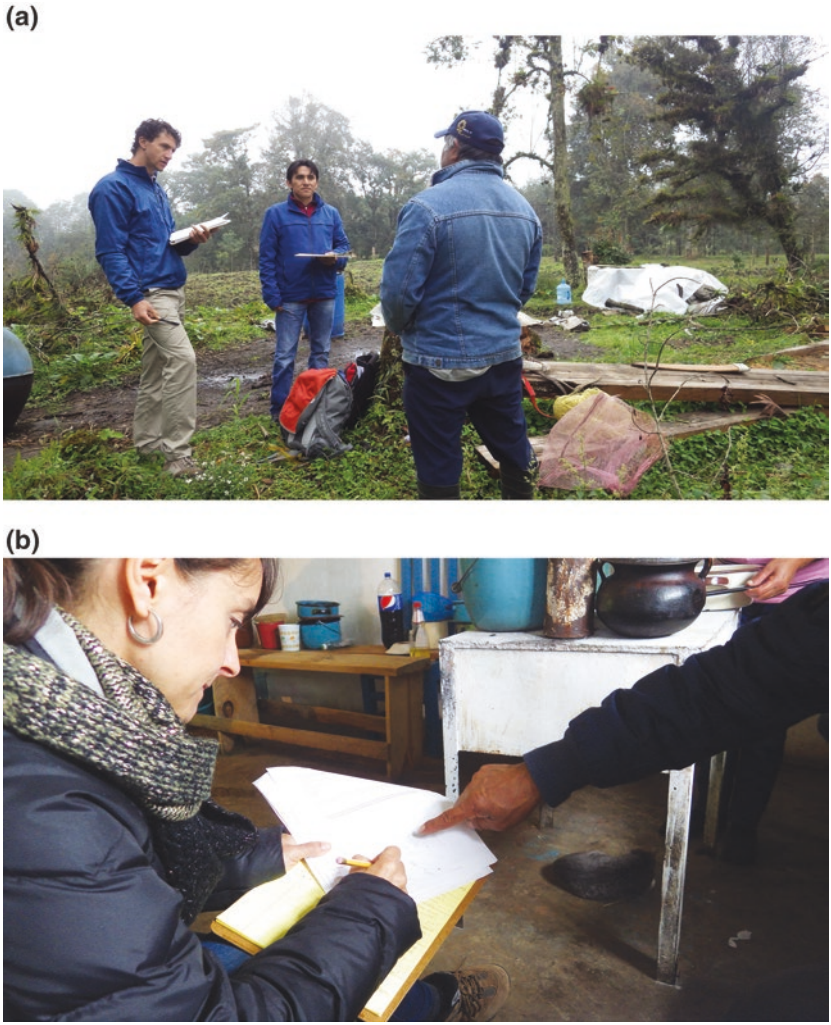

Fig. 2.5 **a** Conducting surveys in the watershed; **b** Conducting surveys in the watershed (*Source* Photographs by Erin Pischke)

2.4.2 Landscape Analysis

A combination of geographic information systems (GIS) and remote sensing technologies, supported by ground verification when necessary, were used to create land cover/land use maps from Landsat and SPOT imagery of our study areas.

2.4.3 Biophysical Methods

Measurements of biophysical properties related to the hydrological biodiversity and carbon ecosystem services were collected in the field and then combined with the landscape analysis to develop spatial maps of watershed characteristics and to support the hydrological modeling (Fig. 2.6). The maps showed land cover/land use throughout the study areas as well as changes over time.

2.4.4 Community-Based Watershed Monitoring

We collaborated with an established non-governmental organization in the region, Global Water Watch (GWW) Mexico, to recruit volunteers to monitor precipitation and water flow in the Gavilanes and Pixquiac watersheds. With the help of GWW-Mexico, we recruited 35 volunteers for ongoing monitoring. We surveyed them prior to training, one week after, and six months after training to determine the profile of potential volunteers, the factors that contribute to their longevity and changes in their perceptions.

2.4.5 Model Integration

We are currently working on integrating the data collected for each of the different components within our conceptual model (Fig. 2.4) to enable the simulation of different PHS program scenarios. For example, these scenarios may involve changing the payment amount, targeting payments based on different criteria, whether biophysical

Fig. 2.6 **a–d** Biophysical data collection in the watershed (*Source* Photographs by Z. Carter Berry)

(e.g., landscape positions with high hydrologic recharge zones; deforestation risk) or socioeconomic (e.g., poverty alleviation; opportunity costs). The objective of this integrated coupled natural-human system model is to assess the impacts of different scenarios on key biophysical outcomes (i.e., trade-offs among different ecosystem services) and socioeconomic benefits and unintended consequences, as a basis for informing and improving payments for hydrological services program design.

2.4.6 Participatory Workshops

We will conduct a participatory workshop that involves local stakeholders in role-play simulations to evaluate scenarios and trade-offs in ecosystem services. The scenarios in the workshop will integrate social and biophysical data gathered in the project and present the models to PHS program stakeholders.

2.5 Team Organization

The initial team composition for this study was defined according to the areas of expertise needed to address the project objectives within the biophysical sciences (e.g., hydrology, soil science, ecology, watershed modeling), social sciences (economics, sociology) and landscape analysis (geospatial analysis and modeling). Another key objective was to create a team that would be capable of working together across boundaries and function as an integrated entity that was more than just the sum of the individual participants (Strober 2006). In particular, we sought collaborators who were willing to invest the necessary time and energy to communicate across disciplinary boundaries and who had a genuine interest in understanding differing perspectives. This required a commitment to listening, patience, respect, teamwork, and balancing of diverse opinions and ideas (Buizer et al. 2015; Hickey and Nitschke 2005). This meant that individuals who tended to seek confrontation and conflict rather than compromise and consensus were not considered

for our team, despite strong scientific qualifications. This criterion was a particularly difficult filter to apply when recruiting new team members, and the learning curve at times was quite steep.

Approximately half of the original team consisted of researchers with whom the co-PIs had worked previously, while others were identified to fill particular needs within the team. In most cases we relied heavily on existing networks of collaborators and recommendations by other team members. Additionally, an effort was made early on to establish and share our common team vision with prospective new members joining the team at different stages of the project, as this was considered critical in minimizing unnecessary misunderstandings and unrealistic expectations.

Given the international nature of our project, another critical aspect to forming our team was identifying collaborators at Mexican universities within each of the disciplines related to the research. We were fortunate to have a strong project leader at our Mexican host institution, who was critical to identifying, recruiting, and engaging local biophysical science researchers, as well as recruiting—and securing local funding to support—Mexican graduate students. We were successful in recruiting research collaborators and their students in the social sciences from both our local host institution and another university in Mexico City who were an excellent fit with our project. This experience underscored the overriding importance of persistence and having a clear team vision, as well as, in one case, recognizing that common research interests and a long-term commitment outweigh geographic proximity and convenience.

Whereas we initially organized our team into three sub-teams (i.e., biophysical, socioeconomic, landscape analysis), we later incorporated the other three sub-teams (i.e., community-based watershed monitoring, model integration, and participatory workshops) as the project evolved and new needs emerged. It is worth noting that these three new sub-teams were inherently interdisciplinary and required explicit integration of researchers, methodologies, and data throughout their entire implementation process.

Given the highly interdisciplinary and international nature of the research, early on we adopted a model of shared responsibility for

project leadership. Overall project coordination and communication was shared by the counterpart lead-PIs from Mexico and the United States. Each sub-team also had a lead United States and Mexican researcher, which was important in enabling sub-teams to make progress toward their disciplinary research objectives and activities, while also providing a mechanism for maintaining communication across sub-teams to ensure coordination and integration. As the project evolved, this model of shared leadership became even more important as new project components emerged that required different skill sets and also because the project was sufficiently large (and participants' or scientists' commitments were already stretched), that sharing these leadership responsibilities allowed us to be more efficient and effective with limited time and budgets.

Another important challenge to spanning boundaries for the research was the need to forge strong partnerships with diverse local and national stakeholders involved in Mexico's PHS program. We incorporated a transdisciplinary aspect to the project by inviting these non-scientific partners (e.g., NGO staff members) to work with us to address the research questions we posed (Buizer et al. 2015; Hirsch Hadorn et al. 2006). To accomplish this, we relied heavily on our local Mexican collaborators to identify partner organizations and facilitate engagement by their representatives within the project. As part of our transdisciplinary approach, we followed Jahn et al.'s (2012) transdisciplinary research typology. To initiate this process, we organized several meetings during the project development stage and extended open invitations to relevant organizations and individuals, during which we shared our overall project vision and solicited their input, ideas and suggestions (Jahn et al. 2012). A key challenge we experienced was how to sustain their active involvement throughout the lifetime of the project, which may be partly attributed to our leadership structure, which was not strictly bottom-up as recommended by some transdisciplinary research scholars (Hirsch Hadorn et al. 2006). We attempted to compensate for this by specifically seeking their input and participation whenever particular issues or activities emerged where their interests and expertise were especially relevant.

The development of the citizen science, community-based watershed monitoring program also provided an important venue for sustained

engagement by diverse local stakeholders during the latter part of the project. This approach was critical in ensuring the support and engagement among the PHS program community at both local and national scales. This, in turn, was crucial in enabling many of the research activities. We further anticipate that sustained stakeholder engagement will be instrumental during the final stage of the project, when we plan to communicate the results to watershed stakeholders through a series of participatory meetings and workshops in ways that will maximize the potential for future impacts on PHS program design and watershed sustainability.

2.6 Challenges of Collaborating Across Boundaries

Several challenges emerged during the project that were, in part, introduced by the interdisciplinary and transdisciplinary nature of the research, can be broadly summarized into the following categories: (1) team organization; (2) fully engaging local stakeholders; (3) integration of different disciplines; (4) matching spatial scales; (5) language and communication; and (6) field site logistics. These challenges have proven to be persistent and at times presented barriers to maintaining progress toward developing an integrated CNH–PHS model. Below, we discuss each of these challenges in greater detail and provide examples of how these challenges were addressed.

2.6.1 Team Organization

We faced real challenges in identifying suitable collaborators to fill some of the areas of expertise in our project's sub-teams, which we attributed to a variety of factors, many of which were beyond our control. A potential reason for the challenges we faced in recruiting local collaborators reflected the apparent differences across academic cultures, with the Mexican research community possibly having more limited experience with interdisciplinary research. However, several of our

project co-PIs had worked previously with several of our Mexican collaborators, which played a critical role in our ability to more quickly build trust and effectively initiate the research, recruit new collaborators and students and ultimately, to the success of the project. Our Mexican research colleagues and NGO counterparts were able to make connections to other potential collaborators on the ground, visit the proposed study areas, and introduce researchers to the PHS program decision-makers and managers before the project started. Those who were based in Mexico—including the US researchers who were temporarily located in Mexico—were able to hold regular in-person meetings with institutional representatives, such as university professors and NGOs, who were providing in-country support or personnel. These frequent meetings helped keep the team informed about changes happening on the ground, build relationships, and obtain access to important databases, as well as show that we were invested in the area and help insure that project results will inform future policy decisions. Additionally, the students of our Mexican colleagues were able to address a number of additional lines of research not contemplated in the original proposal. In exchange, the project funded the field activities of local collaborators and their students and provided the opportunity to participate in published results.

A unique challenge faced by the students and post-docs was that some of them were involved in the beginning but then moved on from the project before it was complete, while others joined the project at later stages. This created a situation whereby the team at times struggled to pass on the institutional memory of earlier participants. For some students, the lack of institutional memory was compounded by the interdisciplinary challenge of fully understanding and relating to project components outside their own discipline. Participation by students in interdisciplinary seminars offered by teams of project researchers greatly helped to address this issue. These seminars allowed new students to hear about the project from many perspectives in conversations that framed the role that each research discipline played within the project. Of equal importance, the students were able to spend extended time asking questions with investigators on the project in small breakout groups. These small group interactions allowed students to engage with

the aspects of the project they were struggling to understand and seek out the right individuals from the team that could best answer their questions. However, one challenge was that not all students were able to participate in these seminars, limiting their ability to establish the connections described here. Additionally, most students participated in the annual full team meetings, which lasted for three to five days and provided substantial opportunities for students to participate in both large team discussions about overall project integration.

2.6.2 Fully Engaging Local Stakeholders

Involving local stakeholders in a meaningful way, while also respecting their time and resource limitations, was a recurring challenge. Developing relationships and trust with these stakeholders required significant time and interaction. Finding local collaborators interested in coleading research committees was difficult, in part due to a lack of funding for local participants. While efforts were made to involve local stakeholders throughout, the funding was pursued predominantly through US-based channels. The increased need for funding from US institutions to help pay for equipment or other resources to support the research in Mexico, some of which was not budgeted for in the original proposal, limited the extent to which everyone on the project could fully participate in all meetings and research-related activities in Mexico.

Another challenge to maintaining project momentum was that many of the US-based researchers who were actively involved in data collection were only able to be in the field in Mexico for short time periods, which may have hindered the continuity of data collection and limited the strength of connections that could be formed with local stakeholders. Furthermore, nearly all of the data-collecting researchers were graduate students who eventually ran out of funding or graduated, in some cases disrupting relationships that had been built over time with stakeholders.

More challenging perhaps was the lack of opportunities to coproduce knowledge together with NGOs and municipal governments. This was partly due to the lack of resources and overcommitted staff within these

organizations, which made it difficult to allocate staff to participate in the research. Moreover, the mission of organizations that work in PHS program implementation does not necessarily consider including the role or influence of knowledge as a prominent priority. This problem was exacerbated by the rapid turnover in the staff of municipal governments that operate PHS programs in 2017. This will be a challenge in transferring results to a new cohort of decision-makers at the state and national level that occurred as a result of state and national elections in July 2018. Another complicating factor associated with the changing leadership was the culture of new decision-makers rejecting programs promoted by previous administrations, which also undermines long-term planning essential to the success of PHS programs.

2.6.3 Integration of Disciplines

Our project was hampered by the very characteristics that inspire multicultural, interdisciplinary approaches. Strong ties to one's discipline and cultural differences among Mexican and US scientists shaped the framing of project objectives in ways that hindered progress. Our team began this project by publishing a paper highlighting the absence of integrated monitoring and evaluation practices for PHS programs, pointing to the failure of evaluation efforts to integrate physical, social, and governance measures (Asbjornsen et al. 2015). Despite recognizing the challenges upfront, our team experienced many difficulties to effectively integrate across disciplines, which each carry their unique theoretical proclivities and other intellectual commitments. We witnessed firsthand the difficulties involved in breaking down academic silos that often served important institutional functions and thus could not simply be abandoned. Different theories and models are used by different disciplines, and the practice of producing specific innovations that advance a particular field can distance one discipline from another, especially when they seek to deepen the sophistication and specificity of the discipline's theory. Consequently, some disciplinary disagreements emerged. For example, there was a misconception that socioeconomic data are less expensive and easier to collect than biophysical data.

At the onset of the project, a central theme of our team meetings was to identify integrated social and biophysical questions and methods. However, it later became apparent that splitting into smaller subgroups was necessary to improve productivity, even at the possible expense of integration. Researchers who have worked on large collaborative teams will appreciate the "inverse meeting size" theorem: the greater the number of people involved in a meeting, the less you can expect to accomplish. Team leaders attempted to account for this issue by organizing a range of different types of meetings, depending on the meeting objectives and the individuals directly involved in the decision-making process, including biweekly to monthly full team video conferences, annual full team in-person meetings, and smaller sub-team and small group teleconferences. Nevertheless, we did experience a tendency to place a greater focus on planning each research component on its own, rather than emphasizing the integration across research components. This challenge can be traced back to the need to balance the focus of sub-teams upon their disciplinary research agendas with achieving broader project goals involving integration. Ultimately, a rich and diverse set of metrics was collected by the team as a whole, ranging from soil hydraulic conductivity to environmental governance networks. But combining different types of measures in an integrated evaluation framework and then modeling future outcomes presents a persistent challenge.

While the project was inter- and transdisciplinary in theory, much of the data was obtained by disciplinary sub-teams of researchers with minimal interaction across teams, making it more multidisciplinary in practice. Although we recognized the need to produce an interdisciplinary rather than multidisciplinary approach to monitoring and evaluation of the PHS program, we did not develop a clear map to facilitate integration at the project's onset. One consequence of the lack of a clear road map is that the task of integration has been an evolving process informed by team learning and growth, rather than guided by a preestablished template. Whether such a template would even have been possible is an interesting question for debate. Only after each sub-team had gained more clarity about their own research focus was it able to begin developing a vision for how the different project components fit within a larger integrated research plan.

Finally, because of the painful work of bridging gaps and the evolution of team integration, interdisciplinary projects are naturally prone to mission creep. Sub-teams and sub-projects, such as the citizen science water monitoring, may increase productivity and impact. However, they can also cause the project to grow simultaneously in different directions. For example, the citizen science project was designed to provide decision-makers involved with the PHS program with information on water flow, while simultaneously improving public perceptions of PHS programs to motivate positive behaviors. On the one hand, this provided a fortuitous opportunity to substantially expand the scope of the citizen science activity that was part of the original project, as by enhancing the ability to examine more closely the motivations of participation of volunteers and impacts on their perceptions of PHS programs. On the other hand, fully taking advantage of these new opportunities required engagement by a larger number of researchers and more resources from the main project. Another consequence of this leveraging across the two projects is that one of the initial goals of the new citizen science project—providing decision-makers with useful information—was not fully accomplished, in part because the contributions of the citizen science activity to the larger project goals were not communicated well at the beginning.

2.6.4 Mismatched Spatial Scales

One of the greatest challenges of this project has been linking observations sampled by the socioeconomic and biophysical teams into an integrated modeling framework. Our team tried to develop a common study design from the onset, one that married biophysical and socioeconomic research methods, but we decided that it was not possible for multiple reasons. While it would have been ideal to sample for both biophysical and social data in the same regions of the watershed, this proved to be infeasible. It was more difficult than expected to match the scale of biophysical measures to the scale of qualitative socioeconomic measures, especially since there was little spatial overlap of where the two teams worked and collected data within the study's two micro-watersheds. Social scientists conducted interviews and surveys of people living in

villages, but biophysical scientists collected measurements of plots and watersheds located outside the boundaries defined by human settlements.

Even within the same disciplinary sub-teams, there were different understandings about where data collection would take place. This often stemmed from the need for repeated sampling, which is very demanding. Some researchers needed many replicate measurements within a few hundred meters of each other to address their research questions, while others required replication across the entire study watershed. We therefore faced significant challenges with developing approaches to obtain the data required to generalize results about PHS program dynamics and ecosystem services provisioning across all indicators and at larger spatial scales.

2.6.5 Communication and Language

Cultural differences are central obstacles to any international collaboration, and these obstacles compound the difficulty of breaking down barriers between disciplines. A shared challenge for all sub-teams concerned changes in the local context and details of PHS policies and management. Despite having knowledgeable local collaborators who were actively engaged at different levels within the PHS program, information gaps still developed between local stakeholders and foreign researchers, particularly regarding the vagaries of the PHS program and its functions.

Another challenge related to language and communication concerns sensitivities to the interests of in-country collaborators. Often, local stakeholders are eager to work with international interdisciplinary teams, but this interest can quickly fade if not adequately nurtured. For example, all of our team calls and most of the meetings were conducted in English because of the presence of US scientists who did not speak Spanish. This may have alienated the Mexicans on our team who did not speak much English and who found it difficult to follow the conversations and decisions. Finding common ground and maintaining momentum requires consistent, and potentially burdensome, efforts at translation to support communication. Cultural differences can thus be

bridged, but collaborator time and persistence are essential ingredients needed to overcome such challenges.

2.6.6 Field Site Logistics

Embedded within these issues are the inherent difficulties in conducting fieldwork in remote locations such as our field sites. Basic logistics such as finding vehicles and personnel for fieldwork, accessing private lands and obtaining needed equipment were ongoing challenges. The project collaborators in Mexico facilitated fieldwork as much as possible but could not solve all the challenges. For the first two years, the post-doc served as field coordinator, and was invaluable in the preparation and communication among team members in both countries. However, because the post-doc was hired for specific skills tied to their research, expertise tied to local logistics was lacking. The post-doc ended up having to troubleshoot local problems while simultaneously trying to conduct their own research. For example, if a technical piece of equipment to measure climate data was needed, a researcher in biodiversity or socioeconomic networks can only suggest others who might help, but not provide the equipment on their own. A central coordinator would have been better able to aid in management of timely researcher availability and leveraging of resources and data needs from local organizations.

Some challenges were due to studying a PHS program that is political in nature. This led to many difficulties, including the desire for immediate local impacts that the research project could not meet, changes in PHS program personnel that hindered key relationships with the research team and changes to PHS program rules that undermined our ability to determine the PHS program's effects. The tumultuous political environment resulted in irregular payments and a lack of baseline data, which hampered our ability to measure the net effects of PHS programs. Involving government institutions and NGOs in our research was critical, as our results are most useful for those organizations. However, getting an accurate and clear message to these groups has proved challenging due to the long and arduous process of obtaining detailed, robust data. Resources for research in these non-academic

institutions are limited, which constrained their ability to engage during different phases of the research project. It was therefore important for our team to carefully prioritize the project activities for engaging local collaborators.

2.7 Opportunities to Advance Collaborative Science Across Boundaries

A major achievement from our project was the completion of a detailed case study analysis that generated a nuanced understanding of the intricate relationships between PHS policies and the placed-based and context-specific CNH occurring at each of the study sites. Researchers were able to integrate models and conduct a policy evaluation with ecological outcomes to shed light on whether PHS programs lead to detectable improvements in the target outcome, hydrological services, while also evaluating the impacts on and trade-offs with other ecosystem services. Another accomplishment was our ability to identify relationships between land use change, decision-making processes, and diverse ecosystem services. We were also able to document unexpected surprises, such as the relatively low additionality resulting from the PHS program because of the lack of a sufficient financial incentive to influence people's decisions. Few previous analyses have fully quantified to a similar extent the complex linkages between policy tools such as PHS, and both the socioeconomic system and diverse ecosystem services.

Several key features of this project were instrumental in realizing these goals. Our pursuit of a transdisciplinary approach enabled us to engage diverse local stakeholders in the research, which consequently enhanced overall knowledge and understanding of the complex issues surrounding PHS programs. By building the project upon long-term collaborative efforts in the study region, involving not only natural and social science researchers from Mexican universities but also partnerships with local NGOs and municipal governments, we promoted synergies to emerge when common goals were identified. For example, we collaborated with a long-term and large-scale project administered by Fondo Mexicano para la Conervación de la Naturaleza, referred to as

the *Conservación de Cuencas Costeras en el Contexto del Cambio Climático* (C6) and supported by Global Environment Facility. This collaboration helped ensure that the transdisciplinary and ecosystem service-based focus of our respective projects obtained broader acceptance, for example, through ecosystem service modeling and stakeholder input to plan activities supported by CONAFOR and the *Instituto de Ecología y Cambio Climático* (INECC) in watersheds around the country. Another example is our collaboration with the organization GWW—Mexico, which had a well-established network of local trainers, volunteers, and sites. This association greatly facilitated our ability to incorporate a new research component with GWW's existing efforts and thereby address common goals of validating measurements, evaluating the impacts of PHS and monitoring on the perceptions of local actors, and communicating findings to stakeholders. In exchange, the results from our project on the importance of monitoring in PHS program evaluations has increased interest in CONAFOR to promote community-based watershed monitoring in PHS programs throughout the country. Finally, collaboration with the municipality of Coatepec and FIDECOAGUA resulted in a unique opportunity to participate in a municipal-wide event called International Water Day, when several of our researchers made presentations on project results to a broad audience of diverse stakeholders. These and other efforts have allowed us to leverage the results of the research well beyond the financial resources initially available. It also allowed us to build trust with local stakeholders, maintain policy relevance despite frequent changes in government decision-makers, and to take advantage of parallel efforts to increase the effectiveness of PHS programs in the region.

The process of engaging diverse local stakeholders as part of this transdisciplinary approach also contributed significantly to advancing knowledge about the study system. For example, the inclusion of local forestry technicians in the research process revealed misunderstandings held by the research team and gaps in the team's knowledge of the PHS program. Without support from the forestry technicians, the researchers would not have been able to fully understand why some rural land managers were able to enroll their forests in the PHS program while others could not. Input from forestry technicians also helped to focus

attention on the changes needed to advance knowledge, and challenged previous understandings and expectations of PHS program participants. This experience in turn helped to motivate other stakeholders who were interested in the research findings and willing to collaborate in the different stages of policy implementation, increasing the probability that research results would be applied in practice. This was reflected in the sustained participation of most of the project's stakeholder collaborators, which allowed us to build a common project vision that would respect and value the contributions of the program participants and of a positive team environment. The diversity of stakeholder participants involved not only increased the social relevance of the research but also prompted some researchers to scale up the lessons learned from the project to improve the design and implementation of their more recent research projects.

Project researchers developed several interdisciplinary practices to overcome methodological challenges. At times it was difficult to reach consensus about how to adapt sampling strategies to satisfy sub-team priorities concerning scale in light of project goals. To overcome this challenge, sub-teams employed methodological tools by learning from other sub-teams. For example, socioeconomic researchers learned to use GIS software to integrate socioeconomic measures with data on watershed ecosystem services. Biophysical researchers learned new field techniques to encompass the wide range of ecosystem services measured in the project. These interdisciplinary methodological practices also increased the transdisciplinary relevance of our research. Moreover, we are currently in the process of developing our integrated CNH–PHS model and applying it to assessment of decision-making processes and associated feedbacks through a role-play simulation workshop. The combination of these activities is fundamentally transdisciplinary and represents an interesting experiment in process that we anticipate will greatly enhance our understanding of the challenges and opportunities associated with advancing transdisciplinary science.

Finally, monthly project meetings provided vital opportunities to determine the needs of the different sub-teams and identify synergies required for data integration. These meetings contributed to greater integration of research components and to facilitate agreement on a

common language to overcome potential misunderstandings that might arise between participants with different disciplinary backgrounds. Although one of the goals of the monthly meetings was to have robust participation of all researchers, small meetings organized around sub-teams also aimed at the integration of data and proved more effective to achieve progress toward specific disciplinary research goals. During the course of the project, the team's ability to assign clear tasks to specific collaborators to ensure someone was responsible for advancing each component within an agreed upon timeline greatly facilitated overall progress.

2.8 Summary of Key Lessons Learned and Conclusions

Our team has learned valuable lessons on how to cross boundaries to conduct integrative and applied research. In this section, we summarize our lessons learned, which coalesce around nine main ideas: (1) hiring a project manager, (2) meeting regularly, (3) requirements for trans-disciplinary research, (4) project expectations and time management, (5) project integration, (6) language, (7) sub-team communication, (8) time spent in-country, and (9) data management.

- ***Hiring a project manager***: We found that hiring a key local person who had a sound understanding of the project and local context, and could thus serve as project manager, was critical in enabling the research team to proceed effectively in terms of coordinated logistics. Ideally, a project manager spans discipline-specific sub-teams to coordinate diverse research activities across all project components. Finding a post-doc that would commit to stay with the project for the full duration was challenging, given the breadth of knowledge needed and the maturity and experience required to lead. Ideally the project manager would be trained in both human and natural systems, and have experience in crossing other boundaries. The project manager also requires sufficient resources to coordinate field logistics among sub-teams in the study region of another country.

Furthermore, we realized that it is sometimes necessary to have an assistant manager for a complex project like ours. By hiring a manager and a second person, you avoid the risk of putting the whole project at the mercy of one person.

- ***Meeting regularly***: In our experience, regular meetings of both the entire team and various research sub-teams were important for consistent communication among team members. This meant having set times (e.g., weekly or monthly) that team members get together (even if remotely) to discuss study progress, timelines, and challenges for the various project components to advance. Co-PIs on our research project had the foresight to designate funding for annual in-country project-wide meetings. The purposes of those meetings multiplied and gained importance over time. These meetings also served as moments to establish and build trust in relationships among team members.
- ***Requirements for transdisciplinary research***: Our goal was to achieve transdisciplinary science. This involves research that moves beyond academic disciplines to involve non-academic collaborators in the research process to more fully understand a complex issue such as the effectiveness of a PHS program (Buizer et al. 2015; Hirsch Hadorn et al. 2006). We found that to achieve a transdisciplinary understanding, planning for integration of various stakeholders needs to begin at the very start of a project and continue throughout as datasets are developed and shared. For us, the involvement of key stakeholders from the Mexican government and other organizations and groups contributed to the transdisciplinary nature of the research by affecting policy that has impacts on livelihoods and local economies (Jahn et al. 2012).
- ***Project expectations and time management***: Leadership on our project needed to be assertive to ensure tasks were completed in a timely manner. Guidelines on how we conducted meetings, shared information, and published collaboratively were critical to establishing those expectations. Expectations and responsibilities of team members, including leadership on sub-teams, also needed to be defined by leadership at the very beginning of our project. At the same time, leadership also recognized that the project would evolve as new

information became available, the external situation changed, and additional needs and expertise were identified. Thus, project leadership had to be flexible and open to effectively accommodate change.

- ***Project integration***: Thinking and planning more explicitly and intentionally about integration across social and biophysical sciences early on would have helped our project achieve greater integration among components. The research questions are perhaps the most important part of a project to define, so starting with specific, overarching research questions was crucial. Our sub-teams worked together to refine their research questions by combining the specialized requirements for students' disciplinary research needs with the needs of the project's transdisciplinary agenda. Otherwise, younger researchers may have been overwhelmed if trying to span disciplinary and organizational boundaries on their own. In the end, it helped to have people from different sub-teams share at least the general methodologies of other sub-teams and then work together to create a shared understanding of larger research endeavor by everyone involved.

  The attention devoted to other issues during start-up hindered our ability to fully integrate data later for modeling and applications in program evaluation. Drafting a clear plan for data integration at the beginning of the project, including the methods to be used, appropriate spatial scales for sampling and specific research questions to address, with specific responsibilities for each member of the team would have helped to address this challenge. A data management plan that features data integration will also facilitate the incorporation of new team members into the project by enhancing the communication process.
- ***Language***: Barriers to effective communication included working in a non-English speaking country. In Mexico, having a large portion of the team being able to speak and understand, as well as read and write, the Spanish language was imperative to our success. Spanish-speaking team members allowed for the credible interaction with important players from the Mexican government, non-profits and university faculty. The logistics of field sampling and conducting surveys were enhanced by having Spanish-speaking team members

who could directly engage with local people. These team members also allowed the research team to better understand the PHS program from the Mexican perspective, which ultimately led to a better overall understanding of the research context.

- ***Sub-team communication***: Consistent communication between sub-teams was also critical. Face-to-face meetings were invaluable and, ideally, should be attended by all project collaborators, including not only lead researchers but also the broader group of collaborating scientists, students, technicians, and representatives of key stakeholder groups. For the latter, we found that given the substantial time constraints faced by both governmental and civic organizations, organizing a one- or half-day meeting specifically focused on soliciting their input was often the most effective approach in fostering meaningful engagement. Webinar meetings were only effective when well-planned, relatively short and resulted in concrete action items that sub-teams were then held accountable to achieve by a stated deadline. Understanding the motivations of key stakeholders and processes operating at multiple temporal and spatial scales—and how these affected the target variables being measured—was also a key to the project's success.
- ***Time spent in-country***: Our PI and some co-PIs spent considerable time in-country with local experts and stakeholders, so they fully understood the context of the research from the outset. The process of spending significant time up front in the study region building relationships, understanding the local context and engaging scientists and practitioners from a wide range of institutions and disciplines was critical to both our understanding of the local context and to eventually building a broad base of partnerships and cultivating an environment conducive to transdisciplinary science. Collaborating and employing people from the area for significant periods of time to build trust and relationships with people on the ground also lent credibility to our research team, which facilitated the day-to-day implementation of the research activities and generated additional transfers of information in multiple directions.
- ***Data management***: Developing an effective data management plan (including a data repository, meta-data protocols and discussions

about data management early and often) that featured how data from different disciplinary sub-teams would be integrated during the project demanded a substantial amount of time and effort by the team. A key lesson learned was that this process could have been greatly improved by conducting frequent inventories of data collected and data processing (i.e., at least every six months) and carefully reviewing the data with an eye toward identifying possible problems that require attention, as well as ensuring that the potential for effective integration of diverse datasets is being maintained.

In this chapter, we presented the challenges and opportunities that our team faced while conducting transdisciplinary research within a CNH system's context. In the process, we developed approaches to integration, both in terms of the research itself, but also in the way we worked as a team and with stakeholders. The science-policy components of our research have implications for not only advancing fundamental theory about conducting transdisciplinary research but also for impacting decision-making, especially related to PHS programs. We worked across six sub-teams which entailed crossing disciplinary boundaries, but also crossing conceptual, methodological, and language barriers. The various challenges we experienced, the lessons we learned and the recommendations we offer can often be boiled down to devoting time and energy to effective communication. We highlight the importance of clearly stating to project participants and partners from diverse stakeholder groups.

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3

Adapting to the Challenges of International and Interdisciplinary Research of Coupled Human and Natural Systems

Sarah Laborde, Sui Chian Phang and Mark Moritz

3.1 Introduction

Interdisciplinary research teams are increasingly prevalent, and there is growing interest in understanding the processes by which knowledge emerges in practice across team members with heterogeneous cultural and research backgrounds. Here, we present the case study of a large Coupled Human and Natural System (CHANS) collaborative research project that involved social scientists, earth scientists, ecologists, computer scientists,

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local fishers, and rural development specialists across Cameroonian non-governmental organizations and the Universities of Maroua, Cameroon, and The Ohio State University, USA. Our CHANS project was entitled *Exploring social, ecological, and hydrological regime shifts in the Logone Floodplain, Cameroon* and was funded by the National Science Foundation (BCS-1211986)—the project is called *Modeling Regime Shifts in the Logone Floodplain* (MORSL) hereafter. Our team investigated the coupled dynamics of the social-ecological system of the Logone Floodplain fishery in Cameroon using a combination of field research, remote sensing analysis, and numerical modeling. A key research objective of the MORSL project was to develop an integrated computer model to simulate the dynamic couplings among social, ecological, and hydrological systems of the floodplain, to investigate the effects of system couplings and the nature of regime shifts in the floodplain.

At an early stage, one of the postdoctoral researchers involved in the project, the first author, noted that our involvement in interdisciplinary research was an opportunity to learn about interdisciplinary research itself, a necessary but often challenging component of CHANS research (Liu et al. 2007). To examine the challenges and dynamics of interdisciplinary collaboration in practice, she designed a reflexive study to collect data on researchers' perceptions of team dynamics and progress as we worked jointly toward our MORSL research objectives. Results from that study inform this chapter.

In this chapter, we first describe the study area and the processes within and couplings between the different systems of the Logone Floodplain. We then discuss the challenges that we encountered as an interdisciplinary and international team, and how we addressed these challenges to make progress toward understanding the coupled system of the Logone Floodplain.

3.2 Study Area

The Logone Floodplain is one of a number of seasonally flooded flatlands that are an integral part of the watershed of the Chad Basin (Delclaux et al. 2010). The floodplain is located south of Lake Chad in

the Far North Region of Cameroon, bordering Nigeria in the West and Chad in the East (see Fig. 3.1). The plain is flooded from September through December when the discharge of the Logone River is sufficient for overbank flow (Fernández et al. 2016). The area flooded depends directly on the flow rate of the Logone River (Jung et al. 2011). In a semi-arid region, the flooding supports a vital ecosystem for terrestrial and aquatic animal and plant biodiversity, migratory birds, and its ecological productivity supports the livelihoods of fishers, farmers, and herders (Loth 2004; Scholte 2005).

In the last four decades, there have been major changes in the hydrological regime of the Logone River system, and these have had direct and indirect impacts on the floodplain's social-ecological system. These changes were due to climatic variability combined with engineering interventions on the hydraulic landscape. The first major hydrological change occurred in 1979, when the Cameroonian government embarked on a large-scale infrastructural project to increase domestic rice production. The project involved a 30-kilometer dam upstream of the floodplain to create a reservoir—Lake Maga—that was fed by seasonal rivers in the west and by the Logone River (Loth 2004; Scholte 2005). The reservoir was purposed to irrigate rice fields located just north of Maga Dam (i.e., downstream of Lake Maga as the Logone River flows northwards to Lake Chad, Fig. 3.1). To protect the reservoir and rice fields from potential damage from uncontrolled flooding, an approximately 50-kilometer long embankment was built along the west bank of the Logone River to control overbank flow.

However, the impact of the dam and embankment on the flooding regime, compounded by the multiple year-long period of Sahel drought in the 1980s, was greater than planned. The floodplain's total flooded area shrank severely, and this led to negative direct and indirect impacts on the floodplain's CHANS (Loth 2004). The system's natural productivity declined because of decreased habitat, changes in flow timing and loss of riverine connectivity. To cope with this decline, local residents who depended on natural system production for livelihoods and food, including fishers and farmers, were forced to emigrate or adapt their livelihood strategies (Loth 2004; Scholte 2005).

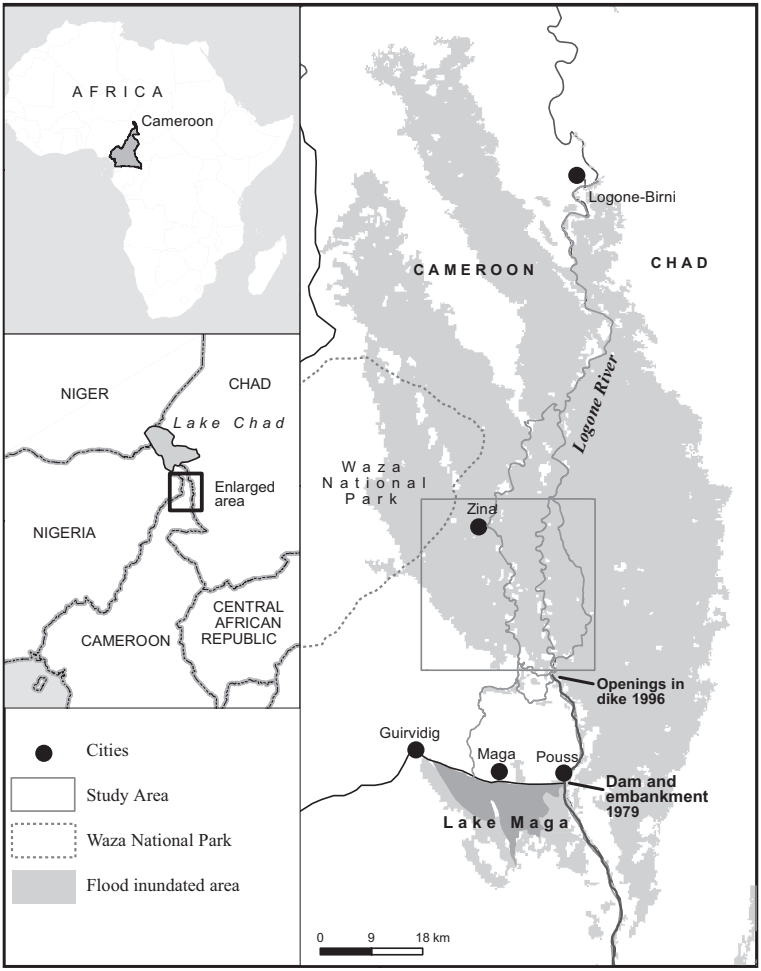

Fig. 3.1 Map of the Logone Floodplain in the Far North Region of Cameroon (*Source* Map created by the authors using ArcGIS software [ESRI Corp., Redlands, CA])

The second large change in the floodplain's recent flooding regime followed a reflooding project that began in 1994 with the purpose to reverse the loss of biodiversity and livelihood from the construction of Maga Dam. The impact of the dam on the floodplain's social-ecological systems was being studied by researchers of Leiden University in the

Netherlands, Garoua Wildlife College, and the University of Dschang in Cameroon (de Iongh et al. 2010). Their research efforts and commitment to reversing the ecological damage of the 1980s led to the Waza-Logone Project. The project started in 1992 and aimed to develop and implement an integrated management plan that supported sustainable livelihoods for local populations as well as biodiversity in and outside Waza National Park (de Noray 2002; Loth 2004). The project restored two openings in the embankment along the Logone River in 1994 and 1996 (Fig. 3.1). This allowed floodwaters back onto the plain. Livelihoods and biodiversity in the floodplain gradually recovered, although not to the pre-Maga Dam levels (Loth 2004).

In addition to the Maga Dam and the reflooding project, a third large change to the floodplain's flooding pattern is potential currently ongoing, caused by the increase in fishing canals, a technique that has seen its use grow exponentially since the 1970s (Laborde et al. 2016). A single canal can extend for several kilometers, and they currently number in the thousands across the floodplain. Fish canals drain floodwater to catch fish, and residents are concerned that the cumulative drainage of floodwater is altering the overall flooding pattern. This concern about major hydrological changes driven by fishing was the focus of our project, which was funded by the NSF Dynamics of Coupled Natural and Human Systems (CNH) program.

3.3 Coupled Human and Natural System Under Study

One line of inquiry in CHANS research is to detect the occurrence of regime shifts (Scheffer 2009) and, if they are present, to determine whether transitions between system states are linear, nonlinear, or critical. Regime shifts, and the couplings and feedbacks that create them, have been described in complex ecological systems, like coral reefs and turbid lakes, as well as in social-ecological systems, like rangelands (Coppock 1994; Scheffer 2009; Scheffer et al. 2001). African floodplains, however, are less frequently studied as coupled systems, despite

clear couplings between and within their human and natural systems (Moritz et al. 2016). Instead, it is more common for hydrological, ecological, or social systems to be studied separately, with the linkages to other systems included as exogenous variables. However, the couplings are an integral part of floodplain systems as they are associated with feedbacks that can drive system dynamics (Laborde et al. 2016).

One example of a regime shift is dams and their impact on a river's natural flow regime. The loss of discharge alters flooding and natural flow processes and can shift ecological productivity. Dams in African floodplains have been shown to have devastating and unpredicted impacts on social, ecological, and hydrological systems (Denny 1993; Drijver and Marchand 1986; Hollis et al. 1993). The decision to build a dam is often made by agencies external to the floodplain with the aim to support local economies and protect local capital, but the dynamic responses of the social-ecological system following the construction of a dam are not well understood.

A regime shift may also occur because of nonlinear dynamics associated with smaller and more gradual changes in a social-ecological system. Signals of an impending regime shift are observable in theory but much more difficult to document in real systems (Bauch et al. 2016). An example of a regime shift caused by small gradual change is eutrophication of lakes, when increasing nitrogen and phosphate concentrations lead to a regime shift in a lake's ecological community. Cascading effects in population dynamics and community composition cause the ecosystem to become dominated by algae, and the resulting community composition hinders a return the initial system state (Biggs et al. 2009).

When studying regime shifts in CHANS, the ability of humans to modify the environment adds a further layer of complexity to the analysis. In contrast to a regime shift arising from exogenous inputs to the system (e.g., bounding the system to the lake as described above, and considering nutrient input as an exogenous variable), the change in coupled systems can arise from feedbacks within the system itself, making the analysis of the dynamics more difficult (Bauch et al. 2016). The explicit focus on couplings in the CHANS approach is suited to studying feedbacks and regime shifts in social-ecological systems.

Floodplain ecosystems are driven by flooding patterns, which are a function of both natural and human processes. All over the world, humans have modified floodplain flooding through the construction of canals, dams, fields, and mounds for flood protection and to increase yields. In the Logone Floodplain in Cameroon, fishers have been modifying the hydrology of the floodplain by constructing thousands of individually owned fish canals to catch fish. Since the 1970s, the number of canals has exponentially grown in our study area (Fig. 3.2) (Delclaux et al. 2010; Mahamat and Diaouré 2008; Laborde et al. 2016). Our project hypothesized that the underlying driver(s) of the growth in fish canal numbers can be found in the feedbacks within the floodplain's social-ecological system.

3.4 The Logone Floodplain as a Coupled System: Processes and Couplings

The underlying motivation of this research project was to examine the role and impact of fish canals in the Logone Floodplain because of the concerns raised by inhabitants about canal impacts on flooding patterns, fish populations, and vegetation dynamics. Our starting hypothesis was that the cumulative impact of the exponentially increasing number of fish canals would result in a nonlinear transition in system state—a regime shift. Specifically, the cumulative drainage of fish canals would: (1) result in a shift in flooding and associated biodiversity and livelihood loss and (2) this impact may rival the impacts associated with the construction of Maga Dam. The coupled system of the Logone Floodplain has had at least two regime shifts, and both were the result of major infrastructural interventions—Maga Dam and the subsequent reflooding program. These were externally driven events, unlike fish canals which are endogenous to the Logone Floodplain coupled systems (Moritz et al. 2016). While the floodplain is an anthropogenic landscape—a product of both human and natural processes—it is useful to make the analytical distinction between human and natural systems in the research framework for an in-depth examination of the interplay of these processes.

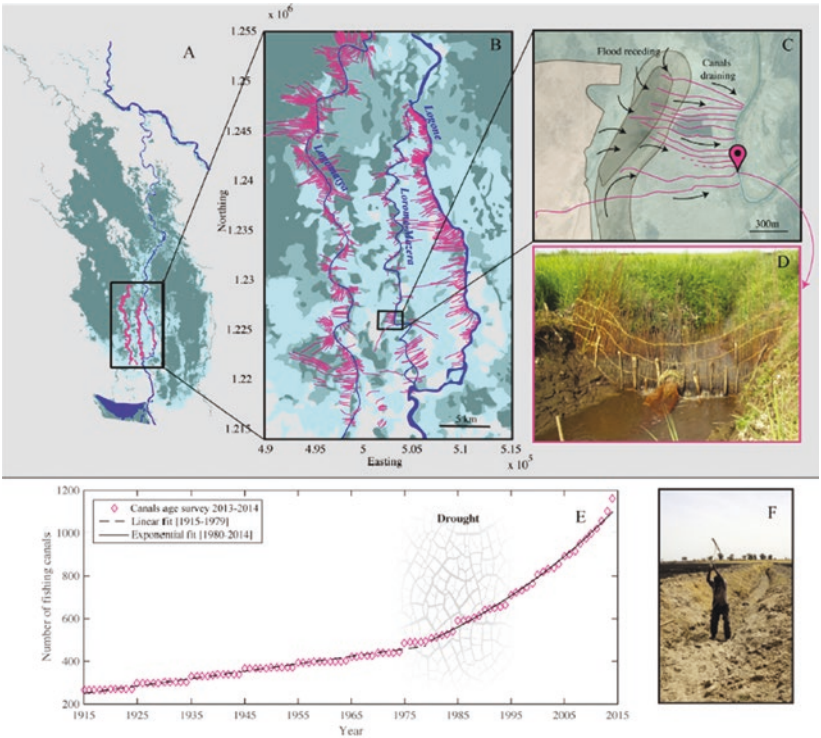

Fig. 3.2 Fishing canals are changing the landscape of the Logone Floodplain. **A** Flooded area from three over-imposed Landsat images and field-surveyed fishing canals (pink markers). **B** Zoom of the black frame in A—pink lines are fishing canals. **C** Zoom of the black frame in B—black arrows represent flow paths of water during flood recession. **D** Photograph of fish trap located at the pin on frame C, at the end of a canal (Photograph by O. Atti). **E** Number of fishing canals in the Logone floodplain since 1915, reconstituted from the age of canals surveyed; linear fit until 1979 ($R^2 = 0.974$ for 1915–1979), then exponential fit ($R^2 = 0.993$ for 1980–2014). **F** A Chadian worker deepening a canal in the dry season (*Source* Reproduced with permission from Laborde et al. (2016); Figure created by the authors using Adobe Illustrator) (Color figure online)

The MORSL project aimed to: (1) contribute to the scientific understanding and sustainable management of African floodplains; and (2) train graduate and undergraduate students at the Ohio State University and Maroua University in the transdisciplinary study of coupled

systems. One of the project objectives was to develop an integrated, quantitative model coupling the floodplain's natural and human systems. Because they affect flood hydraulics, fishing canals are also connected to other systems, such as vegetation growth and pastoralism. For example, there are indications that pastures now support fewer pastoralists in the dry season because of reduced in soil moisture, which no longer sustains as much regrowth after fire. Floodplain fish productivity and biodiversity is also driven by flood-dependent processes, including the duration and timing of flooding, habitat quality, and connectivity. Our research emphasized feedbacks between the human and natural systems and examined how these may lead to regime shifts over time. To that end, we pursued the development of an integrated, quantitative model of the floodplain's dynamics.

Our coupled system's conceptual model encompasses key natural and human subsystems of the floodplain system (Fig. 3.3). Briefly, the natural system is composed of the (1) the physical environment that determines flooding processes (e.g., precipitation, topography, discharge), and (2) the ecological system dependent on the flooding (e.g., floodplain vegetation and fishes). The human system is composed of the communities exploiting the natural system (i.e., floodplain fishers). The processes linking the natural system to the human system are

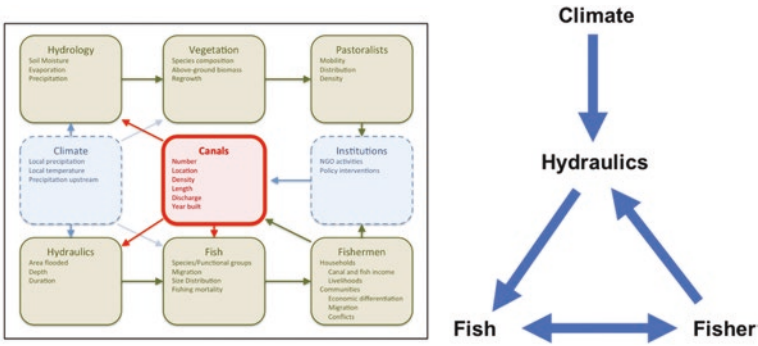

Fig. 3.3 The initial conceptual model of coupled system and key variables (*Source* left; reproduced from *African Journal of Aquatic Science* (2016) 41(1): 99–108 with permission © NISC (Pty) Ltd) and the conceptual model at the end of the project (*Source* right; *Source* figure created by the authors)

the interactions between flooding and fish population dynamics that generate resource availability and the efficiency of resource harvesting. The human system impacts the natural system through the removal of fish and thereby directly affects fish populations. Fish canals can also have an impact on flood hydraulics, which can indirectly alter fish populations because fish population dynamics and growth are driven by flood conditions.

The conceptual coupled model we created at the start of the project encompassed a large and complex social-ecological system, and the integrated model we worked on toward the end of the project ended up being smaller and simpler. The initial coupled model, in addition to modeling fishery processes, also included the pastoral ecosystem of the floodplain, which encompassed vegetation dynamics and the dynamics of pastoral movements. We limited the scope of our research and left the modeling of the pastoral ecosystems for a future date because of unexpected change in our ability to access the field due to regional insecurity caused by Boko Haram (Laborde et al. 2018a).

3.4.1 Processes Within the Natural System

Floodplain ecosystem dynamics are driven by flooding patterns and floods occur when river discharge exceeds a threshold and overbank flow enters onto the land. A river's discharge is a complex product of multiple factors including, but not limited to, the timing and intensity of the climatic regime and weather events (e.g., precipitation, temperature, and evaporation), with variability in these processes causing variability in flooding. In the Logone Floodplain, the rainy seasons occur from May to July, hydrating the top layer of soil and reducing the infiltration rate. In August, rain upstream in the river basin causes the Logone River to flow overbank, and flooding follows a spatial pattern beginning in the south and spreading northwards across the floodplain. At its peak, this flooded area can exceed 8000 km^2. Floods typically begin receding toward the end of December, with flood recession following the same spatial pattern as the inundation, with drying beginning in the south (upstream) and moving northwards. The floodplain

is typically dry of surface water by the end January, except for large topographical depressions and the main river channels, but the saturation of the soil supporting above-ground vegetation growth allows the floodplain to remain green for longer.

The natural productivity of floodplain ecosystems is driven by the habitat created by flooding and the nutrients deposited by the water. Floodplain fish biodiversity has evolved strategies and behavior linked to the timing of the flood-pulse and the seasonality of productivity during the flooded season as well as the potentially lethal conditions in the dry season. As a result, floodplain fish biomass follows a boom-and-bust pattern that matches the dynamics of floodwater volume (Welcomme and Hagborg 1977). Fish will often reproduce at the onset of flooding to take advantage of the season's high primary productivity and low predator densities. The flooded season is also the main growth period for adult fish.

The challenging conditions in the dry season and the spawning stock for the subsequent flood cycle are the main drivers of floodplain fish population dynamics. There is a sharp decline in fish biomass in the dry season, as the decline in aquatic habitat leads to high fish die-off. To survive, some floodplain fish species have evolved physiological and behavioral responses to cope with low oxygen, high temperature and low productivity conditions of the dry season created by low water volume and stagnation. Other species have evolved migratory behaviors and leave the floodplain with the receding floodwater to find larger and more permanent water bodies like Lake Chad.

3.4.2 Natural to Human System Couplings

Humans living on floodplains can exploit the biodiversity and productivity of the floodplain natural system mainly through fishing, herding, and farming. These activities are sensitive to the spatiotemporal patterns of flooding (Laborde et al. 2018a).

The movements of fish can create spatiotemporal patterns of fish density (DeAngelis et al. 2010). While there are large gaps in our understanding of fish movements in the Logone Floodplain, researchers have

reported fish movements northward off the floodplain with the receding floodwater as well as longitudinally within the Logone River (Bénech and Quensière 1982). The fishing techniques of floodplain fishers are adapted to fish patterns, and the movements of fishers relocating their fishing activities are driven by spatial variability in fish densities within the floodplain (Laborde et al. 2018b).

Welcomme and Hagborg (1977) present a model showing how fish density in a particular volume of water varies as a result of patterns in flooding and fish growth. Fish density is low for the majority of the flooded season because water volume is high, and fish are still growing. It peaks sharply at the onset of flood recession as the water volume falls and density-dependent mortality and emigration off the floodplain are yet to begin. Fish density then falls during the dry season as a result of the loss of fish in the system but is still higher than the density during the flooded season, because of low water volume.

Fish canals are a productive technique in the Logone Floodplain because they are operated during the period of peak fish density, and during this period they continuously drain water, thereby fishing a large volume of water. However, they have a short operating period—typically a couple of weeks—determined by flooding conditions: they can only be used when water on the floodplain is lower than the walls of the canal but when there is still some water left on the floodplain to drain. They are typically not operated at the onset of flooding, when water is flowing from the river channel onto the floodplain, because this initial water is high in silt and fluvial deposits can reduce canal dimensions and drainage later in the flood recession. Many fishers build a temporary wall blocking water flow during the period of inundation and remove the wall when they are ready to fish. Canal maintenance and lengthening are undertaken during the dry season.

3.4.3 Processes Within the Human System

We focused on canal fishery in the Logone Floodplain and found that interrelated socio-economic processes are currently influencing the increase in the number of fish canals, including: (1) demographic changes, (2) economic development, and (3) institutional changes.

These processes contribute to socio-economic feedbacks fostering investment in canals (Laborde et al. 2016).

Over the last twenty-five years, there has been a continuous influx of migrants into the floodplain. Initially, fish canals were constructed across natural landscape features like naturally formed small streams that drained receding floodwater. These were rare features and fish canals were owned and managed at the community level. However, a gradual shift in their governance has led to an increasing number of individually owned fish canals. Furthermore, they are now being artificially constructed by digging on the floodplain. Another socio-economic process facilitating the growth in the canals fishery is its institutionalization in the floodplain economy. An increasing demand in Nigeria for dried catfish has supported a seasonal migration of Nigerian merchants traveling to the floodplain buying the fish caught by canals. The high productivity and seasonality of fish canals, limited to a few weeks of the year, allow merchants to easily buy fish from canal fishers. Other types of fishing that occur in the rest of the year are oriented to local markets and/or involve processing and storage of fish. The synchrony in production and market access allows canal fishers to quickly see the returns from the livelihood activity. These processes contribute to socio-economic feedbacks fostering investment in canals (Laborde et al. 2016).

3.4.4 Human to Natural System Couplings

We found that fish canals shape the anthropogenic landscape of the Logone Floodplain in two ways. First, fishing has a direct impact on fish population dynamics by removing fish. The timing of this fish removal is important as floodplain fish population dynamics are determined by the population of fish surviving the dry season. This surviving population is the spawning stock for the subsequent flooding and fishing season. Notably, fish canals catch fish at peak fish density, which is also the period of high natural mortality, and the current rates of removal of fish during this period likely does not affect future population dynamics as it would in other periods (Welcomme and Hagborg 1977).

The second impact of fish canals is on flood hydraulics. By creating channels draining flood water off the floodplain, fish canals result in a faster flood recession (Laborde et al. 2016). These changes to flooding patterns caused by fish canals can have an indirect impact on fish dynamics. The flood is the main growth period for fish and will be shortened from canal-driven faster flood recession. Key questions still remain concerning the impacts of fish canals on fish, including the presence of critical biological thresholds in the flood season (e.g., young fish are not given enough time to reach a condition necessary to survive the dry season) and in the dry season (e.g., dry conditions extend too long for fish to survive).

Floodplain communities also alter flooding in other ways than with fish canals. Communities are known to construct levees across the main river channel to hold water back in order to extend the inundated period on the floodplain. This extends the growth period of fishes and the fishing opportunities for fishing with gillnets and traps.

3.4.5 Feedbacks Between Human and Natural Systems

Feedbacks in the couplings between human and natural system processes can potentially drive regime shifts, for example, a positive feedback between a fast flood recession caused by fishing canals which leads to smaller fish and drives fishers to construct more canals in order to continue catching fish. Moreover, reversing the trend from a fishing canal-dominated state might be difficult due to the presence of a situation of "canal lock-in" where multiple positive feedbacks (socioeconomic, behavioral, hydrological, and demographic) make it difficult to move away from canal fishing after initial investment (Laborde et al. 2016). Our team is now using the integrated model to predict the potential effects these feedbacks may have on system dynamics.

3.5 The MORSL Team

The MORSL project was a collaboration between the Ohio State University and the University of Maroua, Cameroon. Our relatively diverse team was composed initially of 13 researchers in Columbus

including 5 core PIs, and 8 researchers in Cameroon, but this number fluctuated and grew as the project unfolded (see details in Laborde et al. 2018b). In terms of academic disciplines, the MORSL team included rural development specialists, hydroclimate scientists, ecologists, and social scientists. With regard to research experience, the team ranged from undergraduate and graduate students, postdoctoral researchers and associate and full professors; consequently, they ranged in ages from the early 20s to the mid-50s. Team members represented no less than eight different countries: Cameroon, Canada, Chile, China, France, India, the Netherlands, Malaysia, and the United States. There was little gender diversity however: all the PIs were male and there were only three relatively junior female team members—whether graduate student or postdoctoral researcher. Two of these female researchers are specialists in climate science and hydrology, the third one is an anthropologist who led the reflexive effort reported in this chapter. There were no female team members in Cameroon.

MORSL was an interdisciplinary project, but became increasingly transdisciplinary through an increased number and role of non-academic co-researchers (more detail in Laborde et al. 2018b), in part as a response to security concerns in the field that led to a reorganization of our research team. The academic team was mostly based at The Ohio State University in Columbus, Ohio, and English-speaking as a first or second language. There were also three scientists based in Cameroon (a fish ecologist based in Maroua, Cameroonian and multilingual including in French and English as well as Fulfulde, a visual anthropologist based in Maroua, Cameroonian and multilingual including French, English, Hausa, and Fulfulde, and an ecologist based in Yaoundé, Dutch and also multilingual in Arabic, English, French, and German). Field development specialists and fieldwork assistants, on the other hand, were all based in Maroua or in the floodplain, and French-speaking as well as Fulfulde, and for some also Kotoko and/or Musgum (languages spoken by inhabitants of the Logone Floodplain).

As a result of the cultural and intellectual diversity in the MORSL team, an important challenge to address was the highly varied conceptualizations that each team member had for research on the field site, the Logone floodplain. This is a central issue in inter or transdisciplinary

environmental research, especially when team members are based in different locations, which leads to multiple imaginations of how to conceptualize the key issues to be addressed in the research site (Laborde 2015). For a few of the Cameroonian team, the floodplain has been a home since they were born, and they know the landscape intimately in a way that is embedded and embodied in livelihood practices and habits. In contrast, several of the Columbus-based team did not have the opportunity to travel to Cameroon and were not able to physically experience the floodplain. A major barrier to visiting the Logone Floodplain during the project were the security concerns caused by Boko Haram, a Salafist sect based in Northern Nigeria, whose Arabic name translates as "People Committed to the Propagation of the Prophet's Teachings and Jihad" (de Montclos 2014; MacEachern 2018). Since 2012, a faction of the Boko Haram organization has been increasingly active in areas surrounding the Cameroonian Logone Floodplain. As a result of these difficulties to access the field site, experiencing the floodplain for some of the Columbus-based team members was solely through satellite images, maps, models, and—increasingly as the project unfolded—photographs and video provided by other team members (e.g., Laborde and Ahmadou 2017; Laborde et al. 2018b). Like many other CNH teams, we had to navigate across geographies, cultures, languages, and disciplinary backgrounds, with the added constraint of limited access to the field site.

The team organized organically around the PI Mark Moritz due to long-standing collaborative ties with team members in Cameroon. The responsibilities in the MORSL team were organized as follows. Each PI was responsible for studying and modeling one of the systems in the floodplain and worked with a graduate student and/or postdoctoral researcher. Most of the work—organizing the data collection, managing the data, analyzing the data, and writing the papers was done by the postdoctoral researchers under supervision or mentorship of the PIs. The project activities were discussed in the weekly meetings in which the sub-teams presented their progress and problems in studying their respective systems. The presentations and discussions often devoted considerable time to explaining concepts, methods, and questions of the respective fields and disciplines. All team members were involved in

decision-making, but everyone deferred to and/or trusted the sub-team's expertise when it came to final decisions about data collection and/or model building. In the beginning of the project, the PI led and organized the weekly meetings, but later the postdoctoral researchers took over that role and responsibility.

Figure 3.4 (modified from Laborde et al. 2018b) illustrates the team organization by showing the MORSL team network in 2014 across (a) geographies, (b) languages, and (c) expertise. The same nodes represent the same researchers in the three graphics, so the reader can see the intersection of different attributes (language, expertise, connection with the field site) for each researcher. Our team was quite clustered initially, with relatively little communication between Cameroon and US-based team members; and in Columbus, disciplinary subgroups studying the different systems of the floodplain rather independently (climate, hydraulics, fish dynamics, and socio-economic systems). To gradually

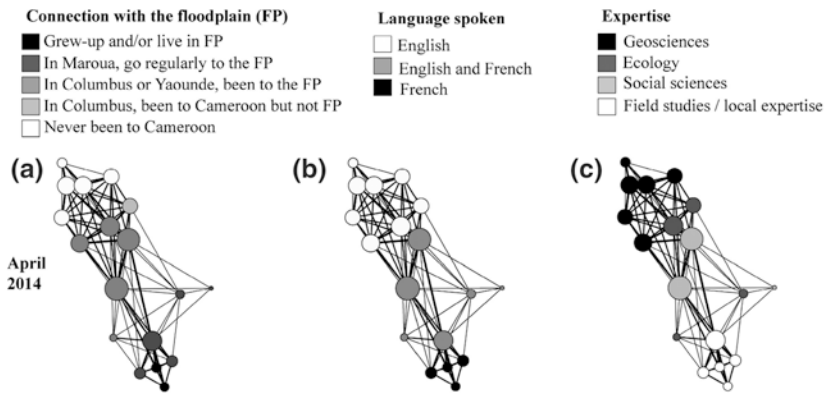

Fig. 3.4 Networks showing the MORSL team organization across (**a**) geographies, (**b**) languages and (**c**) expertise as of April 2014, a few months after starting the project. Each node is a researcher in the network. The edges are weighted based on the frequency of collaborative interactions between two researchers: (1) have met, rare interactions; (2) interact regularly, e.g., weekly meetings; (3) more frequent interactions, for logistics or based on a formal relationship (e.g., supervision, or partnership on other projects). The size of nodes is proportional to their weighted degree (number of edges, considering the weight of edges) (*Source* Figure adapted by the authors using Gephi, modified from Laborde et al. 2018a to show only 2014 networks)

achieve a more integrated research approach across disciplines among the academic team, the PIs, postdocs, graduate, and undergraduate students from the Columbus team held weekly meetings. These meetings involved researchers from all academic disciplines represented in the team, and the meeting themes alternated between disciplinary specific issues and progress, discussion and preparation for interdisciplinary fieldwork, and our joint work toward an integrated quantitative model. We also used a file-sharing service for continuous sharing and discussion of data, findings, and publications with researchers at both The Ohio State University and Maroua University.

The MORSL team engaged in reciprocal capacity building with two NGOs that were research partners working on behalf of floodplain inhabitants: the Cameroonian Association for Environmental Education (ACEEN) and the Center for Research and Development of Pastoralism (CARPA). These NGOs were involved in data collection and analysis, and shared data that they used in their own outreach and development activities. The MORSL team also trained postdoctoral researchers, graduate, and undergraduate students at the Ohio State University in the interdisciplinary study of coupled systems. However, students were unable to get to the field as originally planned because of security concerns stemming from Boko Haram activities; and their focus consequently shifted to spatial analysis and agent-based modeling (Laborde et al. 2018b).

In addition, the team organized a four-day workshop in Cameroon in May 2017 in research and modeling of coupled systems, for twenty-five MA and Ph.D. students from the Universities of Maroua and Ngaoundéré. The workshop was a success, and students indicated in the evaluations that the workshop gave them a better understanding of the CHANS framework and were excited about pursuing what one of them called, the "CHANS-ization of their research". Education objectives had always been a key part of the MORSL project, with initial plans for the support to develop a lab to study coupled systems at the University of Maroua. After safety concerns increased in Maroua we were unable to pursue these objectives besides the individual mentorship and involvement of one Ph.D. student, one Masters student and four Honors students from the University of Maroua in the MORSL project.

The idea to run a week-long workshop instead in Ngaoundéré and bring more research students from Maroua as well as other universities in Cameroon came from the complex systems summer school at the Santa Fe Institute and the related annual week-long winter workshops in complex systems, which the first author attended. We organized and ran the workshop at the end of the project (in 2017), with a format inspired by these complex systems workshops.

The immersive workshop with students was followed by a day-long meeting to share research results with senior community members from the floodplain, who made the trip for the occasion. During that day we discussed MORSL results and their meaning for floodplain communities, with a dozen senior fishermen, customary chiefs, and interpreters. The workshop and the meeting were an opportunity for three of the MORSL team members who had never been to Cameroon to meet collaborators, students, and senior community members from the floodplain, albeit doing so at the end of the project and a few hundred kilometers away from the actual field site.

3.6 Challenges Crossing Boundaries in a CHANS Project

To examine and learn from the MORSL collaborative process, we decided from the start of the project to take a reflexive approach that included continuous data collection about the challenges and dynamics of our interdisciplinary collaboration in practice. To this end, the first author designed and led a research project to study these challenges and dynamics by sending a short survey to participating team members after each MORSL team meeting. The meeting themes were also recorded. The survey, reproduced in Fig. 3.5, included four questions prompting each researcher to: (1) review their understanding of the research by rating their overall grasp of the meeting; (2) identify individual challenges to the project's interdisciplinary research by describing what were the most challenging topics for them during the meeting; (3) reflect on how the overall project was progressing toward its end goals by rating their

MORSL meeting feedback

This is a quick survey to try and see how the MORSL meeting went from our diverse perspectives. It should take you no more than 5 minutes. Hopefully the results help us in the long run.

Thanks for your time! Sarah

****

1. **Your name**
   (this is to connect these answers to your discipline and background - your name will not be published)

2. **1.**
   We come from a broad range of backgrounds, and the topics of the meetings also vary widely. How would you rate your grasp of the content of today's meeting overall?
   Mark only one oval.

	1	2	3	4	5	
Couldn't follow anything	◯	◯	◯	◯	◯	Perfectly clear

3. **2.**
   What was the topic most challenging for you to follow, if any?

4. **3.**
   Progress is never linear. After today's meeting, how do you feel with regards to our common direction, as a group:
   Mark only one oval.
   - ◯ Clearer: new connections emerged
   - ◯ Same as before the meeting
   - ◯ More confused, more disconnected

5. **4.**
   How do you feel right now with regards to your own contribution to the project?
   Mark only one oval.
   - ◯ Very clear about how my work fits in, and which next steps I should undertake
   - ◯ Quite clear about my own next steps, but not about how my work connects with other components
   - ◯ Quite clear about how my work fits in, but waiting on someone else's results to progress
   - ◯ Unclear: I can't see the connections with other components, I'm not sure what to do next

6. **Additional comments**
   Room to share extra thoughts if you want to

Fig. 3.5 Weekly survey that was sent to researchers that participated in that week's MORSL meeting (*Source* Figure created by the authors using Google Forms)

feeling for group progress; and (4) record the cohesiveness of the overall work by choosing between four options for how they felt their individual work fit into the group process. There was also an open text box for further comments. All of the quotes in this chapter were collected via this questionnaire. Data were collected after 56 weekly, one-hour long team meetings, with an approximately equal proportion of meetings focused on fieldwork, the individual respective hydroclimate and hydraulic, socio-economic, and ecological components of the MORSL project, and, lastly, the integrated model. Trends and quotes from an analysis of survey responses were presented in MORSL group meetings in two instances for reflexive purposes, and contributed to strengthening the commitment to the process of developing the integrated model.

In their study of several collaborative teams, Boix Mansilla and colleagues (2016) found that factors leading to successful interdisciplinarity encompass three dimensions: cognitive, emotional, and interactional. These themes also emerged from an analysis of comments gathered through the MORSL survey, so we use this framework here to analyze the challenges encountered during our interdisciplinary and international project. In the context of CHANS research in general and the MORSL project in particular, we add one more category pertaining to logistical challenges, which were particularly salient in our case because of the international nature of the research in a rapidly changing geopolitical context surrounding the field site.

3.6.1 Logistical Challenges

We begin this section by describing the logistical challenges that faced the MORSL project because they influenced the team's ability to manage the other three types of challenges. Working internationally and in a relatively remote field area, our project was faced with important logistical challenges related to the movement of researchers and the acquisition and transportation of field instruments. These challenges were exacerbated by the insecurities caused by the Boko Haram insurgency, which led to increased fieldwork precautions and later the cancellation of field trips. As a result, most of the Columbus-based team was unable

to visit the floodplain. Logistics thus constituted a central challenge to the MORSL project, and the consequences are addressed in more detail elsewhere (Laborde et al. 2018a). We mention them here as key background to the other challenges of our collaborative research. For example, there were significant emotional challenges associated with the necessity of constant risk-assessment in an insecure working environment. Further, insecurity posed cognitive challenges, as perceptions of risk varied enormously among team members. This variation stemmed in part from factors related to team diversity, including age, personality and family situation, as well as different degrees of connection and familiarity with the field site.

Logistical challenges led the team to rely on its administrative support system, for example financial and risk management administrators. We found that in our research context, there is a real need for such administrators who understand the challenges posed by interdisciplinary, international research. For example, Boko Haram-related restrictions forced us to make unconventional arrangements to buy equipment (i.e., buy a boat in Cameroon and a boat engine in Nigeria, and arrange transport for the engine across the border), which required the support of a flexible and understanding fiscal officer in Columbus. The Ohio State University's risk management officer also became a relevant external member of the team, providing information on fieldwork risk assessment for the team. Because the insecure geopolitical context led to logistical complications, we requested and received two no-cost extensions from NSF to complete our research activities. These administrators could be considered satellite team members that are critical in adapting to the challenges of interdisciplinary and international research.

3.6.2 Cognitive Challenges

Our project required building bridges across multiple floodplains in a conceptual sense, as the Logone Floodplain was understood and imagined very differently across collaborators. For example, during the first meeting between an anthropologist and a senior ecologist of the

MORSL team, the latter explained that he conceptualized the floodplain as "a bunch of differential equations." This stood in contrast to the understanding of this particular anthropologist and team member, who later described the floodplain in terms of the threads of human (and nonhuman) stories. As another example, our first few team meetings were led by earth scientists (a hydrologist, a geographer, and a climate scientist) and focused on the need for an appropriately accurate Digital Elevation Model to study the floodplain. It became clear that to them, the work could not start without a proper model for the floodplain's *ground* as a relatively unchanging base. In contrast, a Cameroonian collaborator later talked about the floodplain as a "living body," emphasizing its fluxes and constantly changing nature (Laborde et al. 2018a).

These different points of view across team members reflected different epistemologies or ways of developing knowledge about the floodplain, and thus different expectations for how the project should unfold methodologically, and what the research findings should look like. One researcher expressed in the early stages of research concerns for "How the different groups deal with data and what each group expects as results," and another natural scientist, their difficulties in "imagining papers from social data." Such conceptual and methodological differences posed challenges to progress from a collective intentionality (what we were aiming to do together—model a coupled system) to operationalizing some of this "togetherness" (actually doing it, together).

The initial methodological gaps between research cultures were never fully bridged: while the team settled relatively early on the expectation that coupled systems analyses should be highly quantitative—in the words of the lead-PI: "CHANS research is about *how* and *how much* systems are coupled, especially when it concerns the study of regime shifts"—our lack of access to the field site led to the gradual realization that we would not be able to gather the necessary data for such analyses. The team consequently shifted toward more inclusion of qualitative understandings and theoretical modeling (see Laborde et al. 2016). This shift was more or less comfortable for researchers within the team, and was especially difficult for earth scientists who had to accept they would never have a relatively accurate Digital Elevation Model of the floodplain for their hydraulic model.

Some of the other challenges stemming from cognitive tensions were related to scales of inquiry. Team members from different disciplines had their own norms and criteria for determining system boundaries and the temporal and spatial scales for data collection. For example, hydroclimate analyses were based on satellite and historical data that spanned decades and the whole river catchment, while fish catch data was collected every fishing season and across various villages and water bodies in the floodplain, in a much smaller area than the spatial scale of hydroclimate analyses. The different human and natural systems had to be integrated across spatiotemporal scales and the linking parameters were hard to define. One researcher wrote after a meeting that a key challenge was conceptualizing the articulation of these various scales: "conceptualizing the integrated model connections vis-a-vis fish and coarse scale hydro(climate) is tricky."

3.6.3 Interactional Challenges

Communication among members of interdisciplinary teams is challenging (McGreavy et al. 2015). Consequently, working on knowledge integration in the model posed interactional challenges. Within the MORSL team, these pertained largely to the different languages spoken across the team, which reflected different cultural backgrounds tied to nationality, as well as the different epistemologies outlined above, or research cultures. For example, one of the researchers said after a meeting focused on model integration that a key challenge for them was "terminology: *agents* mean something different in anthropology, ABM [Agent Based Modeling] and other fields I guess, and so does *class*, and *object*…" To cross the boundary of these different languages and the assumptions embedded in them, much time was dedicated in team meetings to spell out tacit disciplinary-specific knowledge and unpack taken-for-granted terminology. This made our team process slow and frustrating at times, as expressed in a couple of instances by researchers. That said, explicit attention to clarifying terms for effective communication also contributed to the development of interactional expertise across the team. Interactional expertise is a kind of expertise

that sits on a continuum between *contributory expertise*, the ability to contribute to a field of knowledge, and no expertise in that field: it has been described as the ability to "walk the talk of [an] expert community, just as one can watch, understand, and discuss a tennis match without being a great tennis player" (Collins et al. 2007). The crucial benefit of interactional expertise is that it permits effective communication between experts and nonexperts to work jointly toward shared goals.

Interactional expertise is a social skill, which emerges from time spent together across fields of expertise for the sake of becoming familiar with each other's languages, and thus their assumptions, concepts, methodologies, and models. After a few months of joints meetings, one of the team's anthropologists said about the most challenging topic after a hydrology-focused meeting: "It's still the hydrology (DEM and flow models), but I'm becoming more familiar with [their] terminology and methods … I understand where the model is at and the results it puts out, but I cannot add anything to the discussion about how best it [model development] should proceed." An ecologist expressed a similar sentiment after a climate science-focused meeting: "I understand the jist of what is being proposed (sic), but am unsure of the details of getting it done. But that's ok—because it's with the geographers and climate scientists." These comments highlight improvements in the ability of researchers to understand the work produced by specialists, while still not being able to contribute to those specialties. This illustrates the development of interactional expertise: a kind of expertise that is not meant to deepen knowledge within specific disciplines but to support the ability to communicate, see connections and thereby build bridges across areas of expertise in order to constitute communities of practice. As highlighted by the second quote, trust in each other's disciplinary-specific expertise is also developed through time spent exchanging across specialty areas.

Beyond disciplines, the related issue of communication across national languages (English and French) and among local groups in the field (Fulfulde, Musgum, and Kotoko) posed interactional challenges for the MORSL team, because not all researchers spoke a common language (Fig. 3.4). Initial proposals for field protocols were developed in a three-step process. They were first designed in English

in interdisciplinary meetings in Columbus, and were then translated into French by one bilingual anthropologist in the team. The third step involved workshops with the field team in Cameroon, which then provided additional feedback for further refinements. Through this process of recursive translation, the bilingual (French-English) members of the research team became more central in the network for communication between Cameroon and US-based networks, and their workload and responsibility also increased (Laborde et al. 2018b).

3.6.4 Emotional Challenges

The uncertainty of constant navigations across boundaries that characterizes collaborative research on coupled systems carried associated feelings of emotional vulnerability among MORSL team members. These in turn led to a level of stress about the interdependencies between research components and the ability, or lack thereof, of the team to meet project objectives. A co-PI (non-hydrologist) made the following comment in 2014: "The most challenging for me is how to get the hydraulic model right. We made decisions about channels, but we do not know whether these are the rights ones. There is so much uncertainty in the model, but it is one of the most important models in our integrated model. That is stressful. We are getting a better understanding, but I fear it will be a challenge to get the model right (fit the flooding extent and duration) for a long time."

The uncertainty about the team's ability to obtain sufficient and appropriate data to develop and then validate interdependent components of our integrated model was exacerbated in the MORSL project by the rapidly changing and risky circumstances at the field site, and the consequent inability of the team to carry out the project as initially planned (Laborde et al. 2018b). Researchers also reported a related feeling of overwhelming complexity associated with large, CHANS-type projects. One researcher commented, more than halfway through the project: "I think the dominant feeling is that we are so far behind, I'm afraid we won't be done in time. Not time enough to follow everything out. My tendency is then to tunnel vision, and focus on getting

something (anything!) fully done […] but that hides the worries of all the angles and dimensions we are missing out on, and sweeping under the rug." This quote illustrates the anxieties with remaining committed to interdisciplinary research, and the tendency to retreat to a disciplinary focus as a response to the complexities of collaboration. These concerns affected junior researchers in different ways than tenured professors, who did not feel the same pressure to establish their research pathways (see also Rhoten and Parker 2004).

Uncertainty and insecurity in the field also led to more direct emotional issues related to personal security. While these may not be relevant to most CHANS projects, they were part of the reality of our project. Maroua-based team members lived and worked in a highly stressful context after the expansion of Boko Haram operations to the Far North of Cameroon. In 2015, for example, suicide bombings occurred in public places in Maroua where many of our collaborators lived and still live. One US-based field researcher also faced direct gender-related threats in the field (a female researcher being threatened by a man in a position of power), and stressful events such as being woken up in the middle of the night by army personnel in assault gear, searching the neighborhood for Boko Haram terrorists. Despite the care and discretion applied in the field when MORSL team members were able to carry out research activities (see Laborde et al. 2018b), the volatile circumstances in the field area undeniably took an extra emotional toll on several MORSL researchers.

3.7 MORSL's Approach to These Challenges

To address the logistical, cognitive, interactional, and emotional challenges stemming from crossing boundaries, the MORSL team pursued three key strategic practices: (1) recognizing and supporting the work of network brokers (Perz et al. 2010); (2) pursuing a commitment to copresence in the face of relational friction (Beaulieu 2010); and (3) recognizing the importance of interdisciplinary process and relationships over outcomes. We discuss these three practices in more detail below.

3.7.1 Network Brokers, Building Epistemological Bridges

Our research team was diverse, and geopolitical issues prevented us from working together in the field as originally planned. As a result, our joint progress was particularly dependent on network brokers: researchers able to bridge areas of expertise and geographies through their engagement with multiple networks, disciplines, and languages, and thus multiple understandings of the Logone Floodplain. In our case, the team's two anthropologists based in Columbus emerged as central brokers in the research team (represented by the central light grey nodes in Fig. 3.4c). This was for several reasons. One concerned the shared history of the lead PI with key collaborators in Cameroon. Another involved bilingual abilities, and the translational nature of anthropological inquiry that provided a training background well-disposed to building bridges across research cultures. The team's anthropologist based in Maroua also took an increasingly central role in the team, as his mastery of visual media provided researchers across the MORSL team—including those with no access to the field site—with a window into the sights and sounds of the Logone Floodplain.

Later, our adaptation strategy to the lack of access to the field was to expand and strengthen our collaborative relationships. Network brokers connected the MORSL team with existing and new colleagues in Cameroon, including those in nonacademic organizations but with deep field knowledge. One MORSL anthropologist leveraged relationships with other French researchers working in Cameroon to extend the MORSL network to staff and students at the University of Ngaoundéré, via meetings and guest lectures. These broad transdisciplinary networks supported the adaptation of the MORSL project to the fast-changing field conditions (Laborde et al. 2018b).

3.7.2 Co-presence and Friction

Co-presence occurs through time spent listening and exchanging (Beaulieu 2010). Hence co-presence in the context of CHANS research

involves researchers from different research cultures in regular dialogues. Co-presence need not involve co-location. In the case of our MORSL project, co-presence across disciplines and countries involved many remote, information technology-mediated interactions, as well as weekly interdisciplinary lab meetings in Columbus, with some collaborators regularly joining via Skype from Cameroon and other countries. Co-presence was the basis for developing interactional expertise (Collins et al. 2007) and collective intentionality that was the basis for joint progress. Progress was certainly not smooth or linear, and at times the team experienced inertia, blockages, and frustration. We argue however that some of these difficulties are required for interdisciplinarity to emerge through "friction," which Anna Tsing describes as "the awkward, unequal, unstable, and creative qualities of interconnection across difference" (2005: 3).

Accepting and even embracing friction in interdisciplinary research processes means accepting the cognitive tension of epistemological pluralism rather than seeking epistemological consensus. This means that researchers across disciplines accept from the onset of collaboration that multiple approaches are valid to study a given system. That entrains a commitment to find ways to articulate those approaches. Consequently, the interdisciplinary process then becomes one of developing the skills to navigate, translate, and connect across disciplinary fields rather than seeking to create a middle-ground. Accepting multi-epistemological friction requires promoting an intersubjective rather than objective research framework within the team, by supporting respectful and non-threatening disagreement during meetings. On an interactional level, accepting friction means emphasizing translation over persuasion, and striving toward a *workable* dialogical interface among team members. On an emotional level, it is associated with the respect and value for different disciplinary perspectives, and therefore a supportive and trusting environment.

The coupled systems conceptual framework facilitated epistemological friction by playing the role of a boundary object that structured and anchored our interdisciplinary thinking. "Boundary objects are plastic enough to adapt to local needs and constraints of the several parties employing them, yet robust enough to maintain a common

identity across sites. They are weakly structured in common use, and become strongly structured in individual-site use" (Star and Griesemer 1989: 387). The coupled systems framework shaped team interactions and gradually led to what one of the co-PIs called "CNH-think" among the group. This notion expands on Friston and Frith's (2015) definition of interacting minds as "two-way mutual adaptation" to more than two collaborating minds. As the lead-PI reflected on the MORSL project: "The PIs, who have been working together for more than five years now, since the writing of the first CNH proposal, are all thinking in terms of coupled systems, resilience and complexity. We have a MORSL-think or CNH-think that allows us to quickly approach a social-ecological system and conceptualize it in CNH terms for proposals."

This "CNH-think," however, was relatively loose and still required the practical articulation of different disciplinary perspectives within the team on how to interpret and operationalize the coupled systems framework: a difficult process of unpacking disciplinary-specific assumptions and looking for linkages. Much of this work was done for the MORSL team in interdisciplinary meetings and was supported by one of our key goals: building an integrated model. The model served as an epistemological artifact for our team process where research coming from different disciplinary points of view could "hang together," and it materialized the shared memory of our interdisciplinary progress. When epistemological differences led to tensions and team inertia, the model helped the team refocus conversations on tangible tasks, such as how to articulate data collected at different scales within the model database. The MORSL team held many meetings dedicated to integrated modeling. The meetings were necessary in particular to spell out the process of data collection in order to permit data integration in a conceptually coherent numerical model. This work was recursive, and frustrating at times as illustrated by this quote of a PI after one such meeting: "At the end of the meeting I had a discussion with [an other PI, from an other discipline] about the integrated computer model … They had different ideas about how to organize the model … so that was a little frustrating … primarily because I thought I had finally figured it out." Data collected via the reflexive survey showed however that these integrated model meetings scored the highest averages for the researchers' ratings

of *meeting grasp* and *group progress*, compared to group meetings discussing separately the ecological, hydroclimate, or socio-economic components of our research project—showing that despite the frustrations, there were significant benefits of focusing on a tangible interdisciplinary product like the integrated model, in terms of joint learning and group progress.

3.7.3 Commitment to Process

Finally, productive interdisciplinary relationships require commitment, not only to explicit and concrete outcomes, but also more importantly to the process of interdisciplinary work itself and to the relationships that develop through it. In our case, enacting this commitment meant, in part, showing up at weekly lab meetings, during which important dialogues and exchanges occurred to build an interdisciplinary rapport. This type of commitment is required because interdisciplinary collaboration is difficult, and the process will unavoidably lead to the temptation to retreat to disciplinary safe spaces, as manifest in the "tunnel vision" mentioned earlier, or to focus on other academic tasks. The reasons for commitment to interdisciplinary relationships vary for each researcher and depend on seniority, research interests, and career prospects; and reasons for the occasional absences also vary, for example, during the course of the MORSL project, three co-PIs had sabbatical years and three team members' babies were born. We found that scheduling a weekly lab meeting time at the beginning of each semester, via consensus among team members, helped commitment.

However, when issues arose in relation to the emotional challenges highlighted above, these affected the commitment of team members. The weekly lab meetings were not the best place to deal with them, as these meetings were focused on technical and intellectual work. We generally relied on one-to-one mentorships within the team to address those issues. We think here that it is important for large interdisciplinary teams to be explicit about the need to dedicate time and resources to the "soft" work of developing relationships and connections among team members (see in another context, McCallin and Bamford 2007). Fieldwork is often an important time for the social and emotional

integration of a research team, as team members spend more time together than the structured meeting time. Our team did not have a joint fieldwork campaign, and upon reflection we should have compensated with more social events to build relationships and bypass boundaries beyond the intellectual dimension.

3.8 Conclusion

We examined the collaborative process of a large CHANS team that worked across geographical, disciplinary, and language boundaries. We noted that logistics pose significant challenges in addition to cognitive, emotional, and interactional challenges. We argued that key elements of successful collaboration are (1) recognition of the work of network brokers to expand and strengthen networks, (2) embracing co-presence to manage friction rather than seeking epistemological consensus, and (3) a commitment to process and relationships over outcomes.

If we were to carry out MORSL again, we would make sure to have regular, formal meetings, to help keep researchers committed to the interdisciplinary process and to some extent accountable to this commitment. We would also probably spend more time early on developing principles for enacting epistemological pluralism in the research team. This could be done by pushing our reflexive approach further, and allowing more time for a dedicated researcher to listen to and document team members' expectations and epistemological priors from the onset—for example in relation to methodological frameworks and research outputs—by complementing our short survey approach with a series of in-depth interviews and regularly reporting back on the research process. We would also dedicate more time and resources to supporting relationship building among the team, outside of formal research meetings. The intellectual work required to cross boundaries in large interdisciplinary CHANS-like projects needs foundations of trust, openness, and reflexivity. These "soft" dimensions of interdisciplinary work should be recognized as central, and supported by some dedicated time, resources and expertise.

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4

Collaborative Research Across Boundaries: Mangrove Ecosystem Services and Poverty Traps as a Coupled Natural-Human System

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4.1 Introduction to Mangrove Ecosystem Services and Poverty Traps: A Coupled Nature-Human System

More than 35% of mangrove areas worldwide have been degraded or lost in the past 20 years (Polidoro et al. 2010; Giri et al. 2011; Friess and Webb 2014). The majority of losses and degradation have been associated with the conversion of mangroves to aquaculture and agricultural uses, with the highest rates both locally and globally in Southeast Asia (Thomas et al. 2017). This degradation has significant

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consequences for economic development and mangrove ecosystem functioning. Mangrove forests dominate tropical and subtropical coastlines and provide a number of ecosystem services to impoverished communities, including extractive goods (raw materials and energy), the provision of nursery habitats for fish and shrimp, water quality improvement, as well as shoreline protection from erosion and floods that also regulate changes in salinity regimes caused by saltwater intrusion (Ajonina et al. 2008). Recently, the mitigation of greenhouse gasses through carbon storage and sequestration in vegetation (above and belowground) and soil has also been recognized as an important ecosystem service by mangrove forests (Mcleod et al. 2011; Murdiyarso et al. 2015; Lovelock et al. 2017). This "natural capital" can contribute

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disproportionately to the welfare of impoverished populations because they often have a severely limited capacity to purchase substitutable goods and services (World Bank 2007). Ecosystem services can also serve as "safety nets" for impoverished communities (Ewel et al. 1998; Barbier 2007). However, their dependence on natural resources can be the cause of resource degradation. Globally, it is estimated that 26% of mangrove wetlands have been degraded due to overexploitation for fuelwood and timber production (Valiela et al. 2001). Therefore, there remains a significant gap in our understanding of mangroves and coastal communities as coupled nature-human (CNH) systems in terms of their ecosystem services and the mechanisms that cause poverty to persist (i.e., poverty traps, Azariadis and Stachurski 2005).

This chapter elaborates on the experience of our interdisciplinary and international research team to examine the CNH system of mangrove ecosystem services and poverty traps. This research was conducted in rural coastal Tanzania, where chronic poverty occurs alongside declining mangrove forests. Studying this complex problem required a talented, interdisciplinary team of natural and social scientists and other professionals. Equally critical was the constitution of strong partnerships with collaborators who have the local knowledge, connections, and capacity for project implementation.[1] Our research team was comprised of junior and senior faculty, undergraduate and graduate students, research scientists, and other professionals with expertise in economics, ecology, fisheries, hydrology, and climatology. Our team collaborated in an interdisciplinary mode to organize an integrated approach to the study of the CNH system. Sub-teams then collected field data, conducted analyses and modeling, and disseminated the research findings. This chapter highlights the major boundaries that existed in our collaboration, and practices that made it possible for the research team to manage the resulting challenges.

Our approach is a first step toward building the understanding of ecosystem services through the lens of poverty traps by empirically investigating the key feedback loops and conditioning factors, and by scaling

[1]This project is still ongoing at the time of writing this chapter. The funding is expected to end August 2019 and continuing efforts will be made for dissemination of research results.

up to the landscape level to understand the system dynamics. Our project has two objectives: (1) conceptualize and provide empirical evidence for various mechanisms—drivers, feedback loops, and thresholds—within and across the natural and human systems for different ecogeomorphological settings and poverty conditions in coastal Tanzania; and (2) use the decision rules and switching behaviors inferred from the empirical evidence to build an agent-based model (ABM) in order to scale up to a regional level and identify system-wide effects under alternative scenarios and simulate directions in which the CNH system can evolve. This project focused on four ecosystem services of mangrove forests. Of those four, three services were identified through our preliminary data that are likely to be related to poverty dynamics: extractive goods from mangroves (fuelwood, building poles, and charcoal), fish and shrimp habitats, and coastal protection. We also assessed carbon storage in coastal mangrove forests (vegetation and soil) as a fourth ecosystem service representing a potential source of revenue for communities that could alleviate the poverty-environment trap: carbon credits from reducing deforestation or restoring mangroves can potentially be sold in the carbon markets to mitigate greenhouse gas emissions.

The rest of this chapter is structured as follows. Section 4.2 discusses the components and relationships of the CNH framework employed in this study. Section 4.3 describes the study area in Tanzania and data collection efforts. Section 4.4 discusses how we organized our team for the collaborative effort, identifying partners and challenges in the process. Section 4.5 discusses the salient issues and challenges, and focuses on strategic practices that we pursued to address those challenges and thereby advance sustainability science. Finally, Sect. 4.6 concludes with insights we learned through this collaborative project.

4.2 The CNH Framework: Mangrove Ecosystem Services and Poverty Traps

As the first step in our research, we conceptualized the mechanisms—drivers, feedback loops, and thresholds—that link mangrove ecosystem services and poverty traps (Uchida et al. 2018). We adapted and

contextualized a general conceptual framework to study CNH systems (Collins et al. 2011) to a setting where ecosystem services and poverty dynamics are linked bidirectionally.

4.2.1 Dynamics Within the Mangrove Ecosystem

Variability in environmental gradients (e.g., salinity, nutrients) at the local scale, along with regional climate and geophysical processes (river input, tidal amplitude, wave energy) have been shown to control regional and local patterns in mangrove ecosystem structure and function (Thom 1982; Twilley 1995; Twilley and Rivera-Monroy 2005; Rovai et al. 2018). Local variations in hydrology and topography result in the development of distinct ecological types or "ecotypes" of mangroves (e.g., riverine, basin, fringe, scrub; sensu Lugo and Snedaker 1974). Such ecotypes are defined by the interactions of three environmental gradients: regulators (e.g., salinity), resources (e.g., nutrients, light), and hydroperiod (frequency, duration, and depth of water). Such gradients constrain the production envelope of mangrove wetlands (Twilley and Rivera-Monroy 2009; Castañeda-Moya et al. 2013). Thus, not all mangrove ecotypes provide the same type and quality of ecosystems services, so each ecotype represents a site-specific capacity to provide some mix of ecosystem services including carbon storage, nursery habitat for fisheries, land building capacity, or shoreline protection (Fig. 4.1, Arrows 2, Lee et al. 2014). Although this differential capacity in providing ecosystem services has been historically recognized (Ewel et al. 1998), there is a major knowledge gap in identifying and quantifying the link between mangrove functional attributes (e.g., net primary productivity, biomass, carbon storage) and ecosystem services flux (Fig. 4.1, Arrow 2).

4.2.2 Dynamics Within the Human System

The livelihoods of coastal rural households rely heavily on ecosystem services that are provided by natural resources, and the degradation of such resources can create conditions that trap households in poverty

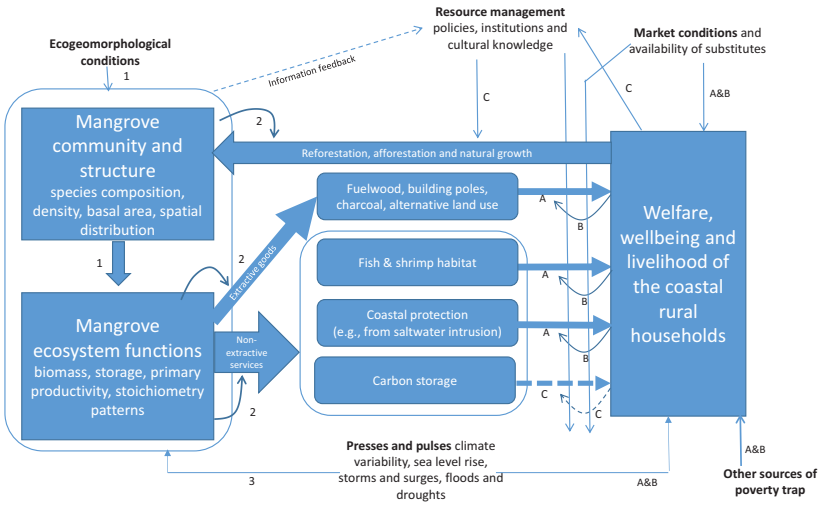

Fig. 4.1 Mangrove ecosystem services and poverty traps framework. In this diagram, stock is represented by rectangles and flows by thick arrows and rounded rectangles indicating ecosystem services. Curved arrows represent feedback loops while thin straight arrows show conditioning factors and drivers. Dotted arrows represent nonexisting flows or feedback loops (*Source* Figure created by the authors)

(Fig. 4.1, Arrows A). Mangroves are cut for fuelwood, building poles, and charcoal; mangroves are sometimes cleared to allow for alternative land uses such as salt production; fish and shrimp, which rely on mangroves for habitat, are often the sole source of income in coastal households; and in impoverished villages, a well or river is often the only source of drinking water and irrigation for crops. Compounding this loss of resources, coastal freshwater can be contaminated by salt through exposure to saltwater flows generated by expansions of tidal creeks and aquaculture ponds associated with mangrove destruction and shoreline changes (Knighton et al. 1991; Mulrennan and Woodroffe 1998; Ong 1995). Indeed, damage from saltwater intrusion can persist for prolonged periods, triggering changes in vegetation species composition where other plants (e.g., *Salicornia* sp., *Batis*) adapted to hypersaline soil conditions (>70 ppt) can replace mangrove forests, especially in dry climates as in the case of coastal Tanzania.

Moreover, changes in household welfare can create a feedback effect in the CNH system leading to changes in demand for ecosystem services (Fig. 4.1, Arrows B). When households become poorer, they may increase their consumption of natural resources. In moments of external shocks, households may turn to mangrove and fish resources as a "safety net." While this is beneficial for those who lack alternative means to manage risk, resource exploitation can deteriorate the ecosystem and reduce provision of those services in the future, which, in turn, increases the risk of poverty traps. With greater wealth, demand for goods such as fuelwood and building poles may diminish when households can switch to other sources of energy and construction. However, households may also invest in better technologies that allow them to harvest fish and shrimp more intensively. These reinforcing feedback loops are likely to depend on market conditions and availability of affordable substitutes. In contrast, carbon storage (Fig. 4.1, Arrows C) has little value to the poor and will be eventually degraded if there is not a payment mechanism in place. If mangrove carbon can generate revenue, if distributed appropriately, it could be made to alleviate the poverty trap and become a positive feedback.

4.2.3 Linkages Between the Natural and Human Systems

Variations in the net flow of mangrove ecosystem services, both extractive and non-extractive, can affect the livelihoods and well-being of rural coastal households (Fig. 4.1, Arrows 1, 2, and 3–Arrows A). These can in turn catalyze feedback effects (Fig. 4.1, Arrows B) via changes in decisions about extraction of mangrove and fish resources or reforestation decisions. These responses can change mangrove forest structure, and hence their production of ecosystem services.

Such decisions are largely determined by incentives created through policies, institutions, and cultural knowledge of resource management (Fig. 4.1, Arrows C). Different types of governance are likely to result in different extraction and restoration/rehabilitation decisions at a local level. Such decisions may in turn lead to different trajectories of

mangrove structure and their ecosystem services, which may then affect future human welfare. Finally, both human and natural systems are subject to external shocks (Fig. 4.1, Arrows 3 and A and B, Collins et al. 2011). For instance, repeated natural hazards can push households into a poverty trap, while at the same time other shocks can have negative effects on mangroves (e.g., hydrological changes that lead to hypersalinity and loss of mangroves). Together, negative effects on both systems can become mutually reinforcing (Barrett et al. 2011).

4.3 Study Site and Data Collection

Tanzania, located in coastal East Africa, provides an ideal environmental setting to study the dynamics of mangrove ecosystem services and poverty traps. With an estimated population of 55.6 million, Tanzania continues to suffer from high poverty rates, with nearly 50% of the population falling below the international poverty line (U$1.9/day; World Bank 2015). Yet, Tanzania has world-renowned coastal biodiversity. The region is a priority area identified by the World Wildlife Fund where mangroves are under intense exploitation pressure (Mangora et al. 2016). Mangroves occur along the continental coast of Tanzania and on Zanzibar Island, covering around 1760 km^2 (total biomass: 11,037,800 Mg; Fatoyinbo and Simard 2012). The largest mangrove area along Tanzania's extensive coastline (1424 km) is located in the Rufiji River Delta, followed by the Tanga and Kilwa blocks and estuaries of the Ruvu, Wami, Pangani, and Ruvuma Rivers (Mangora et al. 2016). These mangroves play significant ecological, economic, and cultural roles in coastal communities around Africa (Ajonina et al. 2008).

We coordinated fieldwork in selected villages surrounding the Kipumbwi–Sange estuarine mangroves in Pangani District and in Rufiji River Delta in Kibiti District. We assessed the distinct ecogeomorphological and poverty dimensions in the two areas, characterized by riverine, fringe and scrub mangrove forests, to document major changes in environmental drivers such as tides and relative elevation. The team organized into four sub-teams—Team Mangrove & Climate, Team Fish, Team Village, and Team Water—each of which developed its protocol for

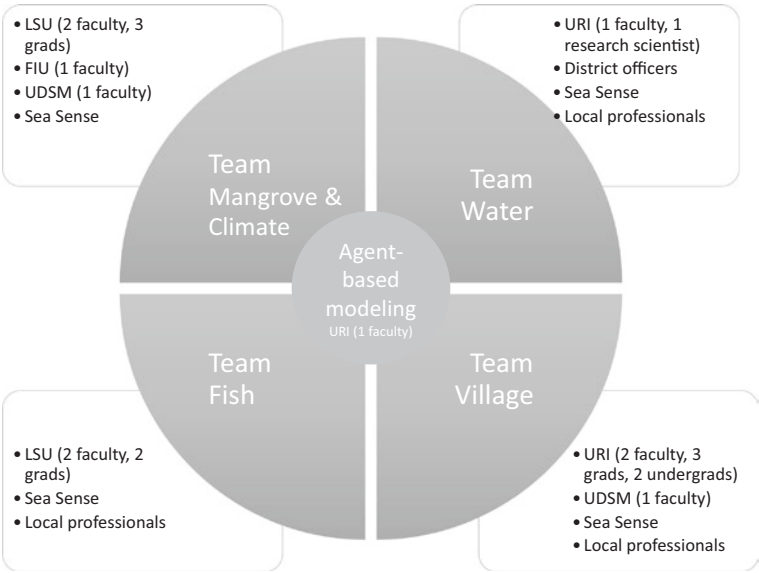

Fig. 4.2 Research team structure (*Source* Figure created by the authors)

sampling and data collection while coordinating the site selection and logistics (Fig. 4.2).

4.3.1 Mangrove Data

The goal of the ecology component of the study is to evaluate the spatial extent and health of mangrove forests in the Tanzania coastal zone. The research team focused sampling efforts on two locations: the lower region of the Rufiji Delta and Kipumbwi–Sange in Pangani District. In each location, we collected soil and forest structure data from several sites.

To assess forest health, Team Mangrove focused on forest structure, soil physicochemical variables, and tree species diversity. The forest structure variables included the following: tree height, diameter, and density. These variables allowed the research team to calculate forest biomass above and belowground to determine short and long-term vulnerability to wood harvesting and deforestation. Once we know the level of

vulnerability, we can recommend management strategies to avoid reductions in forest health, especially the loss of large trees (more than 10 m tall) needed for mangrove regeneration and sustainable productivity.

The team collected soil cores at different depths (0–50 cm and 0–100 cm) to determine carbon and nutrient concentrations (nitrogen, phosphorus). Soil nutrients reflect soil fertility conditions because they are vital for plant growth and regulate forest tree species composition and diversity. Soil carbon concentration is used to measure carbon storage in the long term (>20 years). Soil carbon storage is a key functional property because it indicates how mangroves can potentially help in reducing carbon dioxide concentrations in the atmosphere, and thereby help mitigate negative effects on the climate (e.g., increasing temperature and droughts). Mangroves can sequester carbon, which is considered an ecosystem service that has an economic value. That is in turn a powerful argument to promote mangrove conservation and help design and implement cost-effective mangrove restoration and rehabilitation programs in areas impacted by deforestation.

4.3.2 Fish Data

Coastal villages in Tanzania are heavily dependent on fishery resources produced from fishing activities for both home consumption and income through sale. Therefore, it was important to characterize both the types and amounts of fish caught, as well as the biology and ecology of the harvested fishes.

Obtaining accurate fishery catch data is a notoriously difficult task. Fishing is often a solitary behavior, and fishers across the globe are not always interested in sharing their catch information, especially with government agencies. Given our project's limited coverage across space and time, we also knew that we would need to rely on harvest data about fishes collected by others. Fortunately, the Tanzanian coast has 204 Beach Management Units (BMUs), a form of a community-based co-management program that was established in 2003 by the Tanzanian government in collaboration with the World Wildlife Fund. BMUs were established to manage many activities that occur on village

beaches. One of their main activities is to use local fishers as data enumerators in catch assessment surveys. While many BMUs are not operating due to a lack of resources, several are actively collecting fishery data. These fishery data were collected via intercept-interviews with fishers returning from fishing trips, so the unit of inference for each interview is the individual fishing trip.

Through contacts made in Tanzania, Team Fish traveled to two BMUs and held face-to-face meetings with district-level BMU officers and various village officials. We discussed the status of their local fisheries, how the fisheries were managed, and what issues they regularly faced. It was imperative that we made trips into the communities and explained our intentions to the holders of the data. Without these on-the-ground efforts, we would not have been able to collect fish landing data. At the end, we were able to secure copies of fish landing data for eight BMUs in Pangani District and six BMUs in Rufiji District. We were given the hand-recorded paper data sheets from which we made digital copies and returned the original copies to their respective BMU offices. The digital datasheets were later translated from Swahili to English using a combination of online references and discussions with local fishers and BMU officers, both in country and through the use of WhatsApp when out of country. Once in spreadsheet format, we evaluated data quality and removed some data if the handwriting was too difficult to interpret or when recorded values were not biologically or economically realistic.

Understanding fish ecology is critical for sustaining the fisheries and, consequently, the livelihoods of many people living along the coast. Assessing both the relative importance of coastal habitats to fish and fisheries production is challenging (Saenger et al. 2013). Stable isotope analysis (SIA) provides a robust approach to studying habitat use of fish because ratios of carbon and nitrogen stable isotopes in fish tissues are largely determined by isotopic ratios in natural habitats where fish forage (Melville and Connolly 2003). Therefore, by collecting and analyzing a small amount of tissue, it is possible to draw conclusions about recent habitat use by fish (Lugendo et al. 2006; Kimirei et al. 2013). If SIA indicates that certain habitats are represented isotopically among many fish species, the findings would constitute evidence that

said habitat warrants particular consideration for conservation to sustain fisheries productivity.

Acquiring a substantial amount of stable isotope data requires a considerable effort, often involving the hauling of seine nets through habitats, gathering of potential sources of forage such as mangrove leaves or macroalgae, and extracting muscle tissue from numerous fishes. This is where local expertise, by both Tanzanian technicians and local fisherman, makes the difference between a successful research effort and a failed one. During our two visits to Tanzania, working with district fisheries officers and fishermen, we collected over 1500 fish and invertebrate samples representing over 100 unique species. Such a collection simply would not have been possible without the knowledge of experienced local fishermen and the social/family connections that only a person living in the area for many years could have.

4.3.3 Household and Village Survey Data

Team Village conducted structured surveys with households and village leaders to understand the extent communities depend on mangrove ecosystem services, and their linkages with external shocks that can threaten households with chronic poverty. Since both the demand for mangrove ecosystem services and shocks are likely to be highly seasonal, we designed and implemented a three-wave household and village survey in one year.

We used stratified sampling to select 140 households for the survey in 14 sub-villages selected based on probability proportionate to population size. The survey included questions on mangrove use, fishing, drinking water, long-term and short-term shocks, energy sources, and perceptions of future risks, sociodemographic information and economic indicators. For the second and third rounds, the enumerators revisited the same households to construct a panel dataset.

We administered the household surveys via computer-assisted personal interviews (CAPI) using the software application "Surveybe" installed on android tablets. Surveybe allows the enumerator to display

information collected in earlier rounds, which becomes useful when collecting new information about specific members of the household. All enumerators had experience with smartphones or tablets, and quickly became comfortable using the devices.

Implementing surveys to statistically validate our study focused on rural communities required well-trained enumerators who were not only talented in conducting in-person surveys, but who also understand the cultural protocols. We formed a team of four to five Tanzanian enumerators for each round. During the first round, faculty, research scientists and undergraduate student from the US assisted the team. Since US researchers were not available on site for rounds two and three, we had either daily check-in calls and/or field updates via WhatsApp group messaging. These updates helped the US researchers keep track of progress, be alert to unexpected issues, and assist the enumerators to deal with problems quickly. The Director of Sea Sense, our in-country partner, was in close communication at all times and offered guidance whenever important decisions were needed.

4.3.4 Water Well Data

Team Water collected data in parallel to the three rounds of household survey implementation. In the first round, a team of researchers from Sea Sense and URI visited the same 14 sub-villages to measure various characteristics of drinking wells including their structure (lined with concrete or brick well tiles versus open pit), dimensions, depth to water, and salinity levels (measured via electrical conductivity). In each sub-village, a community member accompanied the team to each well and took part in the sampling if (s)he wished. For the Rufiji District sub-villages, a Community Development Officer from the Rufiji District Council and a Sea Sense Conservation Officer also joined the sampling team. Their presence was extremely helpful, as it allowed the research team to gather richer qualitative data via informal discussions with some of the community members, who helped situate the quantitative measurements in a broader spatial context. In total, the team visited 70 wells

and conducted elevation surveys at the wells located in closest proximity to a coastal feature (e.g., tidal creeks, mangrove wetlands, and the coastline).

To understand the seasonality in salinity and water levels, data collection was repeated two additional times. Although scientists from the United States were not available to collect the data during these two rounds, a few enumerators, the district-level Community Development Officer, and the Sea Sense Conservation Officer who assisted the US scientists during the first round were able to collect the data for all wells previously sampled. A manual was created to describe how to use the instruments and record the data; additionally, a US researcher generated maps with accompanying photos and GPS coordinates of the wells to ensure data quality (i.e., avoid any misidentification of wells). The enumerators communicated with US researchers via phone or Skype from the field when any technical issues arose.

4.3.5 Climatic Data for Rural Tanzania

Reliable, accurate, long-term atmospheric data in developing countries is sparse and Tanzania is not an exception. Starting circa 1980, remotely sensed atmospheric and environmental information have been collected globally, which evened out the quantity and quality of data available for sites around the world. Now that nearly four decades of satellite data have been amassed, a reliable climate history of Tanzania can be reconstructed. Modern-era data offer many advantages over gridded datasets, not only in spatial resolution and period of data availability, but also based on free accessibility of the data via Internet and inclusion of a wide array of atmospheric and environmental variables.

Nonetheless, significant challenges exist in finding appropriate datasets for some types of analysis, especially in understudied areas such as Sub-Saharan Africa. Some datasets are not freely available or only include monthly averaged data. Others offer a limited array of the variables that are needed. The spatial and temporal interpolation procedures used to convert the raw data to a gridded format are often not specified. Algorithms for "filling in" missing data are usually not specified. Data availability often lags by many months, complicating real-time analysis.

4.4 Team Organization

4.4.1 Origins

The genesis of this project began with a Ph.D. student who was a fellow in an Integrative Graduate Education and Research Training (IGERT) program at URI, an NSF-funded program to develop and deliver a new way of educating Ph.D. students in coastal ecosystems management. As a trainee, she did an internship for a project in Tanzania through URI's Coastal Resources Center (CRC), which had a multiyear project in integrated coastal management funded by USAID. Following the internship, she engaged in projects in coastal Tanzania, assisting with rapid ecological assessments, participatory rural appraisals, and qualitative and quantitative socioeconomic surveys examining topics such as ecosystem services, population health and environment, and alternative livelihoods.[2]

This research scientist's experience became a catalyst for the larger project described in this chapter. She and her Ph.D. advisor in hydrology then recruited an economist, the principal investigator of this project, to add a social science dimension to the research. This joint effort examined the impact of a protected area in Tanzania on mangrove ecosystem services and led to a publication in a highly cited journal (McNally et al. 2011). They then conceived a new proposal for an NSF planning grant to foster a new collaborative project on poverty and mangrove ecosystem services. This planning grant brought together the starting members of this collaboration and eventually became the team of the CNH project outlined here.

4.4.2 Identifying the Starting Members of the Team

The hydrologist and the economist at URI started to identify collaborators for the international planning grant. Since the proposal was going

[2]The research scientist's dissertation focused on the ecosystem goods and services in the estuaries in Tanzania. For more, see McNally (2014).

to be about mangrove ecosystem services and poverty, it was essential to involve the best mangrove ecologist available. We started with a textbook in wetland ecology and identified an active member of a team of highly cited mangrove ecologists. Upon our inquiry, we were delighted to learn that in addition to his expertise in mangrove ecology, he had a genuine interest in the social science aspects of mangrove forest management, including deforestation and the development of restoration and rehabilitation programs connecting interdependent socioeconomic and ecological issues in developing countries.

These three then brought in other researchers to expand the team. For instance, the PI met a resource economist from Tanzania at an international conference in environmental economics and initiated a conversation about collaboration. This Tanzanian economist then introduced us to ecologists at his university, who had rich scientific and institutional knowledge about mangrove ecology and management. A fisheries economist from URI was brought in because fish and shrimp habitats are important mangrove ecosystem services in coastal Tanzania. It was also critical to bring in URI's CRC because they had long-standing experience collaborating with stakeholders in coastal management in Tanzania. Moreover, there was a nonprofit organization they helped establish, the Tanzania Coastal Management Partnership (TCMP), that was willing to be our on-the-ground partner in implementing a scoping trip. Finally, the mangrove ecologist from LSU recruited his postdoctoral researcher, who had extensive field experience in Latin America and the United States, to participate in the trip.

4.4.3 Shared Experiences in Crossing Boundaries

In building a team, these researchers faced several boundaries, most importantly across disciplines and cultures. In the initial stages, researchers came from several different disciplines noted above, among others. Collaboration between researchers at URI, LSU, and the University of Dar es Salaam (UDSM) was new. The PIs had little fieldwork experience in Sub-Saharan Africa, let alone Tanzania, and had to rely on the network and trust that URI's CRC had cultivated over the fifteen years in Tanzania through USAID projects.

As a first step toward team building, the researchers received funding for a planning trip from the NSF and visited Tanzania. It created an opportunity to start the research collaboration right, with proper introductions (cf. Perz 2016). The planning trip included several joint activities intended to foster communication and identify shared interests at multiple scales.

Our team building activities included many conventional ones, some of which began before the team traveled to Tanzania. The focus during the early phase of the project was to exchange research interests and discuss how each member saw their contribution to the overall goal of the project. This was done primarily by sharing a set of carefully selected articles.

The trip itself focused on physically sharing an experience to foster a genuine sense of collaboration between scientists in different disciplines and countries. In addition to the sharing of past experiences by passing around articles and discussing research interests prior to the trip, we placed a strong emphasis on experiencing various activities *together* during the trip. To the extent possible, *all* team members—from the United States and Tanzania, regardless of discipline—participated in *all* of the proposed research activities. Economists got their feet wet sinking in the mud and swam across tidal pools to access patches of mangrove trees, while ecologists sat down with villagers and listened firsthand to what they had to say about their use of mangroves. It was an eye-opening experience and also a lot of fun doing something entirely new. Every evening after dinner, all team members sat down with drinks and discussed the day's findings, gave feedback, and made plans for the next day.

Sharing the experience in this fashion had many benefits. First, both sides understood how much work and planning are involved in conducting the various research activities competently. These ranged from establishing reliable protocols to move samples and equipment from one continent to another based on research priorities and project objectives, to considering regional and country level rules and laws to perform field research and visiting remote communities (i.e., sampling permits and export, interviewing local and government officials). This mutual understanding of how much time is needed for planning and implementing data collection helped the team organize future field trips

and negotiate how much time to allocate for each activity within the time budget constraint. Second, it fostered broadly participatory discussions about the project. An example is restoration (planting) of mangrove trees. Ecologists might have blindly pushed for species that best fit the local environmental conditions. (One thing social scientists learned is that a five-inch difference in elevation can be a "cliff," the exact word used by the ecologist to describe it for mangroves.) Economists might have blindly pushed for species that best match the needs of the villagers (e.g., species with less smoke when burned for cooking). But because we had experienced "both sides" firsthand in the field, all members had developed a keen sense of the trade-offs that exist: the mangrove species that the villagers want most may not be the species with the best fit to the local environment. This experience and the resulting shared understanding supported the process of developing a project that evolved into our CNH grant.

4.4.4 Recruitment of the Full Research Team: The NSF CNH Proposals

After the planning trip, there was considerable momentum to write a research proposal on "mangrove ecosystem services and poverty traps" to NSF's CNH program. Three months after the trip, the team developed and submitted a proposal to NSF as a "small" grant (<$500,000). We determined that it was better to request a small grant rather than a multi-million-dollar grant, because this would be the first time for this group to collaborate on a project in Sub-Saharan Africa.

This first attempt, however, was not funded. The reviewers pointed to weaknesses that we needed to address. For example, the first proposal lacked a clear approach to integrate different research components into the model. It was imperative to propose an integrative approach to model the socio-ecological system as a whole instead of analyzing each linkage individually. Hence, we recruited an assistant professor at URI who had experience with ABM, and the mindset to see the research components as part of a larger system. Another key critique was that although the focus of this research was on poverty and

mangrove ecosystem services, we did not include fish habitat, which is likely to benefit the poor significantly. At the same time, some reviewers also questioned why we had included carbon storage as a mangrove ecosystem service when it currently does not benefit the underprivileged directly.

Given these weaknesses, LSU recruited two new assistant professors, a food web ecologist, and a fisheries ecologist. Although the food web ecologist's prior research was done in the context of studying food webs involving penguins, his techniques of using isotopes to understand fish habitat fit well with our project because we wanted to add a component that links mangrove forests with fish habitat. We also recruited a climatologist at LSU because climatic variability was a key factor affecting both the mangrove ecosystem and poverty dynamics. The second proposal also added new collaborators from Tanzania, each of whom has played an important role in this project. The economist and other participants from UDSM helped us recruit a very knowledgeable and experienced mangrove ecologist from UDSM.

Additionally, URI's CRC helped us to involve a new nonprofit organization, Sea Sense, to play the important role of providing information about the local communities and supporting the logistics of our fieldwork. Sea Sense is a small NGO with extensive experience of conducting research in coastal communities in Tanzania, both independently and as part of regional collaborations. After we started the project, we quickly learned that Sea Sense had a lot more to contribute beyond logistical support. The Director, as well as their core staff, had extensive experience working with all levels of stakeholders and decision makers related to coastal and marine issues in Tanzania, from local communities to national and regional agencies to international organizations. Their knowledge and human network created an enabling environment to design and implement fieldwork and workshops. Nevertheless, this project became the first time that Sea Sense had been involved in an international research collaboration on this scale.

This second proposal to NSF's CNH program was successfully funded. The research team expanded by adding graduate and undergraduate students, as well as Tanzanian technicians and fieldwork staff. To date, at least 33 individuals have been directly involved in this project.

This includes 11 university faculty, 3 research scientists, 7 graduate students, 3 undergraduate students, and 9 professionals supporting fieldwork. Our project has a balanced mix of social and natural scientists, a reasonable balance of genders (one-third female, two-thirds male), and countries (21 US, 12 Tanzania). Notably, 4 of the 11 faculty researchers were pre-tenure. Each sub-team included US and Tanzania members. Sea Sense, the nonprofit organization, played a central role in all four sub-teams. In addition to the NSF funding, small grants from LSU and URI allowed us to expand our team and enhance the project.

4.5 Collaboration Across Boundaries

Guided by common issues raised in the literature of collaboration and team science in interdisciplinary research (Perz 2016; National Research Council et al. 2015), this section describes our most prominent challenges to collaboration across boundaries, and the practices we developed to address those challenges. These challenges include: (1) integrating common interests into research design; (2) team and project management; and (3) creating an enabling environment for field data collection under conditions of high uncertainty.

4.5.1 Integrating Common Interests into Research Design

4.5.1.1 Research Design

One major challenge in interdisciplinary projects involves the incorporation of participant research interests and the optimal use of the team member expertise. This has to be defined within a conceptual framework that promotes the participatory exchange of ideas about research design. If this exchange is not implemented explicitly at the outset, the prospect of accomplishing truly interdisciplinary science becomes difficult. Most of the team members initially tended to stay within a comfort zone where their contribution was focused solely in their area of interest.

The first step in the process of research design was to construct a conceptual framework that links the mangrove ecosystem and poverty traps in the social system. Constructing a coherent framework while incorporating US and Tanzanian collaborators' interests across disciplines, while considering their respective capabilities, was a fairly difficult task.

In our case, the overall problem definition was straightforward: we shared a common understanding that mangrove resources were declining rapidly, while rural coastal communities suffered from chronic poverty, and that the two were interrelated. However, the mechanisms linking the two still needed to be identified to fully develop the CNH framework and the associated hypotheses. To accomplish this task, the lead PI invested a part of her sabbatical time to become familiar with the concepts in systems dynamics such as feedback loops and thresholds. She worked with the core members of the team to develop the framework by invoking theory and concepts in economics and ecology acquired through the planning trip and other discussions.

Our experience in using a CNH conceptual framework (Collins et al. 2011) has been productive given the explicit linkage between the social and economic sciences with the natural sciences. This is accomplished via the explicit definition of common "objects" of study that allows the visualization of a "map" helping researchers and sub-teams to identify their "location" in the overall project framework. Although this could be considered an oversimplification, this worked by allowing us to define the physical boundaries of the study region and specify the spatial and temporal scales for data collection to operationalize the research questions. This also was a critical step to frame the scope of the study, especially with budget constraints and challenging field logistics.

4.5.1.2 Balancing Disciplinary and Integrative Research with Early and Mid-Career Researchers

One of our major challenges centered around the explicit coordination in the acquisition and interpretation of field data to address the dynamics of the natural and human subsystems and the interactions between the subsystems. The participation of early and mid-career researchers

with knowledge in the latest techniques and methods has been critical given the motivation of the team to produce and publish findings, since those outputs lead to tenure and promotion. Project goals thus aligned with promotion criteria, which represented a clear advantage for individual team members to maximize their productivity by expanding their knowledge about other disciplines. Additionally, the integrative nature of a dynamic modeling component required each faculty member to contribute systematically, given the need to develop the ABM and use it to generate answers to specific questions. This exercise is complex and time-consuming but rewarding, as the opportunity leveraged project outputs into later funding for downstream research. Moreover, if the project is successful in addressing the interdisciplinary questions, individual members are motivated to pursue similar opportunities in the future, an example of a win-win outcome.

4.5.1.3 Integration as a CNH System: Agent-Based Modeling

Our ABM links feedbacks from changes in mangrove stocks to ecosystem services and villager decisions about fishing and mangrove harvesting, whereby each subsystem influences the other. One major advantage of the ABM is that it does not impose an equilibrium state on the CNH system; instead it investigates whether there are multiple equilibria, and what drivers push the system toward a particular equilibrium.

While many challenges were experienced in planning the ABM, we focus on the team's decisions on behavioral adaptations and incorporating feedbacks. For a large, diverse team in multiple locations, jointly taking decisions in designing an integrative model is both challenging and rewarding. Integration of different disciplines in a model typically means the model will have many inputs and relationships. Each aspect of an integrated CNH system model may be important to the model outputs. Model decisions therefore require continual communication to understand each team member's data and system processes. Integration can be challenging as members of diverse disciplines often think about their data and key processes differently. We believe that sensitivity tests (such as Monte Carlo simulations or other tests), are helpful in

understanding how the inputs and relationships in the model influence model outputs. More broadly, our experience is that a benefit of building an integrated CNH system model is the growth in interdisciplinary literacy among team members, which stimulates new and interesting research questions.

4.5.2 Team and Project Management

A main objective of our project was to support professional development initiatives for graduate students and early career researchers. Although this is a default requirement when seeking research funding by most US federal agencies, this becomes more challenging when crossing disciplinary and national boundaries. Because individual interests frequently differ among groups, the fulfillment of specific research objectives relies heavily on the subgroup member goals. We addressed boundary challenges by introducing new and/or early career researchers to the goals and challenges in socio-ecological research with an interdisciplinary framework. Facilitating interdisciplinary interactions between team members in our multi-institutional driven project in turn improved international communications and thereby fostered collaborative advantage. The particular benefit of these interactions has been the promotion of the development of a cohort of early career professionals who can continue networking and contributing to productive interdisciplinary research in the future. We pursued trainings that have yielded immediate results as participants have since incorporated the practices conveyed in their syllabi, exams, and other curricular materials. The materials can in turn be designed for different purposes, from use in formal classroom settings to outreach and as content in the preparation of educational and research proposals, a much-needed skill among early career researchers.

One factor that enabled the formation of the research team and development of the integrated framework was the existence of "network brokers" (Manring 2007). These individuals envision collaborative relationships and then facilitate the process to establish the connections. Although it was not intentional, the original members of this team—an

ecologist, hydrologist, and economist—happen to have network broker skills. In particular, the hydrologist has rich leadership experience in interdisciplinary and international projects. In early discussions among the three brokers, the hydrologist frequently translated ecological concepts for the economist, and economics concepts for the ecologist. At the beginning of the proposal development, this broker wisely suggested to split the budget evenly between the two US institutions. One institution largely had social science PIs, while the other had entirely natural science PIs. Starting from a 50/50 budget was thus indicative of the fact that the team recognized the contribution of the social sciences. Doing otherwise could have led to frustration and undermined collaboration (Ledford 2015). In addition, both the economist and the ecologist had a clear vision of how they would contribute to the broader CNH project and identified other collaborators accordingly. The ecologist recruited fishery ecologists and a climatologist to fill gaps in team needs; similarly, the economist recruited economists with expertise in fisheries economics and system dynamics.

4.5.2.1 Communication and Project Management

Communication in our research team was a challenge because we were dispersed geographically, with members located across multiple universities and countries. Consequently, communication posed challenges to developing shared knowledge and trust. Furthermore, team members were spread across several time zones spanned by the United States, Tanzania, and sometimes Europe and Asia. As a result, there was a narrow window for meeting times that worked for everyone. Further, we relied heavily on online communication, which posed additional challenges. Opportunities for face-to-face meetings have been limited throughout the project. Communication became particularly challenging when discussing intellectual issues that cross disciplines and when integrating components of the ABM and other activities where there was high task interdependence. Emails and conference calls were sometimes ineffective in making progress.

We employed several practices to address communication challenges. First, the researchers self-organized into the four sub-teams noted earlier (Fig. 4.2). We found that assigning tasks to semi-independent teams at each location reduced the burden of constant electronic communication (National Research Council et al. 2015). The sub-teams in our project were organized such that all US researchers in Team Mangrove & Climate, as well as Team Fish, were located in the same department at the same institution (LSU). Likewise, all members in Team Village and Team Water were in departments located in the same building at URI. This arrangement allowed the sub-team members to interact face-to-face frequently, a particular advantage in coordinating fieldwork, discussing research design, and coordinating budgetary issues.

Second, the team relied on several technologies to communicate and thereby share knowledge and resources. For team and sub-team meetings, we used technology by BlueJeans Network, which provides video conferencing and screen sharing capabilities with an option to call in by phone when Internet fails. We also utilized Skype as a backup. Unfortunately, the Internet connection in Tanzania was often intermittent, and it was prohibitively costly for our partners to call into a US number. In those instances, we employed the free messaging app WhatsApp, which is heavily utilized by our Tanzanian collaborators. In addition, we employed Dropbox to share data, literature, photos, and other files, although a few researchers needed to upgrade their licenses as files accumulate quickly. Finally, we used Google Drive and its products (e.g., Google Doc) for collaborative writing.

Despite these efforts, communication during integration, such as in ABM development, has remained a challenge. The PI from LSU stressed from the outset that the ABM would be a highlight of our CNH project and had the foresight to alert everyone to the importance of coordinating early with the ABM in mind. In response, the PIs had two face-to-face meetings dedicated to discussing ABM. At these meetings, the PIs were able to develop a deeper shared understanding of the ABM by discussing the various linkages between the components via sketching on a whiteboard, sharing visuals of the data and subsystem models, and in the process building personal relationships and trust. Although

these meetings were limited to US PIs due to budget and time constraints, we found that face-to-face meetings are essential to foster communication across boundaries and cannot be completely substituted by electronic communication. Our experience has been that face-to-face meetings early on in the project helped deepen shared understanding and the effectiveness of the electronic communications that followed.

4.5.2.2 Site Selection

The research team recognized from the outset that integration of model components in the ABM required synchronized data collection efforts across all sub-teams. During the first six months of our project, the entire team met through conference calls on a monthly basis to select specific sites for field data collection. Several criteria were considered, based on the presence of mangrove forests, the importance of mangrove ecosystem services for people living in local villages adjacent to mangrove forests, and areas where UDSM and other organizations did not already have a high presence (in the spirit of complementing ongoing efforts by other projects).

The difference in spatial scales between economic and ecological data proved to be a challenge in choosing sites. Economics research needed to encompass a larger spatial area to allow for generalizability of the results to a regional level, resulting in 14 sub-villages being sampled. In contrast, sampling for mangrove and fish ecology research was expensive and intense, and the budget only allowed the sub-teams to sample from a handful of sites close to three sub-villages. Therefore, the integrative research was restricted to the areas with both economic and ecological data.

4.5.3 Enabling Field Data Collection by Adapting to Uncertainty

4.5.3.1 In-Country Collaborators in Tanzania

All four sub-teams required field data collection, whether through physical sampling of fish, mangrove trees, soils, and groundwater, or

via interviews with households and community leaders. Each activity required not only permits from the appropriate government agency, but also trust from community leaders, recognition of culturally appropriate protocols before starting, managing logistics and travel arrangements to get to the study sites, and learning from previous and ongoing research efforts on the ground.

Partnering with Tanzanian collaborators was absolutely crucial to collect field data. We relied heavily on scientists at UDSM, Sea Sense, and TCMP. Combined, these organizations created an enabling environment for the research team to learn about the local ecology, people and their culture, as well as to conduct fieldwork.

We structured our team accordingly. The mangrove ecologist and the environmental economist at UDSM are equal partners in our research and frequently offered insights and suggestions for our research design and fieldwork. They also participated in some of the fieldwork. For instance, the environmental economist recruited and trained the enumerators and designed surveys and a field experiment. His presence was especially important to conduct the survey research because faculty at UDSM are highly respected by the communities. The mangrove ecologist is a well-established field researcher and generously shared his knowledge, instruments, and experience while conducting the fieldwork with Team Mangrove. Additionally, they were central in designing and leading a research dissemination workshop in August 2018, where nearly 40 stakeholders from village to regional level participated to learn about the research findings and discuss the implications. One of the scholars reflects on this experience as follows: "…organizing, planning and implementing the research dissemination workshop to the community was an exceptional benefit of being part of this collaboration. The delivery of the workshop was a thrilling lesson; it felt as though the remote presenters from the US were in the same space among participants representing the local communities and authorities."

Sea Sense played a central role in conducting fieldwork for all four sub-teams. Sea Sense has a grassroots approach to conservation, with a network of trained "Conservation Officers" who act as ambassadors for conservation in their village. These Conservation Officers were instrumental in collecting field data, often becoming a liaison

between the researchers, enumerators, and communities. The Director of Sea Sense provides her perspective on the way Conservation Officers were involved in this project as follows: "One of the most unique and rewarding parts of the collaboration was the engagement of several Sea Sense community Conservation Officers in mangrove, fisheries, and well data collection. From a research perspective, access to local knowledge is critical but for the Conservation Officers themselves, it provided important recognition of their knowledge and enabled them to participate as members of the research team rather than as subjects of academic research which is the more usual role for community members…."

4.5.3.2 Adapting to Changing Security Risk

The most unexpected situation this project has faced was the heightened security risk in Kibiti–Rufiji area, one of our two study regions. In 2017, two months before the research team was scheduled to conduct another round of fieldwork, a series of sniper killings targeted local leaders and government security officers. Accordingly, the government launched a crackdown of the perpetrators in the area and declared a state of emergency while they designated the area as a "Special Security Zone." The Tanzania Forest Service advised that researchers avoid visiting the region, including the entire Rufiji Delta area. The security risk forced Team Fish and Team Mangrove to abandon plans for the Rufiji Delta and to return to the Pangani Region where they had collected data the previous year. They thus prioritized expanding existing datasets and obtaining complementary data from additional sites in Pangani. Fortunately, Team Village and Team Water were able to conduct all three rounds of household and groundwater data collection in Rufiji before the state of emergency. The third round of data collection was completed one month before the state of emergency was declared but during a period when sniper incidents had been reported. Sea Sense staff and the enumerators were empowered to make the final decision on the village survey and groundwater collection, putting safety first. However, this also meant that we could only collect both social and

natural science data from Pangani District. While the state of emergency eventually ended, our budget did not allow for another round of fieldwork for Team Fish and Mangrove, and NSF's CNH program did not have a supplementary funding mechanism.

4.5.3.3 Going with the Tide and Rain

Unavoidably when conducting research in a coastal wetland, we were subject to daily tides. Sampling activities by Teams Mangrove and Fish were particularly sensitive to the tidal regime and thus changes in water levels. Low tides stymied sampling by boats and high tides restricted foot access for mangrove soil and vegetation work. Enumerators for the household surveys also needed to be mindful of finishing before low tide so they could travel back to their campsite.

We were also affected by the weather. While other teams conducted fieldwork in August, which is during the dry season, we purposefully chose both the dry and rainy seasons for the household surveys and groundwater sampling to capture seasonal variation in mangroves and poverty. The third-round survey, conducted in May 2017, was severely affected by the weather. It not only transpired during the rainy season in coastal Tanzania, but the region had unusually heavy and continuous rainfall.

Many houses in the sample villages in Rufiji were inundated, and oftentimes enumerators had to walk in floodwaters to reach households. There were concerns about both enumerator safety and fatigue. During the limited communication between the enumerators, Sea Sense, and US researchers, we emphasized that safety must come first and foremost, even if that means we could not continue the surveys. Fortunately, the enumerators safely adapted to the challenges posed by the floodwaters and managed to complete the surveys.

The weather also affected the equipment used in the field. The enumerators used tablets to collect household survey data. Although computer assistance in interviews is convenient to the researcher for a number of reasons, it is also inconvenient in the field because our tablets needed to be charged at least once a day. Finding a power source was a challenge in Kibuti–Rufiji because the enumerators camped on

the beaches; there was no accommodation with electricity within a feasible distance from the villages sampled. In our effort to "go green," the enumerator team brought solar panels, which would only work if there was ample sunshine. Depending on the season, there were periods in which the enumerators relied heavily on the backup generator, which required additional gasoline.

Overall, we have found that the collective knowledge and experience enabled the various field teams to troubleshoot unexpected challenges to allow activities to move forward. Decisions were seldom made by a single researcher; collective knowledge and experience shared by Sea Sense and its Director, the university partners at UDSM, local professionals, and the US scientists were necessary for creative solutions.

4.6 Key Lessons Learned and Recommendations

Understanding the linkages between ecosystem services and poverty traps necessitates the integration of knowledge and skills in a shared research endeavor. Our CNH project therefore involved a large team that spanned boundaries among disciplines, tenure, institutions, countries, and cultures. Large team size can enhance productivity by distributing the work across more individuals, but it also intensifies the effort required to collaborate effectively across boundaries (National Research Council et al. 2015), especially in tasks that involve high levels of interdependence, as exemplified by integration of research components in the ABM. Although it is difficult to assess our success since our project is not yet complete, we identify several key recommendations based on practices that have allowed us to manage the challenges.

4.6.1 Overcoming Geographical Dispersion for Research Integration

Communicating effectively was a challenge for this team because researchers were geographically dispersed and technologies such as

electronic platforms often failed, especially between the United States and Tanzania. Distance and technology proved major barriers when trying to work across countries for discussing integrative research tasks such as the design of the ABM.

The face-to-face interactions, including the planning trip, all the fieldwork trips, and the up-front meetings in the United States, were essential to develop shared knowledge and trust. Our experience has been that face-to-face meetings up front helped deepen the level of trust and thus the effectiveness of electronic communications that followed. That said, the challenges nonetheless posed by the integration tasks in building the ABM suggest in hindsight that our project would have benefited from allocating more resources (both budget and time) to face-to-face meetings at in the early phases of our collaboration, either in the proposal stage or early in the project. This implies the need for supplemental funding for development of integrative tasks in projects that span boundaries.

4.6.2 Assembling the Right Individuals for the Team

If there is one thing that was done correctly in this project, it was in assembling the team. Team composition is foundational for productive team science. Hence careful team formation is a necessary prerequisite for team effectiveness (National Research Council et al. 2015). The process of recruitment was made possible by several founding members of our team who served as network brokers in the initial stages. Those brokers understood the requirements for team members, not only in terms of their training and experience, but also in terms of their attitudes toward collaboration. Each member contributed not only by bringing in cutting edge theories, methodologies, and instruments, but also by having open minds and positive attitudes toward research integration and treated each other and the task at hand with respect.

The importance of careful team building also applied eminently to in-country partners. Beyond the PIs, equally important were the Director of the nonprofit organization in Tanzania and the former Ph.D. student from URI, both of whom attracted talented professionals

in Tanzania. In turn, those Tanzanian partners created an enabling environment. Having supportive in-country partners helped the overall team become resilient to unexpected situations such as extreme weather and heightened security risks.

4.6.3 Building Effective International Partnerships

Truly participatory research between foreign and local researchers can often be challenging to navigate due to inherent power inequalities and the historical or current context of colonialism (Barbour and Schlesinger 2012). As such, it was helpful for the larger team to build on the experience of the starting members as a guidance for building cross-cultural collaborations in a participatory framework. Building meaningful relationships across countries with local partners and gaining a full understanding of its people, an ecosystem, and its interactions are processes that require much more time than is allowed during a three-year project. Sharing of human networks, relationships with the local communities, and exchanging of local and scientific knowledge facilitated capacity building, which in turn permitted more problem-solving during field data collection and thus better science, and opened doors to governments and other stakeholders that increased their access to our findings and thus our relevance to conservation and management priorities in country.

The Director of Sea Sense, a British biologist who has lived in Tanzania for many years, played an essential role in building many bridges for relationships we were seeking; she essentially became our "network broker." She was ideal for this role: she has a Ph.D. in biology, she speaks both Kiswahili and English, she has significant managerial skills and experience, she has built trust and network ties with professionals from NGOs and government agencies from the local to national levels, and most importantly, she understands both Tanzanian and western cultures. Throughout the project, we were provided with guidance and expertise regarding appropriate approaches and interactions with the local communities and government officials, and ways to conduct research in Tanzania.

The way Sea Sense was involved in our project was not all planned at the time of grant proposal development. As the teams were preparing for the fieldwork, we realized that we needed to depend on Sea Sense far more than the US research team had initially expected. The Director of Sea Sense reflects on this challenge as follows: "…An unforeseen challenge of the collaboration was the extent of my role as Sea Sense Director. With limited experience of collaborations on this scale, I did not fully understand the amount of time I would need to commit to the planning and implementation of the research project. Furthermore, arranging the logistics for each sub-team was very demanding in the immediate build up to the field sampling periods, with multiple email requests coming on a daily basis. At times I felt I had committed Sea Sense to a collaboration that was too big to take on alongside our existing work schedule and contractual obligations. In view of the critical role of local partners, the potential time commitment of both management and support staff should be clearly acknowledged from the outset and taken into consideration in the budget design stage." Future projects would need to better anticipate the needs during the proposal development stage.

Nonetheless, these challenges came with profound rewards not only for the researchers but also for Sea Sense. The Director reflects on the rewards from this collaboration as the following: "reflect(ing) on what the research team had achieved, I fully recognized that this collaboration had exceeded all of my expectations. It exposed the Sea Sense team to new ways of thinking about linkages between human and natural systems which was particularly beneficial for the younger members of the Sea Sense team who are early career scientists. From an organizational perspective, the collaboration enabled Sea Sense to work with and learn from a team of well-respected scientists and economists which has raised the profile of Sea Sense as a credible local partner for future collaborations. An unexpected but much-welcomed outcome of the collaboration is new connections with researchers in Tanzania whose interests are well aligned with Sea Sense, opening up the possibility of new in-country collaborations in the future."

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5

Learning About Forest Futures Under Climate Change Through Transdisciplinary Collaboration Across Traditional and Western Knowledge Systems

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5.1 Introduction

Transdisciplinary science is increasingly recognized as critical for sustainability in a time of unprecedented global change (Mauser et al. 2013). However, its effectiveness depends upon addressing many of the challenges

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faced historically with the emergence of interdisciplinary training (Rip 2004; Morse et al. 2007; Borrego and Cutler 2010; Carew and Wickson 2010). Moreover, transdisciplinarity poses additional and unique challenges for successful collaboration (Crowston et al. 2015) when different knowledge systems are involved.

Here we reflect upon the evolution of transdisciplinary collaboration within the context of a coupled natural and human systems (CNH) project about sustainability and future forest landscapes in the context of climate change. Our CNH project integrates diverse expertise and perspectives from a broad span of disciplinary domains including the humanities, natural sciences, and computational sciences, as well as alternative ways of knowing within indigenous and western knowledge systems. While only in the second year of a five-year project, our experience highlights the challenges and opportunities of boundary crossing

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that, upon reflection, have emerged from: (1) the evolution of collaborative networks and team development, (2) group processes and social learning, (3) uncertainties, surprises, and flexibility, (4) inequalities, power, and positionality, and (5) governance and leadership. Our collective navigation through these spaces has illuminated the challenges and practices of transdisciplinary work, while providing a roadmap for deeper learning opportunities.

Transdisciplinary science has many embedded concepts but generally involves elements of (1) *boundary crossing* (disciplinary and research praxis), (2) *critical evaluation and evolution of methodology* ("collaborative deconstruction"), and (3) an intention to *cross knowledge systems* to inform solutions to "wicked" or messy problems (Carew and Wickson 2010; Yarime et al. 2012). Compared to inter- and multi-disciplinary approaches, there is an elevated focus on translational ecology, i.e., including a broader range of stakeholders (Enquist et al. 2017), especially practitioners outside of academia (the scholarship/scholar/praxis nexus),

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and a strong focus on solving problems (Borrego and Cutler 2010; Gibbons et al. 1994). While this mission is aligned perfectly with the purpose of the Sustainable Development Institute (SDI) of the College of Menominee Nation (CMN), a key project partner, it remains a relatively new challenge to western academic institutions. Common barriers to implementation in western academic cultures can include (1) trouble with designing the initial research agenda; (2) advocating for sufficient resources (personnel, time, and money); (3) management of large, complex teams; (4) clear statement of outcomes or impact; and (5) a lack of broadly accepted evaluation metrics (Carew and Wickson 2010).

A key goal of transdisciplinary research is to transcend and transform traditional and often-siloed pathways of knowledge production to unite processes, products, and context (e.g., "Transdisciplinary Wheel" of Carew and Wickson 2010). When transdisciplinarity involves different knowledge systems, as among different cultures, the navigation of differences among pathways of knowledge becomes especially challenging. Given that our CNH project engages in transdisciplinary collaboration spanning indigenous and western knowledge systems, it was necessary to adequately incorporate contributions from both. Moreover, in our project, such translational science is an ongoing evolutionary process in which pathways of knowledge generation are influenced bidirectionally through the interactions of the knowledge systems.

In this chapter, we analyze the challenges of boundary crossing in the context of sustainable forest management under climate change. First, we briefly review our conceptual model of the Menominee forest as a CNH system. Then, we describe key issues and challenges we have encountered thus far, presenting approaches to solutions where applicable. We then discuss some general reflections about how best to manage these challenges in the context of our project. Finally, we conclude with recommendations about stewardship of successful collaboration in the context of transdisciplinary endeavors that address multiple ways of knowing. We hope our lessons learned provide guidance for other transdisciplinary projects with similar struggles or at other stages of project development. More fundamentally, our team aspires to support indigenous peoples' sustainability in the face of the challenges of settler colonialism and climate change, starting with the Menominee

experience and finding common experience to assist other indigenous cultures. We aim to support indigenous planning for sustainability by identifying processes that help give voice to indigenous values and finding innovative practices in support of continuance of indigenous identity and resilience. While outcomes may have relevance for sustainability planning in non-indigenous cultures, our concern is centered on the indigenous planning process specifically (Whyte et al. 2018).

5.2 Project Overview

The impacts of climate change are already being felt by American Indians and Alaska Natives (Bennett et al. 2014; Norton-Smith et al. 2016). While the specific impacts vary by region, there are commonalities in the ways these changes are experienced by indigenous peoples, including reduced social capacity for resistance and resilience in the face of historical and ongoing colonialism (Norton-Smith et al. 2016). In the case of the Menominee and other indigenous cultures, innovation has been central to sustainability in the face of historical colonialism, and will be especially important in the context of the current situation given the magnitude of the expected changes and continued oppression of indigenous action in response to such threats. Resilience in response to climate change thus requires approaches to sustainable planning that deepen and strengthen indigenous capacity for innovation. Our project explores an approach that links human values, ecological projections, and visualizations of future forests, with the expectation that this approach can aid indigenous sustainability planning under deep uncertainty (i.e., where both magnitude and probability of future events are uncertain Lempert 2002).

Our project addresses this challenge through two overarching themes. First, we aim to explore feedbacks within and between CNH systems (Fig. 5.1). Feedbacks within the human system occur due to a reciprocal relationship between values and practices, including traditional knowledge (TK) and decision-making. This feedback dynamic influences how individuals and communities arrive at decisions that are often confounded by competing objectives, values, and ultimately, outcomes (e.g., Singh et al.

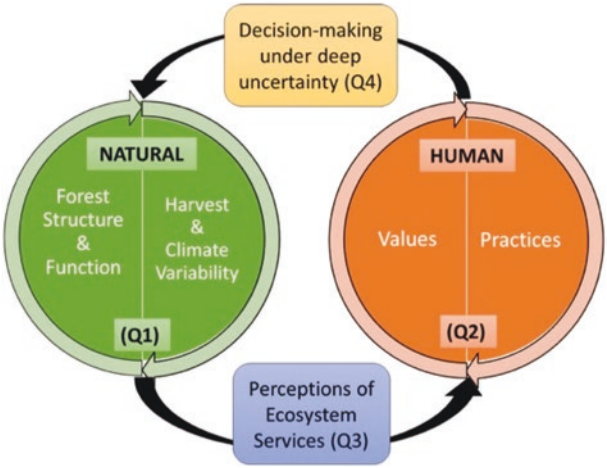

Fig. 5.1 Conceptual diagram showing feedbacks between natural and human systems in the Menominee forest sector (*Source* Figure created by the authors)

2015). Feedbacks within the natural system include interactions between forest change and forest function in the context of climate variability, but are also continuously influenced by processes within the human system, such as management activities that both respond to and cause modification of the natural environment. Feedbacks between the natural and social systems also arise through the benefits people gain from ecosystem services, which inform the decisions they make about natural resource management.

Our second overarching theme is the incorporation of both traditional and western knowledge systems into our science practice. We emphasize this theme to allow a greater space for values transparency. While TK about forests held by many indigenous communities has been recognized as important in the recent US climate change assessment (Bennett et al. 2014), such knowledge does not easily translate into western-style landscape-level planning processes that are often prescriptive and top–down. Rather, tribal planning is often embedded into communal living, through which knowledge evolves through collective planning and doing (a "learning by doing" approach). Our project analyzes these interactions through a collaborative approach that integrates forest change, cultural values, customary practices, immersive

experiences, and decision analysis for forests of the Menominee Nation. We hypothesize that decisions that underpin management practices can be made most sustainable when they embrace values (cultural, spiritual, ethical, aesthetic) held by a broad range of individuals and communities. We ask: (1) What are the human values and customary practices that influence preferences in sustainable forest structure and function, and how do they differ among members of the community? (2) How does climate govern changes in forest species composition, productivity, and disturbance dynamics, and how do these changes influence human perceptions of forest condition? And (3) How will human preferences for future forest condition, including those embedded within traditional ways of knowing, influence forest management choices and, consequently, future landscape structure and function?

5.2.1 Study Area

Our study area includes indigenous forest lands of the Menominee Nation and surrounding watersheds located in northern Wisconsin, United States (Fig. 5.2). This region is climatically sensitive and is already experiencing climate change impacts that are reducing forest health and complicating management decisions (Janowiak et al. 2014). Model projections suggest that increasing temperatures will cause declines in many important tree species in the northern lake states under conventional management practices (Duveneck et al. 2014; Janowiak et al. 2014). Projections similarly indicate future expansions of exotic species (e.g., emerald ash borer, *Agrilus planipennis*) in the area. Both changes present numerous management challenges.

Tribal interests are a component of the National Climate Assessment (Bennett et al. 2014), and many tribal groups, including the Menominee, are actively engaged in developing climate adaptation plans or acquiring resources to prioritize adaptation activities. In the traditional culture of the Menominee people, the relationship with nature is embodied in stories describing Menominee origins and governance. The five main clans of the Menominee that symbolize core Menominee principles are: Bear (law), Golden Eagle (justice), Wolf (hunting/gathering), Crane (art, architecture),

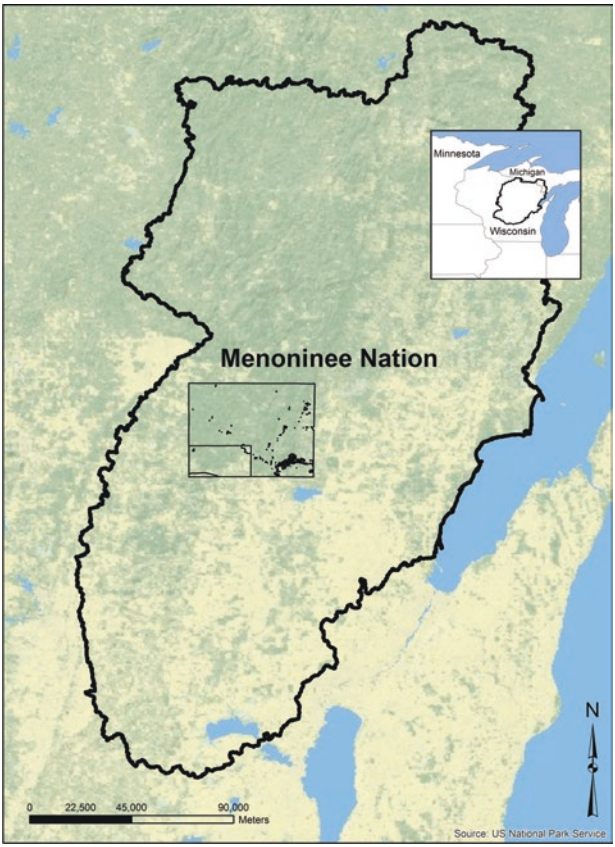

Fig. 5.2 Study area in northern Wisconsin, including Menominee Nation (in box) and adjacent watersheds (*Source* Map created by Melissa Lucash using ArcMap 10.5.1)

and Moose (community and individual security) (MITW 2009). In the nearby region of the Grand Portage Band of Lake Superior Chippewa, moose herds have declined by as much as 60% since the 1990s, which has largely been attributed to changes in climate (Dybas 2009). Biodiversity is thus implicit in the articulation of tribal cultural principles. Hence, threats to biodiversity from climate change could threaten key aspects of tribal identity and management practices.

Through collaborative and sustained work by the SDI of CMN, sustainability has come to be viewed as a dynamic process that spans across at least six dimensions of community life including institutions, economics, natural environment, technology, land and sovereignty, and human behaviors, perceptions, and relationships (Dockry et al. 2015). For example, key *institutions* that influence the governance of the Menominee include the Menominee Tribal Legislature, and the Menominee Indian Tribe of Wisconsin, which is the tribal government structure. In relation to the forest, the Menominee Tribal Constitution, the Trust and Management Agreement, and all forest management plans require that forest lands be managed using sustainable-yield practices. Forest management is conducted by Menominee Tribal Enterprises (MTE), a chartered entity under the Menominee tribal constitution to manage forest harvests, reforest, and produce forest products from Menominee forest lands. *Economic* factors that influence sustainability include the monetary benefits from logging that contribute millions of dollars to the community, as well as subsistence and customary activities such as harvesting of wild rice, medicinal plants, and wild berries, hunting (especially deer), and fishing. In addition to the role of *biodiversity* represented in cultural principles in the creation stories described above, sustainable timber management has been part of Menominee tribal identity and the formal economy since at least the mid-1800s when sawmills were first established on the reservation. Sustainable timber management is driven by a commitment to landscape-level biodiversity and optimal age class distributions to ensure continual productivity for future generations. This stems from the related understanding that forest health and human health are intertwined concepts, which reflects an indigenous worldview in which humans are part of the *natural environment*. *Technology* has been a contributing factor not only in how Menominee community life has changed, but in how they have adapted to change. For example, the Menominee make use of modern technologies such as geographic information systems and harvesting equipment in order to meet sustainable forest management goals as set forward in the MTE forest management plan. Technology has been important in framing tribal identity as well. Satellite imagery of the Menominee reservation clearly demarcates a zone of deeply green forest amidst

a sea of agriculture, affirming the forest as a key component of tribal identity and as evidence of Menominee sustainable forest management practices. *Land and sovereignty* affect Menominee values in many other ways, notably through the importance of land and landscape in creation stories, and the dichotomy between the extent of ancestral lands (>10 million acres) and current reservation allotment (~250,000 acres) due to European settlement/American colonialism.

5.3 Boundary Crossing

Below we describe some of the central issues our team encountered during our initial two years of transboundary collaboration. These issues are (1) the evolution of collaborative networks and team development, (2) group processes and social learning, (3) uncertainties, surprises, and flexibility, (4) inequalities, power, and positionality, and (5) governance and leadership. Given that our project goes beyond transdisciplinary collaboration to also address ways of knowing between indigenous and western knowledge systems, our project may be unusually challenging. We describe each challenge in the context of our specific project, hoping to provide an overarching roadmap for other projects, but assume that these challenges may be represented differently in transboundary efforts in other cultural contexts.

5.3.1 Collaborative Networks and Team Development

The organization of our project reflects an evolving network that links key participants and subgroups across departments and institutions over time (Fig. 5.3). The network structure initially leveraged ongoing or past collaborative experiences among team members (Fig. 5.3a). As the project ideas were developing, Nicholas (RN), Caldwell (CC), Tuana (NT), and Keller (KK) were collaborating on a federally funded research project, providing the connections between the CMN and The Pennsylvania State University. That project (a National Science Foundation research network on Sustainable Climate Risk Management

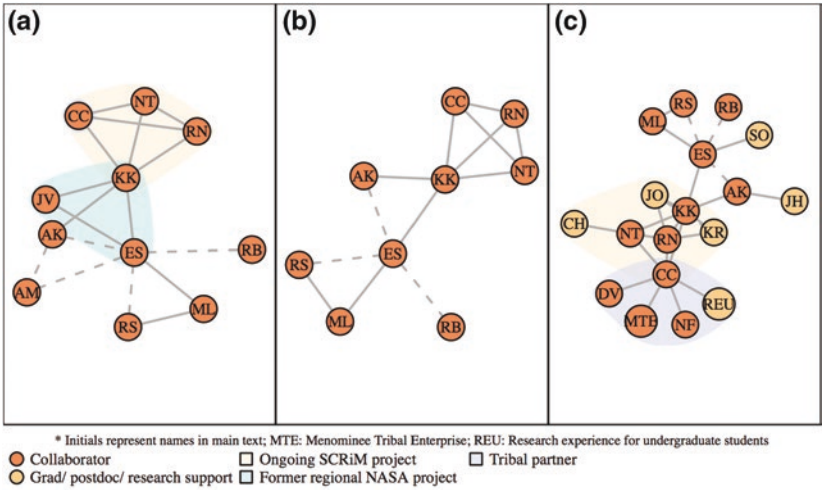

Fig. 5.3 Illustration of the collaborative network evolution of our project. Each node represents an individual who was connected to the project in some way. Solid lines represent formal academic linkage (funded project, co-authorship), whereas dotted lines indicate informal academic relationships (current or former colleagues or peers) (*Source* Figure created by the authors)

(SCRiM)) was a critical foundation for developing trust among institutions and personnel. Moreover, key network brokers Smithwick (ES) and Keller had collaborated on a federally funded NASA research project (Chequamegon-Nicolet Ecosystem-Atmosphere Project (ChEASii)) that had recently concluded, and it was through that experience that trust had developed, and through which familiarity with the region and collaborations with other stakeholders in the region (e.g., US Forest Service) had been initiated. In addition to previous and ongoing funding, other academic roots had been established when Smithwick met Lucash (ML) at a workshop on modeling root dynamics in ecosystems, an experience that led to a co-authored paper (Smithwick et al. 2014). Smithwick and Scheller (RS) had known each other from their time at the University of Wisconsin in their roles as a postdoc and grad student, respectively. Thus, when Smithwick was looking for a modeling group with whom to collaborate, that positive work experience and historical connection was critical, as it provided confidence in a productive

relationship. Smithwick was the node that connected the various subnetworks into a larger whole, serving as a network broker. Equally critical was the receptiveness of the subnetworks to engage in initial project discussions. That process was facilitated by respective leaders in each subnetwork, which set the intellectual stage and purpose for deeper interactions among members of the full team.

These past and ongoing relationships were important but did not provide sufficient capacity to carry forward the research plan that was envisioned. Fulfillment of the project's mission also required expertise from people not actively connected through past or current projects. These new participants were familiar to Smithwick or others, either as departmental colleagues or through interdisciplinary centers and institutes. At its core, it was clear we needed people with expertise in philosophy (Tuana), TK and sustainability (Caldwell), landscape ecology (Smithwick), ecological modeling (Lucash, Scheller), robust decision-making (Keller), and climate (Nicholas). In our first proposal, we planned to visualize forests through LiDAR data, via remotely sensed 3-D visualizations of forest structure based on existing datasets. We also sought to include a decision analysis tool and to utilize geoanalytics and geovisualization to aid decision-making. However, our proposal was not successful in this first submission. As a result, the shape of the network shifted as we incorporated reviewer and panel feedback, with the result that two members (JV and AM) voluntarily dropped out between the first and second submission of the proposal as their expertise became less relevant to the direction the project was moving (Fig. 5.3b). These uneasy decisions were made carefully over time, through group deliberations and subsequent one-on-one discussions led by Smithwick. We then added expertise in immersive technologies (Klippel (AK)) and anthropology (Bird (RB)).

Importantly, the project network has continued to evolve over time, as new people have joined the project (e.g., postdoctoral scholars, undergraduate and graduate students, and Menominee faculty; Fig. 5.3c). From the initial set of nine faculty in the submission, we subsequently added informal collaborations with other faculty at CMN (Dennis Vickers (DV)), student interns with the SDI as part of our Research Experience for Undergraduate (REU) program (Curtis Wilhelmi,

Nicholas Schwitzer, and Jacob Schwitzer). We also hired computer/data technicians (Jared Oyler (JO) and Kelsey Ruckert (KR)), graduate students (Jiawei Huang (JH) and Stacey Olson (SO), and a postdoc (Casey Helgeson (CH)). We have also strengthened relationships with key personnel at MTE in the context of our project. We continue to build our network as new collaborative opportunities emerge. Recognition of the dynamic evolution of the team network, both in terms of its composition and configuration, has continued to shape the collaboration process. Inclusion of new members brings energy and new expertise, while also building capacity. Yet, it also requires efforts to conscientiously foster inclusion and to provide learning spaces for new members, in order for them to feel fully integrated and empowered to contribute.

5.3.2 Group Processes and Social Learning

In our project, learning has occurred through several types of social experiences, both in the proposal phase and during implementation (Fig. 5.4). Sharing information about the region and about our specific disciplinary tools was a critical process that occurred through meetings and at team events. In addition, we posit that our group also developed collectively as a unit (across disciplines, geographies, and cultures) at key pivot points that went beyond information exchange to involve the development of common purpose and deeper personal bonds that cemented the network structure; we call this "social learning." Across time, we have identified three main phases of this collaboration: Idea generation/courtship, proposal/team development, and official collaboration. As described above, subnetwork structures (e.g., SCRiM, ChEASii) provided momentum and leadership that spawned initial meetings and informal discussions. This led to a visit by the project PI and other team members to the Menominee Nation for a climate summit (further described below), which cemented the common commitment to write a proposal. Proposal development also involved meetings to set the stage for common terminology, problem framing, and the identification of transformative approaches that would be competitive at NSF. The subsequent failure to secure the award in the first proposal (accompanied by

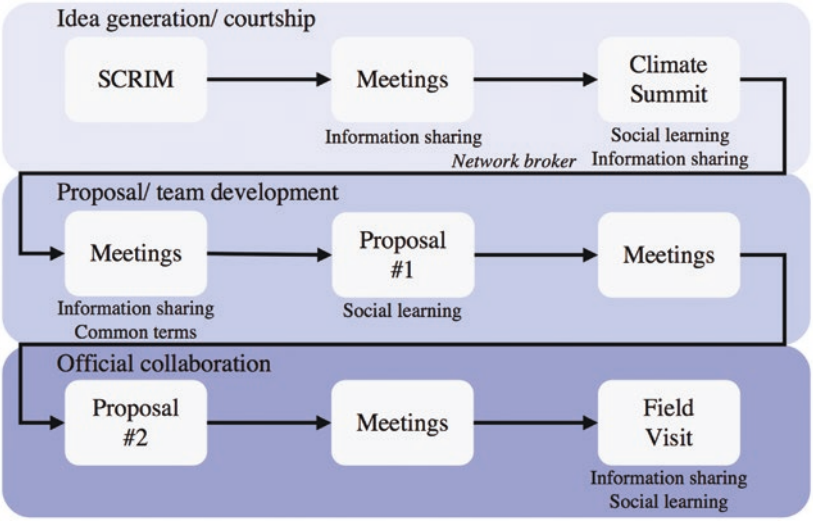

Fig. 5.4 Important phases and group processes that occurred through project development. Official collaboration did not occur until the project was funded on the second submission, almost two years after initial discussions (*Source* Figure created by the authors)

overall positive reviews) provided motivation for continued discussions and meetings that ultimately led to the resubmission. Official collaboration after we secured our award was thus preceded by at least two years of group work. Our group dynamics continued to evolve through initial stages of the project, both through meetings and in-person field visits. Below we describe the importance of some of these key group processes.

One of the most critical group processes has been regular, bi-weekly meetings for information exchange. In addition to discussing regular project management tasks, these meetings have been seen by the team as important for identifying divergent understandings of important technical concepts and stewarding group decision-making. In addition, social learning has occurred informally and at team events. For example, during the proposal phase, it was not uncommon for key discussions to occur while walking across campus or in the hallway. In these cases, it was important that the results of those discussions be communicated

back out to the full group, which was usually the responsibility of the PI, either via email or meetings.

Two events in Fig. 5.4 represent longer, in-depth experiences that were critical to team evolution and social learning. In the proposal phase, this included a trip by three faculty members from Penn State to visit the Menominee Nation to participate in a tribal summit on climate change adaptation. This event was critical for better understanding of the locale for the Penn State team members and also allowed for deeper and richer conversations with Menominee tribal members, extant academic experts, practitioners, and project personnel. The meeting was a watershed event in several ways. It provided time to discuss key issues in person with our Menominee partner (Christopher Caldwell) and provided ample opportunity to consider indigenous perspectives on climate change adaptation. The fact that we had this collective experience helped to build trust and provided a common platform for subsequent discussions.

The second experience occurred approximately one year after the project was funded: a field trip with all PIs and Senior Personnel to the region, hosted by the CMN. The experience allowed all team members, particularly those not from the Menominee Nation, to come to the same intellectual place in terms of understanding the geography, institutions, and stakeholders. It allowed space for the team to have common though sometimes difficult or uncomfortable experiences, which were very important for shared learning. For example, the team had to consider how best to introduce our project so as to be respectful of other ways of knowing and other perspectives that were not, perhaps, adequately considered in the proposal phase. For this, we were guided by our co-PI, Chris Caldwell, a tribal member and Director of the SDI at CMN. Interestingly, the team was continuing to learn as a group and to navigate relationships across boundaries, even though we had already received our funding and had an agenda, or we feared, a perceived agenda. The field trip allowed for navigation of tensions among participants via formal and informal vetting of these concerns that would not have been possible within shorter meetings or video conferencing. In the process, the field trip also provided a chance for social bonding, especially for members of the team who had not yet met in person. Opportunities for breakfasts, dinners, long car drives, etc. allowed for

telling of tales and shared experiences that gave rise to inside jokes. We now know who needs coffee first thing in the morning, what pizza not to order, and how to be flexible if the rental car gets a flat tire. These intangible shared understandings, which occurred early in our project, were critical for fostering social cohesion and a sense of common purpose in the team thereafter.

5.3.3 Uncertainties, Surprises, and Flexibility

Inevitably, every large project is met with uncertainties and surprises along the way, and ours was no different. In just the first two years of the project, we had turnover of staff helping to manage our budgets, leadership changes at key partner institutions, one PI switched institutions, babies were born, team members or their families got sick, and graduate students and postdocs were recruited and brought into the fold. These events typically bring new opportunities as well as management challenges. Most changes can be navigated logistically by shifting resources or adjusting timelines to ensure that every individual has the capacity to participate in their healthiest and most robust ways. Professional development and personal and family health are profoundly important at the individual level, and should be anticipated at the project level. Thus, we felt it was important to our team to navigate these changes respectfully and swiftly. By doing so, we gained confidence in our ability to adapt to unanticipated events.

A true test of team flexibility in response to uncertainties and surprises occurred across some of the intellectual boundaries spanned by the project. The first of these surprises, to many of us, was the gulf between modeling communities. In our project, we are deploying computational modeling approaches that have developed in two different disciplinary communities. Consequently, each modeling approach has its own scholarly literatures, data streams, technical requirements, software development practices, and objectives. While their union is, in and of itself, a scientific outcome of the project, we are continually surprised at how hard it is to bring them together. Challenges of integrating modeling approaches are not new, and we were not naïve about

them. Indeed, we tried to anticipate roadblocks by devoting personnel and computing capacity to the effort and constraining our proposed outcomes to be commensurate with the task at hand. Yet, challenges have remained. At the outset, it became clear that the promised work of the proposal would require more computational resources than anticipated. Put simply, this is because one model (the donor model) feeds into the second model (the receiver model), but the former is computationally expensive, i.e., takes significant time and computer power to do the work. We thus faced challenges and questions such as the following: Would we be able to run enough modeling scenarios to sample the deep uncertainties sufficiently? Should we port the model across institutions to enhance its speed? Should we consider changes to the model software design and programing language to facilitate better model integration? Did we have the time and resources to devote to improving the donor model such that we would be able to implement the receiver model?

In addition to these challenges, the science of the donor model was itself being updated as a normal part of its evolution, causing necessary but unanticipated delays. As these issues were being navigated, a more esoteric but ultimately foundational quandary arose: What was meant by model calibration, and were the approaches translatable in a way that was trustworthy by both groups? Put simply, one approach was grounded in expert knowledge, skill, and empirical relationships (which was seen by some as containing more subjective elements than desirable to the other modelers and missing key diagnostics), while the other is rooted in physical logic and statistical metrics (which was perceived by some to have lower flexibility and transparency). In truth, these remain more as conceptual roadblocks than practical ones, but have fostered rich and unanticipated conversations about scientific practice.

While many issues remain, we have addressed some of these challenges in a preliminary fashion through several practices. First, we conducted an exercise to individually define key terms (e.g., calibration) by all project participants (not just the modelers). Although we have not converged on common definitions, and perhaps never will, the process enhanced transparency which has facilitated communication and common understanding. Second, we were able to leverage resources from other sources to devote more personnel time to port the model from desktop to high-performance

computing systems. Our issues also aligned with strategies that Penn State was taking, in general, to improve high-performance computing and cloud-based resources; as a result, we donated some of our code to Penn State computing personnel to test. Subsequent discussions led to insights about how the donor model could be recoded to meet modern standards, an effort that has been pursued and completed outside our specific project objectives. Finally, we made the decision to have separate meetings devoted to modeling and computing capacity to allow for longer discussions about how to navigate these and future challenges.

A third surprise in our project occurred due to obstacles in the implementation of our human participant research. Approval was delayed due to institutional concerns about, most importantly, the sovereignty of TK. The surprises in question stemmed from the delay itself, which had cascading effects on project implementation. Although we had approval to commence our project, we were forced to consider a slower ramp-up to our human participant work. In the meantime, we decided to initiate a set of pilot projects, which could be done in advance, that would provide a testbed, incubator, and accelerator of our intended methods. Each of the pilot projects yielded pleasant surprises in the form of valuable insights that have facilitated important decisions regarding future directions of the overarching project. In the first pilot project, we recruited students at Penn State to test how best to elicit values from immersive virtual reality imagery, in this case related to trees on campus. This project has helped us refine our sampling strategy to be more efficient. In the second pilot, we are modeling the implications of emerald ash borer killing all ash trees in the region with the goal of providing proof-of-concept results that could be used in subsequent conversations with stakeholders, while providing insights into general data-model gaps or issues. In a third pilot, we attempted to develop a workflow for translating preliminary model results into virtual reality forest imagery. The work has resulted in a submitted publication. Finally, we came to depend more heavily than intended at this early stage of our project on archival data from previously completed interviews with tribal elders that were part of the public record. This accelerated analysis of archival data allowed us to move forward with the scenario modeling (i.e., the importance of emerald ash borer to multiple dimensions of

the Menominee sustainability model). The scenarios in turn provided insights into customary practices of the Menominee (i.e., the cultural importance of understory plants), which is helping us identify opportunities for anthropological studies that intersect with the overarching goals of the project.

5.3.4 Inequalities, Power, and Positionality

Though our project is still in its early stages, our awareness of transdisciplinarity has engendered an openness to considerations of how inequalities, power, and positionality are already impacting our work. Political ecology (Adger 2001; Ingalls and Stedman 2016; Robbins et al. 2010), critical physical geography (Lave et al. 2018), work within science and technology studies (e.g., Jasanoff et al. 1995), critical indigenous studies (Moreton-Robinson 2016), to name a few subfields engaged in this discussion, all point to the very nature of what we are studying, why we are studying it, and how we are studying it as exemplifying both implicit and explicit power relations. Why are we studying forestry and not rice cultivation given that Menominee identity, though now rooted in forestry, was historically in rice cultivation? How do we acknowledge this colonial influence while still bounding our project around forests? Does work on individual interviews unveil a western assumption that imposes a value on individual knowledge, versus relational and collective knowledge? Does our choice of model design, by not explicitly including understory plants, create the perception that our project undervalues cultural, spiritual, and customary relations of those species? Even more fundamentally, the Menominee already view their decisions as being made with the best possible information, even in the face of uncertainty, and do conceptualize they are making "trade-offs" among competing objectives in this decision space. Rather, objectives are often seen as synergistic and mutually reinforcing. To what degree does greater transparency of these decisions actually add to the planning process? These and other questions underpin many aspects of our current and future project development.

In addition, the positionality of participants within the power structures of their own community or institution imposes unintentional

imbalances within the team. For example, because many team members are positioned within a research-based, academic system, the professional (and personal) benefit of crossing ways of knowing is rarely recognized through traditional academic reward systems. In absence of this feedback, individual satisfaction about the process becomes more important for ensuring continued participation. Similarly, CMN does not have a graduate program and does not require its faculty to engage in research, reducing potential incentives for engagement. Moreover, because CMN is a tribal college, resources and staffing are a continual challenge for SDI, despite an increasing number of projects and tasks.

The very fact that our project is funded by the US National Science Foundation means that there is an obligation that the federal dollars spent on the project result in products that have "intellectual merit" and "broader impacts." This funding similarly supports the careers of both junior and senior students, postdocs, and faculty. As a result, for many project participants, there is an expectation of publishing in peer-reviewed journals, despite the fact that the project's goal (and, in particular, SDI's participation) is rooted in responding to the needs of the community. Although recognizing the needs of publication for project participants, there is concern from the Menominee about how those results may be interpreted in the future. As a result, deliberations about how to use TK in western publications and respect for data sovereignty are critical for building trust in the publication process. On top of this challenge, publication expectations are different among disciplines (e.g., humanities versus natural sciences). Making these disciplinary assumptions explicit constitutes an additional challenge to navigating differential expectations of benefits from the collaborative process. Spanning disciplinary and deep cultural boundaries represent different manifestations of how our position influences work flows and goals.

In addition to these philosophical and cultural considerations, there are more practical issues relating to project structure and management. For example, due to the fact that students and postdocs joined the team after project initiation, there has been uneven participation in social learning processes. Fostering a sense of inclusion is challenging when the team includes members who were not part of the original network, who joined at different times, or who have narrower or more specific

roles in the project. Relating lessons learned from previous experiences to newer members is challenging out of context and could, in and of itself, be seen to foster boundaries (e.g., "you had to be there"). In addition, the evolving nature of the network means that not everyone entered the project with the same common understanding about how and why people or activities were stitched together. An inherited sense of team cohesion built from early experience may have inadvertently intimidated newer team members, especially those with positions that explicitly have less agency or power, from feeling comfortable to speak up. Navigating these perceived power differentials and communication deficits requires continual and intentional trust building. Cultivating common experiences throughout the project remains a critical priority to ensure that knowledge co-production includes all team members to the greatest degree possible.

Finally, latent power dynamics among senior and junior members of the team are inevitable in any academic endeavor. In our case, some participants are representative experts in their respective intellectual domain and the team depends on their guidance, especially at pivotal moments. However, respect for this contribution ought not to be conflated with power such that assumptions, ontologies, and epistemologies are not challenged or questioned. Being aware of such blind trust can subvert deeper critiques of contributions that may in fact have deeper value to the long-term project. Creating a space where those deeper questions are discussed (i.e., How does robust decision-making differ from other forms of decision-making? How do values-informed mental models actually work in practice? Why is it hard to model a tree in virtual reality?) has been critical to subverting tensions and finding common purpose.

5.3.5 Governance and Leadership

Among team members, there is uneven understanding of the management structure of our project. Based on an informal, internal review, some team members view the project as run through a "standard" PI type management structure in which PIs and Senior Personnel lead the decision-making, with an absence of a formal group decision-making

process. To others, the management structure is seen to be part of an egalitarian group planning process with space for significant individual self-direction, as part of a "weak hierarchy." Yet others see the project as multi-core in that there are "specializing groups" that meet outside of the full group to work on separate topics, exchanging products and thoughts intermittently with the full group, but that decision-making within the full group is collaborative.

Regardless of its label, the lack of group consensus about the management structure has both fostered and constrained our team's work. On the positive side, there is a shared sense of ownership about the project, i.e., that everyone has a role and that everyone's ideas are welcomed and addressed. Everyone is genuinely interested in advancing the project science and is thus willing to contribute. The relatively egalitarian collaboration among PIs has been a necessity because of the extensive breadth of disciplines involved; everyone needs each other to push the project forward.

On the other hand, the complexity of the project can be overwhelming, especially when there are conceptual or practical misunderstandings. We all bring different knowledge and skills to the project, but this can be confusing at times, especially if there is not enough sustained work to unpack some of the more critical questions. Our early approach to this has been to split into subgroups for the deeper work, coming together regularly for face-to-face meetings to report back and prompt group decision-making. There simply have not been sufficient resources in our project to promote deeper collaborative interfaces. Though arguably a necessity for the early stage of the project, an unfortunate outcome is a perception of "stove-piping" project elements, in which subgroups focus on a narrow subset of the full problem before regrouping, which could result in some aspects moving forward more quickly than others or dismissing the important but hard work of collaborating on difficult problems with input from the larger team. One example of this has been model integration. Over time, different disciplinary workflows, conceptual framings, and technical limitations among model subgroups have become increasingly transparent. Being aware of conceptual or practical differences has however only emerged slowly over time as groups re-align their efforts. The differences are not necessarily

bad—they enhance learning, once perceived—but there is an argument for addressing them up-front.

Navigating such a complex research team and set of challenges and their cryptic opportunities naturally places a significant spotlight on the leadership of the PI. Being receptive to input from others and ensuring that all parts of the project are integrated, at the right times and in the right ways, is a crucial duty. This is particularly challenging when work occurs in subgroups, as there are expectations that the PI ought to be aware of their progress, as well as emerging issues in subgroups that might threaten that progress or undermine team cohesion. This necessarily means more meetings and emails, of course, and more work to tether groups together along the way. Being aware of when to intervene, and alert to when issues rise to the level that they ought to be discussed in the full group, is critical for gaining trust by team members. To date, this has largely manifested in respectfully "leading from behind," allowing subgroups or individuals to move forward at their own pace, while coordinating their interactions from above. Such an approach is dependent on the PI having deep trust in the workings of those groups, based on a sense of the underlying group cohesion and common purpose. Ensuring that everyone is on the same page—even if it is only clear to the PI—can be difficult. Shadowy understandings of the plan, within or among subgroups, can foster insecurity about the group's common purpose, which can sow group tension. It is the role of the PI to detect when the group may be stuck, heading into potential dead-end situations, or mired in uncertainty. While a natural part of science generally, leadership that navigates these difficulties well is even more critical in transdisciplinary teams.

5.4 Discussion: Managing the Challenges of Transdisciplinarity

A transdisciplinary approach includes team-based efforts to engage deeply with and understand the methodological approaches of each other's disciplines to the point that those methods can be deployed effectively and synergistically with other approaches to meet project goals.

This is expressed through iterative evaluation and evolution of methods, including the development of new methods that facilitate interactions *across* disciplines. As described in the previous section, it has become clear in the first couple years of the project that surface-level comprehension of, for example, how a particular model works, has been insufficient to provide meaningful understanding of how that model (1) can be effectively utilized or (2) can be tethered to other tools or models. More generally, it has become clear that the need to understand "under-the-hood" workings of particular methodologies necessarily permeates across all our project components (e.g., ecosystem modeling, values-informed mental models, robust decision-making, immersive virtual reality, and customary practice), and that collaborative deconstruction requires a substantial devotion of time.

Although there is no expectation that other team members become experts in each other's tools, the success of our project depends on elements being expertly interwoven throughout the duration of the collective enterprise. While other interdisciplinary projects may get by through passing off completed products from one subgroup to another, or merging stove-piped work packages only at end of the project, our project requires and is motivated by the idea that integration occurs early and often. Specifically, we rely on ecosystem model results to produce visualizations of forest futures, from which we aim to elicit values. This had to happen early in the project, since a key later step is to evaluate how trade-offs among values can inform robust decision analysis in the context of value framings and model uncertainties. What is more, these efforts are iterative, such that new information about value trade-offs can support new strategies in ecosystem modeling and visualization.

Managing disciplinary gaps is an inevitable but critical process for managing our transdisciplinary collaboration. First, many of us are not used to working in close collaboration with scholars from disciplines as diverse as the physical or biophysical sciences and the humanities. While many researchers entered the project with experience in interdisciplinary teams, these experiences could only marginally inform the current project. This is because all participants are working with at least one, if not more, new disciplines, such that none of us were exempt from climbing a steep learning curve. Second, as in any endeavor involving multiple

disciplines, the challenges are often emergent, and how a team responds is dependent on the individuals in the group and the particular problem being addressed. In our case, we identified significant language barriers around key terms (for example, "sustainability" or "calibration") that continue to cloud coherent application of the terms in the work of the project. While language or ontological barriers are not a particularly novel challenge in interdisciplinary work, the particular terms, and the particular ways in which the communication challenges are manifest, is likely to be a project-specific problem. However, early identification of these challenges are also targeted opportunities for group learning and consensus building, as demonstrated earlier in Fig. 5.4.

In addition to disciplinary boundaries, our project also crosses boundaries of ways of knowing across indigenous and western knowledge systems, providing additional lessons about managing collaboration. Though our project embraces this challenge explicitly, many of us continue to struggle to understand when we are crossing boundaries across knowledge systems. Although members of the Menominee nation are included in the leadership team, and although many of us have experience working with people from other cultures, detecting signposts that we have inadvertently misinterpreted each other's intentions or overstepped cultural norms is a persistent challenge. While our project has hopefully not committed any grievous error in this regard, the conscious awareness that we *could* do so provides a cautionary (and, we think, healthy) overtone to most of our interactions. Yet, in most cases, we do not know what we do not know and cannot anticipate lines that could be crossed, despite good intentions. Deepening cultural competency about Menominee history, traditions, practices, and worldviews is a critical, and ongoing, necessity for our team moving forward. Practices and opportunities for doing so are difficult. To ameliorate this, we have a common shared computer folder for sharing important papers about practices for engaging scientifically with TK. We also place value in on-site field visits for gaining cultural competencies. And, we rightly have a member of the Menominee Nation (Caldwell) as a co-PI on our project, who can guide us and be a network broker in the community.

Finding new ways to communicate and collaborate across physical boundaries has been a key component of our team's successful

collaboration. This is a critical consideration given that our academic institutions are spatially remote across four states: Pennsylvania, Wisconsin, North Carolina, and Oregon. Although critical for the deeper work of collective, sustained deliberation and opportunities for gaining cultural competencies, it strains the financial resources of the project. Despite these efforts, we are aware that we are continually crossing cultural divides and ways of knowing among knowledge systems, likely missing opportunities for informal learning. Also, given that we are meant to create immersive experiences about the forest environment, being in and near the forest is critical, but this has not been possible on a regular basis for many on our team, particularly those charged with developing the imagery and stories. Thus, we continue to leverage our project to seek additional internal and external resources to support this travel, with some success. For example, we have provided resources to CMN for personnel from the college to be trained on how to use the cameras so that they can collect imagery on behalf of the project. One of the most salient ways we have addressed the problem of not having resources for senior personnel to collect digital data is by bundling project activities. Specifically, we decided to focus our REU program on immersive experiences. In its first year, our REU program supported three interns at the SDI at CMN to collect and develop immersive digital videos. Having students engaged for up to 10 weeks with the sole purpose of focusing on immersive products was extremely helpful. The students were able to interact with tribal elders, visit key forest areas, and then subsequently come to Penn State to use virtual laboratory space and software to develop a product that was shared back to the community and which provided imagery and information that we will use in subsequent scientific efforts.

5.5 Recommendations

Based on the reflections above, we put forward a set of overarching recommendations for stewardship of successful collaboration in the context of transdisciplinary endeavors.

5.5.1 Recommendation #1. Adopt an Iterative, Reflexive, Respectful, and Reciprocal Social Learning Process

Our project development and initial implementation has highlighted the importance of an iterative and a multi-tiered and social learning process. Lessons from other domains (e.g., in software development: Royce 1970; Boehm 1988; Scheller et al. 2010) also point to the importance of evolutionary and adaptive processes in group learning. In our case, this has manifested through multiple levels of learning experiences (e.g., meetings, field trips, breakout groups). For example, given everyone's busy schedules, it is easy to dismiss the importance of the regular bi-weekly meetings. In contrast, our team finds these to be critical for regular communication as well as for shorter deliberations around key issues. In addition to these iterative events, there is also a craving for experiences that provide opportunities for reflexive learning, where the hard work of reconciling ontologies or methods is done. For example, our approaches to model calibration are very different between ecological modelers and those involved in robust decision analysis. While an interdisciplinary approach would have the potential for success if one model group passed off the model results to another team, our transdisciplinary project necessitates richer conversations about how choices about calibration inform uncertainty or constrain computational capacity in light of downstream applications with non-academic stakeholder groups. Ensuring a multi-tiered approach that embraces both iterative and reflexive components requires greater attention to project management, more time, and greater flexibility and patience among participants.

Moreover, navigating opportunities for reciprocal social learning across western and TK systems requires respectful and reciprocal engagement among participants. Logistical constraints (funding, time, geographic distance, differential institutional obligations) hinder the ability to react quickly and can slow the learning process. To address this, it is important to embrace respectful and reflexive approaches from an early stage in the process so as to anticipate challenges and, as much as possible, start from a position of shared trust. Many of these approaches are well-studied in critical indigenous research methodologies (Angal et al. 2016; Harding et al.

2012). In our case, there was also a recognition that it would be important to involve tribal members purposefully as project leaders, with the understanding that this could increase the resilience of indigenous planning processes for climate change (Norton-Smith et al. 2016). We included tribal members as co-PIs in the project, beginning with the proposal phase. We also ensured a tribal review as part of the institutional review board (IRB) approval process for participatory research. Finding additional ways to decolonize our methodology presents an opportunity to be reflexive in response to Menominee culture and history, while respecting ways of knowing that may be unfamiliar to western knowledge systems. Ensuring there is respect for this process, as well as for all participants at a personal level, is very important for spurring intentional, integrative work.

5.5.2 Recommendation #2. Foster Curiosity

Curiosity is vital to discovery. Thus, in order to explore the interstitial spaces among disciplines, it is critical to turn any uncertainties into questions. In so doing, unsettled intellectual spaces between disciplines can lead to new questions and new insights. Individuals may have uneven capacity to embrace these uncertain spaces. It is therefore critical that the PI work to ensure that (1) exploration of these intersections is a positive and mutually enriching experience, by (2) communicating to all participants (especially new and junior participants) that they are in a space that is not fully understood (even by the PIs), in order to then (3) provide the guidance needed to navigate these gray areas. To do so, it is important to nurture and embrace curiosity by being aware of when the project has hit a gray space between disciplines and calling for reflection as an opportunity for learning. It is also critical that the project ensures an equitable environment that stimulates healthy and robust discussions about the true nature of inter-domain question(s) and whether there are resources to adequately address them.

5.5.3 Recommendation #3. Cultivate Common Purpose

Overall, despite the challenges of navigating transdisciplinarity and the hard work involved, our group has been dedicated, actively engaged,

and productive, and we are enjoying it. Why? One reason may be the tremendous *respect* about what each individual contributes to the team effort. Even if some understanding is lacking, we are respectful in the way people—and their disciplines or knowledge systems—are treated in the team. Respect is revealed in interactions at a personal, individual level, in one-on-one dialogues, and in group settings. Another reason concerns a sense of *integrity,* a general sense that we all want to do the project well. This may partially reflect a collective humility that we are seeking to cross wide, deep boundaries, as between very different disciplines and profoundly different knowledge systems, that are difficult to navigate. Yet, we, individually and collectively, feel the work is important, *right*, and meaningful.

Our project is based on a shared understanding stemming from a common framing of the general challenge of transdisciplinarity: that there are difficult trade-offs among epistemic and ethical values when spanning knowledge systems. Perhaps more so than in many interdisciplinary projects, or other transdisciplinary and translational projects, our explicit focus on crossing knowledge systems between indigenous and western cultures necessitates that we have a deep understanding of these epistemic and ethical issues. As such, our project promotes a sense of integrity from its very foundation, which is further promulgated by individual intentionality rooted in mutual respect. As a result, there is a current permeating our work which is to do the right kind of science that helps humans and non-humans navigate uncertain futures. Dedication, respect, responsibility, reciprocity, and integrity are the roots that support our stem of common purpose, which in turn branches out into our joint activities, bearing the fruits of learning about sustainable systems.

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6

Sustaining Interdisciplinary Collaboration Across Continents and Cultures: Lessons from the Mongolian Rangelands and Resilience Project

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6.1 Introduction

In popular Western imagination, the Mongolian steppe and its inhabitants represent an archetype of "otherness"—a remote and windswept landscape of horseback nomads pursuing a lifeway of subsistence pastoralism at the dawn of a market economy. Various narratives of what happens next populate films, news articles and social media, reifying a storyline of the vanishing nomad and desertified steppe. Behind

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these simplistic narratives is the more complex reality of a dynamic coupled human-natural system; the lived experience of herders, government officials, conservation practitioners, and researchers from Mongolia and abroad; and the web of policies, programs, projects, and personal relationships that connect and divide them. This chapter tells the story of an international transdisciplinary and cross-cultural research team that sought to challenge the dominant discourse about Mongolian rangelands and pastoral systems by working together with herders, policymakers and conservation practitioners to design and implement solutions-oriented research. The project took advantage of a "social experiment" in formal community-based rangeland management (CBRM) underway in Mongolia in the late 2000s, to investigate whether this institutional innovation leads to better social, livelihood, and/or ecological outcomes compared to traditional management.

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We hypothesized that formal community-based management would increase system resilience to climate change and political-economic shocks. Our project was therefore nicknamed "Mongolian Rangelands and Resilience" (MOR2). This central question framed the MOR2 project, which also studied the individual and interacting effects of grazing and climate change on steppe ecosystems and herders' livelihoods, and experimented with multiple approaches to public engagement and capacity building across scientific disciplines, social sectors, and cultures.

Throughout the collaborative research process, members of the MOR2 team reflected upon the factors and dynamics that influenced their capacity for interdisciplinary collaboration. Studies in the "science of team science" often use a grounded theory or ethnographic approach to analyze the context(s) for the success of large-scale, transdisciplinary research efforts (e.g., Stokols et al. 2008; Thompson 2009; Wagner et al. 2011). Using a similar approach, our team used multiple qualitative techniques to elicit insights from the team members as they worked across continents, cultures, and disciplines. Like any team of this size and scope, there were challenges to successful collaboration. These challenges included: (1) different assumptions and expectations about how data would be integrated and analyzed, (2) data management across

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disciplinary and national boundaries, (3) scientific collaboration across cultural and linguistic boundaries, including the different "cultures of science" within the team and expectations for data sharing and authorship, and (4) maintaining engagement and honoring commitments to research participants and stakeholders. Two themes underlying these major challenges were the diversity of epistemologies or ways of knowing held by researchers of different disciplines and cultures, and their differing methodological paradigms. These challenges provided opportunities for the MOR2 team to reflect and openly discuss frustrations and underlying assumptions. The team's attentiveness to these issues became one of its greatest strengths and improved our capacity for boundary-spanning collaboration and knowledge sharing.

6.2 Mongolian Pastoralism as a Coupled Natural and Human System

Eighty percent of Mongolia's 1.56 million km^2 (NSOM 2018a) is classified as rangelands, which support over 66.2 million livestock (NSOM 2018b), and constitute one of the largest intact grassland ecosystems on Earth. These grasslands have supported a semi-nomadic pastoral population and their herds for over 4000 years, with minimal lasting ecological impacts until the late twentieth century (Fernández-Giménez et al. 2017). Mongolia's pastoral populations have ebbed and flowed over millennia, becoming "herder-farmers" in some eras, and "pure pastoralists" in others (Honeychurch 2010, 2014). Over time the accumulated traditional ecological knowledge of Mongolian nomads enabled them to exploit the grasslands sustainably, and adapt to fluctuating climatic and socio-political conditions, relying on a suite of adaptive strategies including use of diverse livestock species, habitats and livelihood strategies; pastoral mobility; resource pooling; reciprocity and exchange; and flexibility (Fernández-Giménez, Batkhishig, Batbuyan, et al. 2015).

Since the beginning of the twentieth century, Mongolia's pastoral social-ecological system has weathered several major shifts in governance, the most recent being the shift to a democratic system of

government and market economy in 1990. From ~1950 to 1990, socialist collectives regulated pasture use and mobility, and provided social and production support (Fernández-Giménez 1999). Following Mongolia's first democratic election in 1990, collective livestock and assets were privatized and herders became self-sufficient owner-operators, with little or no government support or regulation of pasture use. Livestock numbers increased quickly, pastoral mobility declined, and herders began to graze traditionally seasonal pastures year-round (Fernández-Giménez 2001; Mearns 1996). At the same time, temperatures increased significantly (2.07 °C from 1940 to 2013, more than twice the global average), and precipitation became more variable (Dagvadorj et al. 2014; Hijioka et al. 2014). Concern increased about the perceived decline in pasture conditions (Eckert et al. 2015; Hilker et al. 2014; Liu et al. 2013), which were primarily attributed to growing livestock numbers, especially goats (Hilker et al. 2014; John et al. 2016). Following privatization, rural poverty and income inequality rose rapidly (Griffin 2003; Nixson and Walters 2006). Several winter disasters (*dzud* in Mongolian), in 1999–2003 and 2009–2010, caused considerable livestock mortality and human hardship (Fernández-Giménez et al. 2012; Rao et al. 2015). The combination of increasing rural poverty and risk, declining pasture conditions, and lack of effective governance, led to the donor-assisted formation of over 2000 CBRM groups by 2006. These formally organized herder groups created the opportunity to conduct the first large-scale case-control study of CBRM effectiveness in the world.

In light of these challenges and opportunities, we designed MOR2 to (1) understand the impacts of changes in climate and grazing management on pasture conditions and herder livelihoods, (2) assess the outcomes of formal CBRM compared to traditional herder communities, and (3) evaluate the role of CBRM in building system resilience to climatic and socio-economic changes. As depicted in Fig. 6.1, we hypothesized that in the absence of monitoring, learning, and adaptation fostered by CBRM organizations, the major feedback between the ecosystem and social system is livestock productivity, which affects individual household conditions and decisions, and is insufficient to stimulate a change in community-level management. We posited that CBRM

organizations strengthen self-regulating feedbacks between ecological and social systems by promoting deliberate and collective monitoring, learning, rule-making and enforcement, and the resulting adaptive management actions. With respect to feedbacks among climate, rangeland ecosystems, livestock populations, and social systems, we expected that changes in precipitation and temperature would make herders in systems like the steppe, which is shifting from more mesic, equilibrium dynamics toward more arid, non-equilibrium dynamics, more vulnerable by increasing their exposure to climate change and sensitivity to its impacts. Herders' management actions depend on feedback from the ecosystem via livestock productivity and populations, and the influence of policy (e.g., land tenure) and markets (e.g., cashmere and consumer prices). Where CBRM organizations are present, we expected that collective decision-making would shape herders' management actions, taking into account changing ecological conditions and coordinating the goals and needs of multiple community members, leading to more adaptive management decisions and greater capacity to deal with climate change and natural disasters.

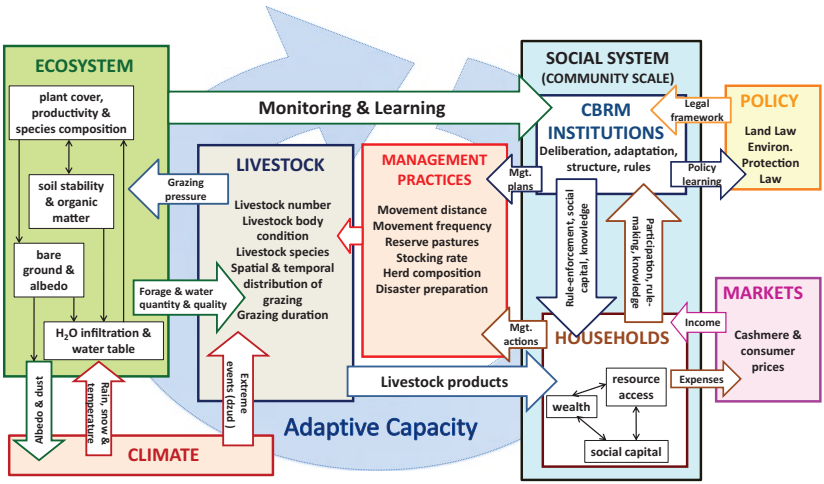

Fig. 6.1 MOR2 coupled natural-human systems conceptual model (*Source* Figure adapted by the authors from Reid et al. 2014)

6.3 Initial Team Formation and Research Co-design, 2008

The MOR2 team combined existing long-term relationships and continual efforts to engage diverse stakeholders in project design. The MOR2 PI had worked in Mongolia since 1993, with a hiatus from 2000 to 2006. Upon returning to Mongolia in 2006, the proliferation of CBRM organizations impressed her, and she began to meet the sponsoring donors and NGOs, observing limited communication and coordination among many distinct but parallel efforts. In 2008, the PI, a CBRM program director, and a Mongolian graduate student with CBRM experience sought financial support to organize a meeting of scientists and stakeholders in Mongolia. The purpose of this meeting was to identify common issues and questions for a research effort to inform rangeland management and governance in Mongolia. An internal university mini-grant, coupled with support from several donors and development agencies, provided the resources to convene a 2-week collaborative research planning effort. The PI reached out to other colleagues within her university who had appropriate expertise and international experience. Their backgrounds included hydrology, geography, rangeland ecology, collaborative conservation, and environmental communication with specialization in the science of team science. The PI is a rangeland and human ecologist. All but one of the initial US members of the core team had substantial international experience and/or multicultural/multinational backgrounds. In addition, the PI invited her long-term Mongolian collaborator, a human geographer based in Ulaanbaatar, to join the core team.

In June 2008, this initial team organized a 2-week collaborative research planning event in Mongolia. The first week involved a field trip designed to (1) orient US team members new to Mongolia to the ecological and socio-cultural contexts of Mongolian pastoral CNH, (2) build trust and relationships among team members, and (3) share methods and knowledge in an informal, collegial setting. The second week involved a multiday research planning meeting attended by 120 individuals from government, academia, national and community NGOs,

donor organizations, and 20 herders. The meeting began with a "state of knowledge" mini conference that alternated presentations by international and Mongolian scientists on community-based resource management, rangeland ecology, and climate change. The second day was interactive and engaged a wide array of stakeholders in identifying and prioritizing the major issues facing Mongolian rangelands, and developing a set of principles of collaboration for the group. The third and fourth days were dedicated to developing research questions and hypotheses based on the priority issues and outlining a preliminary research design. These days featured researcher participants, but some herders and practitioners remained throughout. On the final day, the group presented the main questions, hypotheses, and design back to key stakeholders from the donor/NGO organizations and ministries. The outcomes of this meeting included an outline for a CNH research proposal, and commitments of collaboration and support from a variety of research organizations and NGOs.

6.4 Study Locations and Research Design

Based on the 2008 planning meeting, the team developed a research design to investigate 2 main questions: (1) How resilient or vulnerable are Mongolian pastoral social-ecological systems to climate change? (2) Does CBRM increase coupled systems' resilience to climate change? The team designed research to provide robust generalizable inferences about the effectiveness of formal CBRM in improving ecological, social and livelihood outcomes for herders. Figure 6.1 displays our CNH diagram depicting the hypothesized relationships and feedbacks in this system.

An inventory of CBRM groups in Mongolia conducted at the 2008 meeting formed the sampling frame. Using this inventory, we identified all counties (*soums*) with formal CBRM initiatives and selected adjacent pairs of counties in the same ecological zones with and without formal CBRM initiatives (Fig. 6.2). This resulted in 18 pairs of counties (36 total) distributed across Mongolia's four major ecological zones: mountain and forest steppe, Eastern steppe, steppe, and desert steppe, and representing three different major donor/NGO-supported

CBRM initiatives. Within each county, we identified all formal CBRM groups and informal herder neighborhoods, and randomly selected 5 groups for study (4 in non-CBRM counties). We established ecological and social sampling protocols that ensured spatially and temporally linked social and ecological data collection. Social sampling took place first, including herder household surveys. Then, ecological field teams located the winter pasture of one sampled household in each group and conducted ecological sampling on the household's pasture. Three plots represented each household's winter pasture area along a livestock use gradient from the household's winter corral with plots located at 100, 500, and 1000 m from the corral. All plots on a given pasture were selected to have similar elevations, aspects, and landforms, to limit environmental variability.

MOR2 collected social and ecological data at multiple organizational levels and spatial scales. County-level social data included government statistics, interviews with county leaders, and county-level focus groups. Herder group data included interviews with CBRM and traditional neighborhood group leaders and focus groups with group members. The team collected information on individual household demographics,

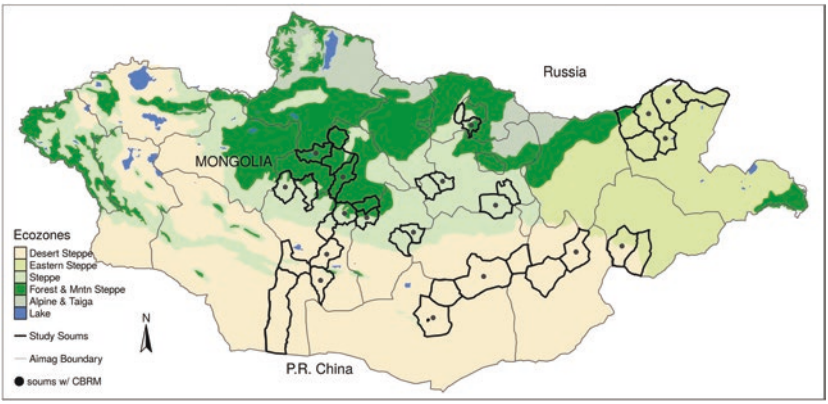

Fig. 6.2 MOR2 study sites. Dark outlines are study counties (*soum*). Soums with triangles indicate counties with formal CBRM organization and those without were non-CBRM counties with traditional herder neighborhoods (*Source* Figure created by G. Allington in R, adapted from Fernández-Giménez et al. 2018)

management practices, land tenure, social capital, and livelihoods using a household survey. Ecological data included plot-level soils and vegetation data, as well as remotely sensed data (NDVI). Hydro-meteorological data included meteorological station data, interpolated climate datasets (CRU [Harris et al. 2014], GPCC [Schneider et al. 2014], and WorldClim [Hijmans et al. 2005], among others), streamflow data, and tree-ring data. To understand how climate and ecological change over time were understood and experienced by herders, we studied herder observations, including both a large sample using a closed-ended questionnaire and a small sample of in-depth interviews with herders at the winter pastures we sampled. At a few sites we facilitated participatory mapping activities with herders to learn more about the complex overlapping social, ecological, and administrative boundaries that influence pasture access and herder mobility.

6.5 Team Development and Project Launch, 2010–2011

An initial CNH proposal submitted in 2008 was not funded. The 2009 resubmission was funded, as was a proposal to the World Bank following the *dzud* of 2009–2010. In 2010, we began recruiting potential graduate students for the project. We reserved two of the four graduate student positions on the project for Mongolian nationals, as one of our main objectives was to build the capacity of Mongolian scientists to conduct interdisciplinary natural resource research. We recruited two excellent Mongolian students to pursue Ph.Ds at CSU; both were mid-career women with extensive professional experience in rural community development in Mongolia. In addition, as we consolidated our core team and identified specific sub-teams, we ensured that each sub-team (ecology, social science, hydro-climatic) included a Mongolian leader or co-leader to the US Co-PI. Our field teams had a similar structure. The ecology field teams were led or co-led by Mongolians and the social field teams were all led by Mongolians under oversight by the PI, who co-led the overall social team with two Mongolians. Another Mongolian who earned her Ph.D. at CSU and assisted in proposal

development became the Mongolian project coordinator, counterpart to the PI, and liaison with all participating Mongolian research institutions—a critical role within the project. These leadership partnerships were critical to managing field logistics and data collection, fostering intercultural learning and communication, planning and executing capacity-building and engagement activities, and ensuring that those who collected the data were deeply invested in the project and its outcomes. They also presented a number of challenges, as we discuss later in the chapter. Figure 6.3 illustrates the MOR2 core team composition with respect to gender, national origin, discipline, and role.

6.6 Fieldwork, Capacity Building, Engagement, Analysis, and Integration, 2010–2018

Space limitations preclude a detailed narrative of all MOR2 activities between the active grant period 2010–2015 or the following years (2016–2018) as the team continued to work together on integrated analyses and outreach. However, Table 6.1 lists the strategies used to develop and maintain communication across disciplinary, cultural/linguistic and sectoral boundaries within the MOR2 core team and extended team. Engagement and outreach (broader impacts) activities are described later in the Sects. 6.8.4 and 6.9.

6.7 Analysis of Team Collaboration Across Boundaries

Documenting and understanding interdisciplinary and cross-cultural collaboration was a goal of MOR2 from its inception. This case study represents the results of an iterative, reflective adaptive process (RAP) for analyzing team collaboration (Allegretti et al. 2015; Roux et al. 2010). RAP is a qualitative approach with an action-research orientation to understanding coupled-systems team dynamics. Under this approach, the entire team held dual roles as participant observers and research "subjects." Awareness of these dual roles, and of the team's

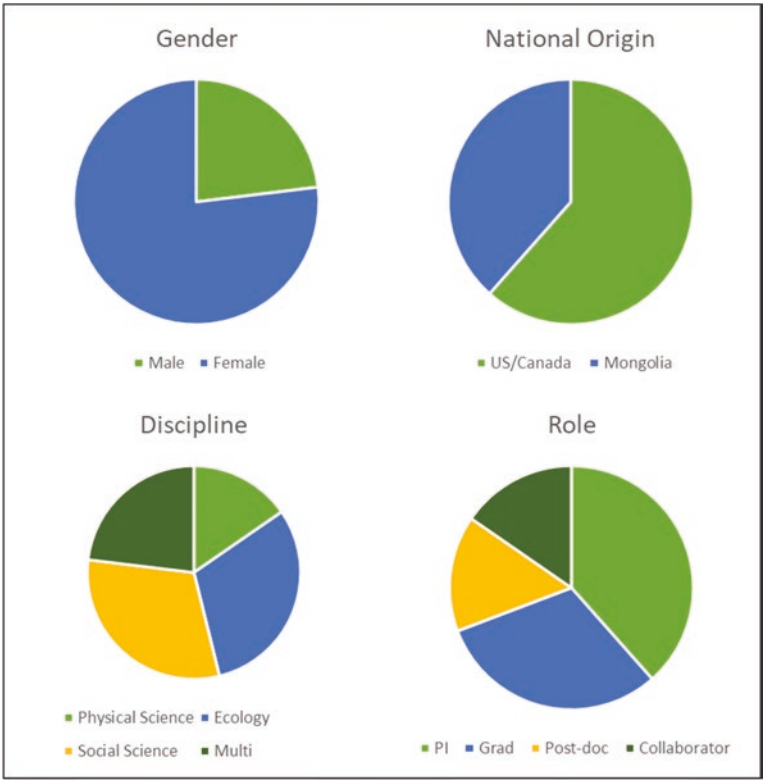

Fig. 6.3 MOR2 core team composition. The core team comprised 13 individuals, including all PIs, graduate students, post-docs, and two collaborating scientists, one based in Mongolia and one in the United States (*Source* Figure created by the authors)

objective to learn from our collaborative process, created a communication climate in which team members were encouraged to express their thoughts about the team in interviews, surveys, reflective essays, and team meetings and retreats. This chapter is based on data collected from 2011 to 2018 and discussion among team members during the writing process. Research was conducted under CSU IRB 09-965H, and team members agreed to participate following a formal informed consent process, recognizing that anonymity would be impossible given the relatively small size of the MOR2 core team.

Table 6.1 Communication and collaboration strategies for MOR2 core team and extended team

	MOR2 core team (PIs, graduate students, post-docs, US collaborators—13 individuals)	MOR2 extended team (Core team plus all Mongolian partners and collaborators—40+ individuals)
2008	Initial Mongolia field visit	Research planning meeting
2008	Visits to CO by Mongolia-based team members	Visits to CO by Mongolia-based team members
2010–2015	Monthly team coordination meetings (2 hr/month; in Colorado, Mongolia-based members participate via Skype)	Mongolian Project Coordinator and Liaison hired to maintain communication with all Mongolian partners and lead outreach/engagement
2011–2015	Thematic sub-team formation and meetings (research domain, outreach/engagement)	Mongolian sub-team Leads/Co-Leads established and maintained
2011–2013		Field methods training workshops Data analysis workshops Joint fieldwork (social, ecological, hydro-climatic, herder observations, participatory mapping)
2011–2018	Team social events & cultural celebrations (lunar new year) Collaboration on herder observation/hydro-climatic data collection and analysis	Co-authorship/writing partnerships
2012–2015	Annual core team retreat and reflection (1–3 days/year in Colorado)	Annual extended team meeting and reflection (2–3 days/year in Ulaanbaatar)
2013		Data sharing and authorship norms adopted Proposal writing workshops
2014–2015	Monthly writing retreats	Data analysis and scientific writing workshops
2015	Team scenario planning activity	Scientific conference planning and organization
2016	Review and synthesis article	
2017–2018	Integrated data analysis	

Two team members (a Co-PI and a graduate student) were charged with collecting and analyzing these data and maintaining confidentiality per the IRB protocol. At the initial and final team retreats, the Co-PI who served as RAP facilitator presented themes distilled from coding the data as the basis for a facilitated team discussion. This reflective iteration sought to connect the data with emerging insights (Srivastava and Hopwood 2009). MOR2's RAP approach created space for the team to talk about challenges that are often left "unsaid" in complex research teams, and opened up discussions of these challenges in a productive manner. Writing this chapter together enabled the team to reconvene and reflect with several years of distance from the active project, and the insights presented here are the product of this continued collective dialog.

This chapter, like the MOR2 project, has been a collaborative effort. As such, different participants drafted different sections, and the authors met (in person and virtually) several times during the writing process to discuss the structure, content, lessons learned and recommendations. All the authors reviewed and agreed upon the final submitted version. This said, the lead author, who was the MOR2 PI, framed and drafted much of the chapter, including the introduction, background, several of the challenge sections, and the lessons learned and recommendations. While she has tried to present a balanced account on the collaborative process, her subjective lived experiences as the project lead, a researcher with 2.5 decades of experience in Mongolia, a person from a Euro-American cultural background, and an interdisciplinary scientist trained in a post-positivist "western science" tradition inevitably shape her perspective. In an attempt to ensure that the Mongolian voices and those of other core team members are reflected here, the team decided to include additional text boxes of first-person reflections by team members with different positionalities.

6.8 Challenges of Collaboration Across Boundaries

Challenges are inherent to collaboration, but how a team identifies and deals with typical challenges differentiates an ordinary team from a highly effective boundary-spanning team. Here we discuss three

types of boundaries experienced in the MOR2 project—disciplinary (among physical, natural, and social sciences), national/cultural/linguistic (between US and Mongolian team members), and sectoral (between scientists and non-researcher stakeholders)—and the challenges and strategies for addressing them that emerged from our cross-boundary collaborations. Many of the issues faced by the team involved collaboration and communication across multiple dimensions of boundaries simultaneously. Rather than offer an exhaustive description of all challenges, we focus on critical challenges that came up repeatedly in interviews and reflective team discussions, ones that generated novel or transferable strategies, and/or which led to significant lessons learned that can inform future work of this team and others.

6.8.1 Interdisciplinary Collaboration Challenges: Conceptual and Analytical Integration

Disciplinary language barriers remain a challenge to achieving conceptual and analytical integration, as illustrated in this quotation from a MOR2 team member's reflective essay. "A challenge and thus an opportunity is language, in particular coming to a common meaning. This is more than a consensus but a mutual understanding of what specific words mean." In this quotation "language" refers not only to individual disciplinary languages, but also to associated epistemologies and methodologies that all group members must be conversant in to generate integrative project results.

6.8.1.1 Conceptual Integration and Research Design

The conceptual model for the MOR2 project (Fig. 6.1) delineates key relationships between objects of disciplinary study (e.g., ecosystems, livestock, people, climate) and associated natural-human processes. Although the conceptual model expresses these relationships clearly, this clarity did not transfer to a shared understanding of how to operationalize the conceptual model to collect and analyze hydro-climatic, ecological, and social data in a fully integrated fashion. Physical science

researchers felt they needed to understand their own system more deeply before they could contribute to an integrated framework for research design and analysis. As one physical scientist commented, "We had to dig within our individual disciplines. We didn't get to the point where we could integrate into a systems approach. We are still working on understanding the information within our discipline." This suggests not an unwillingness to collaborate, but a need to better understand one's own work before trying to work from an integrated concept of a system. In contrast, the PI (a social scientist and ecologist) had a clear idea of how social and ecological data would be integrated and analyzed but did not have sufficient understanding of hydro-climatic methodologies to outline how integration would occur. In addition, the social and ecological theories that informed the research design contrasted with the kinds of theories that inform physical science. As one team member responded in a reflective essay, "The ecological and social research aspects build on theory, but this is a different approach to the work, and even a different definition of theory, i.e., social behavior theory rather than laws of physics, [that is used by physical scientists]."

Box 6.1. Reflection of former US Ph.D. student

As a new graduate student researcher who had never been abroad or studied Mongolian hydro-climatology before, I found that not only did I not know the data, but I didn't know the people that managed the data. There is a hierarchy of people and things that you have to honor in Mongolia. Not like in the US where you can cold call someone and [probably] get the information you need, or at least find out who to talk to. Another frustration was realizing that the data availability and quality were not what I initially expected them to be, having only worked with the comparatively rich and complete datasets from the US. This led me to consider other research questions/projects that I could finish in time to graduate. I completed a separate research project using additional funding from the American Center for Mongolian Studies collecting data I could use with that from the MOR2 project. The upside to the additional work was it gave me more time abroad to immerse myself in the

> hydro-climatic and cultural issues, to more fully study the systems in situ and talk to Mongolian scientists, something I could not have done if I only worked remotely in the US. I learned so much on this project, even if the research didn't work out the way the hydro-climate team initially thought it would. I am who I am now—a Ph.D., researcher, and multi-disciplinary collaborator—because of this experience.

An example of this integrative challenge comes from the hydro-climate and ecology sub-teams. The ecological team sampled vegetation and soils in winter pasture locations. While certain hydro-meteorological and physical considerations were included in sampling design, these decisions were made by the ecology team alone. The hydro-climatologists assumed the role of data service providers, supporting the data needs of the ecological team, but with no direct feedback to hydrological research needs. While some of this choice likely stemmed from the short time-frame to organize fieldwork, some of it may have related to hierarchies of power in disciplinary knowledge and control of primary data collection methods, or not recognizing possible synergistic benefits to broader disciplinary participation. Similarly, some hydro-climate researchers used herder-observed environmental data in their work but did not directly participate in the initial collection or design of surveys or include further input from social-ecological researchers in the integrative work.

Strategies for coping with a lack of integration in research design while making research progress ranged from not actively collaborating on parts of the research, to incorporating parts of others' research findings, to revisiting research elements. An example of such revisiting occurred when hydro-climate and social-ecological team members consulted with one another to include more specific hydro-climate questions in revised herder questionnaires. In future research, we recommend spending more time in the field together during research planning, in order to foster greater mutual understanding of different disciplinary theories and methodologies.

6.8.1.2 Challenges to Integrated Analysis

The original MOR2 proposal envisioned using hydro-climatic simulation models as a means of integrating physical and ecological data, and informing the larger integrated research questions, but lack of essential hydro-climatic data prevented this approach. Unlike the other subteams, the hydro-climatologists collected little new data, relying on existing government climate data and information from international data repositories. Compared to the United States, Mongolian hydro-climate networks are sparse and published information regarding climate change and its effects have only been internationally available for a decade or so. Challenges communicating with government officials often resulted in unanswered questions about data quality and confidentiality. One researcher commented, "We had assumptions about data availability and systems relations, what data would be available from working in data rich areas… [In the end] we did go in some different directions." The US researcher continued, "[There are] not enough data to understand the basic hydrological function. The lack and uncertainty in data made it a lot bigger challenge to do the modeling we wanted to do and have it be meaningful."

MOR2 research questions explicitly asked about the resilience of coupled human-natural systems to climate change, suggesting a strong need to determine metrics related to the past, current, and future climate in Mongolia. Filling this need became a main goal of the hydro-climatological team, as the team recognized the infeasibility of the originally planned hydrological modeling. As a result, climate data were included as context and drivers for the social and ecological fieldwork, but feedbacks from the social and ecological systems to hydro-climatic systems were not addressed.

Finally, differences in spatiotemporal scales and disciplinary interpretation of results complicated integration with other team datasets. As one hydro-climate researcher commented, "In hindsight I see the linkages between the physical and ecological, but there is still a challenge of spatial and temporal scales… I am still grappling with what information can link… what are we going to do with this information."

A strategy for addressing problems with data availability is to complete a "data review," similar to a standard literature review, to determine what data are available for the envisioned work. The team used other strategies to integrate across social, ecological, and hydro-climatic data and results, including a literature review and synthesis; participatory scenario planning; and comparisons of herder observations, remote sensing, and hydro-climatic data.

6.8.2 Data Management Across Disciplinary and National Boundaries

Data brings research teams together, but it can also drive team members apart. Empirical data collection through multiple discipline-specific methods is difficult, at best; adding a cross-cultural component increases the complexity of data management and integration. The MOR2 dataset is a unique assemblage of multiple types of data: results of ecological, hydrological, and social science surveys; extensive qualitative data including interview and focus group audio-recordings and transcripts; photographs; remotely sensed data; government statistics on human and livestock populations; climate data products at various scales (plot, district, national); participatory mapping outputs; documents such as group by-laws, pasture management plans, and local government resolutions; and scholarly literature. These are organized into different thematic datasets and databases based on the distinct data collection methods, scales, units of analysis, and analytical techniques used (Table 6.2). The database evolved organically over the five-year project, and discussions about database development were ongoing in response to data collection and management activities.

Agreed upon and clearly documented data collection and management protocols, supported by training for researchers, were crucial to ensure data quality. In MOR2, data collection protocols, field forms, and social survey instruments were translated into both languages, field-tested and revised to eliminate ambiguity, and field teams carefully and repeatedly trained in the protocols. Field coding schemes created a spatially explicit hierarchy to link the different thematic datasets, allowing

for the creation of customized linked databases to address specific research questions. Methods for database versioning ensured that the best data are captured and organized for use and analysis. Naming conventions with dates were essential for metadata, data provenance, and for reducing redundancy.

The fluid structure of the research teams, with some members participating in multiple sub-teams (e.g., social and ecological sub-teams), strengthened the interdisciplinarity of database development resulting in a database that is a loosely integrated collection of data organized by disciplinary themes and linked through common key fields such as province, county, group, and household using multiple data platforms (i.e., geodatabases, Access databases, spreadsheets).

In the context of the interdisciplinary and cross-cultural MOR2 project, disciplinary vocabularies needed clear definitions to avoid misunderstandings. Working across different languages and alphabets complicated efforts to manage data. A simple database designed around research themes provides an organizational framework, but is still not an integrated database.

Table 6.2 MOR2 sub-teams and data collected

Sub-teams	Data collected
Social	Focus groups discussions, group leader interviews, and surveys at county, herder group, and household levels for 36 counties
Ecological	Rangeland soil, plant community composition, diversity, and production
Physical	Hydro-climatic surveys/assessments, climate data, and tree-ring analyses, and remote sensing data
Herder observation	Surveys and interviews of herder observations of hydro-climatic and rangeland soil and vegetation changes
Boundaries	Participatory mapping of herders' socio-ecological boundaries
Interdisciplinary team dynamics	Interviews and surveys of US and Mongolian research team members, participant observation, transcripts of team meetings, annual meeting evaluations, reflective essays by team members

Technological challenges of data storage and access across different computer networks and institutional network protection police complicated data sharing, with the access to and sharing of data being a particular sticking point for MOR2 researchers. A lesson learned by the team about data management is the need to dedicate time and effort to support this often-overlooked activity, including long-term data curation after the end of the project. The Colorado State University Data Repository currently maintains the MOR2 database, where access is provided through a tiered structure of permissions. However, work remains to ensure the database is complete, quality-controlled, and accessible, with provisions for long-term maintenance and curation.

6.8.3 Scientific Collaboration Across Cultural and Linguistic Boundaries

MOR2 involved collaborations with senior and junior researchers from five different Mongolian research institutes and several donor organizations and NGOs. In addition to anticipated challenges such as translation and interpretation between languages, we encountered challenges related to different cultures of science, social hierarchies within scientific institutions, and differing understandings and standards of scientific rigor.

6.8.3.1 Translation

MOR2's US team members, even those with extensive experience in Mongolia, had limited Mongolian language skills. The PI, once fluent in Mongolian, had lost language facility during a long break from doing research in Mongolia. In contrast, MOR2 Mongolian core team members all were multilingual, with English usually a 3rd or 4th language. However, most Mongolian research partners from other institutions (MOR2 extended team) had limited English proficiency. As a result, communication between US MOR2 core team members and Mongolian partners was a major challenge. Correspondingly, translation

became a critical function of the multilingual Mongolian team members. Mongolian graduate students and postdoctoral fellows served as both translators and cultural boundary-spanners, and were indispensable at translating research protocols and instruments, and interpreting during research meetings and workshops (Mendezona Allegretti 2015).

MOR2's boundary-spanners also made enormous efforts to manage tensions between Mongolian norms of conducting science and US standards. According to one Mongolian core team member, "I made efforts to mediate and did double, sometimes triple level of translation and interpretation/solutions to manage such differences." These efforts were both a strength, because the team had members who were able to translate and interpret language and culture, and a limitation, because these team members' energies were often focused on translation and coordination among Mongolian partners, rather than substantive research work. These dynamics also highlight the power differences between the US PIs and Mongolian students and collaborators (Mendezona Allegretti 2015).

When feasible, MOR2 attempted to mitigate the burden of translation on our Mongolian core team members by hiring professional translators. However, the professional translators sometimes lacked knowledge of herding or rangeland vocabularies or failed to appreciate nuanced but critical distinctions among Mongolian terms. Even among our multilingual core team members and research partners, there were persistent disagreements about the meaning and translation of key terms such as "resilience" into Mongolian. At the 2008 planning meeting, annual meetings, and the final MOR2 Conference, we hired professional translators, and presented all proceedings on two screens, with text in English on one and Mongolian on the other. The proceedings papers of the 2015 MOR2 Conference (Fernández-Giménez, Batkhishig, Fassnacht, et al. 2015) were completely bilingual.

Key insights gained are to anticipate and take seriously the complications of language translation. This is especially important if the project aims to facilitate genuine scientific collaboration among international colleagues, or to conduct meaningful engagement with non-researcher stakeholders. This means budgeting for translation of project

materials, presentations, and, especially, conversations among collaborators. We recommend developing a working glossary of key terms in both languages with translations. Although multilingual team members served an invaluable function in MOR2, it is critical not to relegate peer scientists to the role of translators without prior agreement and compensation.

Multilingual and multicultural researchers on the project filled critical roles as boundary-spanners and interpreters. Only individuals who were fully part of the project team and deeply understood both the research questions and methods and the Mongolian cultural context and scientific culture, could fill these roles. Although the US team members took basic Mongolian language instruction, there was no time to gain the fluency needed for in-depth ethnographic research. In retrospect, the PIs reflected on their own arrogance in not allocating more time and resources to gaining greater fluency in Mongolian and not insisting that US students take more Mongolian language training prior to their fieldwork.

6.8.3.2 Different Cultures of Science

MOR2 encountered challenges in reconciling differing views of science and scientific methods between Mongolian and US researchers, as well as different social norms and hierarchies within scientific institutions (Boxes 6.1–6.3). As one team member reflected, "Of course there were frustrating times since the way we do science is different between Mongolian and US scientists and we were trying hard to teach and learn from each other." Most senior researchers in Mongolia were educated during the Socialist era, when much ecological and social science research was oriented toward natural history and descriptive studies, rather than theoretically driven research or hypothesis testing. Mongolian field ecologists had experience with vegetation classification (e.g., Ulziikhutag 1989) and conducting exquisitely detailed studies of plant community composition and production dynamics at a few study sites (e.g., Lhagvajav 1992). Senior social scientists had

deep understanding of herder lifeways, vocabulary, management practices, and concerns (Bazargur et al. 1993), enabling them to contribute to design and implementation of social data collection instruments and protocols. But often, the aim of Mongolian research during the socialist era was to support the state's political ideology or policy agenda (e.g., Chogni 1989). Even when there was no overt political agenda behind research, the approach to data collection was generally confirmatory—to support a pre-determined conclusion rather than to test a hypothesis. Basic principles of experimental design such as replication, randomization, and independence of samples were not part of Mongolian scientists' education until recently, nor were the associated analysis methods such as inferential statistics or qualitative data analysis.

Box 6.2. Reflection of Mongolian Ph.D. student

By joining the MOR2 Project, I have learned much about developing research questions, hypotheses and study design, which I had no experience with before. During my Master study in Mongolia, I did not develop research questions and hypotheses for my study and I used only descriptive statistics for analyzing data. Therefore, it was challenging for me to learn all of these when I first joined the MOR2 project. I observed that one of the cultural differences between the researchers in these two countries is researchers in the US organize many discussions among team members/participants about steps of research work before starting and during research, or about issues around a particular topic before making any conclusion. I think this process helps all participants to be on same page as much as possible and provides an opportunity for participants to contribute their perspective on an issue. I think this is a very important process that we, Mongolian researchers, should practice broadly. Overall, I am very grateful for the opportunity of working with and learning from researchers from different disciplines and cultures as a member of MOR2 project, and I am and will be sharing my learning and experience with my Mongolian colleagues widely.

Box 6.3. Reflection of Mongolian post-doctoral fellow

Mongolians are very hospitable and welcoming people, especially nomads, who live in countryside. The education system is influenced by socialist development for many years and controlled by the government and their leaders. People always used to follow their leaders and rules and socialist 5-year development plans. Kids listen to their parents, teachers, adults and their leaders and follow the instructions. The academic system had certain detailed programs and topics to study. Students always followed and studied what their advisors told them to research. For me, when I came to the US, it was totally new to come up with my own hypothesis and study questions. Therefore, I understand why it was hard for Mongolian researchers to come up with research proposals to use our data and I tried to help them to write research proposals during our annual meetings and trainings face to face, and through emails in other times. Also, Mongolians are very shy. Many of them are not comfortable sharing and discussing their opinions, maybe due to the education system. I personally did not have any classes in Mongolia where we had active discussion. So I tried my best to make the Mongolian students and researchers feel welcomed and tried to be as open as possible making friends and encouraging them to talk and express. I think every member of MOR2 tried to overcome this difference. I personally am really thankful that all the MOR2 US researchers were patient with this difference, listened to local researchers' and local people's concerns, and tried to make this research really collaborative. They tried to benefit local people and build capacity. I think our MOR2 project was really helpful in introducing the western way of doing science to Mongolian researchers.

In addition to different understandings of science, the social norms and hierarchies within Mongolian research institutions presented challenges for collaboration with US MOR2 PIs (Mendezona Allegretti 2015). According to Mongolian custom, official collaboration and communication must go through the Institute Head and/or the lead senior scientist, who then makes decisions about which researchers to assign to a project. Participation in MOR2 presented an important learning and

capacity-building opportunity for junior researchers, who were sometimes graduate students. MOR2 leaders provided multiple formal and informal training opportunities for junior researchers to build their capacity as researchers in their own right. For example, we encouraged all participating Mongolian researchers to propose their own research questions to address using MOR2 data. The team's well-intentioned efforts at science capacity building, however, were sometimes at odds with the interests of senior researchers or even challenged their authority by teaching their students a different set of standards for what constitutes good or valid research, and by modeling a more democratic and collaborative approach to research. In one case, a senior researcher prohibited their students from attending further MOR2 workshops. Nevertheless, the investment in science capacity building and the experience of participating in a large interdisciplinary collaborative research project had profound impacts on some participants. As junior Mongolian researchers stated at our closing meeting in 2015, "So much of my career and my life were linked with this project," and "[MOR2] provided so much encouragement and incentive for young scientists to get themselves out to the world, to test their skills, to expose themselves and be peers with international scientists." Mongolian core team members echoed these experiences (Boxes 6.2 and 6.3).

6.8.3.3 Data Sharing and Authorship

The differences in understandings about the scientific method presented significant challenges for data sharing. The issue of data sharing was mentioned multiple times in the reflective essays: "In my opinion, the main challenge we faced was misunderstanding about data sharing with the Mongolian and other colleagues…," "We should have had discussed from the very beginning about the data sharing protocol and its processes." "We had some problems over data sharing, but in the end, we produced [a] data sharing protocol, agreement and it solved the way it [is] supposed to be."

MOR2 always intended that all researchers who participated in the research design, and/or data collection, and/or analysis/interpretation

would have the right to access and use the data to publish their own research. As the project progressed, however, the differences in scientific culture became more apparent. Some of the US PIs became concerned about how to ensure that the data were properly analyzed and that appropriate conclusions were drawn from the results, based on US standards of scientific inference. The PI was especially concerned because of the important policy and management implications of the research findings, and the potential for misconstruing or misrepresenting their meaning. To fulfill the commitment of sharing data while ensuring appropriate use, the MOR2 core team developed a data sharing protocol, which required any team member or partner wishing to use project data to provide a short (1-page) proposal outlining their data request, research question, and hypotheses and proposed analysis methods. The protocol also outlined an internal peer review process where a committee of senior researchers would review research manuscripts before submission for publication. A partner organization requesting data for non-research uses could also make a request and sign an agreement that included provisions for acknowledging the source of the data and funding source. At the same time that the data sharing protocol was developed, the MOR2 core team recognized the need to have a team discussion about authorship on manuscripts from the project. This led to a series of discussions and adoption of a formal document called MOR2 Authorship Norms, which clarified contributions meriting authorship and necessary acknowledgment of individuals, including herder groups, students, and researchers who contributed insights and data collection. These discussions and the resulting Authorship Norms helped cultivate a culture of collaboration rather than competition around publishing within MOR2.

The process of requesting to use MOR2 data seemed simple to the US MOR2 PIs, but for reasons related to scientific cultures noted above, writing even a one-page proposal in Mongolian was a barrier for Mongolian research partners. The realization that most of the Mongolian partners lacked experience writing research proposals led the MOR2 core team to revise its outreach and engagement plans to focus on building our Mongolian partners' science capacity so that they would have full access to the data (Box 6.3).

MOR2's science capacity-building efforts included a variety of activities, some led by MOR2 PIs and others by Mongolian core team members. Mongolian core team members taught a graduate seminar at the Mongolian University of Life Sciences and hosted a monthly "Happy Learning Hour" focused on various theoretical and methodological issues. Both the seminar and the learning hour encouraged junior Mongolian researchers to read and discuss the international scientific literature, to become better acquainted with international scientific theories, research design, and writing. Another series of activities targeted MOR2 Mongolian researchers, especially junior scientists, and included a workshop on research design and proposal writing, a proposal feedback workshop, multiple workshops on qualitative and quantitative data analysis, and a week-long data analysis and scientific writing workshop. This series culminated with organization of a major international scientific conference in Ulaanbaatar, Mongolia in June 2015, with bilingual peer-reviewed proceedings. Undergoing the process of peer review was an important part of the science capacity-building strategy. In addition, junior researchers and graduate students had the opportunity to participate in a scientific poster presentation competition judged by a panel of international and senior Mongolian scholars. MOR2 thus developed a variety of strategies to address challenges related to different cultures of science and specifically to data sharing.

6.8.4 Transdisciplinary Collaboration: Knowledge Sharing with Non-scientists

MOR2 valued both local/traditional knowledge and scientific ways of knowing and attempted to respect and draw on both to address the central research questions. The project also upheld an ethic of reciprocity, whereby the team was committed to returning usable research findings to the communities where data were collected, as well as to practitioners and policymakers who helped design the research.

Local, traditional and practitioner knowledge informed the project in a variety of ways. The concept for and collaborative relationships that underpinned MOR2 emerged from a series of meetings between

the PI and conservation and development practitioners in Mongolia in 2006–2007, which led to organization of the 2008 planning meeting. The involvement of practitioners and herders helped ensure that research questions were relevant and that Mongolian researchers and practitioners viewed the research design as credible and legitimate. Mongolian team members also served as cultural guides and helped to integrate local perspectives into the methods. In addition, MOR2 evolved to include several traditional ecological knowledge studies that documented herders' observations of environmental changes, and their use of ecological indicators to assess rangeland health and degradation (Bruegger et al. 2014; Fassnacht et al. 2011; Fernández-Giménez, Angerer, et al. 2015; Venable 2017).

The PIs expected that the broad stakeholder participation in identifying research questions and designing the research, would result in a ready audience for the research findings among Mongolian policymakers and conservation practitioners. Although MOR2 was committed to returning the results to communities where the team collected data, and to regional and national decision-makers, the team encountered logistical and financial challenges in meeting this commitment. Mongolian core team members held the whole team accountable for meeting this goal. By the second year of data collection, the Mongolian Project Coordinator frequently reminded the PIs that it was difficult to send ecological research teams back to communities where social data had already been collected without results in hand.

This led to the formation of a MOR2 outreach sub-team, which developed an outreach and engagement plan to ensure that the 36 participating communities received usable and meaningful information from the project. Several Mongolian core team members sought supplemental funding from sources outside of the team's NSF grant to support outreach and engagement activities. One Ph.D. student hosted a weekly radio talk show in Mongolia to discuss collaborative conservation and research results. A Mongolian postdoctoral fellow with the project obtained a grant to work with research participants from several study communities to produce a book in Mongolian that integrated MOR2 research results specific to that county with local knowledge and stories. The MOR2 core team created fact sheets for most of the

participating counties that summarized key ecological and social data from that county and displayed it in relation to the averages for other counties in their region. The team also organized three regional workshops, attended by participants from most of the study counties. These workshops combined formal presentations of key research findings with interactive small group discussions to "ground truth" the research results. Workshops also included participatory scenario planning to help participants integrate research findings and local knowledge while thinking about the future of their communities and landscapes.

Communicating research findings to practitioners and policymakers also took a variety of forms, including policy briefs, annual meetings with policymakers, a national policy workshop, and continual informal engagement with key donors, NGOs and policy stakeholders. Many practitioners also attended the 2015 conference. One Mongolian MOR2 core team member became a key liaison to policymakers and a sought-after television talk show guest. Another took a high-level post in the Ministry of Environment. A Mongolian student who earned her Ph.D. on the project was subsequently hired by a major donor/NGO in Mongolia to head their Resilient Communities project, an initiative partially inspired by the MOR2 project findings. Another former Ph.D. worked with The Nature Conservancy's Mongolia program to develop a community-based conservation project.

A persistent challenge was the turnover of Ministry leadership and staff. NGO/donor organization staff tended to be much more stable over time, facilitating enduring collaborative relationships. The project ended in 2015, and as MOR2 research continues to reach publication, the team finds that some results have catalyzed broad discussions in the donor and practitioner communities about policy needs. This is an important and healthy role that science can play in national policy debates.

6.9 Outcomes and Impacts

The MOR2 project produced important scientific products (e.g., Fernández-Giménez et al. 2018; Jamsranjav et al. 2018; Ulambayar et al. 2017). Here we focus on the transformational outcomes and

impacts of collaboration across boundaries for individuals, the MOR2 team, rangeland management and policy, and the broader practice of boundary-spanning team science. As reflections from both US and Mongolian team members note, participation in this project shaped participants' lives, careers, and how they practice science. This was the case both for students and PIs, as well as participants on the extended MOR2 team. These transformations include enhanced understanding of US science by Mongolians, greater appreciation of herder knowledge by US scientists, and a model of cross-cultural transdisciplinary research design, research team management, and engagement for future research initiatives.

At the team level, the continued engagement by most members of the core team—years after funding ceased—speaks to the relationships formed and the meaningful learning that occurred across disciplines and cultures. In addition to continuing to periodically meet and celebrate as a team, various subgroups that include both US and Mongolian participants are working together on a variety of follow-up or "spin-off" projects, including everything from designing a new study-abroad experience for undergraduates in Mongolia to developing new research proposals. By engaging diverse stakeholders in the co-design of the project, and returning results to research participants, the MOR2 experience serves as an example of a more participatory model of "big science" than is typical in academia.

Impacts of MOR2's cross-sectoral collaborations are visible in Mongolia's policy, international development, and private sector arenas. For example, MOR2 scientific results combined with ongoing engagement with policymakers have influenced the rangeland policy discourse in Mongolia related to proposed new rangeland management legislation. The 2015 Mongolian Rangelands conference, a national policy workshop, and informal consultations influenced a major new initiative in one donor organization: Mercy Corps' Resilient Communities Program. A MOR2 Mongolian postdoctoral fellow is now the Country Director for the Sustainable Fibre Alliance (SFA), an organization advancing sustainability certification for cashmere. The SFA's draft sustainability certification standards for grassland stewardship are informed by results and learning from MOR2. At least one of the Mongolian

research institutes that participated in MOR2 applied lessons in interdisciplinary collaboration and dialog to facilitate team-building across departments within their organization. Four MOR2 student interns from Mongolian universities have gone on to pursue advanced degrees at international universities. Mongolian organizations have replicated MOR2 science capacity-building activities for young researchers, such as training workshops and scientific conferences. Several Mongolian universities have invited MOR2 team members to advise them on curriculum development to enhance interdisciplinary graduate education, and several of the PIs have applied lessons learned from MOR2 to design of graduate and undergraduate curricula at Colorado State University. Although evaluations were positive, it is not possible to know the long-term impacts of the regional workshops on community research participants.

6.10 Lessons Learned and Recommendations

The MOR2 project was transformative in several ways and had a large number of activities and outputs. Nevertheless, several tensions persist and represent key challenges of spanning boundaries across disciplines, sectors, and cultures in a large collaborative research project, and the power relationships inherent in these dynamics. Although the team co-developed a detailed conceptual model, and planned how it would integrate ecological, social, and physical data through statistical and simulation modeling, limited availability of physical data combined with different epistemologies and methodologies hindered the team from carrying out the proposed modeling.

From its inception in 2008, the MOR2 team was committed to engaging stakeholders from all sectors and doing solution-oriented science that would be meaningful, useful, and credible. Likewise, the team was committed to data sharing with the extended MOR2 team of Mongolian research partners. However, the team experienced tensions between providing access to data for all Mongolian partners, while ensuring that US standards of scientific quality and inference were met. The MOR2 team feels it is important to acknowledge, and

not to minimize, these and other fundamental challenges of collaborating across disciplinary, cultural and sectoral boundaries. We close this chapter by reflecting on both "what we did right"—the strategies and practices, whether deliberate or emergent, that helped us to address and partially overcome these challenges—and "what we would do differently"—how we would operationalize our lessons learned with additional or different approaches if we were to embark on a new collaboration across boundaries.

6.10.1 What Did We Do Right? Strategies That Worked in MOR2

Individual and collective team reflections reveal deep levels of respect, trust, and care among core team participants and many extended team participants. Despite inevitable frustrations and power dynamics, interpersonal relationships among team members were overwhelmingly characterized by a culture of mutual support and reciprocity in matters both personal and intellectual, rather than a culture of competition focused on individual gain. Several factors and strategies likely contributed to this culture.

First, MOR2 emerged from a long-term research collaboration and friendship between the US PI and a Mongolian core team member. This foundation of trust and reciprocity, deep knowledge of place, and mutual boundary-spanning across cultural, linguistic and disciplinary differences, served as a model for the wider team as it evolved. Crucially, the core team involved multiple individuals who were able to serve as boundary-spanners across disciplines, sectors, and/or between Mongolian and US cultures and languages.

Second, trust is built in part upon the willingness of individuals to be vulnerable, and on opportunities for repeated interactions over time. The initial team trip to Mongolia in 2008 involved pre-trip conversations and a week-long field trip which helped solidify core team relationships and develop new relationships with Mongolian partners through repeated informal interactions in the field such as shared meals, drives, field trips, joking, and spontaneous adventures. This emphasis

on communication and rapport continued throughout the project, with monthly team meetings that evolved into monthly day-long analysis and writing retreats, cultural celebrations, and social interactions. The writing retreats were important for facilitating informal interactions that advanced integration and synthesis across disciplines and project components, and also allowed graduate students to observe intellectual vulnerability and collaboration among senior scientists, making more transparent the messy process of interdisciplinary science.

Third, the team was deliberate in building in a culture of reflexivity and focus on team process from its inception. The inclusion of a "science of team science" collaboration expert as a PI on the project reflected this commitment, which the team operationalized through regular informal and formal reflections as individuals and as a team. Producing high-quality scientific results was paramount, but the team was committed to an inclusive process in which all participants felt ownership and belonging on the team. In this regard, MOR2 prioritized process over product in the short term, by investing significant effort in developing relationships and maintaining an inclusive process. Over the longer term, the investment in process led to high-quality scientific results and meaningful broader impacts beyond the project lifetime. The foundation of trust and practice of facilitated reflection enabled team members to discuss openly significant tensions around interdisciplinary communication and power dynamics that might otherwise have festered and undermined team functioning. Similarly, the team openly discussed and developed explicit written policies for data use, sharing, and authorship, which helped advance a culture of collaboration rather than competition within the team.

Fourth, building on this reflexive practice was the core team's willingness to listen and to adapt in response to feedback from various members of the extended team. The team's emphasis on re-engaging practitioner/herder communities through regional workshops at the end of the project, and the decision to organize a major conference in Mongolia, both emerged from reflective feedback from Mongolian boundary-spanners and partners.

In addition, MOR2 was committed from the outset to collaboration across sectoral boundaries. Although the spatial dispersion of study sites

and the scope of the project precluded true participatory research relationships with all study communities, a broad group of stakeholders co-designed the MOR2 project to respond to their questions and needs. The initial research planning meeting in 2008 laid a critical foundation for everything that came afterward. Similarly, the team's dedication to ensuring that data were returned to communities, practitioners, and policymakers in a variety of forms, including face-to-face workshops and consultations, policy briefs, and other media, helped deliver on the promise that the scientific findings were available, understood, and applied beyond the research arena.

Finally, although interdisciplinary integration remained a challenge, especially between physical science and the social and ecological components, several strategies and practices facilitated this endeavor. First, team members of all disciplines co-developed the project conceptual model and overall research design, which avoided depicting any of the major subsystems (physical, ecological, social) as a "black box." Second, MOR2 collected, organized, and stored data in a manner that allowed the incorporation of quantitative physical, ecological, and social datasets into integrated databases at different spatial scales for analysis. Third, although the integrated modeling that MOR2 originally planned was not possible, the team remained open to exploring a variety of alternative approaches to synthesizing across disciplines and system components, including novel quantitative analyses of herder observations, remote sensing and climate data, and qualitative approaches such as thematic literature review and participatory scenario planning.

6.10.2 What Would We Do Differently? Recommendations for Future Transdisciplinary Cross-Cultural Projects

Much of what we would do differently pertains to investing even more time at the inception of the project and team formation in activities to foster mutual understanding and communication across disciplinary and cultural/linguistic boundaries. For example, the team might have avoided some challenges of interdisciplinary integration had we spent

more time (1) on understanding each discipline's epistemologies and methodologies, and developing and sharing detailed discipline-specific conceptual models, and (2) in the field together as an interdisciplinary team during the research design process. For example, had we done a pilot sample and analysis under US conditions, we might have anticipated some of the challenges we would face under Mongolian conditions. We might also have thought more deeply about how the physical, ecological, and social data would fit together for integrated analyses. We also recommend a "data review" early on to avoid incorrect assumptions about data availability.

With regard to the challenges of cross-cultural collaboration in MOR2, we recommend building in language training and cultural immersion for the US team members, in order to increase the quality of communication and reduce the burden on Mongolian boundary-spanners. We also recommend recognizing from the inception of the project the critical role of cultural and linguistic boundary-spanners, making sure to clearly specify and acknowledge this role at the outset, and providing cultural boundary-spanners with necessary resources to enable them to be effective. These resources might include external translators and time and funding to develop glossaries of key terms, and to work with both US and Mongolian scientists to construct a shared vocabulary in both languages.

Finally, although MOR2 leaves a legacy of a unique multidisciplinary database, some of which is currently publicly accessible, we recommend allocating more resources to professional data management, including quality assurance/quality control, data organization, metadata, and long-term storage and access options. If we were starting over, we would design an integrated database including ecological, social, and hydro-climatic data from the beginning.

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7

Challenges of Boundary Crossing in Graduate Training for Coupled Human-Natural Systems Research

Elizabeth G. King and Nathan Nibbelink

7.1 Introduction

Research to understand the dynamics of coupled natural and human systems (CNH) entails boundary crossing work and collaborative challenges in multiple arenas. Perz (2016)[1] distinguished three main classes of boundary crossings in conservation and development projects; they arise as collaborators come together from different communities whose identity is related to (1) academic discipline, (2) realm of practice, and (3) culture and/or geographical location. While not all CNH projects address conservation or development per se, many of the same classes

[1]Throughout the chapter, when we make attributions to Perz, they are drawn from (Perz 2016), with page numbers cited where appropriate.

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of boundary crossings occur. First, an *interdisciplinary* research agenda requires bridging boundaries between academic disciplinary domains. Second, *transdisciplinary* research engages academic researchers and non-academic partners, with boundaries to be crossed between them. Thirdly, when CNH research entails empirical study, there are *cultural and/or geographic* divides between the research community and the stakeholders within the study system, which may add to the challenges of collaboration across other boundaries.

In each class, boundaries exist because there are varying degrees of divergence in the objectives, beliefs, and norms of practice held by people from different interacting communities. Perz identifies a set of seven challenges that arise when participants come from different disciplines, communities of practice, or geographical contexts. Perz also argues that there are common strategies that can help mitigate those challenges as collaborations begin, take shape, and progress to increase the advantages gained as a result of partners' complementarities. In the majority of projects funded under the National Science Foundation's (NSF) CNH program, academic researchers mentor graduate students to become effective scholars and practitioners in the realm of CNH teams. But faculty and graduate students, as well as project coordinators and university administrators, also have different objectives, beliefs, and norms of practice. As such, many of the same boundary-crossing challenges arise. In this chapter, we explore how Perz's seven challenges are manifest in the academic research/training environment. With that as our aim, we do not focus on the interdisciplinary research agenda in our CNH project in Kenya, nor on the transdisciplinary and cultural/geographic boundary crossings we navigated. Instead, we focus on an interdisciplinary graduate training program at the University of Georgia (USA), called the Integrative Conservation (ICON) Ph.D. Program, which provided the academic context for our CNH project.

The ICON program was developed by social and natural science faculty specifically to provide PhD-level training in the craft of interdisciplinary, transdisciplinary, and culture-spanning research (Welch-Devine et al. 2014). A prominent goal of the program is, therefore, to train what we call "agile scientists"—scholars and practitioners who can navigate the challenges of boundary-crossing collaborations. We highlight

that there are boundaries and challenges *within* academia which must also be navigated in order to train agile scientists.

We begin by outlining some distinctions between different approaches to CNH research, which have bearing on goals and approaches to graduate training for interdisciplinary research. First, we disaggregate three aspects of interdisciplinary research that tend to get lumped together under the banners of "disciplines," namely: what academic traditions are employed (disciplines), what is studied (research topics and domains), and how knowledge is created (epistemology). We argue that these distinctions are important because interdisciplinary projects and graduate training programs may focus on these dimensions differentially. Then we discuss different models for *individual collaborator engagement* in interdisciplinary boundary-crossing. These models pose distinct challenges for the research endeavor and for graduate training. This is followed by a synopsis of the ICON Ph.D. program, including an explanation of its goals in terms of the types of boundaries students are challenged to cross, the models of individual engagement students may utilize, and the pedagogical design of the program for achieving those goals. This sets the stage for the remainder of the chapter, in which we discuss intra-academic boundary-crossings, noting the ways that Perz's seven challenges can manifest in the realm of graduate training for CNH research, followed by a discussion of the ways that the ICON Ph.D. program seeks to navigate them.

7.2 Interdisciplinary and Inter-epistemological Ways of Coupling Natural and Human Domains

The NSF CNH program prioritizes the generation of knowledge about the dynamics of complex systems through interdisciplinary research. Recent solicitations have further specified that proposals must explore: (1) dynamics within the natural systems (NS) domain, (2) dynamics within the human systems (HS) domain, (3) processes by which NS affect HS, and (4) vice versa. Since the research domains associated with

different disciplines have traditionally fallen within either NS or HS, linking NS and HS is typically achieved through an interdisciplinary approach. However, the CNH criteria for NS and HS components refer only to topical domains, leaving open the question of which disciplines' theories and methods to employ, and which epistemological perspectives to adopt.

Although the concept of an academic discipline is not precisely bounded, it generally refers to a research domain with a defined body of theory and some common methodological approaches. Importantly, disciplines are also often associated with certain epistemologies, or philosophical perspectives and assumptions about appropriate and valid ways to gain knowledge about a system/object of study. Here we note a key asymmetry: NS disciplines tend to be distinguished by the study subject, yet are by and large founded on a common epistemology, objectivism. This refers to the idea that because an objective reality exists independent of the observer, we can gain objective, verifiable, generalizable knowledge of it through deductive analysis of empirical observations. An important consequence of the shared epistemological basis of NS-oriented disciplines is that they tend to be commensurable, in that they generate similar kinds of understandings about subjects of research. Meanwhile, HS disciplines such as anthropology, sociology, and human geography may have strongly overlapping study subjects, but may adopt any of several epistemological approaches ranging from objectivism to subjectivism. Subjectivism is the idea that reality exists through individuals' subjective perceptions of it, which are influenced by and reflect feelings, emotions, values, and cultural context. Research builds knowledge inductively to understand how people ascribe meaning to their world, and it is contextually unique rather than generalizable. Objectivism and subjectivism are ends of a spectrum of divergent epistemologies, with many more nuanced schools of thought in between (Evely et al. 2008; Moon and Blackman 2014). HS-oriented disciplines, with their diverse epistemologies, can offer quite disparate or even competing understandings of the same subject (Lélé and Norgaard 2005).

We draw attention to epistemologies because they are a frequently-overlooked, often implicit, dimension of the intellectual commitments that shape, narrow, and legitimize research approaches within

disciplines. Yet precisely because they are so fundamental, and rarely articulated or questioned within a given field of inquiry, they can present some of the most challenging barriers in interdisciplinary research (Eigenbrode et al. 2007; Evely et al. 2008; Miller et al. 2008; Moon and Blackman 2014). Many researchers are not consciously aware of their epistemic[2] commitments, how they may differ from researchers from other disciplines, or that knowledges produced may not be commensurable (O'Rourke and Crowley 2013). Disciplinary commitments form over the long course of academic training and practice. It is therefore not surprising that seasoned scientists may be leery or even dismissive of differing perspectives on what constitutes valid science or important research questions (Eigenbrode et al. 2007). Natural scientists rarely have to characterize or justify the philosophical foundations of what constitutes knowledge and evidence in their disciplines, because (1) objectivism is a common underpinning for their scholarship, and (2) it enjoys privilege as the dominant basis for inference in society and policy (Murphy 2011; Brister 2016). Furthermore, as Miller and others (2008) noted, "the applied nature of much interdisciplinary work minimizes reflexivity regarding the role of epistemologies, the importance of process, the nature of uncertainty, etc. Such issues are perceived as inconsequential or secondary to the more immediate concern of producing 'hard' knowledge." Whether due to lack of awareness, unequal epistemic authority, or low prioritization, interdisciplinary teams often do not openly address and establish a plan for dealing with epistemic divergence, which can pose substantial communication barriers and compromise the team's ability to achieve its goals (Eigenbrode et al. 2007). Overcoming these epistemic boundaries therefore requires not only learning and communication but also intentional reflexivity and a commitment to pluralism (Miller et al. 2008; Popa et al. 2015). As Lélé and Norgaard (2005: 970) aptly advised, "Natural scientists need to expect to take considerable time learning the cultures of the different

[2]While commonly used interchangeably, we have tried to use the adjective "epistemological" only when referring to the study or philosophy of knowledge acquisition, and otherwise use the (much shorter) adjective "epistemic" when referring the act or process of knowledge acquisition, rather than the formal study of it.

social sciences if they are even to think about how to put together or join an interdisciplinary team, let alone actually work with the social science members of the team." We add to this that social scientists must be prepared to explain their epistemic perspectives without assuming that their NS-oriented counterparts will readily grasp the implications. This challenge can usefully be addressed in graduate training programs that prepare future researchers to effectively communicate their epistemic perspectives, recognize the value of different approaches, and work fluently across those different perspectives. The ICON Ph.D. program was specifically designed to train scientists to span inter-epistemic boundaries, as this is one of the most problematic challenges of interdisciplinary work (Miller et al. 2008; Fortuin and van Koppen 2016).

Not all interdisciplinary projects or team members grapple with spanning inter-epistemic boundaries to the same extent. In CNH research, applying an objectivist approach to both HS and NS can serve as a convenient common denominator for addressing the required four research components. This can reduce epistemic tensions and yield more commensurable NS and HS data. Yet this approach substantially limits the scope of inferences that can be made regarding HS, and the contributions that social sciences can make to interdisciplinary inquiry. In the case of CNH research, we feel that subjectivist inquiry is critically valuable. We know that different people perceive the world differently. As humans act to influence NS dynamics, people's decisions and behaviors are guided by how they perceive, understand, and value the elements and processes in NS. Thus, understanding how people ascribe meanings and values to things in their world helps us understand human–environment interactions. This knowledge can illuminate potential blind spots and unanticipated consequences that have in the past arisen when research includes only natural science and economic perspectives. The trajectories of conservation and sustainability science indicate a growing demand for broader understandings of problems that are not attainable from single epistemic perspectives (Brister 2016).

7.3 Modes of Individual Engagement in Interdisciplinary CNH Research

Interdisciplinary projects can be structured so that individual researchers can contribute in different ways. We consider three different models for boundary crossing, which vary in terms of the scope of individual roles on research teams. Distinguishing the range of individual roles is useful because the challenges and strategies for boundary crossing are different in each model, and different types of training are appropriate for different roles. NSF CNH projects must cross NS–HS boundaries, but these models also apply to individuals spanning other disciplinary boundaries.

In the first model, individuals work within their own discipline, and employ practices to link their research products conceptually at the planning stage, and practically at the analysis stage. Interdisciplinary research questions get addressed by individual team members who communicate and share data across disciplinary boundaries (Fig. 7.1a). This process may be straightforward when studies in different disciplines share a common epistemological approach. Integrating knowledge produced by inductive inference can be more challenging, especially if partners are unfamiliar or unaware of other epistemologies. In studies of interdisciplinary projects that adopted a data sharing model, a lack of appreciation for epistemic differences presented a major barrier to knowledge integration (Eigenbrode et al. 2007; O'Rourke and Crowley 2013). When partners have breadth of knowledge in disciplines that are rooted in different epistemologies, this facilitates the process. This model is similar to Uhlenbrook and de Jong's (2012) aim of "T-shaped competency" in graduate training at the UNESCO-IHE Institute for Water Education, wherein students acquire "vertical" depth in one field, but also "horizontal" awareness or working knowledge across other fields. Duke University's Ph.D. Program in Environmental Policy is another example; students specialize in economics or political science and gain breadth across intersecting disciplines.

In a second model (Fig. 7.1b), individuals adopt a conceptual focus for research that links domains or disciplines, heuristically conceived of

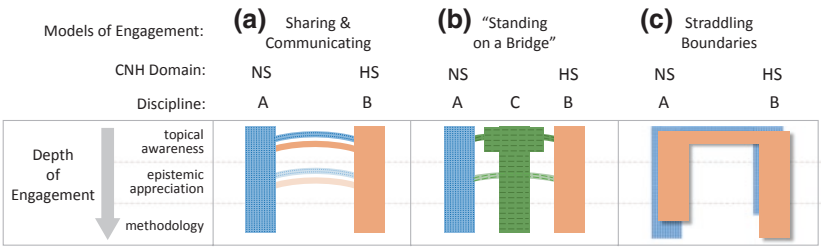

Fig. 7.1 Modes of individual engagement in interdisciplinary research. Colored shapes represent individual researchers, whose scientific approach is aligned to a particular domain (NS or HS) in CNH research, or discipline. Increasing depth of engagement in disciplinary research is represented vertically, from awareness of research topics, to epistemic appreciation, to utilization of methodologies to conduct research. **a:** Sharing and Communicating model: researchers are grounded in the epistemic perspective and methodologies of their own domain or discipline, and mostly connect with other approaches at the awareness level through planned data sharing, though some team members may have deeper appreciation for other approaches. **b:** "Standing on a Bridge" model: the discipline-bridging field has its own epistemic commitments and methodologies, and the researcher (dashed) connects with traditional disciplinary scholarship as in the Sharing and Communication model. **c:** Straddling Boundaries model: researchers have depth of knowledge in more than one discipline, and use theories and methodologies from both to conduct research (*Source* Figure created by the authors) (Color figure online)

as "standing on a bridge". For example, the emerging field of ecosystem services is positioned as a linking discipline. Also, resilience theory provides a systems-based framework for inquiry to study the interactions and feedbacks in social-ecological systems. However, the fields also entail their own intellectual and epistemic commitments. With only a few existing programs specifically oriented to a linking discipline, such as the Stockholm Resilience Center's graduate programs, training occurs within the context of other disciplinary and interdisciplinary programs.

In a third model, an individual may participate in research activities in different domains or disciplines, such as a qualitative social scientist who collects ecological data while visiting rural households (Fig. 7.1c). Here individuals straddle boundaries between disciplines. When the disciplines are rooted in different epistemologies, this model requires that individuals appreciate and utilize multiple epistemologies in their own work. Because directly engaging in those research activities provides

experiential learning, we argue this model can help individuals build a deeper understanding of other ways of producing knowledge (Kolb and Kolb 2012), and thereby achieve a greater degree of epistemic pluralism. Furthermore, by engaging in other research enterprises, an individual can learn about other pragmatic and normative intellectual commitments, such as methods, analytical and interpretive frameworks, values associated with different types of knowledge, and standards for writing and publication. This is similar to the recently-described "shield model" of graduate training (Bosque-Pérez et al. 2016), wherein individuals develop more than one area of "vertical" disciplinary depth. While the third model may not be desired by established disciplinary scholars, we see it as exceptionally valuable in graduate training, when students are still developing a suite of intellectual commitments. The ICON program therefore requires students to adopt the Straddling Boundaries model and conduct some component of their dissertation research from a different epistemic perspective than their home discipline, allowing them to experientially gain reflexive appreciation for the gamut of otherwise latent commitments inhered in their own, and other, disciplines.

7.4 Integrative Conservation (ICON) Ph.D. Program: Training Agile Scientists for Conservation and Sustainability

The ICON program was formed to train doctoral students to conduct research and work effectively across three boundaries, between disciplines, organizations, and cultures. Here we outline the goals, structure and training elements of the program designed to foster boundary-crossing capabilities. We then delve into a fourth category of boundary spanning that occurs during the degree-earning process—boundaries between different communities of actors within the university who collaborate in the degree program. In this intra-academic realm, we note strong parallels to the seven challenges that Perz (2016) has described as common elements in boundary-spanning work.

Students enter the ICON Ph.D. program through one of four home units (currently Anthropology, Geography, Ecology, or Forestry & Natural Resources). The ICON graduate affairs committee selects a cohort of 7–10 students in which a balance of disciplinary/epistemological perspectives is one consideration. In each of the home units, Ph.D. students typically enter with their major advisor already determined, and any major professor from the home units can advise an ICON student. ICON students are supported via the same range of mechanisms as others in their home unit: typically through external funds acquired by the student or advisor, or departmental or university-wide assistantships. ICON students basically function like other Ph.D. students in their home programs, fulfilling all the regular curricular elements and degree requirements, with the addition of several ICON-specific elements. The program began in 2011, and currently has 46 students and 13 alumni.

A central training goal for ICON students is to become agile scientists with pluralistic research competence. ICON's approach to this goal differs from many interdisciplinary programs. While the NSF CNH program and many graduate programs promote interdisciplinarity by studying different *subjects or topics* spanning natural and human domains, ICON students are expected to include different *epistemic approaches and methods* in their research. This means adopting a "Straddling Boundaries" model of individual engagement (Fig. 7.1c). Consider for instance, an NS-oriented student studying environmental regulations in an Appalachian mining town. In addition to studying the ecological impacts of water contamination from an objectivist NS perspective, they may also employ a qualitative, more subjectivist approach to the HS by studying ways in which sense of place influences narratives and allegiance-forming in citizen groups. If they instead used household surveys to find correlations between education level, employment sector, and support for environmental regulation, that would satisfy the CNH criteria for studying the HS domain, but it would not meet ICON's criterion of a different epistemic perspective, because the mode of inquiry is still objectivist. Thus, the program's definition of "integrative research" refers specifically to work that uses different epistemological perspectives, rather than different disciplines as defined by subjects/

topics or traditional academic disciplines.[3] Furthermore, the program emphasizes that the processes and outcomes of research from different epistemic perspectives should be regarded pluralistically, respecting the value of different perspectives, even if they are not commensurable. Regardless of whether research from different epistemic perspectives is formally coupled in analysis, students are expected to use reflection to draw insights that would not have emerged if they employed only one epistemic perspective.

The curriculum aims to train agile scientists through required courses, an additional program of study elements, and several "integrative mechanisms" outside of classes. Incoming students take a required two-semester core course sequence, intended to help student cultivate their capacity for integrative research and develop an integrative research plan. Each course is co-taught by one natural and one social scientist. First is a reading and discussion-based course to engage students in the challenges of thinking across epistemological perspectives, with strategic communication exercises to address the challenges of working across cultural divides. The second course is a research practicum, in which the team of students work with stakeholders as clients to address a transdisciplinary research need using multiple research approaches. ICON students also take a minimum of two elective courses outside their home discipline/epistemology. To develop transdisciplinarity and cross-cultural engagement, students' programs of study must include an 8-week internship with a non-academic organization, and they must develop a strategic communication project that complements their research. The program also encourages participation in elective integrative mechanisms such as reading groups, themed brown bag discussions, and workshops with visiting scholars. These are intended to maintain cross-epistemic momentum and dialogue later when students

[3]Interestingly, two of ICON's home unit disciplines, natural resources and geography, are not aligned with the divide between HS and NS domains, and ecology is the only discipline aligned with a single epistemology. This has contributed to the program's careful attention to distinctions between epistemology, HS/NS domains, and academic departments when speaking of interdisciplinarity.

in interdisciplinary Ph.D. programs tend to fall back into more disciplinary spheres of interaction (Hackett and Rhoten 2009).

To facilitate students' integrative focus as they formulate and conduct their integrative research, one of their required 5 dissertation committee members acts as the ICON representative (ICON rep hereafter). The ICON reps are familiar with the program aims and philosophy, and work with the student and major advisor to ensure that the research proposal embraces integration, recognizing that different students will do so to varying degrees and in different ways. In the qualifying exams for candidacy, the ICON reps are responsible for assessment of students' inter-epistemic capacity, reflexivity, and vision for transdisciplinary engagement. The ICON rep must also consider faculty goals for research and mentorship. Faculty recruit Ph.D. students with their own sets of motivations, and embrace interdisciplinary/inter-epistemic research and transdisciplinarity to varying degrees. The ICON rep emerged as an individualized, flexible approach for the program to influence student–mentor relations in order to help achieve a balance between student, advisor, and program aspirations. Faculty who have taught in the core courses, served as ICON major professors, or otherwise demonstrated their understanding and commitment to the program's training mission, especially in terms of epistemic pluralism, serve as ICON reps.

ICON dissertations can be organized under different models. In some, at least one chapter in their dissertation employs a different research approach; others interweave multiple perspectives within chapters. Research is considered "integrative" if it entertains multiple perspectives either through synthesis or through juxtapositioning and reflection on divergent understandings. Students do not necessarily engage in team science as part of their dissertation research, nor do they necessarily develop a transdisciplinary research program though it is encouraged. The transdisciplinary training goals are pursued through the strategic communication component and the internship requirement, where students "walk in the shoes" of non-academic collaborators.

The ICON program also seeks to advance the pedagogy of interdisciplinary graduate training (Welch-Devine et al. 2014). The ICON

curriculum committee, comprised of faculty who have taught in the core sequence or contributed to the program's development, analyzes feedback from students and major advisors on an ongoing basis, seeking ways to strengthen pedagogical outcomes. This has led to ongoing modifications and adjustments in the core curriculum, as well as program policies and integrative mechanisms. Negotiating student, faculty, and program goals is a complex process, with numerous boundaries to cross between different actors and institutions: not only students, major advisors, and ICON reps but also other committee members, home unit graduate coordinators, and off-campus research and internship collaborators.

7.5 Boundary Crossing for Collaboration Within the ICON Ph.D. Program

Our experience is situated at the nexus of ICON's student, faculty, and programmatic goals, along with the research goals of an NSF CNH project. The first author came to UGA specifically to participate in the ICON program and pursue inter-epistemic research, and partnered with another newly hired ICON-affiliated faculty member to develop a successful NSF CNH proposal. The second author served as the ICON program graduate coordinator for 2 years, and now directs the Center for Integrative Conservation Research, which gave rise to the program. Thus, the ICON program has been central to both the evolution of a CNH research project, as well as our experiences in graduate training for boundary crossing. The challenges described by Perz (2016) resonate with our own ICON collaboration experiences and those we have observed, though there are also points of divergence. We offer reflections on the manifestation of those challenges as encountered in the ICON program, and discuss some of our programmatic and pedagogical strategies for addressing them.

One key point of divergence between the context of collaborative conservation research and application that Perz (2016) addresses, and the context of collaboration for ICON graduate training, is his

assumption that collaborators share a common goal and need each other to achieve it. Perz notes that successful collaboration involves commitment, non-competitive behavior, and mutual accountability (p. 4), with a key outcome that collaborators forge "loyalty to each other stemming from the understanding that they are both necessary to achieving said goal" (p. 11). In academia, however, collaborations do not arise only when partners need each other. Some partnerships are mandated through degree program requirements, and there can be profound asymmetries in terms of who needs whom. Service on graduate committees, for instance, often falls outside the range of interdependencies that are typical in collaborative conservation. Rather than mutualistic relationships that benefit each partner, some relationships may be viewed as benefitting one participant, but providing no benefit or even exacting a cost to the other. These asymmetries can exacerbate the challenges of boundary crossing, leading to the issues we describe below.

7.5.1 Introductions and Communication

Perz (2016) identifies introductions as the first key challenge in boundary crossings, emphasizing that effective communication and shared learning experiences help establish mutual understanding as a cornerstone for collaboration (p. 60). The academic community is a large and diverse body in which to identify potential collaborators. Introductions are ongoing, not just for incoming students but also for faculty mentors, and for everyone already associated with the program. We highlight two realms where ICON program elements have been developed to address the challenge of introductions: (1) incoming cohorts of students who establish collaborative relationships with one another and their instructors; and (2) student–advisor-committee introductions that set the stage for the teams that support their academic progress.

In the core course sequence, the cohort of incoming students serves as one another's experiential context and thus the sequence constitutes a training tool for learning about interdisciplinarity, epistemic pluralism, and team science. They learn from, through, and with one another. Thus, their introduction to one another is a significant moment.

For entering students, we hold a day-long orientation before classes start. It begins with the new cohort playing a 3-hour game developed for the ICON program (Epstein and Stein 2014). On the surface, the game is a four-team negotiating and planning exercise with conflicting priorities around shared resources. Its underlying purpose, however, is to stimulate and then reflect on cross-boundary communication. The instructors for the first core course facilitate and observe the game, which provides a structured opportunity to establish a supportive rapport with the students, to witness initial shared experiences to serve as points of reference later, and to observe student personalities and styles of engagement. Introductions begin with the game, but then proceed as a unique, gradual process over the first year of study. Since instructors have a meaningful role in shaping that process, examining our observations of game dynamics and students' written reflections can give instructors ideas for learning moments tailored to the particular cohort, which can be explored intersubjectively over the semester.

Perz (2016) stresses the importance of introductions in framing collaborations and establishing effective, complementary roles among partners (p. 55). We have seen that faculty appreciation for the ICON program's core ideas can facilitate the development of complementary roles and student experiences. We strive to foster that appreciation at the introduction stage. The ICON orientation includes a session for prospective, new, and active advisors, in which we explain the ideas and principles of the program, as well as the degree requirements. If mentors do not attend the orientation, the ICON Graduate Coordinator makes office visits to share program materials and create opportunities for questions and discussion.

The process of selecting the ICON rep has, in itself, two challenging facets relating to introductions. Students are supposed to select their ICON rep by the beginning of their second year, which can feel uncomfortably early, and yet also uncomfortably late. After the first year of study, students have gained a keener understanding of the complexity of the ICON undertaking, and most are struggling with the daunting task of defining an integrative vision for their dissertation. They know the ICON rep will play a key role in guiding and evaluating the integrative dimensions of the student's training. Objectively, it seems advisable

for students to make appointments with more than one faculty member to "vet" them as ICON reps. Yet most students have had limited opportunities for introductions to build rapport with the 15 faculty who can serve as ICON reps. As a result, such "vetting" can be socially awkward, and it is unrealistic to expect students to ask a question like "how well do you get along with my advisor?" Furthermore, students are still at a formative stage, so they are often unsure what qualities would in fact make for a good ICON rep for their project. On the other hand, waiting until students have a clearer sense of their research plans can help them make appropriate choices for an ICON rep. But at this point, the ICON rep is a late-comer in the introduction process, and established commitments can lead to potentially awkward efforts to renegotiate roles, relationships, and research plans. ICON encourages students to approach and meet multiple times with different ICON reps and other faculty early in their program of study, even before their research ideas have fully crystallized. ICON has also placed increasing priority on clearer communication and information-sharing with new faculty mentors, particularly regarding the roles of the ICON rep and the expectation of epistemic diversity on the committee, to reduce the need for renegotiations.

For their part, students appear to use a range of avenues to navigate the challenges of introductions and identify potential committee members: communication with peers, their advisor and ICON reps, the graduate coordinator, and a new peer-mentorship program between continuing and new students that was started by ICON students. Programmatically, we have found few effective mechanisms to more formally orchestrate this organic process at the program level. Every year we offer a team-building exercise on a weekend early in the fall semester, especially for incoming students but the rest of the ICON community is encouraged to participate. Aspirationally, providing more opportunities for shared experiences with more ICON reps outside of individual meetings could open up space for introductions. More strongly encouraging ICON rep participation, or creating another team-building opportunity in Spring, could help ameliorate the introductory tensions. Key barriers are time constraints and faculty priorities.

7.5.2 Inequalities

Perz (2016) stresses the tension between the benefits of complementarity when diverse perspectives are brought together, versus the inequalities in terms of power that are associated with actors from different organizations (p. 56). Academia is inherently hierarchical, with all sorts of inequalities in faculty-student collaborations related to approval, decision-making, intellectual autonomy, etc. For the most part, these hierarchical inequalities are useful as the basis for graduate mentorship. Students can benefit from faculty members' more extensive knowledge, experience, and social leverage. Inequalities can thus be viewed as part of academic culture, though with notorious variability among individual advisors. But when hierarchical inequalities interact with interdisciplinary inequalities, they can affect student training and the benefits that advisors and committee members get out of the collaboration. This meeting-of-inequalities poses challenges in terms of who determines the student's research agenda. For ICON students, the interdisciplinary breadth of their research is a programmatic priority, yet it almost always extends beyond the scope of their advisor's and their home unit's breadth. The advisor may not have the requisite knowledge and experience across disciplines to provide leadership when it comes to selecting courses or committee members, or evaluating student research.

The aspiration is that major advisors will collaborate horizontally with the ICON rep and other committee members in mentoring. But it is important to recognize that doing so in an interdisciplinary context imposes costs and trade-offs for the major advisor. It takes reflexivity and diplomacy, which are all costly in terms of time and energy. An ICON dissertation often produces less disciplinary scholarship, upon which advisors may be evaluated for promotion and tenure. Unfamiliar research modes introduce uncertainty over the progress toward degree completion. In the ICON program, we have seen that benefits tend to outweigh costs when faculty value the process of interdisciplinary training and research, when they receive recognition for offering such training, when committee members are comfortable in deferring to one another's expertise, and thus horizontal collaboration reduces the time and energy costs of advising.

Committees should discuss the amount of disciplinary scholarship to meet advisor and student goals, and work within those constraints to delineate the student's interdisciplinary research agenda. Striking a balance between the disciplinary versus interdisciplinary inquiry will inevitably be influenced by hierarchical inequalities and advisors' mentorship customs. The balance should not, however, be based on epistemological prejudice. When advisors place lesser value on the scholarly contributions of other disciplines, even horizontal collaborations can evolve detrimental inequalities and power dynamics. The core ICON principle of pluralism is a rejection of normative inequality between disciplines. Power dynamics and epistemic bias can combine to limit students' ability to achieve ICON's training goals, so most of ICON's programmatic elements for faculty are aimed at reducing the impact of epistemic prejudice on graduate student experiences. Incorporating reflexivity and intersubjective communication exercises into faculty orientation would likely enhance those efforts, as these approaches have proven instrumental in helping people adopt more pluralistic stances (O'Rourke and Crowley 2013).

7.5.3 Shared Interests and Complementary Capacities

Perz (2016: 69) notes that obstacles arise in clearly framing a problem in terms of common interests, because people on different sides of boundaries may have different understandings of the problem. The objective in ICON training is not to resolve those differences, but instead to acknowledge, engage with, and learn from them. By adopting a boundary straddling approach, students seek to entertain more than one set of meanings regarding their topic. This is different from interdisciplinary training programs that focus on building commensurable knowledge about different domains of a system. Commensurable approaches are certainly valuable for addressing complex issues (NRC 2014). However, when this approach is taken, one epistemological perspective tends to dominate the unified framing (Murphy 2011). Thus we may get a fairly holistic picture of the study system in terms of domains that are explored, but not necessarily holistic in terms of

diverse perspectives that explain those domains. ICON training therefore emphasizes that different ways of knowing need not be reconciled with one another or reduced to a common framing. Rather, epistemic pluralism posits that insights from different ways of knowing can help reveal the complexity of conservation and sustainability challenges. This approach is less tidy, but it is more likely to reveal tensions and otherwise unrecognized trade-offs that can undermine seemingly holistic solutions to complex conservation and sustainability problems (McShane et al. 2011).

Advisors and students may also diverge in their expectations with respect to models of individual engagement. Advisors, committee members, and students may hold different values regarding the desirable depth of engagement in another discipline. Most disciplinary scientists have greater familiarity with the Sharing & Communicating model (Fig. 7.1a), but ICON's training goal firmly prioritizes the "Straddling Boundaries" model. Faculty and student orientation, along with the ICON rep's responsibility to raise the issue explicitly in committee meetings, are instrumental practices for building a shared vision for each student's planned depth of engagement to meet ICON's expectations.

Perz (2016: 99–100) points out that collaborative teams are optimally effective when there is an intermediate level of overlap of individuals' capacities and interests. Team members with similar, overlapping capacities and interests may communicate more easily with one another, yet having team members with different capacities improves efficiency in accomplishing multiple tasks. Figure 7.2a represents this idea by plotting the relationship between degree of overlap among collaborators and collaboration effectiveness. On ICON graduate committees, disciplinary expertise and attitude toward interdisciplinarity represent types of capacities and interests that influence the collaboration, and optimal levels of each can be considered from the point of view of the advisory committee or the student.

In terms of the disciplinary scope of the committee (Fig. 7.2b), high overlap is suboptimal for everyone because diverse expertise is needed for advising across ICON students' various lines of inquiry. For committee members, the curve is similar to that suggested by Perz (Fig. 7.2b, dashed line). A lack of disciplinary overlap not only poses

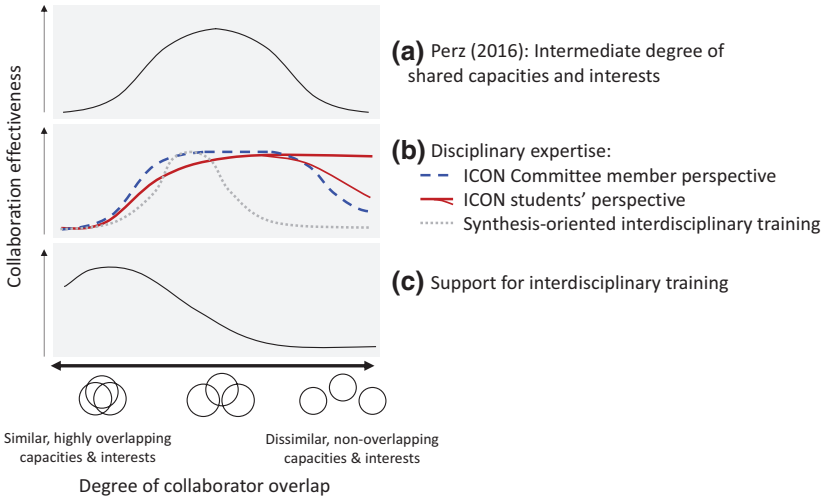

Fig. 7.2 Conceptual plots of collaboration effectiveness resulting from with varying degrees of overlap in disciplinary expertise (a and b) or support for interdisciplinary training (c). **a:** Perz's argument that an intermediate degree of overlapping capacities and interests is optimal for maximizing collaboration effectiveness. **b:** Collaboration effectiveness curves may be different for ICON students (solid) and committee members (dashed), but for both, greater dissimilarity can be effective because the ICON rep can help span communication barriers. When the goal of collaboration is knowledge synthesis (dotted), the optimum shifts toward greater similarity in expertise, and has a narrower peak because research products must fit into an overarching framework. **c:** When considering support for interdisciplinary education, a generously overlapping degree of shared commitment is always valuable (*Source* Figure created by the authors) (Color figure online)

communication barriers, but may be demotivating if they feel intellectually isolated, and may reify epistemic inequalities. From the student's perspective, the effectiveness of highly dissimilar committee expertise may vary (Fig. 7.2b, solid lines). It has proven valuable to students who felt that immersion in a different research approach, detached from their home discipline, enhanced their appreciation for that approach. For other students, too little overlap has led to difficulties resolving conflicting advice. For committee members and for students, the ICON rep facilitates shared understandings across non-overlapping epistemic approaches, thereby increasing the degree of dissimilarity among

committee members that can still be effective. We contrast the ICON scenario to the expected shape of the collaboration effectiveness curve when the goal is to produce commensurate knowledge for synthesis in a unified analytic framework (Fig. 7.2b, dotted line). This is the goal of NSF's Convergence Research theme in the natural sciences (NRC 2014), as well as many CNH projects. In order to balance overall scope and commensurability, effectiveness would be optimized by a greater degree, and narrower range, of disciplinary overlap. Different interdisciplinary training programs are likely to have different optimal degrees of overlapping expertise, according to the goals and forms of interdisciplinarity they pursue.

In terms of attitude toward interdisciplinarity (Fig. 7.2c), there is clearly an advantage for strong overlap among team members in terms of their support for interdisciplinary training. Given that interdisciplinarity can take many forms, having team members familiar with different approaches can expose ICON students to a range of possible ways to contribute to interdisciplinary research. Thus, some degree of divergent attitudes can increase collaboration effectiveness. While engaging with those who do not value interdisciplinary research as a valuable learning experience, we see divergent support for the ICON endeavor as increasingly disadvantageous for students. It can make the already complex terrain of hierarchical and epistemological inequalities even more difficult to navigate, and compromise the student's ability to achieve their interdisciplinary objectives.

7.5.4 Goals and Objectives

In discussing challenges associated with setting goals and objectives, Perz (2016: 71) notes that collaborations should not necessarily begin with an agreement. Instead, goals evolve as collaborators negotiate while taking into account internal and external constraints and opportunities (pp. 71–72). This aptly describes the way in which ICON students approach the programmatic aspirations of their transdisciplinary research. The aims of transdisciplinarity training are twofold: (1) making scientists aware that their understanding of the topic is not the only

way (Popa et al. 2015); and (2) building skills necessary to engage effectively and inclusively with non-academic collaborators (Murphy 2011; Lang et al. 2012; Fortuin and van Koppen 2016).

ICON training for transdisciplinarity entails procedural and cultural boundary crossings within the academic milieu. Transdisciplinary research is not a typical format for dissertation research in the ICON home units (though it is more common in Forestry & Natural Resources). The majority of dissertation projects are developed through the traditional process, which originates on campus as students, advisors, and committee members craft a project to meet the diverse interests noted under the previous challenge. Adding in "deep transdisciplinarity," whereby initial ideas for projects are coproduced with non-academic partners, can be disruptive or incompatible with program-specific practices for student recruitment and for defining the dissertation research plan. Culturally, academic collaborators may view the value of transdisciplinary research differently. Home units, advisors, and students themselves may see the extra effort of transdisciplinary work as an extraneous distraction and unwelcome complication to their research and training priorities, while others see stakeholder engagement as a paragon for their research agenda.

ICON's programmatic efforts to promote transdisciplinary training respect the diverse values held by the different partners. ICON has no formal requirements or guidelines for transdisciplinarity in student research. Instead, it has a sequence of four required components intended to encourage reflexivity and build skills for transdisciplinary engagement. The first component occurs in the first core course, where students read and reflect on literature regarding transdisciplinarity, work through a number of exercises that reinforce the need to listen and understand other ways of thinking, and learn to communicate their own ideas to diverse partners. The second is in the core practicum course, which is an exercise in transdisciplinary team research with cohort members and non-academic stakeholders. The third is an internship with a non-academic organization, where the experience is intended to give students direct experience "walking in the shoes" of practitioners outside of academia. The fourth is the strategic communication component, where the student engages in some activity that

involves two-way communication and learning among stakeholders or non-academic audiences, and creates some product based on that engagement.

While they vary in the degree to which they pursue transdisciplinarity, we have found that ICON students develop mature, reflexive appreciation of sensitive transdisciplinary issues, recognize their own strengths and weaknesses, and many find meaningful ways to enhance their research through transdisciplinary practice. In light of the ICON program's training aspirations, the current mechanisms seem to strike a needed balance in offering training, allowing individualized degrees of transdisciplinary pursuit, exposing an increasing number of advisors to the desirability of transdisciplinary work, while not forcing students to cross institutional and cultural boundaries that may not be feasible in their research.

7.5.5 Leadership, Governance, and Management

Governance, leadership, and management serve to ensure that all collaborating partners fulfill their roles in a consistent, predictable way in order to achieve agreed-upon goals (Perz 2016: 75–77). In the ICON program, however, the goals of students are heterogeneous and evolving, with many governance and leadership processes deferred to home units and advisors. Consequently, governance is not coordinated in ways that one would find in a multinational conservation project. Instead, the emphasis of ICON governance and leadership is focused on sustaining overall program function through continuous negotiation with other units in the university community, while also maintaining the program's agility to deal with diverse student trajectories and inevitable surprises. In this context, we have found that the most salient challenges for leadership, governance, and management are not issues of responsibilities, accountability, and efficiency, but are instead the cultivation of relationships with home departments and administrative units so the ICON program can function flexibly in response to diverse situations and changing conditions.

These are themes emphasized in the literature on adaptive governance (Folke et al. 2005; Adger 2009; Armitage and Plummer 2010).

We therefore use adaptive governance as a lens through which to examine the ICON program's governance, leadership, and management. Thought and practice concerning adaptive governance is grounded in the concept of resilience, the capacity to incur external shocks and maintain system function (Walker et al. 2004). In theory, resilience is improved when governance structures and processes (1) are themselves flexible and responsive, (2) work to build and share knowledge across different organizational levels and stakeholders (social and organizational learning), (3) incorporate updated knowledge into decision-making (adaptive management), and (4) foster social networks and relationships that support the above processes (social capital).

The governance system of the ICON program seeks to sustain its functioning on two levels: maintaining "internal resilience" for delivering integrative training to diverse students, and maintaining "external resilience" to ensure the viability of a small, unusual Ph.D. program, interfacing with diverse departments and operating within a large state university system. Internal resilience is facilitated by a small governance structure that allows deliberate efforts to be responsive. The main governing committee includes all ICON reps and past and present core course instructors. Collectively, the governing committee has direct knowledge and experience with every student, major advisor, and dissertation committee in the program, as well as every version of the core courses that has been taught. This is extremely useful for organizational learning in order to respond to new situations and make programmatic adjustments.

The ICON rep policy is perhaps the program's most significant innovation for adaptive governance. It does, however, present challenges in terms of leadership. Each ICON rep acts individually as they represent the program's training goals on student committees. Reps must negotiate their leadership role with the advisor, which can require diplomacy and care to build trust and navigate power dynamics. As students choose an ICON rep, they must form a relationship that legitimizes the rep's leadership role. Furthermore, the individuality of ICON reps and student projects leads to variability in rep guidance regarding the degree of integration expected in dissertation projects. Students in the program therefore tend to struggle with the question of "is my project integrative

enough?" Anxieties can be compounded when they learn that their peers are receiving different advice from their ICON reps. We have sought to address this issue by holding more frequent, in-depth discussions to clarify, debate, and build consensus around the principles that guide ICON reps, and by continuing to refine and update guidance and policy documents. Our aspiration is to give students confidence that ICON reps are adhering to the same principles, even if their leadership styles and individual recommendations may vary.

Adaptive governance for external resilience is heavily predicated on maintaining and cultivating social capital. This entails building and encouraging trust, respectful communication, and mutually supportive attitudes between ICON program leaders and participating unit heads, graduate coordinators, deans, and other university administrators. The ICON program's organizational structure is unique within the university, so there are no other examples or precedents to refer to when making decisions or establishing agreements with other campus units. The resilience of the program depends on its leadership being pluralistic, cooperative, persuasive, patient, and creative as they deal with other administrators, recognizing that those administrators are themselves often negotiating conflicting mandates. By building social capital with the individuals in administration, this strategy promotes organizational learning and encourages responsiveness and flexibility.

7.5.6 Expectations and Benefits

In the context of boundary-crossing conservation projects, Perz (2016: 81) notes that many partner expectations regarding responsibilities and benefits are implicitly held and can be uncomfortable to discuss openly. However, there are myriad pitfalls that can be avoided if partners go through the effort to sit down and make everything clear. Negotiating expectations and benefits between advisors and students is a longstanding issue in graduate training writ large, and the situation of disciplinary major advisors mentoring interdisciplinary students can complicate matters. Students have five sources of expectations to negotiate: their own aspirations, their advisor's, their committee members', their home

unit's programmatic requirements, and the ICON program's training objectives. Here, we focus on two salient challenges that arise from the ICON program itself: expectations about "integrativeness" and its benefits.

Students struggle with understanding and setting goals regarding the epistemic pluralism and reflexivity entailed in the program's definition of the word integrativeness. This is in part because it is intentionally open-ended and conceptual rather than specific or concrete. That said, students receive extensive mentorship to help them decide how to achieve integrativeness in their work. Students undergo a semester of dedicated instruction, including research proposal development exercises, and a semester of mentored, self-reflexive experiential learning to appreciate what transdisciplinary team research involves. The ICON student handbook contains a three-page section that discusses core principles of plurality and reflexivity, and provides guidance for how those principles can be practiced in integrative research, by: drawing on different epistemological theoretical framings, employing mixed methodologies, engaging in transdisciplinary communication, and linking research to practice. The program leadership has thus outlined practices for integrativeness while resisting the specification of benchmarks. Integrativeness is thus conveyed as an aspiration for which students develop a vision, which can take many forms, including new innovative forms.

Another challenge that arises from ICON's expectations is whether students will benefit from their investment in developing interdisciplinary expertise. There was perhaps a time when the majority of ecology, natural resource, anthropology, and geography Ph.D. recipients went on to academic research careers. National statistics clearly show that it is not the case today (Weissmann 2013; Larson et al. 2014; Kolata 2016; National Science Board 2016). Some faculty worry that there are no jobs for people with interdisciplinary Ph.D.'s; others may place a lower value on interdisciplinary science and training. Thus, program representatives and administrators need to proactively share information about the benefits that ICON students can expect. Jobs for people with interdisciplinary conservation and sustainability expertise, both within and outside of academia, are in rather high demand, as a recent review

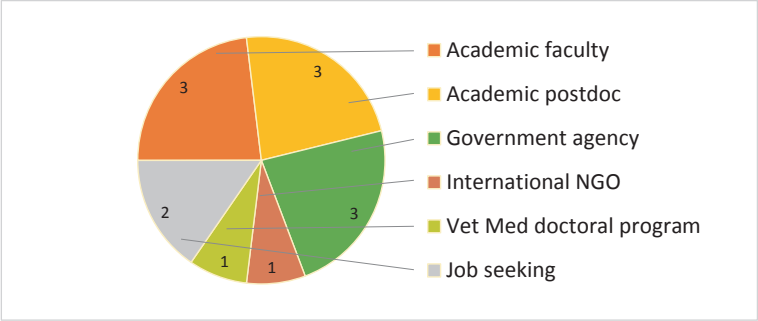

Fig. 7.3 Career placement of the 13 ICON program graduates to date (*Source* Figure created by the authors)

of the global conservation job market documented (Lucas et al. 2017). Another recent article further argued that universities should regard the real-world need for interdisciplinary and transdisciplinary scientists as a mandate for better training to provide the needed workforce (Schwartz et al. 2017). Both articles mentioned ICON as a leading program for today's conservation workforce demands. ICON has graduated 13 students from 2015 to the present; 6 have successfully attained academic positions, and 5 non-academic jobs, in the sectors they pursued (Fig. 7.3). These outside perspectives and placement trends are valuable talking points to build shared respect, buy-in, and enthusiasm regarding the benefits of ICON training.

7.5.7 Surprises and Uncertainty

Multi-partner projects need solid planning, as well as mechanisms to make adjustments in response to change and surprises. In the case of boundary-crossing collaborations, Perz (2016: 84) notes the challenge of making coordinated adjustments. Because of webs of interdependencies among partners, adjustments by one partner may have cascading effects on others. Here we discuss surprises and uncertainty in the ICON program with regard to student programs of study and the program's broader institutional context.

All Ph.D. students deal with surprises and uncertainty as they progress toward their degree. Given that the ICON program takes an exceptional amount of effort to coordinate, one may expect making ad hoc adjustments to be particularly tricky. Interestingly, that has not been the case. We reviewed our list of current students and graduates, and did not identify anyone for whom adjustments in response to surprises were more complicated because of the ICON program's boundary-spanning challenges. It is possible that because advisors and committees are typically well aware of the added complexity of ICON dissertations, they may be more flexible and accommodating when surprises necessitate adjustments. In comparison to collaborative conservation projects, graduate training collaborations can be highly asymmetrical in terms of who needs whom. If students and their committee members are not so strongly mutually interdependent, this may reduce the cascading complications that tend to make coordinated adjustments more problematic.

The story is quite different in terms of the uncertainty and surprises that challenge the program at an institutional level. ICON is enmeshed within a complex institutional environment, and requires coordination through extensive and unique arrangements between departments and administrative units. Because of the program's novel structure, many of those arrangements have no previous precedent, and when surprises and uncertainties arise, they must be addressed via interactions with individual administrators. Administrative turnover has thus greatly complicated matters. In the seven years since the program's inception, we have had three different provosts, two different graduate school deans, and seven different unit heads plus various changes of graduate coordinators in the four participating units. Uncertainty thus stems from the fact that new actors vary in terms of their disposition to support ICON's mission, necessitating repeated introductions to rebuild social capital and ensure adaptability. When administrators change, especially upper level administrators, it tends to affect ICON's other partners as well, raising the challenge of making multiple coordinated adjustments.

In the adaptive governance literature, Olsson and others (2006) stress that capacity to navigate such periods of transition can be built in advance of inevitable surprises and changes, even if the nature of

those changes is uncertain. Specifically, they highlight key factors for preparing for change: awareness of existing problems through knowledge building, identification of new opportunities and available solutions through networking, and agile leadership to implement adaptive measures. These are all manifestations of an organization's social capital. Our experiences of navigating uncertainty and surprises corroborate the importance of these factors in achieving coordinated adjustments. Thus far, the proactive efforts to cultivate social capital, along with the establishment of more precedents through time, have helped the program to navigate the challenge of administrative changes and surprises to keep the program on a fairly steady course.

7.6 Conclusions

Our chapter focused on intra-academic challenges in ICON, a Ph.D. program that specifically aims to provide students with skills needed to work effectively across multiple types of boundaries. ICON's curriculum promotes not just interdisciplinary work by featuring a pluralistic inter-epistemological approach to span the human and natural domains of coupled systems, but also transdisciplinary training to engage non-academic stakeholders and foster communication skills in conservation practice. As program leaders, faculty, and students engage with the ICON program, they negotiate challenges that resonate with the seven themes outlined by Perz (2016).

Using Perz's (2016) seven challenges as a lens to evaluate the ICON program's challenges, we highlight strategies that have proven useful thus far, and identify ongoing issues and aspirations to better equip our trainees to be agile scientists for careers in conservation and sustainability (Table 7.1). With regard to introductions and communication, the ICON program uses a range of facilitative mechanisms, including a specifically-designed role-playing game. Introductions are also key for students as they seek to build an effective collaborative team for their committee. Programmatic efforts to provide sufficient opportunities for diverse faculty and students to get to know one another is an ongoing challenge. Inequalities in authority are inherent to graduate training,

Table 7.1 Summary of the seven issues identified by Perz (2016) as challenges in boundary-crossing collaborations; the manifestations of those challenges in the intra-academic context of the ICON Ph.D. program; the desired outcomes of those challenges; and the strategies and program elements that have been instrumental in addressing them

Issue	Manifestation of challenges in ICON program's intra-academic context	Desired outcomes	Programmatic and pedagogical strategies currently employed
1. Introductions and communication	a. Setting a collaborative stage for the incoming student cohort	a. Introduction processes and communication that encourage reflexivity and build respectful collaborative relations	a. Communication game to build shared experience, reflexivity, and communication; core course emphasizing strategic communication
	b. Establishing collaborative roles for students, advisors, and interdisciplinary committee members that meet the diverse expectations of all involved	b. Introduction processes that ensure that the student can bring together a disciplinarily diverse yet cooperative and supportive advising team	b. Student and advisor orientation program; ICON rep as committee member; grad coordinator and ICON rep advisor in committee selection
2. Inequalities and politics	Who determines the student's research agenda? Tensions between faculty and student visions of the depth of interdisciplinarity that should be pursued	Advisors' support of students engaging with multiple epistemic perspectives; horizontal collaboration among diverse committee members to share complex mentorship burden	Explicit role of the ICON rep as broker and advocate at different stages of dissertation process. Many ICON-affiliated faculty are gaining experience working with one another on committees

(continued)

Table 7.1 (continued)

Issue	Manifestation of challenges in ICON program's intra-academic context	Desired outcomes	Programmatic and pedagogical strategies currently employed
3. Common interests and complementary capacities	a. Navigating divergence among students, advisors, and committee members regarding the value of inter-epistemological research	a. Committee selection and programs of study that reflect a common commitment to integrative scholarship	a. Core course content helps students situate their interests in the broader spectrum of epistemic approaches, anticipate limits of their own epistemic comfort zone, and decide what arenas they may want to span
	b. Committee members with highly divergent epistemic commitments may struggle to identify complementarities between their approaches	b. Committees with genuine epistemic breadth, yet able to work together to avoid conflicting demands on students	b. Core readings, and consultation with graduate advisor, peers, and ICON reps help students recognize epistemic orientations and identify complementary committee members
4. Goals and objectives	Transdisciplinarity is not part of standard graduate training; variable views regarding whether it is worth the effort	Efforts toward transdisciplinarity are required as part of the degree program, though not necessarily as part of their formal research	Core sequence provides transdisciplinary research experience and strategic communication training; internship requirement provides a non-academic perspective

(continued)

Table 7.1 (continued)

Issue	Manifestation of challenges in ICON program's intra-academic context	Desired outcomes	Programmatic and pedagogical strategies currently employed
5. Leadership, governance, and management	Sustaining the ICON program and its training objectives in the context of an otherwise traditionally structured university	Coordinating mechanisms and buy-in from faculty, home units, and university administrators to sustain the desired training experience	ICON's governance approach prioritizes communication and building social capital to maintain flexibility and trust needed to accommodate diverse students and projects
6. Expectations and benefits	a. ICON's goal of 'integrative' research is conceptually rather than specifically defined, leaving students and committees with the challenge of operationalizing the goal	a. Student experiences that develop individualized and novel avenues to embrace the core ICON principles, leading to personal growth as agile scientists as well as relevant research products	a. ICON rep as advisor and network broker to facilitate the development of an integrative program of study and dissertation; integrative mechanisms beyond the first year maintain and deepen students' interdisciplinary and transdisciplinary growth
	b. Advisors place varying value on interdisciplinary training and have varying expectations for its benefits	b. Graduates secure rewarding opportunities to apply their unique assets and strengths.	b. Successful career placement and ICON's growing reputation help build faculty and student confidence around the potential benefits their training will yield

(continued)

Table 7.1 (continued)

Issue	Manifestation of challenges in ICON program's intra-academic context	Desired outcomes	Programmatic and pedagogical strategies currently employed
7. Surprises and uncertainty	Administrative changes add surprises and uncertainty to the complex institutional environment	Foster and maintain interpersonal relationships within the university structure that afford resilience and adaptive capacity	Leadership commitment to advocacy, diplomacy, flexibility, respect for conflicting agendas has been essential to success in navigating surprises and uncertainty thus far

but they also complicate the challenge of establishing shared interests and common goals. ICON incorporates programmatic elements like workshops and guiding documentation to promote shared goals. In addition, a central strategic feature of ICON for managing inequalities is the ICON rep required on each student's committee. This individual acts as a "network broker," a pivotal role for managing challenges of crossing boundaries (Perz 2016: 63). The ICON rep is formally tasked with advocating for the program's training goals and thereby helping to balance competing interests among committee members that may affect the student's progress. All that said, the ICON program offers no specific, standardized expectations regarding how to achieve integrativeness in student dissertations. This open-ended aspect of the program was a key strategic decision by program leadership to allow flexibility and innovation, but it also means that partners experience ongoing boundary-crossing challenges throughout each course of study.

Many of the challenges that arise in the ICON program, such as imperfect contexts for introductions, the need to engage in intersubjective learning, the difficult and often humbling work of self-reflexivity; the political and logistical struggles to establish shared interests and goals, and setting pluralistic and realistic expectations for benefits from collaboration, are all important parts of CNH research. By experiencing these challenges in a training program, students are building their capacity for inter-epistemic and transdisciplinary research in tandem with the practices they will need in their later endeavors in conservation and sustainability. On a programmatic level, the faculty who administer the program and advise students are also learning powerful lessons regarding governance, leadership, and building program resilience in the face of uncertainty and surprises, enhancing our collective capacity to engage in coordinated CNH research.

ICON offers an example of a graduate training program that provides guided inter-epistemic pedagogy for students, and experiential training for everyone involved, to successfully navigate boundary crossings in collaborative endeavors. By reflecting on the seven challenges that Perz (2016) identified as they apply to the intra-academic context, we hope that our insights will stimulate others to view the academic

environment of graduate training as a parallel context in which to build the collaborative capacities of agile scientists for future CNH projects and other conservation and sustainability endeavors.

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8

Understanding the Central Great Plains as a Coupled Climatic-Hydrological-Human System: Lessons Learned in Operationalizing Interdisciplinary Collaboration

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8.1 Introduction

Water is a critical component of Earth's surficial system. However, less than 3% of all water on Earth is freshwater (Gleick 1996). Freshwater is essential to sustain life and it is central to agriculture, industry, residential development, and other aspects of the United States economy.

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Water provides essential ecosystem goods and services for society and maintains the health of the biota that inhabits aquatic ecosystems (Gleick 1998; Postel 2000; Baron et al. 2002). Existing freshwater resources presently are being threatened by increasingly unsustainable land use and water use practices (Vörösmarty et al. 2000; Malmqvist and Rundle 2002; Tilman et al. 2002). The distribution, abundance, and quality of freshwater supplies will undoubtedly be affected by projected climate change and increasing climatic variability.

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In the United States, the Central Great Plains (CGP) is a region with long-standing concerns about water quality and quantity. In this semi-arid, highly erodible and agriculturally intensive region, historical climatic fluctuations have been extreme, with a close coupling between the dynamic climate and human systems, as witnessed during the Dust Bowl of the 1930s. This classic example of the intersection among climatic variables, human land use, and significant societal consequences illustrates the economic, demographic, and cultural consequences for a region and nation when unsustainable land use collides with climatic change and variability.

It is also important to note that while much attention has been devoted to populations of the CGP depending on the Ogallala Aquifer (*aka* the High Plains), comparatively little research has been conducted on coupled climate-water-human system dynamics in the CGP to the east of the Ogallala—a region that is more vulnerable and sensitive in that there is no vast groundwater supply to buffer the effects of climate change. Rather, CGP hydro-, agro- and ecosystems are entirely reliant on water supplied via direct precipitation, runoff, and shallow alluvial storage zones strongly connected to surface water systems. Thus, understanding how these systems interact and how they affect river landscapes and biodiversity can provide science-based support for sustainable water use planning in several ways.

First, individuals, populations, and communities that comprise natural biodiversity are important for ecosystem function. For example, niche partitioning via increased habitat heterogeneity can improve water quality (Cardinale 2011). Also, understanding the relationship between biodiversity and ecosystem function (Hooper et al. 2005), especially the overall direction, strength, and shape of these relationships, is an active focus of ecology that has direct applications for sustainable land and water conservation planning. Ecologists generally agree that high native biodiversity is a desirable trait (Tilman et al. 1996; Dawson et al. 2011), even though the full range of mechanisms by which biodiversity affects ecosystem function is, as yet, poorly understood (Loreau et al. 2001). Second, the structure of communities, especially biodiversity, can increase resilience, i.e., the ability of ecosystems to resist and recover from change. Third, the biota that populates streams, rivers, wetlands,

and reservoirs provide important ecosystem goods and services (e.g., aesthetic and recreational opportunities that are important to conservation and recreational fishing groups). Thus, as climate changes and land use intensifies in the region, these stressors will increase in scope, greatly hindering the provision of essential ecological goods and services for humans in northwestern Kansas.

Coupled with these bio-physical surficial systems is a socio-economic system already under great stress due to dramatic population shifts, concentration of land tenure, dependency on highly variable and limited water supplies, high economic uncertainty, cultural resistance to top-down management, and skepticism of climate science. Contemporary rates of ecosystem loss and degradation could be reduced through creation of successful management strategies for these systems such as (1) societal recognition of the value of these ecosystems to humans; (2) flexible conservation options that allow landowners and producers to customize conservation to their specific farming and ranching operations; and (3) understanding of the linkages of isolated ecosystems like wetlands that form networks and contribute ecological goods and services (e.g., biodiversity) which are much greater than the sum of benefits provided by individual wetland sites.

In complex problems of this nature, interdisciplinary collaboration between social and natural scientists is seen as critical to solve the problem of sustainable management. However, major challenges in developing effective sustainable management strategies are centered in environmental policy, and in the development of integrative frameworks that account explicitly for human–environment interactions. Nonetheless, in pursuing these integrative approaches, natural and social scientists have still worked within the boundaries of their own specific disciplines, thus neglecting the integrative relationship between these systems. Our research approach seeks to couple mechanistic natural-human models.

In doing this, we try to cross disciplinary boundaries and address challenges facing interdisciplinary research teams. For instance, our research team had to overcome challenges related to different disciplinary definitions of key concepts (e.g., biodiversity). In addition, due to our particular disciplinary training, we had to discuss different

approaches and develop a shared conceptual framework to identify the linkages and interactions between systems components. We also had to find ways to derive metrics able to quantitatively represent system components. Finally, discussions across disciplines were necessary to pursue data and model integration in order to implement simulations of the interactions and feedbacks among the hydrological, ecological, and socioeconomic systems in our study region.

Our research team also addresses some significant transdisciplinary barriers. A key goal of our modeling effort was not only to generate output that indicated the effects of various policies affecting human decisions about land and water use that in turn influence the sustainability of the system, but also to recognize that stakeholder support for policies may also affect policy implementation in the first place. This required a specific means of accounting for stakeholder cultural values, beliefs and norms, which inform their perceptions and preferences about environmental policies. We therefore gathered data on stakeholder cultural orientations about environmental changes in the study region and explicitly model the corresponding perceptions about the possible implementation of alternative environmental policies. To do that required engagement of diverse stakeholders representing different cultural orientations in the study region, which itself was no simple task, precisely because stakeholders also varied in terms of their support for science itself as well as government interventions. We thus pursued substantial stakeholder engagement in the process of developing our models, with the goal of explicitly incorporating stakeholder cultural orientations as they influence not only stakeholder land and water use decisions but also as they affect what policies might get implemented.

In this chapter, we first give a brief introduction to the GCP, our study region. We then discuss our project system, noting the key components and their interactions and feedbacks. We then describe the organization of our interdisciplinary research team and how we identified and surmounted disciplinary and transdisciplinary barriers we encountered. Finally, we summarize our reflections on our interdisciplinary research process, offer some key lessons we learned, and provide recommendations for interdisciplinary science.

8.2 The Smoky Hill River Watershed (SHRW)

Our study area is the Smoky Hill River Watershed (SHRW), a major tributary to the Kansas River (Fig. 8.1). The SHRW originates in the High Plains of Eastern Colorado and crosses Kansas in an eastward direction (Summerfelt 1967). This watershed can be characterized as a semiarid agricultural region that encompasses eleven counties in the central-western part of Kansas in the CGP. The SHRW traverses strong west-to-east gradients in terms of climate, topography, ecosystems, land

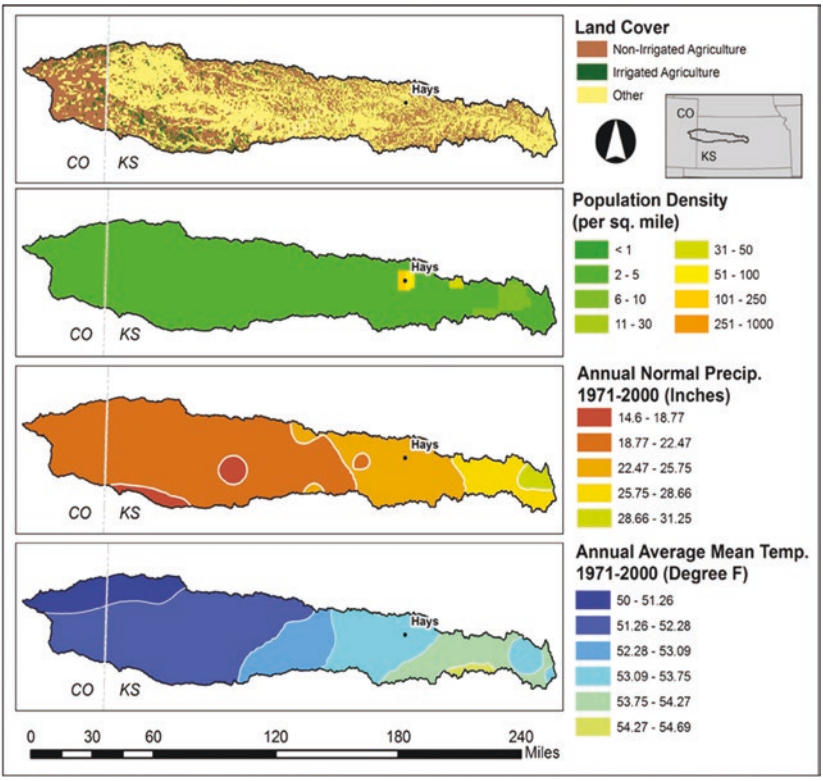

Fig. 8.1 Gradients of land cover, population density, precipitation, and temperature in the Smoky Hill watershed, Kansas and Colorado (*Source* Figure created by Robert Daniels using ArcGIS)

use, and population density. These west-to-east gradients are representative of the larger CGP. Because of this and because of its tractable size, we selected the SHRW as our study site. It has already been the focus of extensive hydrosystem modeling efforts and land use and land cover (LULC) change analysis (Tuppad et al. 2010; Campbell et al. 2016; Mankin et al. 2006; Peck 1986).

The SHRW is a CNH system because of human modifications to both the rivers and land. The stream network in the SHRW is extremely fragmented by small dams on the tributaries, and two large US Army Corps of Engineers flood control dams on the main stem (Chatterjee et al. 2018). Land uses in the watershed include row crops, primarily winter wheat, sorghum, and corn; cattle grazing of grassland; and tracts enrolled in the Conservation Reserve Program of the US Department of Agriculture. Cropland and grassland are each responsible for 47% of the land use, with the remaining 6% of the watershed in other land uses (e.g., water, urbanization, forest, etc.) (Gao et al. 2017a). Precipitation in this region is highly variable. For a 40-year period between 1950 and 1990, annual precipitation ranged from 37.1 to 61.8 cm, with an average annual temperature between 10 and 12 °C (Goodin et al. 1995). Due to such variability in precipitation, corn is typically irrigated in the western part of the watershed and rotated annually with winter wheat and fallow (Gao et al. 2017a).

Past data collection efforts in the GCP (Gao et al. 2017b) have produced excellent geospatial data coverages for the SHRW, but have not addressed the critical interactions between humans and the landscape that will determine the region's future water supply and quality.

8.3 Challenges to Understanding Human–Environment Interactions

Our CNH (Coupled Natural-Human System) project attempts to understand and model interactions between three main systems controlling water supply and water quality in the CGP: (1) the hydrosystem, defined as all components of the hydrological budget, including precipitation,

groundwater, surface water/runoff, stream flow, evapotranspiration, etc.; (2) the aquatic ecosystem, which includes the biological components of the system; and (3) the human system (Fig. 8.2). Here we discuss some of the significant challenges in conducting research and modeling this CNH system.

The hydrosystem component of this study was developed through an integrative model to simulate hydrologic responses of land (soil, vegetation), streams, wetlands, shallow groundwaters, and reservoirs to their interactions with climatic, human, and ecological systems. Data for hydrological processes were obtained using the Soil and Water Assessment Tool (SWAT: Arnold et al. 2015), a process-based, spatially distributed, continuous, watershed scale simulation model developed by the USDA Agricultural Research Service (Arnold et al. 1998).

The aquatic ecosystem was conceptualized in concert with the hydro and human systems. The aquatic ecosystem includes interactions among physical (e.g., hydrological, geomorphological) and ecological components (e.g., biotic community at multiple trophic levels) of instream river channels (i.e., historically watered habitats) and wetlands. The aquatic ecosystem extends longitudinally from headwaters to

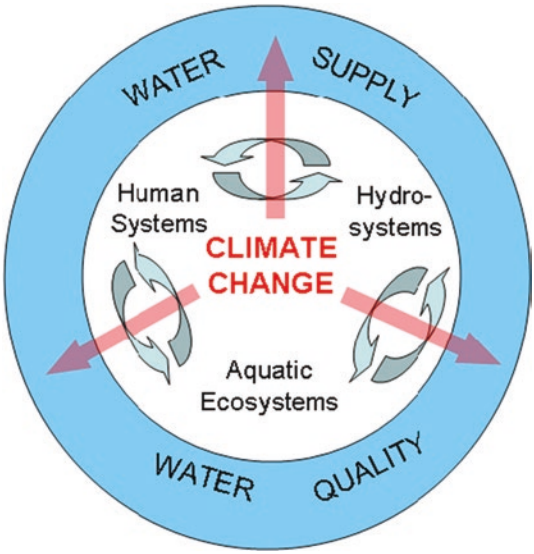

Fig. 8.2 The research components (*Source* Figure created by the authors)

downstream portions of the watershed, and it is influenced by terrestrial connections to stream channels (i.e., land use, water withdrawals).

Practically speaking, the entire geographic and taxonomic expanse of the aquatic ecosystem cannot be examined because flow, habitat, and organismal communities vary at very small scales, as well as across a very large watershed scale. Determining the appropriate scale for sampling was one of our first challenges. The difficulty of choosing the appropriate scale for the ecological question and linking ecological patterns and processes across scales have been grand challenges in ecology for decades (Levin 1992; Chave 2013). The problem of scale continues to bedevil field ecologists. In our interdisciplinary study, an additional scale challenge was to match ecological data to the human component data. To solve this problem, we focused on abiotic and biotic drivers at the watershed scale as that was the scale at which anthropogenic and natural drivers both affect ecological patterns and at which public policies are implemented. The challenge of agreeing on an acceptable geographic scale was a difficult one for our interdisciplinary team. Although a series of discussions were required to focus the team on a common scale, initial disagreements were related more to individual conceptualizations of the problem rather than differences in disciplinary paradigms.

Our second challenge was to identify appropriate metrics that reflected concepts agreed upon as being important to both the natural and social science disciplines represented on our team. Specifically, we needed to link a natural system response that human behavior altered (a focus of social scientists) to a system response that ecologists viewed as important to ecosystem functioning (a focus of the natural scientists). We chose biodiversity because it is a response variable that both ecologists and social scientists agree represents patterns of ecosystem structure and function (Fleishman et al. 2006; Feld et al. 2010; Smith and Mather 2012; Pinto et al. 2014; Laurila-Pant et al. 2015).

This brought us to face our third challenge: to define which component of the aquatic community to study. This involved a discussion of which biodiversity data would be important for linking the physical, ecological, and human research in the SHRW, and in which areas. We discussed which animal communities are more resilient by being better adapted to respond to human and climatic disturbances. Although

we could have chosen several taxa to reflect human impacts on ecosystems, we chose fish for the SHRW. They have attributes that make them an ideal focus for interdisciplinary research. For one thing, fish distributions are strongly linked to geomorphology, hydrology, and land use. Furthermore, fish comprise a large portion of the biomass in aquatic systems, and they represent an important component of biodiversity. As such, fish encompass good taxa to examine how biodiversity is affected by human and climatic influences. Finally, many human groups value fish and wildlife. As one example, in 2016, 35.8 million anglers spent $46.1 billion on recreational fishing (U.S. Department of the Interior, 2016). Thus, we related fish biodiversity data to environmental drivers including water discharge and water withdrawal, as well as climate change and LULCC processes that degraded aquatic habitat. By focusing on fish, our interdisciplinary team could document variations in an indicator of social and ecological importance, which in turn would permit identification of science-based policies that could affect fish sustainability, such as the creation of conservation areas that provide refuges for fish and wildlife.

In the CGP, native fish communities are prized ecological resources. This is because of the attachment that some stakeholders have to charismatic fauna such as fish (Frank et al. 2009). Consequently, a subset of stakeholders often responds favorably to science-based recommendations to protect their favorite organisms. In addition to the fish community data, we chose amphibians and birds for wetlands located in the SHRW. In northwestern Kansas, wetlands offer a variety of ecological goods and services such as retention and slow release of floodwater, natural filters that improve water quality, wildlife habitat, and recreational opportunities. Major threats to wetland functioning include direct anthropogenic modifications of the wetland (e.g., filling, hydrologic disruption, cultivation) and alteration of surrounding watersheds (e.g., cultivation of native grassland, hydrologic modifications). Palustrine freshwater emergent wetlands ("playas") are the dominant wetland type, representing 99% of the wetland systems in the SHRW. However, cropland has replaced 48% of the grassland in the watershed and 44% of the wetland area. We therefore evaluated the status of playas and other

wetlands in the SHRW in terms of physical loss, functional reduction due to anthropogenic modification, and avian and plant diversity.

These decisions led to our fourth challenge. How to stimulate public engagement? This was an important question because the effects of climate on hydrosystems and aquatic ecosystems are mediated by stakeholder decisions regarding water use, land use, and infrastructure development (Fig. 8.2). Therefore, any attempt to understand the CNH system would require engaging key stakeholders affecting the system itself. Further, stakeholder acceptance of any scientific findings would be important for the development of policies to advance the sustainability of the SHRW's CNH system.

We therefore conducted in-depth interviews with key stakeholders to collect data on their perceptions of environmental change. We sought out numerous stakeholder constituencies, including farmers, extension agents, conservation district personnel, municipal water managers, farmers' cooperative managers, county and town officials, elected political leaders, state and federal water agency personnel, fish and wildlife managers, economic development interests, and environmental organizations. One priority was to identify the principal economic and environmental factors driving land use and water use decisions in rural areas, as well as in the growing urban centers of the study watershed. We also wanted to understand stakeholder perceptions of environmental change. We therefore included items on climate change (e.g. historic climate variations, projected climate variations, climate science), ecosystem services (e.g. sustainability, fish and wildlife, wetlands, lakes and rivers, aquatic recreation, water supply), economic interests (e.g. crop production costs, crop prices and yields, water usage), and stakeholder attitudes (e.g. towards risk). A particular emphasis of the survey was thus to advance scientific methods for understanding the human decision process behind support for alternative conservation policies. Examples include funding of agricultural best management practices, and establishment of wildlife and riparian areas for habitat preservation (Sanderson et al. 2017). Questions thus also focused on attitudes and awareness of a range of relevant topics including climate change, ecosystem services, biodiversity, water supplies, water quality, aquatic

ecosystems, outdoor recreational opportunities, environmental regulations and policies, and conservation programs.

Some stakeholders were in constituencies that had previously and publicly expressed skepticism about climate change and other conservation issues, which presented a fifth challenge to our CNH project: how to incorporate cultural beliefs into our human decision modeling framework. Culture is a significant variable that mediates the relationship between human decision-making and natural ecosystems. Culture serves as a lens through which local environmental changes are perceived, processed and acted upon (Caldas et al. 2015). To incorporate culture, we adopted the values-beliefs-norms (VBN) framework, which provides a strong empirical approach that disaggregates culture into discrete conceptual dimensions that permit empirical measurement. Via the VBN framework, culture can be quantitatively modeled (Stern 2000; Stern et al. 1995). The VBN framework thus allows for the incorporation of culture as a driver of ecosystem changes based on resident knowledge, political orientation, environmental worldview, values, and norms. Thus, a significant part of the survey was devoted to assessing the VBN of residents (Sanderson et al. 2017).

The sixth challenge in our project concerned the integration of the various modeled components across locations in our CNH system. Stakeholder decisions influence other components of the system and thus the state of the system itself. However, stakeholders in the human system are highly decentralized. That is, no single individual or entity determines all human actions within the human system, so any model of the system must explicitly capture decentralized decision-making. The different, and often conflicting, objectives of different stakeholders in our system can lead to poor system-wide outcomes if policies or programs are not synchronized and lead to negative externalities among stakeholders in different locations.

Thus, the team had to discuss how to account for decentralized human decisions, how to integrate human, hydrological and ecological models, how to incorporate feedbacks from decisions in one location to stakeholders in other locations, and how to use models to evaluate the effects of policies on stakeholder decision-making over time and across space. Two types of models emerged from our discussions: models that

pursue a watershed-level policy optimization approach, and models that permit a decentralized and spatially explicit agent-based model (ABM) simulation approach. The policy optimization approach is a multiple-criteria approach that can be developed to meet multiple policy, social, environmental, and biodiversity objectives (e.g., Prato 1999). The policy optimization approach involves delineation of a global governance model imposed on the area modeled that is assumed to be enforced and obeyed. This approach is more optimistic in its assumptions about policy implementation across the study area. The ABM simulation approach takes advantage of the probabilistic nature of the model to examine what would happen under different climate and local policy scenarios assuming independent decision-making processes among stakeholders across the area modeled, permitting observation of their decisions and the outcomes over time and space as well as aggregated up to the watershed scale. This approach is likely more realistic about current social and economic conditions and their local variability. Both approaches provide distributions of outputs (e.g. species distributions, policy support, water supply, land use) that represent types of decisions that individuals would make based on their utility functions under a given climate-policy scenario.

Our current focus for this chapter is the second approach, the ABM framework. To implement our integrative framework of hydrosystems, ecosystems, and human systems, we developed an integrated ABM to dynamically simulate stakeholder support for an environmental policy designed to improve sustainability in the context of specific climate and policy conditions. The ABM is illustrated in Fig. 8.3. In the ABM, the hydrosystem component directly affects both the river ecosystem and the update of the human system components. The river ecosystem output also affects the update of the human system component. Based on agent attributes and using the VBN data, we derive individual decision rules for supporting specific environmental policies (e.g., the establishment of refuge areas for wildlife and fish), thereby linking culturally shaped decisions to changes in the natural system. The update of the human system component modifies the decision rule by combining the agent's perception of streams and native fish vulnerabilities with the output from the

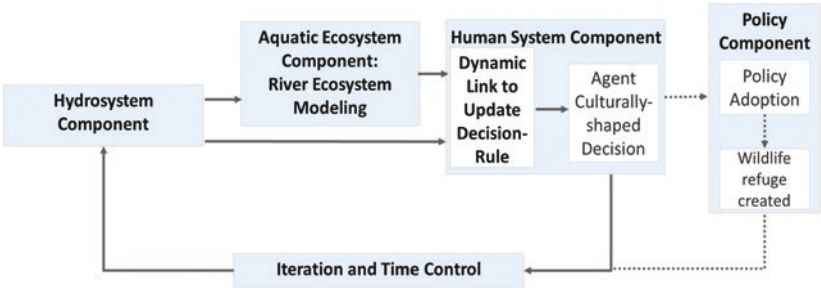

Fig. 8.3 Agent-based model applied to the Smoky Hill River Watershed in Kansas (*Source* Figure created by the authors)

hydrosystem and river ecosystem components. In the human system component, each agent decides on their stance toward the policy.

For its part, the government decides to enact a policy based on landholder support for the policy. If a simple majority of agents support the policy, based on actual voting behavior, the policy will be implemented. This contrasts with many models, which view policies as exogenously determined and imposed on stakeholders. Further, we hypothesized and confirmed that VBN scores of stakeholders vary across the study area. Given that these VBNs play a significant role in shaping and supporting environmental policies (Sanderson et al. 2017), it was important to be able to model spatial variations for policy support and thus policy implementation across the SHRW. We therefore allowed policies to be implemented as a global watershed policy or as more locally specific initiatives, applied in one community but not another. This is important because many existing models only examine average conditions, yet the important patterns are often generated by local variation.

Addressing the transdisciplinary gap between environmental science and policy was challenging but essential for contributing to sustainability and conservation. Very specific scientific results are often difficult to link to relevant policy options. Even when scientific findings can be interpreted as supporting or questioning a specific policy, they often fail to take into account whether the public itself would be favorable to the science in the first place. It is therefore crucial to account for public support for policies, including in the modeling

of policies in terms of their likelihood to gain public support. In the SHRW, our results indicate resistance to various environmental policies, at least under certain conditions. We also found that environmental policies may not have sufficient support for their implementation except under extreme climatic conditions. This suggests that the best opportunities for policy acceptance immediately follow extreme climatic events (Albright 2011; Nohrstedt and Nyberg 2015). Thus, the establishment of protected areas is only likely to occur under conditions of large anthropogenic impacts that adversely affect aquatic ecosystems. This proximate impact-protection link may however limit how convincing scientific predictions and the conservation options they support are to post-truth stakeholders who seek absolute, confirmatory "proof" before supporting conservation. However, protection of core areas is likely to be one of the more powerful policy tools for sustainability. Consequently, a key transdisciplinary challenge emerges for researchers: to convincingly relate specific scientific findings to a policy option that is culturally acceptable under the condition of being specifically relevant to addressing a recognized crisis.

8.4 The Organization of the Interdisciplinary Research Team

Our research team members were selected due to (1) their area of expertise in each of the disciplinary components of the research effort, and (2) transdisciplinary interest in the problems of the study region. This resulted in assembling a team of PIs from Geography, Biology, Agricultural and Biological Engineering, Agricultural and Resource Economics, Industrial and Manufacturing Systems Engineering, Political Science, and Sociology.

Daniels was the lead principal investigator. Her interdisciplinary training in natural resources and geography endowed her with backgrounds in hydrology, ecology, geomorphology, and human dimensions of resource management, and provided her with the ability to communicate with team specialists in watershed modeling, aquatic

ecology, land use modeling, environmental sociology and human decision-making. In both proposal development and project management, one of her most important roles has been to serve as translator and coordinator, expressing how different research elements and data streams fit together, facilitating communications and building functional bridges between disciplines and project components.

Douglas-Mankin initially led the hydrosystem modeling efforts with primary support from Daniels. He focused on deriving the climate-based hydrological parameters to populate the SWAT scenarios, while Daniels led the analysis of the resulting hydrologic regimes for rivers and wetlands in the SHRW. It was important to have a scientist who could model the complexities of the hydrological system and its connection with land use, climate and aquatic ecosystems. When Douglas-Mankin moved to a new position, he recommended Sheshukov as his replacement. Sheshukov was an expert in SWAT, and his research interests in hydrological processes at the watershed scale and best management practices for sustainable watershed management and restoration were a perfect fit for the project. While we are not able to control the exit of people, it is important to be able to find researchers that can take the place of departing collaborators and still meet project objectives.

With a hydrological system team in place, Daniels discussed her ideas with Caldas, an environmental economic geographer and an expert on LULC change modeling. His research examines the interface of humans and the physical environment by combining economic methods with geospatial analysis. Daniels and Caldas discussed the integration of the human component in the CNH modeling effort. While having a strong cadre of scientists for the natural science aspects of the model is crucial, it is also important to recognize the importance of the social sciences in providing expertise in helping to shape research questions, approaches, and policies that account for the complexity of the human system.

Caldas led the LULCC and water use decision modeling and suggested other social scientists to include the human system component of the project. He coordinated with Bergtold, Aistrup, Sanderson, and Heier Stamm. Bergtold was an agricultural economist with expertise in environmental and production economics as well as applied econometric modeling. Aistrup was a political science professor with interest

in the intersection between water policy and communities in water abundant and water scarce environments. Unfortunately, Aistrup took an administrative job at another university. Caldas and Bergtold had worked together in another grant with a sociologist, Sanderson, and they suggested that Sanderson join the human component team. Sanderson is an expert in global social change, focusing particularly on the issue of sustainable development. Heier Stamm is interested in the development of quantitative models and algorithms to understand systems in which decisions affecting systems are made in a decentralized way.

Initially, Caldas and Aistrup conducted the stakeholder survey data collection and analysis, while Caldas and Bergtold focused on the ABM development based on survey results. While survey development was led by the researchers primarily focusing on the human system, it was a coordinated effort with the entire research team. It was critically important that the survey data be translatable into and connected with the natural systems components of the project, which was necessary for the development of the integrated modeling framework. Caldas also led the development of the policy scenarios, while Aistrup and Bergtold focused on policy translation products to deliver to regional governmental stakeholders. After Aistrup left, Bergtold became responsible for the stakeholder survey and Sanderson helped with the survey. Heier Stamm took the lead on the optimization modeling with assistance from the rest of the team.

The Aquatic component of this research was led by Mather and Haukos. Mather was responsible for the biodiversity data collection, statistical analysis, and integration of the biodiversity data with the hydrological and human systems. Haukos was responsible for the wetlands data with Daniels coordinating the aquatic ecosystem and hydrologic regime forecasts derived from the hydrological system modeling efforts.

While our team recognized from the beginning the need to work together to build a functioning coupled model, there were several disciplinary boundaries that presented real challenges. Most of these challenges related to differing disciplinary definitions of key concepts (e.g., biodiversity) and different approaches to how to quantify and derive metrics from various system components. However, there were also

issues of a more institutional nature. The interdisciplinary organization of our team raised questions about the incentive structure of our disciplinary departments and universities. This was a challenge, especially for junior faculty still pre-tenure and for faculty seeking promotions or merit recognition. Many universities do not have a mechanism to incorporate the participation of research on interdisciplinary teams as part of the performance review in the tenure and promotion process. In many cases, departments prefer junior faculty publishing in their disciplinary fields and prize first-authorship or sole authorship publications in high-profile disciplinary journals. If interdisciplinary problems are a priority for society and funders, then universities and their departments need to rethink their merit structure and recognize groups of researchers and not just reward individual scientists who distinguish themselves by working in their disciplinary fields.

8.5 Lessons Learned from Interdisciplinary and Transdisciplinary Collaboration

The question for universities charged with training environmental scientists and other environmental professionals is how to be effective in collaboration across boundaries, not whether to pursue interdisciplinary research. But the skills related to teams interactions are rarely addressed as a part of academic training. As a result, below we identify 15 recommendations, organized into four groups of effective team functioning (Fig. 8.4). We present each group of recommendations with a brief description, noting the importance of each recommendation in team functioning, and how our team managed the recommendation in practice in our CNH project.

The first group of recommendations for working effectively in teams relates to assessing the interests of potential collaborators, especially whether they understand the qualifications required to be part of a successful interdisciplinary team (Fig. 8.4, recommendations 1–4). Interdisciplinary collaborators must be open to new approaches (recommendation 1). Whereas a disciplinary researcher can just address

I. Assess Interest in Interdisciplinary Collaboration

1. Be open to new approaches	2. Balance depth & breadth	3. Define the appropriate question	4. Be willing to develop shared paradigms, scales, and methods

II. Operationalize Interdisciplinary Interactions

5. Take time to develop bridges across disciplines	6. Be willing to listen to all perspectives	7. Focus progress on common goals	8. Set expectations to build trust

III. Encourage Positive Group Behavior

9. Collegiality	10. Inclusiveness, Transparency	11. Create a group identity and *esprit de corps*

IV. Manage Expectations and Productivity

12. Establish expectations for budgets and publications	13. Emphasize the need for up-front time investments	14. Be inclusive on publications	15. Communicate frequently and include all

Fig. 8.4 Recommendations for collaboration in transdisciplinary research (*Source* Figure created by the authors)

focused ideas that they have polished over their career (literature, approaches, and skills), a productive member of an interdisciplinary team must be open to a different, integrated way of thinking about science and problem-solving. For instance, at the beginning of our collaboration, we only approached other researchers that we knew were interested in interdisciplinary research. Each of the original proposal writers had valued colleagues who we immediately identified as inappropriate because they had no experience or interest in being part of an interdisciplinary team. Further, as we lost members of the original group and identified new collaborators, outlining the importance of collaboration to new members was critically important.

Second, a contributing member of a successful interdisciplinary team must be willing to balance the depth of their disciplinary expertise with the breadth needed to reach across disciplines (recommendation 2). As scientists establish their reputations in a discipline, they often become specialized. However, researchers are not likely to be productive members of an interdisciplinary team unless they are willing to balance their expertise with the exploration of new ideas, theories and methods that establish interdisciplinary breadth. Our experience is that most scientists feel more comfortable addressing either the big picture or selected details. Embracing both breadth and depth is very difficult for most researchers. Our decision early on to meet regularly was our attempt to address this issue. During year 2, we had a discussion about how often we needed to meet, and not everyone agreed. Some members of the team prioritized achieving specific but narrow work targets, which we all agreed were important but insufficient. Others argued that if we didn't meet regularly, we would lose our hard-won collective ability to synthesize diverse perspectives. In the end, based on common purpose, we identified a schedule and workplan that balanced the interests of all members. The decision about how much time to spend on one's own project component versus how much investment is required for the overall project is a difficult one.

Third, members of a successful interdisciplinary team must begin very early to formulate the research question in a way that addresses the shared problem in a way that invokes the expertise of relevant disciplines (recommendation 3). Formulation of appropriate

interdisciplinary questions requires creativity and extensive interactions among team members. The presence of different disciplines can be both a joy in that new and creative ideas are identified and a challenge as unfamiliar ideas can be threatening or confusing. In our project, the decision on how our team would define biodiversity was a significant point of contention. But recognizing the importance of the interdisciplinary nature of the project helped the team to focus and reach a consensus about the concept and how to measure it, which were crucial in light of project goals. Key to our ability to move toward consensus was that our topical areas of interest were identified by a core group at the time of proposal writing. For this reason, we started out as a funded collaboration with a strong shared focus. We also allowed enough time in our project development to come to a shared view of the important questions and concepts that permitted us to proceed.

Fourth, members of an interdisciplinary team must be willing to develop shared understandings of key terms, views of scale, and methodological protocols (recommendation 4). Although this seems obvious and rational, it is important to be careful, because the development of a shared integrative research can be potentially risky and time consuming with no guarantees of a consensus or an increase in productivity or impact. While there is a time cost and some degree of risk in light of university reward systems, substantial benefits accrue to scientists who answer important interdisciplinary questions. Our team therefore committed to invest substantial time to meetings to develop a shared understanding of ideas. We specifically scheduled numerous meetings for collaborators from different disciplines to get the time to absorb, react to, and then embrace emergent shared perspectives. Being willing to take the time to process ideas and having respect for other people's understandings were keys to our achievements as an interdisciplinary team.

A second set of recommendations relate to interdisciplinary practices themselves (Fig. 8.4, recommendations 5–8). To be a successful member of an interdisciplinary team, expressions of interest are not enough. Members must actually take the time to develop bridges across disciplines so that each member of the team understands how others view the problem and everyone feels like their views are understood

(recommendation 5). On our project, the entire team attended regularly-scheduled meetings from the beginning. Active participation was very important to overcome communication barriers among team members and to help build a consensus about how issues will be jointly approached by the team.

During the team meetings, team members were expected to exchange perspectives on the issue being discussed (recommendation 6). This was important to break down communication barriers. A team that is diverse in perspective, age, and gender is likely to produce innovative insights, but only if every member of the team is allowed to speak and feel like they have been heard.

At the same time, it is crucial for team leadership to manage the diverse perspectives at hand (recommendation 7). There thus needs to be a strong discussion leader who keeps the team focused on the topic and who can moderate the discussion among diverse perspectives while steering participants toward a common goal. This leader role includes setting the stage for the discussion, allowing each member to speak, bringing comments back to the common goal, summarizing key points, and preparing for the next meeting.

The practice of team meetings is only sustainable if the process incorporates specific practices to develop trust among team members (recommendation 8). Trust stems from a shared belief (1) in the validity of the scientific ideas presented, (2) that all members will do the work required, and (3) that contributions will be acknowledged and rewarded fairly. On our team, we found that setting expectations for shared norms was important to foster shared beliefs and build trust. This was because we hypothesized that disciplinary and personal differences among team members could threaten the productivity of interdisciplinary teams, including ours. Although our group did not have overt disagreements or obvious and prolonged interpersonal clashes, these might have arisen if we had not all been committed to following shared expectations when collaborating. The practice of inclusion and respect by all group members, especially the senior members and leaders, constitutes relations of trust that set a positive tone which can carry the team during conflicts and crises. This is important professional socialization for graduate students, postdoctoral team members and support staff. By

the same expectations and norms, our team made sure that junior team members felt comfortable in speaking up and were thus fully integrated collaborators.

Relations of trust and other collaborative practices, in turn, support specific group behaviors, which lead to a third set of recommendations (Fig. 8.4, recommendations 9–11). One such group behavior concerns displays of collegiality and respect (recommendation 9). These behaviors are of course always important in a professional setting, but they are especially so in collaborative endeavors where frustrations may rise when trying to come to a shared understanding of a term.

Ethical behavior is also especially critical in an interdisciplinary context since the team spans disciplinary cultures and thus has to collectively define its internal norms, though universities and professional associations also govern e.g. intellectual property rights. Most university researchers recognize and respect the independence of their collaborators.

Another desirable behavior for members of interdisciplinary teams is the commitment to transparency and inclusion (recommendation 10). The development of a shared understanding requires the critical interrogation of epistemological, conceptual, and theoretical assumptions. Teams must work to bring implicit assumptions before the team, which can be threatening to those who hold said assumptions. Ideally, the commitment to transparency implies that we recognize our assumptions and bring them to the team ourselves, rather than having somebody else point them out. But because assumptions are often unconsciously held, all team members have to be prepared for critical discussion.

Uncomfortable discussions of cherished assumptions, in turn, make a fourth group behavior, an *esprit de corps*, very important to cultivate (recommendation 11). If one team member is likely to be questioned about assumptions, that is because it must be understood by everybody. But to build *esprit de corps*, it is important to establish opportunities for team members to socialize, within and outside of work. The establishment of a team *esprit de corps* is especially important for senior team members who model behavior, such as questioning each other, for junior members. To foster *esprit de corps*, we organized a number of

activities in which all team members participated. In the initial phase of the project, many of us took a group field trip to see sites of water use. We had a breakfast meeting with a visiting CNH researcher to share ideas. In the middle of the project, natural and human systems scientists participated in stakeholder fairs/festivals and in survey administration. At the end of the project, we jointly prepared and presented posters and talks. This willingness to invest time and help each other led to shared understandings, mutual respect, and thus positive and productive relationships among team members.

A final group of recommendations concerns managing expectations about team interactions and productivity (Fig. 8.4, recommendations 12–15). Establishing transparent expectations for time investments and budgetary or publication rewards is important (recommendation 12). Because most faculty members work alone or with students, it is often unclear who will do what (and get what) relative to faculty–faculty collaboration. Taking the example of publications, this then requires development of a strategic plan in which the responsibilities of senior personnel are made clear. A strategic plan is where each co-PI leads a manuscript from a portion of the project on which they led conceptualization and/or data collection.

An important element of managing expectations is for leadership to convey clearly that considerable start-up time is required at the beginning of interdisciplinary projects (recommendation 13). This expectation about up-front time investment is related to establishing shared understandings and approaches discussed earlier. If some players balk, it is also worth emphasizing that once a common approach is established, interdisciplinary teams have the potential to make major synthetic contributions long after the grant itself ends. Indeed, innovation of new frameworks and methods that can drive new research applications is a central goal of interdisciplinary research.

Setting expectations about co-authorship on project publications is important. Our experience indicates that being inclusive of all publications is sound practice (recommendation 14). The synthetic nature of interdisciplinary projects means that if teams have employed the

foregoing recommendations, which includes open discussions of research ideas, then all the team members will have contributed something unique to the research products. This then supports a policy of inclusion when deciding which team members should be recognized as co-authors (as opposed to the acknowledgments list) on publications. Implementing said policy however requires justification of a contribution to merit recognition. On our collaboration, we frequently discussed publications. Although all had the opportunity to be co-authors and typically added useful components to all manuscripts, different investigators added contributions of different depth and breadth. At times, this made a satisfactory allocation of authorship rank difficult and sometimes even contentious. Identifying and discussing criteria for co-authors early in the project is a useful addition for all interdisciplinary projects.

A final point concerns expectations for communicating with all members of the group when making decisions that affect the project (recommendation 15). As with meeting attendance, exchanges of ideas, transparency, and co-authorship, communication of decisions should be inclusive. When leadership engages in inclusive communication, it helps cement broader expectations of unity and fairness among team members.

8.6 Conclusion

Interdisciplinary CNH research is the foundation on which sustainable systems and environmental protection rests. No individual environmental science discipline can be successful without the cornerstone of effective collaboration among biophysical scientists, social scientists, and resource managers. In the twenty-first century, few environmental scientists would disagree with the need for interdisciplinary collaboration, but success in this endeavor is challenging. In fact, for the success of any CNH project, we need to keep in mind that many challenges will emerge during its development. We have outlined a set of experiences from out CNH project to draw out a suite of recommendations that in many ways feature early investments in team development, shared

conceptualization, and collectively defining key measures and methods. This especially applies to changes in team leadership, as new team members must be incorporated via a process that makes explicit the focus of the shared endeavor as well as common expectations about practices and responsibilities.

Going beyond academia to directly engage non-academic stakeholders in a transdisciplinary mode also brings challenges and led us to specific lessons learned. CNH projects on social-ecological systems may face significant challenges due to the post-truth attitudes of many stakeholders. If some stakeholders decry science because it may not validate their beliefs, but they make decisions affecting the system under study, transdisciplinarity poses daunting challenges. While transdisciplinarity, in any event, requires positive engagement with stakeholders, who in many cases may demand scientific input into policy and other collective decisions, rejection of science calls for practices to find other angles of engagement. It is crucial to keep in mind that we will not solve complex problems by only doing good science without engaging stakeholders. Hence we sought to engage stakeholders on their terms, whether by attending events they organized or by calling attention to environmental changes that affected them. Such approaches helped open doors, culturally speaking, for transdisciplinary engagement, even in the face of post-truth attitudes about environmental change, science, and collaboration.

Our framework for effective collaboration across boundaries offers recommendations but not guarantees. As we have learned from experience, like many others, our understanding of best practice can continue to improve. We had few open disagreements because we took the time to meet, talk, and listen. If we had not recognized the potential for counterproductive interpersonal, interdisciplinary divisions, likely we would not have seen problems coming and would not have taken the time to address them before they erupted. Our approach to dealing with problems and conflicts was to invest the time to watch for them so that we could avert them before they became serious problems. In the process, we learned a shared set of terminologies and approaches that were achieved through significant dialogue, discussion, presentations, and model development. In doing this, we moved from working

in a disciplinary way to developing a model framework and methods that were interdisciplinary (and transdisciplinary) thus providing a more holistic approach to address our problem. The development and implementation of our survey was a good example of this, in that development of questions was critically important to be able to translate outputs from the surveys for integration for analysis with the output from the natural system models.

To conclude, we call attention to a fundamental point about collaboration. Whatever happens, it is vital to develop an inclusive and egalitarian working environment that places all team members, including students and postdoctoral researchers, on an equal footing with respect to responsibility, authorship, and collegiality. That requires that team leaders invest time in project development with all members. Without inputs from every member involved in the research, the team's impact will be limited.

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9

High-Resolution Remote Sensing Data as a Boundary Object to Facilitate Interdisciplinary Collaboration

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9.1 Introduction

Restoring ecosystem function to millions of hectares of degraded tropical forest is central to sustaining human well-being and biodiversity (Lamb et al. 2005). Tropical reforestation has benefits for carbon sequestration (Marin-Spiotta et al. 2007), human livelihoods (Chazdon and Grabowski 2012) and biodiversity (Catterall et al. 2009). Spontaneous (and sometimes deliberate) reforestation is widely occurring in tropical regions

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(Nagendra and Southworth 2009), and land managers and decision-makers increasingly recognize the need for a landscape-level understanding of this important land cover change (Dudley 2007; Chazdon et al. 2015). Managing reforestation at the landscape scale requires an understanding of both the social processes enabling the availability of land for forest regrowth and the ecological processes determining the rate of reforestation when land is available (Lazos-Chavero et al. 2016). For example, the forest landscape restoration program developed by the World Wildlife Fund emphasizes that successful reforestation plans must consider social contexts, including land tenure and agricultural practices, as well as ecological contexts, including the establishment requirements of tree species (Mansourian and Vallauri 2014). However, social and ecological drivers of reforestation have primarily been studied in separate disciplinary frameworks, presenting a major barrier for managing landscapes in which some sites require socioeconomic interventions while other sites require ecological interventions.

A key reason why ecological and social drivers of reforestation have been difficult to study in an integrated fashion is that these drivers operate at different spatial scales. In many tropical countries, spontaneous reforestation depends on large-scale social processes that lead to the cessation of labor that keeps agricultural land in production (Harvey et al. 2008). These social processes include changes in the economic costs and benefits of agricultural production, and the perceived scarcity of forest resources (Rudel 2012). Socioeconomic conditions favoring reforestation are often quantified by analyzing land use and land cover change (LULCC) from satellite imagery in relation to demographic or economic data (Nagendra and Southworth 2009). However, while satellite imagery can reveal increases in tree cover, the tree cover category in classified imagery includes a wide range of habitats, from exotic timber

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monocultures, to "pioneer deserts" dominated by a few disturbance-tolerant species, to secondary forests with a high diversity of native species (Marliana and Rühe 2014; Chazdon, Brancalion, et al. 2016). Consequently, due to the relatively coarse spatial resolution, tree cover classifications from remotely sensed data likely miss important ecological and social information that is vital to evaluating the value of forest vegetation.

Hereafter, we define "reforestation" as an increase in native secondary forest with high conservation value. This category, "native secondary forest," is of great interest to many land managers, because its high species richness and structural complexity provide the greatest benefits for biodiversity conservation, watershed maintenance, and carbon storage (Hall et al. 2011). Although social processes largely determine the dynamics of agricultural activity, and thus the land area available for reforestation, the rate of reforestation depends upon ecological factors, including seed rain and site quality (Holl and Aide 2011; Caughlin, Elliott, et al. 2016), as well as interventions to restore tree cover. In contrast to social science research on reforestation, conducted on a relatively large scale, most ecological research on barriers to reforestation has been conducted at a small spatial extent (often tens of hectares). This scale mismatch hinders the effective integration of insights from ecological concepts to landscapes where socioeconomic barriers may also operate to prevent reforestation.

Because social and ecological processes determining the extent of reforestation differ in terms of the scales on which inquiry about them occurs, and because ecological dynamics are likely influenced by the spatial configuration of reforesting and remnant forest patches, spatial models of vegetation dynamics must somehow link the human and natural processes driving reforestation. In this chapter, we focus on our team's interdisciplinary effort to develop predictive models for reforestation dynamics in a tropical landscape. During the course of our research, we found that high-resolution remote sensing imagery could span the scale mismatch in social and ecological data and thereby overcome disciplinary boundaries to identify cross-scale drivers of reforestation. We argue that remotely sensed data that are fine enough to resolve landscape features at a human scale can act as a boundary object and facilitate

interdisciplinary collaboration for integrated analysis of reforestation as well as transdisciplinary partnering to promote native secondary forest recovery. We conclude the chapter with recommendations for how to apply these novel data sources to understand CNH systems.

9.2 Reforestation in Latin American Cattle Pastures as a Coupled Natural and Human System

The Latin American tropics constitute a region with net gains in forest cover over the past decade (Aide et al. 2013). Land use change in cattle pastures is a primary driver of this regional forest cover change, and represents a critical pathway for carbon sequestration with great potential for cost-effective climate mitigation (Chazdon, Broadbent, et al. 2016; Griscom et al. 2017). Land cover change from cattle pasture to native secondary forest represents a combination of natural and human dynamics across scales, from country-level economic changes to parcel-level variability in biophysical factors that enable tree establishment.

Established socioeconomic theories to explain why reforestation occurs span a range of complexity, from general models that can be applied globally (Mather and Needle 1998; Barbier et al. 2010) to detailed place-specific narratives (Sloan 2016; Walters 2016). Forest transition theory is one general model for regional shifts from decreasing to increasing forested area. This theory posits that deforestation begins with the onset of national development, but switches to reforestation in more developed countries due to agricultural intensification and decelerating population growth (Mather and Needle 1998). Forest transition theory has successfully described some national-scale forest cover trends (Rudel et al. 2005; Mather 2007; Culas 2012). However, the theory has also been criticized for forecasting an inevitable trajectory that ignores socio-political context, is difficult to downscale to subnational levels, and oversimplifies the ecological dynamics of secondary succession (Perz 2007). Rudel et al. (2005) expanded upon forest transition theory by describing two different pathways that explain why forest transitions occur

during economic development: labor scarcity, an unplanned increase in forest regrowth due to agricultural production shifts, and forest scarcity, intentional reforestation initiated by land managers and policymakers due to an unmet demand for the economic and environmental services provided by trees. There is empirical support for both forest transition pathways at multiple spatial scales, from multi-country analyses to household surveys (Meyfroidt and Lambin 2008; Busch and Geoghegan 2010; Walters 2016), and the concept has been expanded to include additional pathways (Lambin and Meyfroidt 2010). Nevertheless, more nuanced place-specific research reveals complexities and contradictions that cannot be easily summarized by a general narrative. For example, in Ecuador, it is not labor scarcity but instead labor availability that promotes the adoption of silvopastoral practices that increase tree cover in cattle pastures (Lerner et al. 2014).

Even if land is potentially available for reforestation, ecological constraints, such as lack of seed dispersal (Duncan and Chapman 1999), competition from invasive grasses (Hooper et al. 2002), and poor soil conditions (Cramer et al. 2008) can limit tree abundance in degraded sites. The spatial configuration of reforesting and remnant forest patches can influence these ecological constraints and ultimately determine the landscape-scale reforestation rate. Environmental variables affecting tree establishment, such as soil fertility, rainfall, and elevation, are spatially heterogeneous (van Breugel et al. 2011). If farmer decision-making results in more patches available for reforestation located in favorable sites, the overall rate of reforestation will be higher. Previous research has shown that the spatial pattern of land abandonment is non-random and depends on land traits that affect vegetation dynamics (Crk et al. 2009). These spatial patterns affect seed arrival, a critical determinant of tree abundance. Seed arrival depends on patch location relative to seed sources (Caughlin, Elliott, et al. 2016; Peña-Domene et al. 2017).

As an emergent property of a complex adaptive system, reforestation depends on interactions between social and ecological processes and feedbacks between these processes over time (Lambin et al. 2003). Farmer decision-making interacts with forest dynamics, ultimately changing landscape-level forest cover, but cross-scale feedbacks between forest cover and farmers are also possible (Fig. 9.1). For example, if

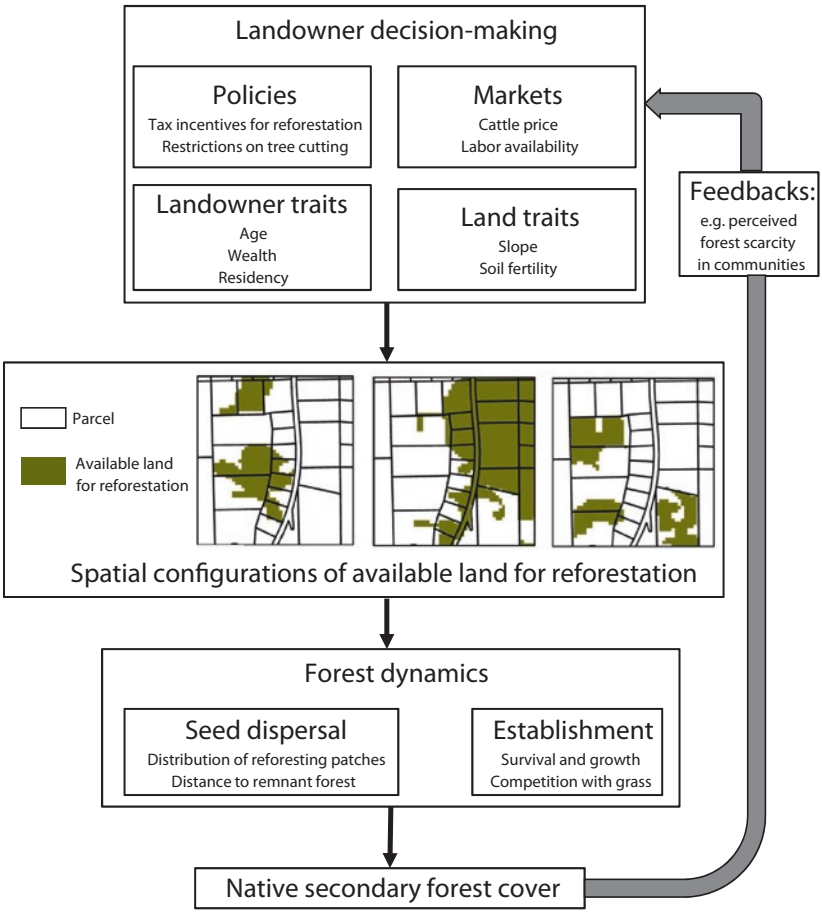

Fig. 9.1 Conceptual diagram of reforestation as a coupled natural-human system. This flowchart displays our initial conceptual model for forest cover increases as the outcome of social and ecological drivers in Latin American cattle pastures (*Source* Figure created by the authors)

forest scarcity drives reforestation, increased forest cover could lower the perception of scarcity and decrease farmer willingness to reforest (Satake and Rudel 2007). Feedbacks between the human and natural components of the model could also result in limited reforestation. For example, if farmers are initially willing to allow land to lay fallow to claim reforestation tax credits, but low seed arrival prevents natural

reforestation, farmers may be discouraged from participating in future forest restoration activities (Zahawi et al. 2014). As a consequence of these feedbacks, analytical techniques that couple human and natural dynamics underlying reforestation will be necessary to produce systemic conservation plans with detailed, site-specific recommendations.

9.3 Study Area

Our research site is the Los Santos Province on the Azuero Peninsula in southwestern Panama (Fig. 9.2), a landscape that was predominantly tropical dry forest prior to Spanish colonization in the mid-1500s. Like many places in Latin America, expansion of agricultural lands in Los Santos during the mid-twentieth century resulted in widespread deforestation (Heckadon-Moreno 2009). By 1992, 71.4% of land cover in the province was agricultural (ANAM 2003) with most of the non-agricultural area concentrated in a national park. More recently, from 1990 to the 2010s, analyses of medium-resolution satellite imagery (30–250 m) suggest that forest cover in the province has increased (Metzel and Pacala 2010; Aide et al. 2013; Sloan 2015; Caughlin, Rifai, et al. 2016). In the 1990s, Panama's rapid rate of economic development and implementation of national policies to increase forest cover led many to suggest Panama was undergoing a forest transition (Wright and Muller-Landau 2006). Indeed, Panama was one of the first countries to be selected for funding in the REDD+ (Reducing Emissions from Deforestation and Forest Degradation) program by the UN-REDD initiative and the Forest Carbon Partnership Facility of the World Bank in partnership with Panama's National Environmental Authority (Pelletier et al. 2011). The broader socioeconomic trends that have enabled these forest cover increases in southwestern Panama are similar to many other Latin American countries (Aide and Grau 2004; Perz and Walker 2002) and include rural to urban migration, household demography, and changes in agricultural markets. In the ecologically similar dry forest region of Costa Rica's Guanacaste Province, these demographic changes occurred in the 1980s, and along with reductions in global beef prices, have since resulted in large areas of reforested land (Aide and Grau 2004).

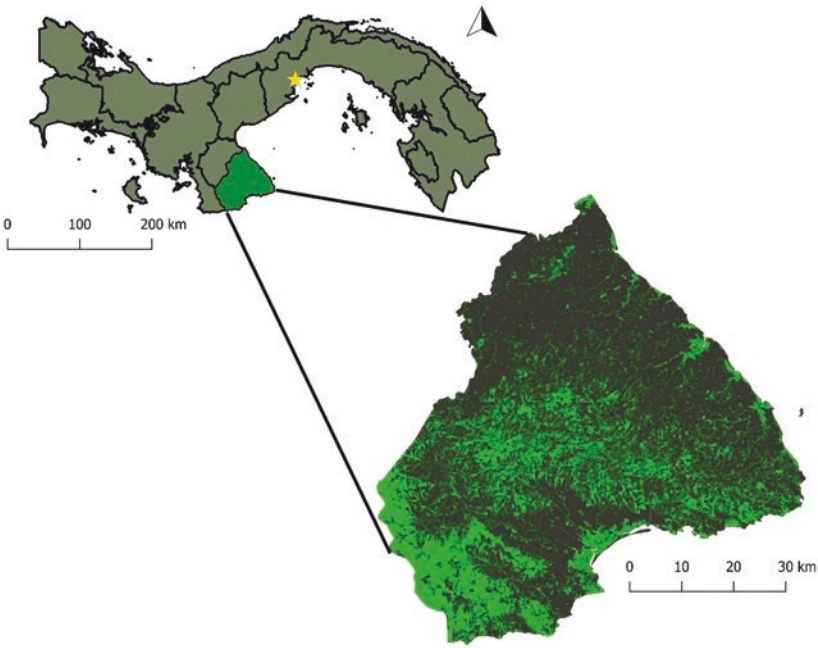

Fig. 9.2 Study area of Los Santos Province, Panama. The upper map in this figure is the country of Panama, with a yellow star indicating the location of the capital city. Black lines represent provincial boundaries. The inset in the map displays our study area, the province of Los Santos. The inset displays a forest cover in 2000 using a forest/non-forest classification from Hansen et al. (2013). Green colors indicate forest, while black indicates non-forest pixels (*Source* Figure created by the authors using QGIS and R) (Color figure online)

In addition to labor scarcity, perceived declines in forest cover have also driven reforestation in Panama by motivating national, community or individual actions to conserve and restore tree cover. Panamanians are increasingly concerned about deforestation and have prioritized increasing national forest cover (Griscom et al. 2011). Perceived forest scarcity has also influenced Panamanian national policy, leading to tax incentives for reforestation and regulations on the minimum percentage of forested land in properties (Sloan 2008). At the individual-level, surveys have revealed that Panamanian farmers increasingly value ecosystem services provided by trees, such as watershed protection, improved

agricultural productivity, and climate regulation, and are consequently receptive to increasing forest cover on their properties (Fischer and Vasseur 2002; Garen et al. 2009).

Despite evidence that favorable socioeconomic conditions are enabling a forest transition in Panama, recent research has revealed considerable spatial heterogeneity in LULCC (Sloan 2015). In Los Santos, nearly all (95.6%) of the province is privately owned land (ANATI 2000). Consequently, farmer decision-making is the predominant proximate cause of the increase in forest cover from 1990 to 2010. Along with differences between individual farmers, soil properties and topography vary widely across southwestern Panama (Garibaldi et al. 2014). Both individual-level decision-making and fine-scale variation in biophysical conditions could explain spatial heterogeneity in reforestation rates in Los Santos. Altogether, previous results from our study site demonstrate the need to examine pathways to reforestation at a smaller spatial grain.

9.4 Organization of Team and Identification of Challenges to Collaboration

To address the scale mismatch between drivers of forest cover change in Los Santos province and regional-scale analyses of LULCC, we developed a proposal to the NSF Science, Engineering, and Education for Sustainability (SEES) program to scale up social and ecological models to forecast reforestation rates in heterogeneous landscapes. Like NSF's Coupled Natural and Human Systems (CNH) program, SEES projects are collaborative and often cross disciplinary and other boundaries for research and outreach tied to sustainability goals. Our initial plan was to link an agent-based model for farmer decision-making with a forest dynamics model for successional change. We planned to parameterize this model using a combination of socioeconomic variables derived from the Panamanian census and tree demographic rates derived from forest inventory plots. After parameterizing the model with these data, our goal was to interpolate results to cover a large spatial extent and collaborate with a local NGO to develop a user-friendly model interface that

could support regional reforestation projects. With this goal in mind, we identified forest ecology, rural sociology, and mathematical modeling as the three major disciplinary boundaries we planned to cross.

We naively anticipated that the most difficult challenge we would face would be to strike a balance between parsimony and realism in model development. In hindsight, our approach relied upon the assumption that, although social and ecological data were collected at different scales (from forest inventory plots to household surveys to census data), these diverse data sources would tell the same story. However, we came to realize early in the project that researchers working at different scales had reached fundamentally different conclusions about forest cover change in our study area, namely whether increases in forest cover were occurring. This significantly complicated our ability to integrate the different data sources into a single model.

Our first step in achieving our project goals was to bring together an interdisciplinary group of researchers to refine our conceptual model of system dynamics. Our initial team included two ecologists and two social science researchers who had previously conducted fieldwork in the region, including a collective total of roughly 60 household interviews. We also identified the Azuero Earth Project (AEP; https://azueroearth-project.org/) as an NGO partner to ensure that our research was relevant to local needs and concerns. The focus of the AEP is on reforestation and sustainable land use, and the NGO has an established presence in the local communities of Southwestern Panama, including a number of outreach programs. The disciplinary composition of our research team (ecology and social science) reflected our initial assumption that the primary barrier to integrating social and ecological data was lack of a model that could incorporate data from both disciplines. The team met over a three-day period to identify knowledge gaps, decide on reasonable modeling assumptions, and synthesize existing results.

During this meeting, we identified a point of dispute and settled on a point of consensus. The point of dispute was that the two researchers with the most on-the-ground field experience were skeptical of the existence of a forest transition in Southwestern Panama. These skeptics argued that there was minimal evidence from farmer interviews that wholesale land abandonment was taking place. They went on to assert

that global data sources on forest cover change derived from medium-resolution satellite imagery (e.g., Hansen et al. 2013) were problematic for measuring heterogeneous tree cover in agricultural landscapes. This first meeting demonstrates the importance of clearly identifying assumptions during introductions between boundary-crossing partners (Perz 2016). The ecologists on the team did not expect our fellow teammates to disagree with what appeared to be straightforward data showing land cover change. Moving forward from this dispute to novel research questions that crossed disciplinary boundaries required a willingness to alter the goals of our first meeting.

We quickly realized that the divided viewpoints on whether or not a forest transition was occurring in the Azuero Peninsula would not be easily resolved during the course of a three-day meeting. Our dispute motivated us to question our fundamental assumptions on land cover change, and in the process, we were able to find some common ground. We began by recognizing that current land cover change maps largely ignored trees outside of forests. An important point of consensus that subsequently emerged was that trees outside forests were critical for a range of human and natural dynamics, including agricultural productivity, wildlife population viability, and as nuclei for reforestation. We also agreed that trees outside forests were ignored by many regional-scale remote sensing analyses, potentially leading to significant uncertainty on the magnitude of land cover change. Hence this question might be illuminated by finding a way to look at individual tree level changes in terms of resolution, but at the landscape scale in terms of extent. In retrospect, while finding an unexpected point of dispute was an important outcome of the first meeting, moving beyond this disagreement to identify a point of consensus was critical to ending the meeting on a positive note. The meeting concluded with an enthusiastic mood as our interdisciplinary team of researchers set out to explore a newly realized knowledge gap.

Our next task was to assemble existing social and ecological datasets that could be used to parameterize initial models of reforestation. We were fortunate to have access to a cadastral dataset that included property boundaries across Los Santos province, acquired from the National Authority for the Administration of Lands (Autoridad Nacional de Administración de Tierras, ANATI). The importance of these property

boundaries for determining spatial patterns of vegetation is visually apparent when overlaid on satellite imagery (Fig. 9.3). Property-level contrasts in land cover likely reflect heterogeneous farmer decision-making. The primary dataset with detailed information on household characteristics was derived from the Panamanian National Population Census, with data aggregated to points representing population centers, from small towns to cities. While one of our main justifications for choosing the Azuero Peninsula as a field site was a history of ecological fieldwork in the area, including forest inventory plots in secondary forest, we soon realized that these long-term field data were limited to only a few parcels along the coast. This presented a problem for interpolating ecological dynamics to the regional scale because we expected tree demography to vary according to local land management practices and land history (Gillet 2008; Murgueitio et al. 2011). In addition, these forest inventory plots were located in second-growth forest areas and

Fig. 9.3 Importance of landowner boundaries for determining patterns of tree cover. Cadastral data indicate the importance of landowner decision-making for driving heterogeneous patterns of tree cover in our study landscape. This figure shows that neighboring parcels frequently have very different amounts and types of tree cover. The black lines indicate boundaries between mapped parcels (derived from ANATI 2000). Imagery courtesy of Google Earth (2018) (*Source* Figure created by the authors using QGIS and R) (Color figure online)

did not measure trees outside forests, such as in working pastures. As a result of the limited spatial extent of the ecological field data, we became convinced that a different source of data was necessary to understand tree cover dynamics at a landscape scale across the province as a whole.

9.5 High Spatial Resolution Remotely Sensed Data as a Boundary Object for Interdisciplinary Research

The need for data that can differentiate ecological dynamics at fine scales over a large spatial extent prompted us to incorporate high spatial resolution remotely sensed data into our interdisciplinary project. During the course of our study, we applied multiple sources of these data, including multispectral satellite imagery, airborne Light Detection and Ranging (LiDAR) data, and airborne hyperspectral data (Fig. 9.4), to address our interdisciplinary research problem. Moving beyond the widely used land cover products produced from medium-resolution satellite data (e.g. Hansen et al. 2013) to cutting-edge remotely sensed data sources also required us to expand our interdisciplinary team to include a partner with expertise acquiring and analyzing these high-resolution data. In this section, we illustrate some of the ways that these data sources have facilitated interdisciplinary research on tree cover change in Southwest Panama.

Many land cover change studies have focused on a discrete switch from non-forest to forest categories. However, secondary succession is inherently a continuous process that occurs as trees gradually establish themselves on degraded land. In many tropical agricultural landscapes, tree cover increases can be ecologically significant without resulting in permanent establishment of mature forests (Jakovac et al. 2015; Schwartz et al. 2017). An example is short-term increases in tree cover as part of swidden agricultural practices (Dutrieux et al. 2016). The distinction between an active and a fallow pasture may be subtle at the scale of medium-resolution satellite imagery (e.g. Landsat), but is critical for land management. Developing tools to quantify these changes from medium-resolution imagery, often the only source of historical

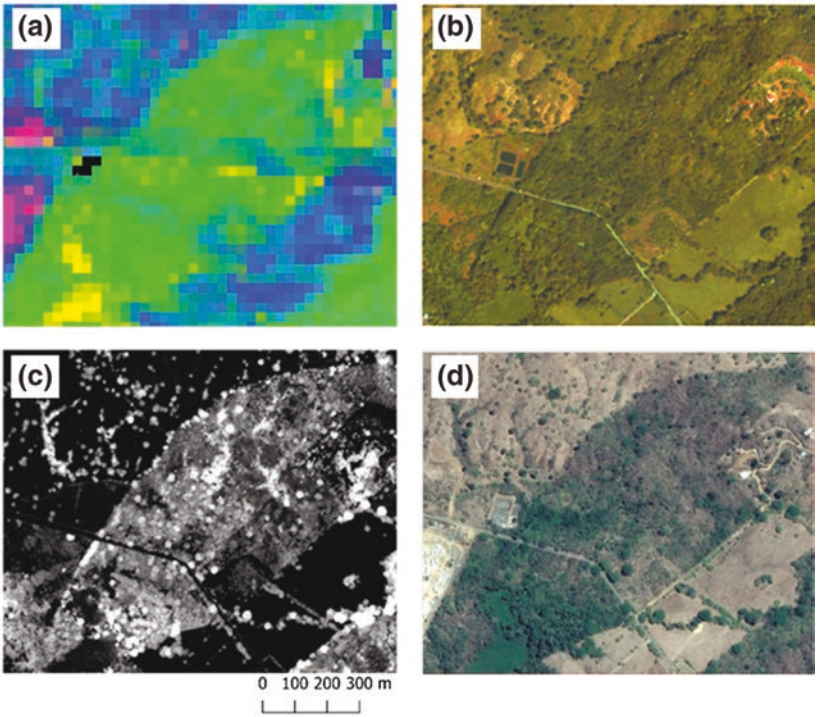

Fig. 9.4 Medium and high-resolution remotely sensed data. This figure contrasts four different sources of remotely sensed imagery we have used to understand reforestation dynamics in Los Santos province. The location chosen for these images includes a patch of secondary forest as well as some actively grazed land with dispersed pasture trees. In a clockwise direction, **a** represents medium-resolution Landsat data (30 × 30 m; Caughlin, Rifai, et al. 2016), **b** represents a subset of the hyperspectral visible-to-shortwave infrared data (2 m; Asner et al. 2012), **c** represents a Canopy Height Model (CHM) derived from LiDAR data (1.3 m; Asner et al. 2012), and **d** represents Google Earth imagery (<0.5 m; Google Earth 2018) (*Source* Figure created by the authors using QGIS and R)

imagery for tropical areas, is a research priority. We addressed the problem of measuring continuous changes in tree cover within 30 × 30 m Landsat pixels by fusing the Landsat archive with high spatial resolution aerial LiDAR data (Asner et al. 2012). The LiDAR data had a spatial resolution of 1.13 m, fine enough to capture many of the essential features of tree cover in our agricultural study area, including live fences,

dispersed pasture trees, and scrubby fallow (Caughlin, Graves, et al. 2016). However, the LiDAR data were limited to a single time period (January 2012) and a relatively small area: approximately 3.5% of Los Santos province. By developing Landsat-LiDAR fusion techniques, we were able to construct change trajectories for tree canopy cover and height change for a ten-year period across the study area. Similar to previous studies using remotely sensed data, we found an overall increase in tree cover in the area. Unlike these previous studies, we were able to demonstrate that most of this increase was due to pixels with relatively small (<2 m) increases in tree height. These measurements of continuous tree cover change complicate the idea that widespread increases in forest cover are occurring in Southwest Panama. The increases in tree cover revealed by Landsat-LiDAR fusion do not imply a trajectory from pasture to primary forest (as they could be due to shifting agriculture) and leave room for interpretations of land cover change that acknowledge the complexity of land management in the region.

While predicting continuous changes in tree cover provides a more realistic view of land cover change in our study area, Landsat pixels are still relatively coarse compared to the scale of tree cover variation in the landscape. A major limitation of the 30 × 30 m scale is that multiple tree cover types with different agronomic and ecological functions could be present within the same pixel. In our landscape, tree cover types include dispersed pasture trees, riparian corridors, fallow shrubland, live fences, and forest fragments, each with different social and ecological values (Harvey et al. 2005; Garen et al. 2011). To examine change between these tree cover types, we digitized historical aerial photographs taken in 1998 and acquired from the Tommy Guardia National Geographic Institute of the Republic of Panama and Google Earth Images from 2014 (Tarbox et al. 2018). Both data sources had high enough spatial resolution (<1 m) to enable differentiation of tree cover types. We then employed research assistants with on-the-ground experience in Latin American cattle pastures to hand-digitize tree cover types in randomly selected subsamples of these images and calculate change between tree cover types. The results of this study demonstrated very different rates of change between the five types of tree cover, with the highest increase for forest fragments, followed by riparian forest, with minimal change in

live fences and dispersed tree cover in pastures. Tree cover change was explained by different social-ecological variables for each of these classes. In some cases, the same variable had opposite effects on different tree cover types. For example, historical forest cover in a 100 m buffer around digitized areas of existing tree cover had a significantly positive effect on forest cover change, but a significantly negative effect on riparian tree cover change. One interpretation of these correlations is that for forest cover, proximity to existing forest fragments promotes forest regrowth due to biological factors such as seed availability, while for riparian tree cover, proximity to existing forest reduces the likelihood that farmers perceive forest scarcity and maintain trees along riparian areas.

While more work remains to be done to understand the drivers behind these various changes, the high-resolution imagery was crucial for understanding the landscape-scale dynamics. Although our hand-digitization procedure did not provide complete spatial coverage, random subsamples of tree cover change were possible from the imagery in many locations that would be difficult or impossible to access via fieldwork. Understanding tree cover change in our study area in terms of tree cover types contributed to our ability to relate land cover changes to factors that relate to both individual trees and farmer decision-making. The high spatial resolution data enabled us to confirm to our partners on the ground that increases in tree cover are occurring and to clarify that much of the increased tree cover is occurring in isolated patches and corridors.

High spatial resolution data alone has proven useful for quantifying canopy cover dynamics at landscape-scale; when combined with field data, high-resolution data can be directly linked to individual trees measured on the ground. This builds a connection between ecologists who work in the field collecting measurements on individual trees and land cover change scientists who work at landscape scales. For example, forest inventory plots, consisting of stem measurements at breast height (Diameter at Breast Height; DBH), represent the vast majority of data on tree communities and population dynamics. Global networks of forest inventory plots are now operational and have led to major advances in our understanding of tropical forest communities (Anderson-Teixeira et al. 2015). Perhaps the biggest challenge in connecting stem measurements to remotely sensed data is that canopy tree crowns may

not share the same location as stems (Schröter et al. 2012), which creates a physical separation between the location of an individual measured on the ground versus measured from the air. To ensure that field measurements are matched to the same individuals in the remote sensing data, we have implemented a mobile mapping system that enables researchers to digitize tree crowns on high spatial resolution images while in the field (Graves, Gearhart, et al. 2018). The system promotes interaction with remotely sensed data on the ground by linking the stem and crown of an individual tree. This enables researchers and practitioners who work in the field or from above to have a way to bring together their datasets and thereby increase their understanding of the system.

We have applied this mapping system to link hyperspectral imagery with stem measurements in the field to predict tree growth in plantations at our study site (Caughlin, Graves, et al. 2016). One result so far is evidence that hyperspectral imagery can be related to tree demography, a finding with implications for mapping and monitoring reforestation plantings at landscape scales. In addition, mapping individual tree crowns has been used in our study site to map the species composition and carbon storage of the trees in agricultural areas (Graves et al. 2016; Graves, Caughlin, et al. 2018). While this study focused on the development of tools to classify trees in a species-rich landscape, the output of this work was the location, size, and predicted species for all trees across the landscape. This work points to how connecting individual trees to field measurements in high spatial resolution imagery can unite disparate data sources that are related to one another in space. The dataset of mapped tree crowns will allow researchers and conservation practitioners to use information about the location, size, and species identity of individuals to support reforestation efforts. For example, a long-term conservation goal of the AEP is to strategically target forest restoration efforts to create a biological corridor between forest fragments in the largely deforested eastern half of the peninsula with a protected area in the west, Cerro Hoya National Park. We anticipate that individually mapped tree crowns will help guide species-planting efforts to facilitate restoration along the planned corridor.

Remotely sensed measurements of ecological data, including tree growth (Caughlin, Graves, et al. 2016) and tree species richness (Graves

et al. 2016), raise the question of what role field data will play in a future where high-resolution imagery is increasingly common. Our belief is that while remotely sensed data will never replace field data, the types of ecological field data that are most valuable for scientific inference will change. Some ecological features (e.g. below-canopy individuals, seedlings) may remain undetectable from satellite and aerial imagery, necessitating the need to focus on these data for field collection. While remotely sensed data are ideal for observational landscape-scale measurements, field experiments will remain critically important (Tewksbury et al. 2002). Where new forest inventory plots are being placed, we suggest that these plots will have the greatest value when they are strategically located to ensure utility for training algorithms that can recover ecological dynamics from remotely sensed data. The way to achieve this goal is to ensure that plots are stratified across landscapes and land cover types (Marvin et al. 2014). Altogether, we anticipate that the growing importance of remote sensing technology will necessitate collaborative projects that involve ecology, land cover change science, and remote sensing. Negotiating disputes over topics including site selection, data interpretation, and cross-scale inference, will benefit from the techniques outlined in this book on crossing boundaries for collaboration.

9.6 Incorporating Stakeholder Feedback on Models

In addition to resolving scale mismatches between natural dynamics and regional-scale LULCC, high-resolution imagery can also provide insight into human dynamics across scales. A fundamental problem we faced was the difficulty of inferring farmer decision-making from the best available data over a large spatial extent (census data) because it represented aggregated populations and their socioeconomic characteristics. We have found that high-resolution imagery has the potential to ameliorate this data gap by facilitating conversations between land managers and researchers.

To receive feedback on our modeling approaches from land managers responsible for land use decisions in Southwestern Panama, we

designed an outreach activity for three farming communities. Our NGO partner (AEP) facilitated access to communities. All three communities had a pre-existing relationship with the AEP, and we incentivized participation by providing a meal during the activity. The activity involved presenting maps of local changes in forest cover, derived from high spatial resolution imagery. We followed this presentation with a board game for farmers designed to represent our conceptual model for the social-ecological dynamics of reforestation (Fig. 9.5). Farmer feedback on the game dynamics enabled us to pinpoint strengths and weaknesses of our research approach in terms of our assumptions about farmer preferences and decision behavior with regard to land management. This outreach activity illustrates how high-resolution imagery can play an increasing role in participatory research that connects local stakeholders to academic research (see also Vergara-Asenjo et al. 2015). The key point is to work with remotely sensed data that has a high enough resolution to ensure that objects we interact with on a human scale are identifiable in the images, in contrast to remotely sensed data with a medium resolution where objects at a "human scale" are challenging to identify and require an understanding of the landscape from a much more distant and abstract perspective. From a fieldwork perspective, the fact that we could show landowners their farm in an airborne image that they could interpret was a powerful way to receive feedback on our research.

The participatory research outcomes reinforce the need to develop new conceptual models for reforestation that include a higher level of detail on tree cover dynamics. While farmers responded positively to labor scarcity as a main socioeconomic driver of forest gain, they criticized our representation of agricultural practices as overly simplistic. Our game assumed that reforestation occurred when land was removed from agricultural production due to lack of available labor to remove encroaching trees. In contrast, the farmers described a range of agricultural practices, including enabling cows to graze in secondary forest and selectively retaining desirable tree species that naturally regenerated in pastures, that were not included in our conceptual model of reforestation. These criticisms of our game design were valuable as they enabled us to view our academic research from the perspective of the stakeholders that are

Fig. 9.5 Local farmers participating in land cover change research. This photo demonstrates local farmers engaging in a board game based on land cover change data. As part of this activity, farmers interpreted tree cover change in high-resolution imagery (*Source* Photo taken by T. Caughlin)

actually responsible for land management decisions. A strong relationship with a local partner that farmers trusted (the AEP), an engaging activity that sparked discussion, and a willingness to listen carefully to farmer feedback were instrumental in the success of this outreach activity.

High-resolution remotely sensed data provided us with a way to turn our initial uncertainty on the degree of forest cover change in the Azuero Peninsula into an actionable research plan. The resultant analyses of land cover and farmer decision-making point to unrecognized complexity in tree cover dynamics at our study area. While our initial goal was to integrate social and ecological data into a single mathematical model to predict forest cover change, the cross-disciplinary dialogue during the course of our research suggests that we will need to revisit our fundamental assumptions before such a model is possible. Our next steps will include more precise knowledge of current and historical land cover as assessed and monitored using high-resolution data of individual properties (or property types) as related to farmer characteristics and behaviors. Novel methods are being developed to spatially disaggregate census data (Stevens et al. 2015; Wardrop et al. 2018) to finer spatial scales. Applying these methods to relate parcel-level variation in tree cover to socioeconomic features has great potential for our system. High-resolution imagery will enable researchers to relate these features to land cover change beyond forest versus non-forest categories, to a level of ecological detail that includes continuous variation in secondary forest structure, tree cover types, and even tree species identity. By evaluating these landscape-scale measurements of tree cover in the context of forest transition theories (Lambin and Meyfroidt 2010), we will move closer towards analyses that can be reconciled with interview data where farmers indicate the importance of varying types of tree cover (e.g. Metzel and Montagnini 2014).

9.7 Challenges to Applying High Spatial Resolution Imagery for CNH Research

The value of high-resolution data is a unifying lesson from the first four years of our interdisciplinary research project. Nonetheless, these data also present challenges for research teams investigating CNH questions. These

challenges include accessibility and technical skills required to access data. Below we describe these challenges, including potential solutions.

High spatial resolution imagery historically has had much lower accessibility to the scientific community, conservation groups and the public than medium-resolution images. Medium-resolution images such as Landsat have been freely available since 2008, whereas high spatial resolution satellite data such as Quickbird, RapidEye, and Planet Labs are relatively expensive. For conservation groups and academics, the high cost is often offset by programs by the satellite providers for free or low-cost images for conservation and research purposes. In addition, high spatial resolution images are available to view, but not download, from Google Earth. The opportunity to visualize high spatial resolution images contributes widely to interpreting lower resolution data (e.g. Giri et al. 2011) and can also be used to interface with farmers and other stakeholders (Peters-Guarin and McCall 2011). In addition, the Google Earth Engine analysis interface allows users to perform analyses on images stored remotely, retrieve the analyses and share results (Hansen et al. 2016). Despite these improvements, greater accessibility is clearly needed to increase the use of high spatial resolution imagery as a boundary object for conservation (Boyle et al. 2014; Turner et al. 2015).

Significant technical expertise may be required to process and use the data, but growing open source programs allow greater ability for anyone to use these data. Analysis of satellite data requires significant technical expertise, especially when using complex data like hyperspectral or LiDAR data. Proprietary software for analyzing these data is expensive, but the availability and usability of open, free software is increasing. Some examples of freely available software with high functionality include QGIS (qgis.org), GDAL (www.gdal.org) and the Google Earth Engine platform (earthengine.google.com). Despite being freely available, these high function software platforms still require a significant time investment for users to become proficient. Other platforms are now available that use images from Google Earth and other sources to perform analysis without a high level of training including openforis (http://www.openforis.org/home.html, server global (https://www.servirglobal.net/), lacowiki (https://laco-wiki.net/en/welcome) and others

(Clark and Aide 2011; Jacobson et al. 2015). Finally, achieving results with minimal remote sensing expertise may be possible in some cases. For example, our analysis of tree cover types was based on manual digitization which required significant human resources but minimal computational experience.

Bringing together the NGO (AEP) and the remote sensing team (the Carnegie Airborne Observatory; CAO) involved organizations with different overall goals than our own for this project. In particular, AEP has focused on community development, organic farming, and recycling initiatives, in addition to reforestation. The remote sensing team had been funded to acquire high resolution hyperspectral-LiDAR data for all of Panama to estimate carbon (Asner et al. 2013), although the RS team was looking to take advantage of these data for other basic and applied environmental questions. Our initial team had to have the connections with these groups to see that they could be brought together for this study. In addition, working with other organizations with different goals was not always straightforward. The work required strong communication, clear explanation of benefits to all parties involved, and flexibility in goals of this project to dovetail with the goals of the NGO and RS teams.

9.8 Conclusions

Scale mismatches are a pervasive problem for coupled natural-human systems research (Cumming et al. 2006; Kramer et al. 2017). While researching the dynamics of reforestation in southwestern Panama, we found that mismatches between household survey data, ecological field plots, and medium-resolution satellite data impeded interdisciplinary collaboration. While LULCC studies suggested that a modest increase from non-forest to forest cover was occurring in our study area, researchers with field experience were skeptical of a large-scale forest transition, pointing to the prevalence of trees outside forests and a perceived lack of new forest patches in the landscape. Ecological field data that could inform the forest dynamics underlying these transitions were limited to forest inventory plots across a small spatial extent, restricting the ability of

these data to inform ecological processes across the heterogeneous landscape. We found that high-resolution remotely sensed data presented a solution to the challenge of collaborating across disciplines that spanned multiple scales. As an increasing variety of high-resolution imagery comes online, we anticipate that these data will provide unprecedented opportunities for spatial analyses that facilitate sustainable land management.

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10

Scientists and Stakeholders, Data and Diagnostics: Crossing Boundaries for Modeling the Impacts of Highway Paving in a Tri-national Frontier in the Amazon

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10.1 Introduction: Road Impacts on Social-Ecological Systems

Roads and other infrastructure bear numerous and complex impacts on affected regions. The economic literature generally highlights the benefits of roads, whether in terms of improved access to urban markets and services for rural producers, increased connectivity among cities and

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regions to foster improved trade, or poverty reduction resulting from the first two (e.g., Gunasekera et al. 2008; Straub 2008). In contrast, the ecology literature has documented a litany of negative impacts of roads, whether by fragmenting habitats and disturbing stream networks that undermine species movements and dispersion and foster the introduction of invasive exotics, or by the common observation of wildlife mortality when crossing roads (e.g. Forman et al. 2003; Trombulak and Frissell 2000). A more dispersed literature on various social impacts of infrastructure also exists, which largely underscores negative outcomes of roads including the routine lack of participatory consultations with extant populations as to their needs and concerns, the arrival of colonizers and consequent agrarian conflicts, increasing inequalities among stakeholder groups (e.g. Devres Inc. 1981; Shriar 2009). In sum, new or improved infrastructure yields a wide array of impacts which unfold according to their own logic and often interact in complicated ways, yielding complex change dynamics as a result. Regions affected by roads are thus complex social-ecological systems (SESs).

This necessitates an integrative approach to the study of the socio-economic and ecological impacts of infrastructure (Perz et al. 2012). Whereas specialty literatures rooted in particular disciplines have tended to draw highly contrasting conclusions about the wisdom of

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roads, there remains a need to better understand the synergistic changes in socioeconomic and ecological subsystems in affected regions. We approach the dynamics entrained by road paving using the keystone concepts of connectivity and resilience (cf. Perz et al. 2012). For present purposes, connectivity refers to spatial connectivity as affected by road paving and other infrastructure investments. We therefore unpack the concept of connectivity in terms of "access" and "linkage" connectivity. Access connectivity refers to the ease of transport among locations, in terms of time and monetary costs. Linkage connectivity, on the other hand, is defined by the edges that link nodes in a network of locations potentially integrated by road paving. We focus on rural communities where producers generate products for sale in one or more of several potential urban markets.

The question then is whether increases in connectivity lead to changes in SES components that in turn bear ramifications for system resilience. Resilience is a concept that has been broadly used and by now has many meanings (e.g., Strunz 2012). For present purposes, we focus on ecological resilience, which refers to potential changes in the state of a system (e.g., Scheffer 2009: 101–103). As complex systems, SESs may exist in one of multiple possible states at any given time. Thus, an SES being impacted by a disturbance may or may not shift to a new and different state. If the SES is resilient to the disturbance, it will remain in its initial state; but if not, it will shift to a different state, whether desirable or undesirable. In the case of road paving and the socioeconomic and ecological dynamics, affected regions may exhibit major changes in natural resource use and local habitats, such that the values of key system indicators change in ways that cannot easily be undone. This requires the identification of key indicators of system state, thresholds for changes in those indicators beyond which they cannot readily change back, and a mode of analysis for evaluating SES resilience in those terms. For the case of infrastructure impacts, we consider socioeconomic indicators like producer income and wealth, along with ecological indicators such as forest cover, soil productivity, and species diversity, as well as "interface" indicators like the predominant forms of resource use, which are affected by both socioeconomic and ecological processes.

We pursued the integrated analysis of socioeconomic and ecological impacts of infrastructure by crossing multiple types of boundaries (Perz 2016). For one, we spanned disciplinary divides between the socioeconomic and biophysical sciences. We also crossed national boundaries, because our study case happens to be a tri-national frontier in the Amazon, which required collaboration between US-based researchers (themselves from several countries) with in-country partners in the affected region. We further spanned divides among organizational types, most notably between universities and non-governmental organizations for complementary research inputs, but also between academic researchers and various governmental agencies and communities. We crossed these boundaries in the process of pursuing an iterative approach to modeling infrastructure impacts.

This led us to recognize additional boundaries at play in our modeling effort. One concerns the divide between "data specialists" who know the details of the region and who collected or manage empirical data on the SES, and "modelers" who had the task of translating and representing the many system components, relationships and processes at play into a useful simulation using computer software. Our team also pursued a sophisticated diagnostic approach that relates model inputs to outputs, which permits a direct and visual means of analysis of ecological resilience. This constitutes yet another boundary of sorts to be spanned, for it extends the research process beyond model development by expanding significantly on traditional model evaluation techniques. In this chapter, we therefore focus on three boundaries of particular interest, though we note others: (1) the boundary between the scientific team leading the inquiry and the numerous stakeholders who informed model parameterization and interpreted model output, (2) the boundary between the technical staff focused on empirics and the modelers who focused on simulation, and (3) the boundary between the modelers who focused on simulation and the analysts who concentrated on model evaluation.

The rest of this chapter proceeds as follows. The next section introduces our study case, the tri-national "MAP" frontier of the southwestern Amazon. We briefly rehearse the area's recent history, noting the paving of the Inter-Oceanic Highway (IOH) and its consequences.

We then outline our conceptual model for understanding road impacts in the Amazon as an SES. There we call particular attention to drivers, interactions, feedbacks, and other generators of nonlinear dynamics. We then discuss our team, noting its origins and composition as related to the key tasks in our project of integrating empirical data into the model as a representation of the MAP frontier as an SES. We also detail how in-country collaborators and other stakeholders participated in model development and interpretation. The heart of the chapter details a suite of issues that arose in the process of collaborating across boundaries in order to achieve our project goals. We offer several vignettes that detail salient tasks and challenges we faced in our collaborative enterprise. We feature the issues at play concerning empirics and models, the iterative process of model development with collaborator input, and development and modifications in the ecological subsystem of the model. We also focus on the key strategic practices we employed to address the challenges and advance toward our shared goals. The chapter then concludes with our reflections on how well our practices addressed our challenges, noting some lessons learned and offering recommendations for other teams seeking to cross multiple boundaries for the sake of modeling SESs.

10.2 Study Region: The Tri-national "MAP" Frontier in the Southwestern Amazon

The Amazon has long been occupied by human societies, starting with indigenous peoples, who were negatively impacted by the arrival of Europeans starting in the sixteenth century. The colonial period in the Amazon was defined by a series of boom-bust economic cycles dependent on the extraction of forest products for export (e.g., Santos 1980). In the twentieth century, the Amazon incurred an acceleration in land settlement. Beginning in the 1960s, public policies in several countries funded road construction and promoted new colonization (e.g., Goodland and Irwin 1975; Mahar 1989). The newcomers pursued non-traditional forms of natural resource use, shifting from forest

extractivism to deforestation for agriculture, ranching, logging and mining (e.g., Walker et al. 2009; Wood and Porro 2002). Conflicts over competing land claims and resource use (Schmink and Wood 1992) prompted governments to recognize various forms of land tenure and regulate resource management.

The tri-national "MAP" frontier where Madre de Dios (Peru), Acre (Brazil), and Pando (Bolivia) meet in the southwestern Amazon (Fig. 10.1) has long been a crossroads for outsiders seeking natural resources (Paredes 2015). This area is exceptionally biodiverse, even by Amazonian standards (e.g., Myers et al. 2000), because it encompasses an altitudinal gradient that defines the transition from the Amazonian lowlands to the Andean highlands. Such biodiversity includes economically valuable forest species. The southwestern Amazon was the epicenter of the rubber boom in the late nineteenth century (e.g., Tocantins 1979). When the boom went bust in the early twentieth century, rubber tappers remained, engaging in small-scale agriculture and living off forest products such as "Brazil nuts" (castaña nuts).

When governments began building roads into the Amazon in the 1960s, they also reached the southwestern corner of the basin. Of particular significance is that Brazil opened the BR-364 highway into Acre. Similarly, the Government of Peru supported colonization in the lowlands and the Government of Bolivia opened a road from La Paz to Cobija in Pando. This resulted in new land settlement, the growth of local towns, and capitalist investments.

Forest extractivism was increasingly replaced by agriculture and cattle ranching, causing land conflicts and rural violence in Brazil. The murder of Chico Mendes in Acre in 1988 drew international attention that related the environmental problem of deforestation to the social problem of agrarian conflicts. Rural communities organized against ranchers, leading to social movements against deforestation and violence. By the 1990s, governments increasingly recognized multiple social groups and different forms of land tenure tied to contrasting forms of resource management (Perz et al. 2013b). In Acre in particular, the "Forest Government" came to power and in the 2000s was promoting numerous innovative policies in support of sustainable forest management (Governo do Acre 2006).

Meanwhile, in 2000, the governments of all of the countries of South America met to constitute the Initiative for the Integration of Regional Infrastructure of South America, or IIRSA (CEPEI 2002). IIRSA amounted to a continent-wide plan to build strategic infrastructure along "axes of integration" to better link countries and thereby foster increased trade (IIRSA 2008). One of the first projects under IIRSA was the IOH, which involved road paving through the southwestern Amazon in order to link Atlantic ports in Brazil to Pacific ports in Peru. During 2006–2010, construction proceeded in Madre de Dios and elsewhere in Peru. To commemorate the onset of construction in 2006, President Lula of Brazil met President Toledo of Peru at the Integration Bridge at the tri-national frontier. In 2011, President Garcia of Peru came to Puerto Maldonado to inaugurate the Intercontinental Bridge over the Madre de Dios River, effectively opening the highway across the entire region.

IIRSA and the IOH have stimulated debate over the economic, ecological and social consequences of highway paving in the southwestern Amazon (Dourojeanni et al. 2010; Killeen 2007). Empirical studies have confirmed an acceleration in deforestation over time across the MAP frontier during paving of the IOH (Southworth et al. 2011; Perz et al. 2013b). At the same time, the global economic crisis in 2008 led to a rise in commodity prices, which prompted a gold boom in Madre de Dios (Swenson et al. 2011). Similarly, illegal logging is common across the MAP frontier (Cossio 2009), along with other illegal activity, such as drug trafficking.

The rapid change dynamics in the MAP frontier, especially those stimulated by the IOH, prompted local social movements to reach out across national borders. Shared recognition of common challenges led to the organization of public forums, which became the social movement called the "MAP Initiative" (Brown et al. 2002; van Oosten 2004). The public forums promoted knowledge exchange and popular participation in regional environmental planning. The MAP Initiative addressed economic development, environmental conservation, social equity, and public policies.

Public participation in MAP Initiative forums grew exponentially during the 2000s (Mendoza et al. 2007). The MAP Initiative caught

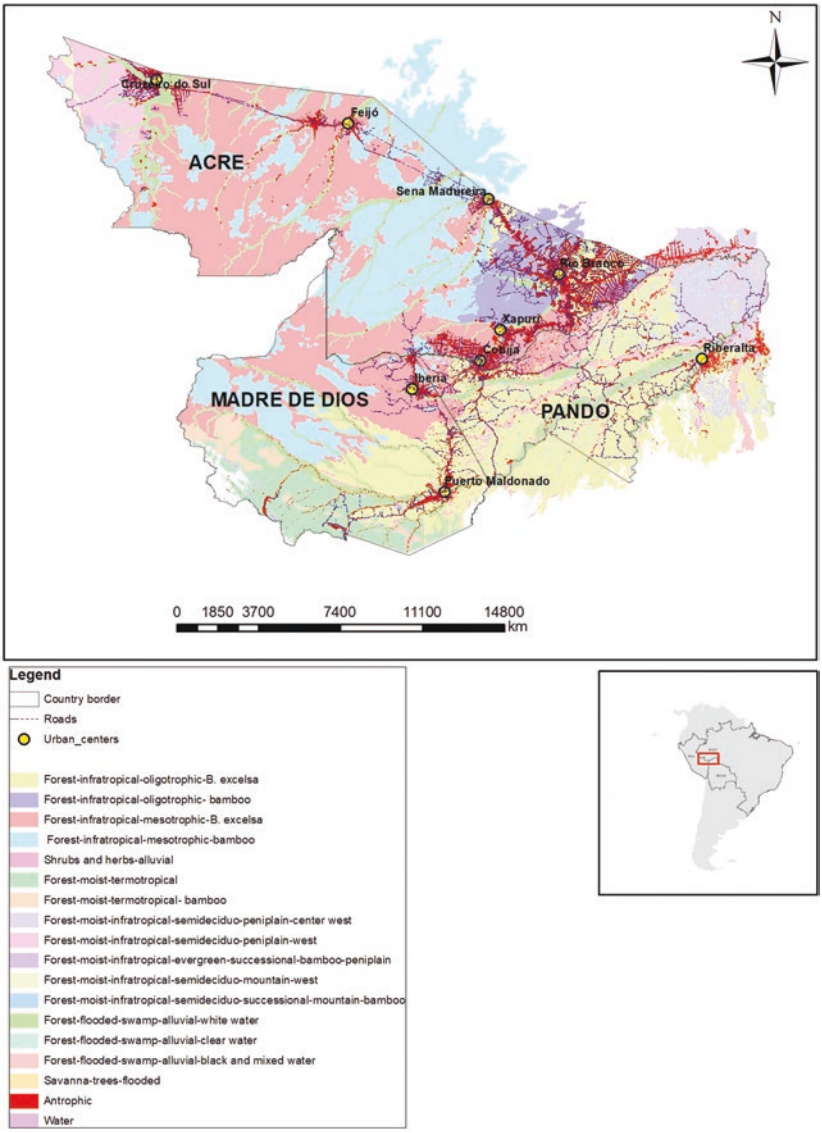

Fig. 10.1 Forest types in the tri-national "MAP" frontier (Madre de Dios/Peru, Acre/Brazil, and Pando/Bolivia) (*Source* Figure created by Galia Selaya using ArcGIS 10.4 with data from Wanderley Ferreira)

the attention of governments, banks, and aid agencies, all looking for opportunities to adopt new ideas as policy. By 2007, the governors of Madre de Dios, Acre, and Pando jointly attended the MAP Forum. As a result, the MAP Initiative prompted the emergence of many "mini-MAP" working groups focused on specific topics. Those working groups, in turn, began developing proposals for collaborative activities to inform public policies. Such proposals generally focused on priorities identified by the public in MAP Initiative forums, and thus drive interdisciplinary research and transdisciplinary conservation and development initiatives. The proposals in many cases resulted in collaborative projects that spanned disciplinary, organizational, and national boundaries, among others.

10.3 Road Corridors in Developing Regions as Complex Social-Ecological Systems

Our project was one result of the public forums of the MAP Initiative, and centered upon modeling the impacts of road paving on resource-dependent rural communities that manage forest and soil resources in the Amazon. Highway paving is a key driver of system change, precisely because infrastructure constitutes an interface between the socioeconomic and ecological subsystems. Road improvements thus affect both of those subsystems, as well as the ways in which they interact with each other. We therefore focused on modeling how paving affects the socioeconomic and ecological dynamics of road corridors as complex SESs.

First, we consider the socioeconomic subsystem. For the case of a developing region like the Amazon, there are many rural communities with families that have properties or concessions to lands they work for agriculture and other activities. Land tenure rights may vary among families, communities, and locations, and may include some access and use restrictions, such as deforestation limits. Rural families have various kinds of household assets, notably their land, labor, and various capitals. Land reflects the size of property or concession as well as the natural

capital it embodies in terms of its soils and forest type. Those variables influence the availability of natural resources to families, and thus their livelihood options and constraints. Beyond land and natural capitals, families have labor to deploy, depending on their household life cycle stage. Households with older children generally have more labor available, which broadens livelihood options. Families also vary in terms of their socioeconomic background (and thus initial wealth) as well as their educational attainment (and thus their ability to obtain urban wage jobs). Households may also access various capitals, including financial capital (credit) and social capital (labor exchanges and informal credit). Households thus deploy these assets as inputs in livelihood strategies that involve various forms of resource management.

Rural families follow an agricultural calendar based on Amazonian seasons. The timing of activities is defined by precipitation, which then dictates key moments for clearing of the forest, burning of vegetation, planting of crops, weeding, harvesting of crops and forest products, and sales. In the Amazonian context, rural households have various livelihood options, including harvesting of non-timber forest products (NTFPs, such as castaña nuts), removing forest stocks (such as timber), clearing forest for crops (for food and/or sale) which have varying characteristics (like annual/row crops as distinct from perennial/tree crops, which affect soils differently), or livestock (especially cattle, which require extensive pastures), and off-farm income sources (like wages or state benefits). Rural household first seek food security to survive, but then seek to produce a surplus for sale. Households thus seek to manage risk before pursuing profit, in part determined by market accessibility.

Sales depend on product prices, production costs and transport costs. Sales can be realized by either hauling produce to market (and incurring transport costs) or waiting for middlemen to come to a farm (they will go farther out from markets than producers can afford to haul in produce, but they pay lower prices), or joining a cooperative (which entrains a membership fee but improves terms but is only available for certain products in some cities). Transport costs depend on market distance as well as paving status, such that closer markets and paved roads lower transport costs. Sales also depend on market size and demand, which affects the likelihood of a seller finding a buyer. Income can be

used to buy food if there is a shortfall in production, or reinvested to increase production, or put to pursue new livelihood activities.

For the ecological subsystem, we focus on vegetation dynamics as influenced by climate and soils and initial vegetation composition. The Amazon has various forest types defined by distinct vegetation communities as documented by botanical inventories (Fig. 10.1). Each forest type thus has a distinct profile of species in terms of their relative abundance. Forest types thus correspond to specific levels of floral biodiversity (and thus the availability of NTFP and timber species) as well as forest carbon. After disturbances, forest type also influences the regeneration of forest species and the rate of carbon sequestration over time. In turn, forest types are associated with soil types with specific chemical properties that have important implications if the forest is disturbed or cleared. Different soil types lead to varying agricultural yields and pasture stocking densities. Under agricultural cultivation or ranching, soil types have distinct levels of soil nutrients and curves over time for nutrient loss and thus productivity. Also important for vegetation including agriculture is climate. Amazonian seasons are defined by variations in precipitation rather than temperature, with marked wet and dry seasons. But precipitation varies among years as well as among months. Further, climate change is increasing climatic variability, making seasons less well-defined and increasing uncertainties for crop productivity as well as forest regeneration. Hence climate and soils influence forest type as well as the dynamics of forest regeneration should forests be disturbed. These dynamics, in turn, influence the profile of species in a forest as well as carbon stocks.

The discussion so far makes evident that the socioeconomic and ecological subsystems have important and reciprocal interactions. The ecological subsystem affects the socioeconomic by determining the forest and soil resources available to households. Some forest types have more NTFPs and timber than others; some soil types permit greater and longer-term agricultural production. The socioeconomic subsystem, in turn, affects the ecological by determining what natural resources get exploited, and whether there is sustainable exploitation, degradation, or outright removal. NTFP extraction is sustainable in the short term, whereas crop cultivation and ranching yield soil degradation over

time, and timber extraction simply removes the resource. Further, forest clearing for agriculture removes many forest tree species and reduces biomass. Soil degradation may necessitate fallowing and thus vegetation regrowth (and carbon sequestration), or possibly a shift to pasture (to maintain an income stream, but preventing vegetation recovery, and worsening soil degradation). The ecological subsystem thus feeds back to the socioeconomic. Management outcomes from decisions in one agricultural year determine whether natural resources remain or are diminished or gone in the next. Climate and soil and forest types bear implications for resource recovery after disturbance and degradation, shifting livelihood options. In turn, the socioeconomic subsystem feeds back to the ecological. Changes in household assets can modify resource use. Increased labor availability or wealth can result in expanded resource management, possibly resulting in more forest degradation or clearing, or more intensified land use and thus soil degradation. Alternatively, new assets may permit new livelihood activities, including some that take labor off-farm and thereby slow resource use.

Highway paving modifies these reciprocal dynamics in road corridors of the Amazon. The key change is that paving reduces transport costs and permits year-round travel, making larger areas accessible and profitable for human resource use. Road paving facilitates rural access to urban markets. A household at a given distance from a market may thus gain new livelihood options as a result of road paving, and improved profitability from pre-existing options. The tendency with road paving is for natural resource management to expand outward spatially and to intensify in areas of established settlement. Hence road paving may accelerate resource use and land and soil degradation. Further, with highway paving comes urban growth, and thus an increase in urban market size. This can facilitate sales of rural products, for larger markets have greater demand and thus improved prospects for producers to find buyers. This can also reinforce rural profitability and ecological degradation.

But improved access to urban markets also means improved access to urban jobs and services. Rural adults may opt to go look for jobs in urban markets, shifting their livelihoods away from resource use and thereby reducing ecological degradation. Finding an urban job depends

on education, household wealth, and urban market size. Rural households may also send older children to urban areas for secondary education, which also reduces rural household labor and thus on-farm resource use.

With these system components and relationships in mind, we sought to develop a simulation model to evaluate how changes in system dynamics due to road paving would affect a suite of indicators of system state. Given the focus on the IOH in MAP as an SES, we identified several socioeconomic indicators (e.g., household income and wealth), functional ecological indicators (e.g., forest cover and carbon stocks), and social-ecological indicators (e.g., crop yields and food security) for purposes of evaluating the resilience of the system to road paving. These variables will likely reflect the interactions among system components that yield feedbacks and generate nonlinear dynamics. Together, these indicators of system state reflect the complex dynamics as well as the multifaceted consequences of road paving.

10.4 The MAP CNH Project: Spanning Many Divides

The conceptual model outlined above was the result of long-term collaboration between personnel at the University of Florida (UF) and in-country MAP partners. With the growth of the MAP Initiative, proposals for scientific research were funded for activities in the MAP frontier. UF had long sent faculty and graduate students to the southwestern Amazon. UF had also formed a working group on infrastructure issues and was developing conceptual frameworks to permit an integrated approach to understanding road impacts. UF was thus among the outside organizations invited to offer presentations in early MAP Initiative forums. Presentations by UF faculty and graduate students interested MAP Initiative organizers and participants and led to discussions about joint projects.

UF engaged in discussions with partner universities in the MAP frontier and received funding from NSF under the Human and Social

Dynamics (HSD) program in 2005, which supported field data collection. UF collaborated with the National Amazonian University of Madre de Dios (Peru), the Federal University of Acre (Brazil) and the Amazonian University of Pando (Bolivia). We formed a management team of faculty from each university for collection and analysis of socioeconomic, botanical and remote sensing data. In total, the team encompassed over 20 faculty plus nearly 70 undergraduate and graduate students from the four institutions (Perz 2016, Chapter 2). The MAP HSD project visited 100 communities across the MAP frontier, conducted nearly 750 household interviews, established roughly 70 botanical parcels, and compiled 8-image mosaics of land cover for 6 different time points from 1986 to 2010. The project generated many posters, pamphlets, and reports for MAP stakeholders, as well as numerous collaborative publications in peer-reviewed international scientific journals.

Stemming from that experience, we proposed a follow-up project to use these and other data to build a simulation model of the economic, ecological, and social impacts of paving the IOH in the MAP frontier. We developed proposals for the NSF Coupled Natural and Human Systems (CNH) program and secured funding in 2011. The project focused on two central goals: (1) development of a simulation model of the effects of road paving on an SES, using the IOH in the MAP frontier as our study case, in order to (2) conduct sensitivity analysis to evaluate the ecological resilience of the system to road paving as a key disturbance.

To address the first goal, we employed the "Questions and Decisions" (QnD) modeling system (Kiker et al. 2006; Kiker and Linkov 2006). QnD is an object-oriented platform that uses Java XML, which permits considerable flexibility in configuring a model. This was important because we sought a simulation model where the key driver, road paving, could change network ties among rural farms and urban markets as key objects in the system. Further, we sought to develop rural households as complex objects since families make numerous decisions about resource management in the context of changing circumstances, defined by factors including road paving, climatic variability, urban population growth, and price fluctuations. We thus took advantage of the strengths of QnD and traded high spatial resolution for greater process

complexity and a larger scale of network ties among locations across the MAP frontier.

For the second goal, we pursued model diagnostics via global sensitivity and uncertainty analysis (GSUA). Whereas the role of uncertainty analysis is to propagate various model input uncertainties onto model output, sensitivity analysis determines how uncertainty in model output can be apportioned to different sources (Saltelli et al. 2000, 2008). In other words, uncertainty analysis indicates the extent of uncertainty in a model, and sensitivity analysis decomposes that uncertainty in order to identify its most important sources. Whereas traditional sensitivity analysis employs "one-at-a-time" (OAT) techniques, in large models of complex SESs, OAT is insufficient, for there are numerous sources of uncertainty, and they may interact. We used GSUA, which considers all sources of uncertainty, screens out the less important sources (cf. Morris 1991; Campolongo et al. 2007), and then focuses on the relative importance of the remaining sources (Cukier et al. 1973; Saltelli et al. 2004).

Crucially, GSUA generates probability distribution functions (PDFs) for model outputs. We selected model outputs as indicators of the state of the MAP frontier as an SES. GSUA runs the model repeatedly, varying the input values of all parameters to observe the consequent distributions of model output values. Previous work has shown that different models of a given complex system yield PDFs of varying shapes (Muñoz-Carpena et al. 2007; Perz et al. 2013a). We relate the shape of PDFs to the "ball-and-cup" diagrams from the ecological resilience literature (e.g., Beisner et al. 2003; Scheffer 2009). Specifically, the width and depth of cups indicate the strength of "basins of attraction" to a particular system state. Resilient systems have deep, wide basins, so disturbances have great difficulty in moving the system into another basin, representing a different system state. Viewed in light of resilience thinking, a PDF from GSUA can be seen as a horizontal mirror image of a ball-and-cup diagram (Perz et al. 2013a). Deep, wide basins of attraction are reflected as high, wide portions of PDF curves, where the system indicator tends to remain even under many variations in model input values. A PDF from GSUA thus permits visualization of the probability that a system indicator's value will fall in the range of one or

more system states (Perz et al. 2013a). This provides a basis for quantitatively evaluating ecological resilience in complex systems.

To pursue these two goals, we formed a collaborative team centered upon model development and diagnostics. Whereas the MAP HSD project team was led by social scientists, botanists, and remote sensing specialists, the MAP CNH team featured the addition of two engineers. Our team thus spanned several disciplines in the social, biological and engineering sciences. In addition to the senior personnel, the team included several junior collaborators at UF as well as our counterparts at the partner universities in the MAP frontier. The team thus spanned organizational divides in terms of seniority, as well as country of the home institution.

Beyond the boundaries between disciplines, seniority, and countries, the MAP CNH team spanned additional divides worthy of note. Some senior personnel stemmed from the earlier MAP HSD effort that featured data collection and a focus on empirical analysis. Those faculty were also in many cases veterans of the earlier effort by the UF working group on infrastructure, and thus wedded in varying degrees to the original conceptual approach. On the other hand were the newcomers, namely the engineers, who were very focused on appropriating conceptual frameworks and data in order to translate them into code for simulation. Hence a suite of boundaries lined up, between a group that had worked together before and was focused on data and empirics, and a group that had not interacted as much with the others and centered upon coding and simulation.

Another distinction in the project team concerned the complementarity among the two engineers, who had decidedly different roles with regard to the modeling. Whereas one led the development of the simulation model itself, the other was responsible for conducting the diagnostics on the model with GSUA. There was thus a quasi-multidisciplinary complementarity between the two engineers, as each was brought into perform distinct functions. Crucial there however, was a key eventuality: the simulation model had to be developed first, before the diagnostics could be performed.

A final wrinkle in the MAP CNH project concerned the participation of two distinct groups of in-country partners. One group included

our counterpart colleagues situated at partner universities in the MAP frontier. The other group encompassed various stakeholders, ranging from government personnel to community members, NGO partners, and others. Both groups were included to provide input for the development of the simulation model and to reflect on the model design and output.

10.5 The MAP CNH Project: Challenges and Strategic Practices for Collaboration Across Boundaries

The many boundaries being spanned on the MAP CNH project led to a suite of challenges in collaboration. Here we provide a set of "vignettes" or short accounts of selected challenges in collaborating across boundaries, along with how we sought to manage the challenges via strategic practices. In some instances, the challenges proved insurmountable, whereas in others, application of strategic practices allowed us to advance.

Vignette 1 concerned the challenge of constructing the simulation model in QnD. Here the boundary that proved crucial was that between the older group of personnel from the MAP HSD project who focused on data and empirics and the newer group of engineers focused on modeling. During meetings, modelers would ask questions about what elements of the system needed to be included in the models. The data personnel would provide detailed discussions of data sources, data collection, and problems in the data. While everyone agreed that the models needed to incorporate data in order to faithfully represent the system, there were disagreements about the level of detail required. Underlying that point of tension lurked the old distinction between systems and models. Maps are not the territory, and models represent systems. This led to negotiations brokered by the PI over the level of detail in the data to enter the model. Data personnel tended to want to retain variations in data values, whereas the modelers tended to focus on

averages and capturing the various processes at play, leaving evaluation of the importance of variations in parameters for the GSUA.

One key strategy was to pursue analysis of the empirical data as compared to model output in order to quantitatively assess whether incorporating more detail would actually matter. This proposal, which came from the modelers, was readily accepted and led to ongoing testing and calibration. It proved a strong test however, for in cases where more details and local variation didn't actually make much difference, data personnel sometimes offered the refrain that adding yet more detail would reveal how important the details were. Conversely, when the model used empirical data for inputs that yielded output values that diverged from empirical output indicators, we considered other elements of model design as affecting output values. The key was for negotiations to continue, and the PI served as interlocutor in separate meetings with data personnel and modelers, and then made decisions about model design and data inputs.

Another strategic practice was to bring in additional collaborators. This occurred with the botanical data, for which we had a relatively low sampling density and less time depth. We hired a post-doctoral fellow with experience in botanical inventories in the MAP frontier. That person pointed out that increasing the team's capacity was insufficient in the face of limited data. We then partnered with other research teams who had collected their own botanical data, and signed cooperative agreements to exchange data, such that everybody then had more information and thus greater statistical power and better spatial coverage. That led to complications stemming from methodological differences among inventories from different sources. Testing also revealed some outliers, which led to suspicions that "the other teams had bad data." Additional analysis using statistical modeling led us to exclude some transects if certain parameters did not line up with other datasets. We therefore hired a third-party NGO with experience in modeling forest types to conduct additional analyses on the botanical data from the various sources, plus theirs. Our goal was to see if they arrived at similar conclusions about suspicious transects and to have them generate a suite of forest types for use in our simulation model. The notion was to get another opinion about problematic data, as well as to go from point

data to area data about forests in the study region. We obtained very useful answers on both counts, and the resulting data products played a crucial role in our simulations. However, the process of getting to that point is its own story.

Vignette 2 concerns the hiring of the NGO to conduct additional analysis of the botanical data. We had roughly 70 botanical transects and had obtained another 80 from other sources, but sampling density remained low, for the MAP frontier still covers nearly 10% of the Amazon's roughly 7 million km^2 of territory. Even with the IOH, much of the MAP frontier remains relatively remote, making forest classifications difficult with any rigor as to the species composition of the forest flora. This was further complicated by the fact that we were trying to obtain a single forest classification across a tri-national frontier. There were indeed many government data sources on vegetation types, but classifications were country-specific. Hence a key boundary to be spanned was national, along with the corresponding methodological differences among the sources of the botanical data.

We thus identified a Bolivian NGO with an international team (led by a Brazilian) with experience in mapping vegetation types. The MAP CNH team post-doc, who was Bolivian, served as the bridge in reaching out. The NGO leadership responded favorably to the proposed work. UF however required a contract for a consultancy, which led to defining the parameters of the work to be done, the deliverables and their deadlines, and of course the amount to be paid. The two institutions signed a contract that defined those terms and thereby permitted the technical work to go forward. Fortunately, no political issues arose for UF or the NGO in having a US university passing funds to Bolivian consultants.

There were however technical devils in the details. The complications stemming from the use of multiple botanical data sources again arose. Point data required the application of assumptions for interpolating values among locations to obtain areal maps. Despite having a contract in place, the NGO imposed the condition that UF not receive or share the additional data going into the analysis. This led to a second round of discussions and resulted in signing a second agreement concerning data access. That left a few black boxes in the methodological protocol,

and raised concerns about explaining methods and reporting findings for peer-reviewed publications. Because the NGO was a private entity, we avoided political complications; but because the NGO was a private entity, we encountered intellectual property issues in data access.

A key strategic practice in this regard was to engage in negotiations in order to clarify the constraints and understand the implications for the value of the products generated. We held several virtual meetings with the NGO to clarify what we would get in the final report and accompanying output files. The key was to identify the shared interests at play, which centered upon seeing the products forward to publications. Eventually an agreement was reached that for publication purposes, the NGO would be included in author lists or at least acknowledgments and be available to respond to possible reviewer concerns about data and methods.

With that goodwill secured, the NGO indeed confirmed that some of the transects surely had misestimated values for some key forest characteristics like biomass. That led to dialogues about the findings from the NGO analysis and removal of some data points. The NGO also identified some issues with governmental data sources which led to additional adjustments in some input parameters. This permitted adjustments in the areal maps of forest types while also converging toward a profile of relative species abundance in each forest type. In the event, both partners gained insights into the data, notably our understanding of the spatial distribution of forest types and the details of their vegetation communities in the southwestern Amazon.

Vignette 3 concerns the collaboration between the UF team and our counterparts in the partner universities. A key asset of QnD is its flexibility in model development, which is intended to facilitate a participatory process. In brief, the modeler consults with knowledgeable experts about the required components and parameters of the model, and produces an initial instantiation. That version is then presented to knowledgeable parties from the study region for their evaluation, with suggestions for adjustments that the modeler can then incorporate. We therefore held a series of workshops with our collaborators in the MAP frontier, including not only university counterparts from the MAP

HSD project but also others including NGO and government technical staff, independent researchers and university students.

We had time for three waves of workshops in each side of the MAP frontier. The first wave occurred before model development, and focused on how the counterparts viewed the MAP frontier as an SES. We asked them to form groups and draw up diagrams showing key system components and relationships. The groups then presented their models to each other for discussion. The second wave occurred during model development and took up issues of parameters not reported in available data sources and publications. We asked participants to provide parameter estimates for e.g. how long one man with an axe takes to clear a hectare of forest, how long the same man takes if he uses a chainsaw, etc. Everyone wrote their answers down on paper and then reported back to the group for discussion. The third wave of workshops came after model development and involved evaluation of model output. This occurred with a broader array of constituencies, and we discuss those workshops further below. For now, we note that the participants were very diverse, as they spanned disciplinary, organizational and national boundaries, among others.

In the first and second waves of workshops, we anticipated that responses would vary, but we underestimated by how much. In retrospect, the responses during the first workshop on SES frameworks were perhaps not surprising: biologists emphasized forest ecology, social scientists emphasized government policies and market prices, and so on. The tendency was to treat SESs in a disciplinary fashion. The discussions therefore sought to integrate what amounted to subsystem models together, and that involved the typical challenges of cross-disciplinary communication about key terms in the boxes, what different arrows mean (causes or flows?), and whether there were pieces missing. The UF team thus played the role of devil's advocates in asking questions about terms, relationships, and system complexity.

In the second workshop, we encountered similar challenges of vocabulary, but they manifested in terms of variation in parameter estimates. Our counterparts relished the opportunity to show their command of the details of production systems in their home region. But they interpreted our questions differently, leading to some startling variation

in the responses. When asked how long it would take a man with an axe to clear a hectare of forest, foresters assumed we were only talking about valuable timber, and gave much shorter time periods than everybody else. We therefore adopted a critical view of our own assumptions about the wording of our questions. On that basis, we pursued the strategic practice of stopping the workshop to get our counterparts to discuss their assumptions, in order to arrive at a shared understanding. Only then did we restate our questions and repeat the exercise. Every time there was a large variation in responses, the "minority group" got laughed at for their misinterpretation, but the ensuing discussion of the importance of clarifying terms and addressing assumptions was taken seriously and narrowed the range of responses. Due to these practices, some workshops ran longer than anticipated, but modelers were reassured that they obtained reasonable parameter estimates.

Vignette 4 concerns the distinction in the roles of the two modelers on our team: one was charged with developing the simulation model in QnD, and the other with the diagnostics using GSUA. Many projects incorporate OAT sensitivity analysis as part of the model development process, but with GSUA, a more "industrial strength" approach, sensitivity analysis requires supercomputer time, and thus constitutes a distinct stage of modeling. Hence the two parts of the modeling enterprise constituted different stages, one after the other. Whereas we featured GSUA in our original proposal, the team encountered delays in model development. A key issue was to contract post-docs to support the modeling effort in both stages. There a key asset of QnD as our modeling platform, its uniqueness in terms of its flexibility, proved to be an impediment, as we encountered difficulties in finding post-docs familiar with the details of the platform. While Java/XML is hardly unknown, ready familiarity with QnD was a taller ask.

As it happened, when recruiting post-docs, we found people ready to contribute to GSUA, for which we were not yet ready, but we had difficulties encountering someone ready to contribute to the simulation modeling. Despite multiple searches, we were unable to identify an available modeler as a post-doc who was ready to proceed with QnD. It was revelatory to the PI as a naïve sociologist to find a high degree of specialization among modelers, which in hindsight is no more

surprising than finding specialists among sociologists. None of this changed the result: we had insufficient human resources to advance the development of the simulation model in order to leave adequate time for the GSUA. The consequence was that we had a mismatch between the available labor and the stage of the modeling, which led to complications among the modelers themselves. Boundaries in modeling impeded our progress on model development and thus our ability to advance to the diagnostic stage.

A final story, Vignette 5, concerns our experience with the workshops after developing the simulation and generating model output, and occurred near the end of the MAP CNH project. Our proposal called for an outreach activity called the "knowledge exchange train" (KET; cf. Mendoza et al. 2007). The basic notion of a KET is to scale up knowledge exchange by having an entire team of researchers travel together, making stops like a train in various locations to hold workshops with stakeholders. A KET requires a substantial time investment, but affords the payoff of quickly reaching large numbers of people. The KET model is especially valuable under conditions of rapid change, diversity of knowledge funds, inequality in access to knowledge, and societal demand for knowledge, all of which obtain in the MAP frontier (Mendoza et al. 2014).

The KET at the end of the MAP CNH project was the fifth such experience, and the UF team worked with the originator of the KET concept as a consultant, so it was surprising that the new KET was quite challenging. The challenges stemmed from the fact that most of the KET team members had not participated in a previous KET, and the team was moreover very diverse, as were the stakeholder participants. The boundaries to be crossed were numerous: between disciplines, organizations, countries, education levels, languages, and more. Expectations among team members about the KET thus varied: for some, the point was merely knowledge transmission, whereas for others true exchange was crucial, and for yet others, the exchanges themselves were not the end, but instead a means to future collaborative relationships. There was consequently much discussion within the KET team, which included many members of the UF CNH team, as to what exactly all this was for.

It was also surprising that while the leaders and older residents of many towns we visited in the MAP frontier knew all about the KET, most participants were there for their first such experience. And despite the many MAP Initiative public forums and several previous KETs, most participants did not know much about the IOH and several other topics on which KET members reported. Demand for knowledge in the MAP frontier has not subsided but instead has increased over time.

No less challenging was the profile of the constituencies who actually appeared in the KET workshops. We knew the peoples of the MAP frontier are highly diverse, but the constituencies who said they would attend were often not the constituencies who actually participated. A given workshop might have local politicians, teachers, and school children, but the groups expected to show were rural producers. Even when those anticipated to participate did show, they were often very different constituencies from participants in the previous workshop. This made for big challenges in adapting to the audience, often during the workshops themselves.

A final challenge was to select topics and findings to bring to stakeholders. UF team members made those decisions on the basis of what they knew and valued in their science and their recent findings, including from our simulation models. Other KET participants similarly selected topics they felt to be important, with the key difference that they were much more grounded in the region and thus aware of the preoccupations of the hour. The result was that stakeholders were semi-comatose during presentations on topics they found uninteresting but became very animated about topics they found important. The topics falling into each category changed from stop to stop.

In the face of the manifold boundaries to be bridged, and the high level of uncertainty about audiences and their responses, we employed the strategic practice of adopting a very flexible approach to how we engaged stakeholders. We pursued a regimen of repeatedly adapting our presentations, generally shortening them and opening more space for stakeholder participation. This involved all manner of activities, including the use of radios to demonstrate communications during flood events when cell phone services fail, short demonstrations of measuring trees for botanical inventories as students measured each

other, and more. We reshuffled some presentations to establish an order we perceived that a given group of stakeholders would see as more interesting. This also meant featuring presentations where stakeholders expressed more interest, leaving more time for discussion. We also trained local people to give presentations to their peers, which proved to be extraordinarily validating to presenters and audiences alike. At one stop, we skipped the presentations almost entirely and switched the format to a poster fair. Much of this happened on the fly, right before or even during workshops, as the KET team sought to proactively respond to audience behavior.

If the exigencies of changing format, presenters, and content from workshop to workshop were rigorous, the value of the learning that transpired was high. As in previous KETs, school teachers and other representatives took posters to share with others in their community. Debriefs among KET team members between workshops permitted critical analysis of the previous day's event and afforded time for reflections and adjustments. A final meeting after the conclusion of the KET led to plans for follow-ups in selected communities.

10.6 Conclusion: Reflections and Lessons Learned

Boundaries come in many forms, and the MAP CNH project revealed many divides within academia, even within disciplines, as well as among non-academic stakeholders. Both significantly impacted our ability to pursue SES science, especially as it requires the integration of many forms of knowledge when modeling complex systems. While it is not surprising to know that community leaders see the world differently than scientists, the differences in perspectives within those groups were also considerable. Among scientists, differences bore implications for data quality and model instantiations. Much of our project was consequently spent on adjudicating the quality of various data sources and debating how to structure key elements of the simulation model.

Meanwhile, other social actors, including the engineer responsible for the GSUA diagnostics, our international counterparts and the broader community of stakeholders, were wondering what exactly was going on. While the modeler for diagnostics tapped his toe waiting for "the FINAL final model," counterparts inquired about manuscripts and co-authorship, and stakeholders wanted to know what was going to happen in their region in the future… according to the model. Managing those expectations in the context of debates over data quality and model design showed that boundaries are everywhere. Further, new ones can become evident during the process of an unfolding project, especially when the team hits a snag and the schedule proposed is not the schedule followed. When crossing boundaries, one finds that different players operate according to clocks ticking on different timescales with different deadlines.

These vagaries in SES projects lead us to reflections on lessons learned that motivate recommendations for future collaborators in similar enterprises. To organize our concluding discussion, we follow the framework in Perz (2016, Chapter 3) on the challenges and strategic practices of collaboration, tailoring our comments to the case of SES science and the boundaries we negotiated in the MAP CNH project. Because our project followed an earlier effort, introductions and trust were not as time-consuming as ongoing communication over disagreements. A key issue in our case concerned the translation of empirical relationships among system components into conditional statements and equations in the model code. The unavoidable stylizing of messy real-world relationships left data personnel discomfited. A key strategy then was to call meetings when several players had to be present, or to have the PI arrange a series of private discussions to let partisans air their concerns. Both however required the PI to set some boundaries on what would guide decisions stemming from the conversations. This was crucial to avoid letting some dispute about the model simmer then and explode later.

Politics and inequalities also reared their ugly heads. In our project, a key issue concerned the politics of data. Never underestimate the potential for doubts about data quality to hinder a multi-step modeling project. As already noted, we pursued a suite of strategies to deal with

limitations in the botanical data, including transect triage, trading of datasets, and adding collaborators. The larger lesson that emerged was to recognize the data limitations and to creatively pursue different avenues for mitigating the problems. In the case of our project, we had a fallback position of applying GSUA to systematically evaluate the sensitivity of model output to uncertainty in model input and thus quantify just how important a given parameter ultimately was. On inequalities, the key lesson stems from the point of departure: inequalities are the flip side of the coin from complementarities. Both bear the implication that everybody stands to learn. Senior scientists need to learn more: more about project management, more from stakeholder interpretations of findings, and more from junior team members. On that note, we hasten to add that junior team members often provided important bridges among senior scientists, even to the point of helping the PI adjudicate debates over data and model design.

Long experience has also shown us that common interests and complementary capacities are eminently valuable, but they have to be supported in collaborative spaces where discussions permit critique with the understanding that the point is not to tear down someone's discipline. Debates over parameter estimates and model design sometimes involved calling out certain players over their intellectual commitments, especially their assumptions. When debates occurred among collaborators who didn't know each other well, it was important for someone to step in and clarify that the issue in question was important and needed to be jointly explored to address a snag in the project. Once people understood that they had to take their disciplinary gatekeeper hats off, it was much easier to critique theoretical frameworks and methodological procedures, both of which facilitated innovative moves during model development. This was because everybody understood that everyone's disciplines, theories, and methods were fair game for the greater good offered by interrogation of ideas, breaking them down and laying bare their assumptions, in order to use the elements that contributed to integration. We also pursued a quantitative approach in model design decisions: how much would it matter if we used data with an upward bias, or if we structured an agent decision in a certain way? Our flexible modeling platform, QnD, permitted testing of such questions.

When all else failed and people around the table were unhappy, we periodically reminded ourselves of the consequences of opting out. This generally led to accommodation after hard decisions, often in the form of caveats or footnotes to be incorporated in manuscripts.

Clarifying goals and objectives is impeded by boundaries, especially if the science itself is complicated and the problems being addressed are of urgent real-world importance. This prompted the team to identify a series of goals tied to modeling and publications. Preliminary models and products for stakeholders thus came first, to be followed later by more definitive statements for scholarly publication. We thus sequenced objectives in graduated terms, rather than staking everything on the final paper in a prestigious journal. We also found our focus on uncertainty to be singularly useful, both for model design and when engaging counterparts and stakeholders. Especially with that last group, uncertainty offered a response to the extension agent's burden before rural producers who often expect clear prescriptions with a high degree of certainty. Explicitly discussing uncertainty helped manage expectations by modifying goals and thus the framing of the purpose of outreach workshops with stakeholders. Instead of proceeding in the mode of making promises in one-way knowledge transmission, we pursued knowledge exchange via discussions of uncertainty, as via scenarios. Worst case scenarios prompted stakeholder responses about how to avoid such eventualities, thus empowering them to reflect with an eye to action.

Leadership, management, and governance are never-ending tasks. Our CNH project was a sequel to an earlier project, but a key insight for the senior personnel is that complicated projects don't get easier with experience. Rather, experience just reminds one of how much work the next project is going to require. A key implication stemming from that daunting realization is to beware the routine, and to uphold best practices and pay attention to old problems as well as new, even if this is one's 15th SES science project. No two projects are the same with regard to their collaborative structures and the predilections of the players at hand. But therein lies a distinct advantage, noted above: the new players and especially junior team members offer new perspectives. Their suggestions might sometimes be naïve due to lack of experience,

but they also offer thinking outside the box of the routines of senior personnel, who should listen up.

Managing expectations and clarifying benefits also constitute persistent challenges. Time is costly, for as we have noted, running long on model design means running short of time for model diagnostics. It did not help that the same problem had transpired to our GSUA modeler on another SES science project, who now has two data points of problematic time management. An advantage in our case however was that the two modelers know each other better than any other dyad on our entire project, which permitted some degree of familiar rancor between them, the right amount to keep things moving forward. A similar principle applies to relations with in-country stakeholders: UF returns to the MAP frontier every year, which fosters familiarity. People know they can ask for things, but they also know what the answers are likely to be, which transits discussions efficiently to negotiations. Sustaining collaborative efforts thus makes management of expectations and benefits less awkward and more workable.

We conclude with remarks on surprise and uncertainty. For better and worse, uncertainty was a hallmark of our CNH project: we recognized from point go that uncertainty is important in model evaluation, but complications in some datasets led to more preoccupation with just how much uncertainty they harbored and their consequences for model output. Beyond data, uncertainty manifested itself in various other respects in our project, to a great degree as a result of crossing boundaries. Finding post-docs to support model development proved surprisingly difficult and led to complications in the simulation modeling and uncertainty for the onset of GSUA runs. It thus became necessary to shift project management from rational planning, since the proposed plan didn't come off, toward adaptive management as we made adjustments based on the results of initial strategies to deal with data and staffing issues. Toward the end of the project, we further engaged in scenario planning by considering various cases where issues got resolved suddenly to issues couldn't be resolved by the eve of the project conclusion. In any complicated project, be ready to scale the ladder of uncertainty, and thus to shift management protocols, all the way to muddling through (cf. Perz 2016).

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11

Collaboration Across Boundaries: Reflections on Studying the Sustainability of the Mississippi River Delta as a Coupled Natural-Human System

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11.1 Introduction

This chapter reports on our experience in collaboration across boundaries, which is derived largely from working on an interdisciplinary project funded by the National Science Foundation under the Dynamics of Coupled Natural-Human Systems (CNH) program. The project

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investigates the sustainability of the Mississippi River Delta (MRD), which is subject to multiple threats from depleting natural resources, natural and man-made hazards, and climate change, and is considered one of the most vulnerable coastal zones in the world. Our overarching research question is: will the MRD reach a tipping point that would make it difficult to sustain in the future? The project answers this key research question by developing dynamic empirical models to quantify the linkages and feedbacks among various natural and human components. The developed models are then used to simulate scenarios to inform policies, planning, and mitigation (Lam et al. 2012; Lam, Xu et al. 2018).

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The project consists of seven components, each led by investigators from different disciplines including hydrology, sedimentology, ecology, geography, political science, economics, and finance. A rather uncommon characteristic of this project within the NSF CNH program is that all the senior investigators are from the same institution—Louisiana State University. Thus, unlike most other CNH projects in which investigators from multiple institutions are often involved, we expected to encounter fewer complications in managing the logistics of the project so that we could spend more time focusing on the research problem itself. Consequently, our experience in working on this project focuses on collaboration across disciplines. Another unique aspect of our project in relation to the other chapters in this book is that our project is the only one addressing the coastal zone in the United States.

To compile our reflections on collaboration across boundaries in a systematic manner, we conducted a brief survey of the research team members. The survey included four open-ended questions, designed to gauge the team members' opinions on the challenges, benefits, and suggestions regarding interdisciplinary collaboration. In the following, we first describe the project, including its framework and some results, to provide a context for the discussion of interdisciplinary collaboration. We then summarize the results from the survey, which could be used to help formulate best practices for collaboration across boundaries.

It is necessary to clarify the terms resilience, vulnerability, and sustainability used in this chapter. These three terms are often used in a confusing manner in the literature, as they are defined differently by researchers in different fields. For ease of discussion, this chapter follows the definitions

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in our previous studies and considers vulnerability as part of the broader concept of resilience (Lam et al. 2014, 2015). Community resilience is the ability of a community to prepare, plan for, absorb, adapt, and recover from adverse events (National Research Council 2012). Sustainability refers to the capacity of society to meet its current needs while ensuring the well-being of future generations (Brundtland 1987). Sustainability considers the tradeoffs between environmental (i.e., ecological) services and human outcomes (Turner 2010). We understand long-term resilience as sustainability (Lam et al. 2016; Lam, Xu et al. 2018).

11.2 The Project

11.2.1 Study Region

Located in southeastern Louisiana, the study region includes a total of 26 parishes (equivalent to counties) spanning from north of Lake Pontchartrain to the coast of the Gulf of Mexico (Fig. 11.1). The study region includes some areas peripheral to the MRD so that we can provide contrast and comparison in our analysis and modeling effort. We defined the study region as a result of combining both the natural boundaries (watersheds) and political boundaries (parishes). The region includes 63 watersheds comprising the Lake Pontchartrain, Terrebonne, and Barataria basins, with a total drainage area of 44,806 km^2. Elevation ranges from −9 to 374 m above sea level (https://maps.ga.lsu.edu/lidar2000/). According to the US 2010 census statistics, the total population in the study area was 2,699,486 (Lam et al. 2012; Lam, Xu et al. 2018).

Because of the distinct differences in both the natural and human environments, we divide the study region into two parts. Using Lake Pontchartrain as an approximate boundary, we consider parishes north of the Lake as the "North", whereas parishes south of Lake Pontchartrain are labeled as the "South". The North, an inland region, is characterized by hardwood forests, agricultural fields, grasslands, and swamps and marshes. The South, on the other hand, is considered one of the most vulnerable coastal systems in the world. The South is vulnerable to multiple threats,

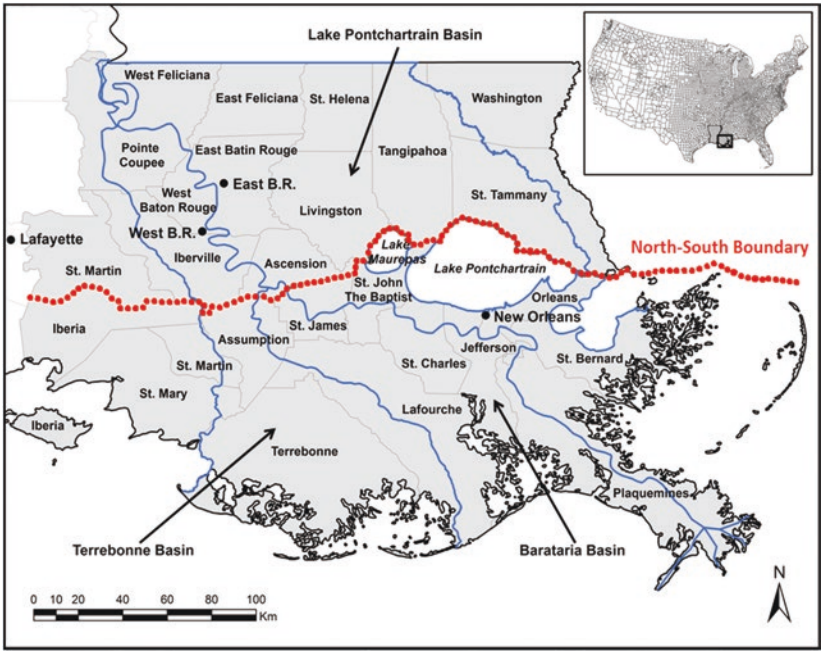


Fig. 11.1 The study area showing Lake Pontchartrain as a hypothetical boundary, with parishes to the north called the "North" whereas parishes to the south called the "South" (Lam, Xu et al. 2018). Reproduced with permission

including hurricanes, sea-level rise, flooding, oil spills, and global energy market fluctuations. A critical issue in the coastal South is land loss and coastline retreat (Twilley et al. 2016). A US Geological Survey estimate shows that during 1985–2010, Louisiana lost about 42.9 km^2 (16.58 square miles) of coastal wetlands per year, equivalent to losing about the size of one football field per hour (Couvillion et al. 2011). Although hurricanes and overbank flooding from rivers can periodically contribute sediments to wetlands (Bianchette et al. 2016), the MRD could be drowned in the near future due to insufficient sediment supply and sea-level rise (Blum and Roberts 2009). The South is highly engineered with various coastal restoration plans to restore wetlands (Coastal Protection and Restoration Authority of Louisiana CPRA 2012, 2017). While there is no single cause of the wetland loss, human factors such as dams and levees

built to prevent the river from flooding human communities block sediments from replenishing the wetlands (Xu and Rosen 2012; Wang and Xu 2018). Debates continue over the question of whether the high cost of coastal restoration ($50 billion over the next 50 years; CPRA 2017) is cost-effective given the continuing threats of sea-level rise and regional subsidence.

At the same time, a trend of declining population in the South has been observed. During 2000–2010, the population of the study region increased marginally by 3.26%, a low rate when compared with the national average of 9.7% (https://www.census.gov/prod/cen2010/briefs/c2010br-01.pdf). However, parishes in the North generally experienced higher population growth, with two parishes having especially large population increases: Ascension (39.9%) and Livingston (39.4%). By contrast, two parishes located in the South experienced significant population decline: St. Bernard (−46.6%) and Orleans (−29.1%). The trend of population decline seems to have accelerated after Hurricane Katrina in 2005 (Qiang and Lam 2016). Despite significant top-down efforts by the State in coastal restoration for the South, there is an underlying "bottom-up" trend where people in the South are making individual decisions on whether to stay or migrate (Lam, Xu et al. 2018). This raises the question: are we restoring land where nobody wants to stay? Despite the many studies of the natural system in the region, a system-level study that incorporates both natural and human systems has yet to be conducted. This project fills in the gap.

11.2.2 The Collaborative Approach

Our CNH project spans a period of six years (September 2012–2018). It has involved at least 30 people, including seven senior investigators, six postdoctoral researchers, 13 graduate students, and several undergraduate assistants at different points in time. During the project period, a number of students graduated and became postdoctoral researchers at LSU or elsewhere, and some postdoctoral researchers moved on to become faculty members in other institutions. This type of personnel turnover is normal and indeed welcomed, as one of our

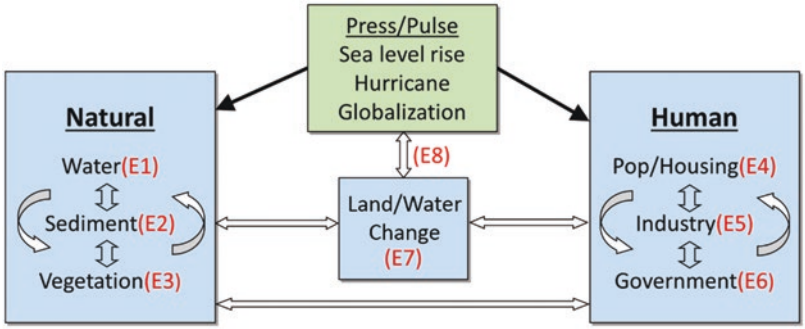
project's goals is to help prepare students and postdoctoral researchers for their future careers.

Because our project involved a multidisciplinary team, we engaged in collaborative practice by holding project meetings for the entire team about three times per semester; each meeting lasted about 2.5 hours. These meetings generally included presentations of research progress from each project component subgroup, which led to discussion of common issues and planning for the next meeting. To the credit of the team, the meetings often involved lively discussions on issues where multiple subgroups had to coordinate, especially toward the end of meeting periods and later in the project. In addition to the whole-team meetings, there were also regular meetings of subgroups.

Over the project period, we organized special sessions at the 2016 AGU Ocean Science Meeting and the 2017 AGU Fall Meeting. Also, at the end of the fourth project year (September 2016), we held a day-long workshop with coastal managers and community stakeholders to cultivate bidirectional communications and knowledge sharing between researchers and practitioners. The workshop thus constituted an outreach activity to nonacademic stakeholders.

11.2.3 The Coupled Natural-Human System Framework

The project considers land and its associated attributes including elevation, land loss, land use land cover (LULC), and their changes as the core component to integrate the natural and human systems throughout the landscape (Fig. 11.2). Land, or rather land loss in the case of MRD, is the main issue in the study region. Land loss is partly a result of insufficient sediment supply, which is caused by human interventions (river diversions, dams, levees), and partly a result of land subsidence, sea-level rise, coastal erosion, and other natural factors. Humans respond to the problem of land loss with more coastal protection and planning by building more dams and levees, which further accelerates the rate of land loss. In addition, human infrastructure such as roads, canals, and oil and gas pipelines that support economic activities also creates a fragmented landscape that accelerates land loss (Lam, Cheng et al. 2018).



E1: Sediment load = f_1 (water yield, LULC, control variables)
E2: Sedimentation rate = f_2 (sediment load, LULC, control variables)
E3: Biomass = f_3 (elevation, LULC, control variables), where Elevation = f_0 (sedimentation rate)
E4: Population/housing = f_4 (land loss, control variables)
E5: Energy industry = f_5 (land loss, population/housing, control variables)
E6: Governance/policy = f_6 (land loss, LULC, control variables)
E7: Land loss = f_7 (elevation, subsidence, sea level rise, human activity, control variables)
E8: LULC (Land change) = f_8 (sea level rise, extreme events, globalization, control variables)

Fig. 11.2 The Mississippi River Delta Coupled Natural-Human dynamics framework (Lam, Xu et al. 2018). Reproduced with permission

At the same time, land loss may decrease population growth, which could lead to reduced land use by humans and hence more vegetation. More vegetation will lead to better ecosystem health, less soil erosion, and a higher level of ecosystem services. Land loss and population growth are interrelated; they are the two main target variables in our modeling. If our final modeling and simulation results show that the region experiences a continuing trend of population decline or land loss, we can suggest that the region is not sustainable (Lam, Xu et al. 2018).

Our CNH framework has seven components, with three from the natural and three from the human systems, linked by the central component of "land". These seven interrelated components and associated processes include:

1. Hydrology—examines the relationships between river dynamics and sediment delivery;
2. Sedimentation—evaluates the changes in sedimentation rates as a result of a variety of natural and human factors;

3. Vegetation—evaluates the multiple interactions among sediment, vegetation, and biomass change;
4. Population/Housing—examines the relationships between land price, elevation (land loss), and population change;
5. Industry—determines the vulnerability of critical energy infrastructure due to land loss and sea-level rise;
6. Government—examines the adaptive governance in response to land loss and other threats.
7. Land—determines the land loss probability as a result of natural and human factors into a single framework.

Computationally, the land component is the core for integrating the other six components. Each component is governed by an equation, which serves to summarize the quantitative relationships among variables. In each equation, there are common variables that are used to model throughout the system, as well as other control variables. These equations are integrated into a raster-based spatial dynamics model to quantify the feedbacks and linkages between the natural and human systems at multiple spatial and temporal scales. In addition to the seven components, a module representing the presses and pulses to the system is included to signify the effects of external factors to the deltaic system such as sea-level rise, hurricanes, and economic globalization. Once the model based on empirical data is developed, we can simulate future land loss and population change over time. If the trajectory indicates low resiliency of the region based on our resilience assessment, then the region is considered not sustainable. By comparing the simulation results between the North and the South, we will be able to test our main hypothesis of whether the MRD will be sustainable in terms of population growth and land loss.

In the following, we elaborate further how each component functions as a submodel and how the seven components are interrelated so that they can be integrated to address the overarching question of whether the MRD is sustainable. Each of the seven components has a set of research questions with hypotheses to test. Each component submodel will employ methods appropriate to the research questions and generate new and original data. Thus, results generated from each component

will add new knowledge to their respective natural and human systems in the study region.

At the same time, each component submodel will generate output data that in turn serve as input to other submodels. Through those common variables, we can integrate submodels into a system-level model (see the equations in Fig. 11.2). These equations are conceptual equations; they could be nonlinear functions that quantitatively summarize the main inputs and outputs among the components. For present purposes, each equation can be regarded as a series of hypotheses describing the linkages between the natural and human subsystems in which common variables are used to ensure that key feedbacks are captured and modeled.

For example, Component 1, the Hydrology component, addresses three main questions: (1) what is the amount of divertible river flow and sediments from the Mississippi River and its tributaries? (2) How are the divertible sediments spatially and temporally restricted? And (3) if the divertible amount of sediments is not used, how much land could be lost in southeastern Louisiana by 2050 due to continuing land subsidence and sea-level rise? The main hypothesis is that if managed properly, riverine sediments are sufficient to counteract the relative sea-level rise in the region. To answer the three research questions and test the main hypothesis, researchers in the hydrological component needed to use a variety of methods. These included: (1) collection and assessment of recent three decades' riverine sediment delivery (1980–present) records for five major river systems in the MRD; (2) determination of the space-time dependent divertible sediment sources; and (3) prediction of future inundation risk and divertible sediment supplies for the South using IPCC climate change scenarios (Joshi and Xu 2017; Wang and Xu 2016, 2018; Xu and Rosen 2012).

Results from Component 1 are linked to Component 2—Sedimentation. The principal output of Component 2 is a set of sedimentation rates (cm/year) measured from various sites for different time periods. The hypotheses in this component are (1) the long-term sedimentation rate in the South has declined during the past century due to the construction of dams and reservoirs along the Mississippi River and its tributaries, which reduces sediment supply to coastal wetlands; (2) on the

contrary, in the North, the long-term sedimentation rate has increased due to increasing human activities that resulted in the conversion of forest to agricultural and urban land uses (LULC changes), thus increasing sediment supply in the form of sediment load; and (3) hurricanes are a major agent of increased sedimentation rates in the fluvial and deltaic wetlands, especially through the effects of heavy rainfall on overbank flooding of the Mississippi River and other local rivers. To test these hypotheses, the research team conducted extensive fieldwork to take lake sediment cores from a number of wetland/lake sites. Through various laboratory analyses and pollen analysis of the sediment cores, historical sedimentation rates were reconstructed. These original field-based sedimentation rate data, coupled with existing databases, were then used to generate the sedimentation rate of the entire study region so that they could be integrated into subsequent system-level modeling (Bianchette et al. 2016).

The sedimentation rate affects land elevation, which in turn affects vegetation responses and biomass (e.g., forest vs. marsh vs. open water), thus forming a link to Component 3—Vegetation. Other natural factors such as salinity, storm surge, and soil type have been shown to influence wetlands vegetation growth. Storm deposition caused by hurricanes can result in an increased sedimentation rate and elevation in the region's wetlands, which will affect vegetation growth and biomass (Liu et al. 2014). On the other hand, human activities, such as road construction, oil extraction, and timber harvesting, can affect the groundwater table and, consequently vegetation and biomass, which would in turn affect soil properties and sedimentation rates (Ryu et al. 2018).

Equations 11.1–11.3 describe the linkages among the three main components in the natural system, as well as linkages to other components through the inclusion of common variables (e.g., LULC) also used in other components.

$$\text{Sediment load} = \text{f1 (discharge, LULC, control variables)} \quad (11.1)$$

$$\text{Sedimentation rate} = \text{f2 (sediment load, LULC, control variables)} \quad (11.2)$$

$$\text{Biomass} = \text{f3 (elevation, LULC, control variables)},$$
$$\text{where Elevation} = \text{f0 (sedimentation rate, subsidence rate, biomass)} \quad (11.3)$$

For the human system, Component 4 (Population/Housing) addresses two related questions: (1) to what degree that elevation affects the pricing of the land, especially in terms of its future use? And (2) how will the land price affect population and migration? The two corresponding hypotheses are: (1) as elevation decreases, land price will decline. However, the response will not be linear. At a certain elevation threshold, the land will be no longer perceived as "useful" by humans and livelihoods surrounding the land will decline (the tipping point). Therefore, (2) population will increase in the North due to higher land prices and greater attractiveness. To answer the research questions and test the hypotheses, the team examined data from a variety of sources and in various formats, including data from the census, Internal Revenue Service (migration data), and US Geological Survey (e.g., elevation, LULC, highways, pipelines). For data processing and analysis, Geographic Information Science (GIS) and econometric methods are the dominant methods in this research component (Eq. 11.4) (Pace and Zhu 2017a, b; Li and Lam 2018a, b).

The research objectives of the Energy component (Component 5) were to: (1) analyze the vulnerability of the energy infrastructure to inundation and (2) quantify the capacity impacts on these energy system assets under different sea-level rise scenarios. The energy component is included in the system because the energy industry is critical to the Louisiana economy as well as the economies of the United States and the world. In 2014, Louisiana was the United States' number one producer of crude oil, number two in petroleum refining capacity, and number three in natural gas production (Louisiana Department of Natural Resources 2014). Land loss, land subsidence, and sea-level rise pose serious threats to the industry. In turn, oil and gas pipelines, canals, and roadways built to support the energy industry and other human activities have been considered a major factor in breaking up the wetlands, making them more fragmented and more likely to result in land loss (Lam, Cheng, et al. 2018). These linkages and feedbacks are complex, and empirical studies that directly address the casual relationships do not exist (Eq. 11.5; Dismukes and Narra 2016, 2018).

The Governance component (Component 6; Eq. 11.6) focuses on adaptive governance and planning. This component examines the

process of planning among Louisiana parishes in response to land loss and other threats. Several independent variables, provided by the other components, can be used in a multiple-regression analysis to assess the linkages with land loss, variables concerning population and housing values (Component 4), and variables concerning the presence of the energy industry within a parish (Component 5). At the same time, the specific land use ordinances and plans adopted by the Parish governments influence future sediment distribution, sedimentation rates, and land loss for certain protected areas. These ordinances constitute rules that can be included in the governance components as a factor that influences key variables in other components, thus permitting prediction of future physical and ecosystem conditions within the study area (Paille et al. 2016). Equations 11.4–11.6 describe the relationships of each of the three human subsystems.

$$\text{Population/housing} = \text{f4 (land loss, control variables)} \tag{11.4}$$

$$\text{Energy industry} = \text{f5 (land loss, industrial growth, control variables)} \tag{11.5}$$

$$\text{Governance/policy} = \text{f6 (land loss, population, LULC, control variables)} \tag{11.6}$$

The central component bridging the natural and human subsystems is Component 7—Land. This component is designed to incorporate the significant variables derived from each of the other components to examine land loss and its feedback effects on population change in the MRD. Land loss is mainly due to the loss of elevation (e.g., sedimentation rate not catching up with the rate of subsidence, erosion, and sea-level rise), which could be exacerbated by human activities such as canal dredging and pipeline construction, leading to fragmentation and saltwater intrusion, as modeled in Eq. 11.7:

$$\text{Land loss} = \text{f7 (elevation, subsidence, sea level rise, human activity, control variables)} \tag{11.7}$$

Long-term coastal sustainability depends on the rate of land loss. If the rate of land loss exceeds the rate of land accretion (increase in elevation),

then that land will not be sustainable as reflected by its negative population growth or diminished human activity (Qiang and Lam 2015, 2016).

Once the overall models and linkages are tested and validated, future scenarios under different climate change scenarios and management practices can be simulated with Eq. 11.8. This equation permits evaluation of the effects of climate change on the coupled system in order to address the question of whether the MRD will be sustainable under different climate scenarios.

$$\text{Land change} = \text{f8 (sea level rise, extreme events, globalization, control variables)} \tag{11.8}$$

In this project, we employ a combined cellular automata, genetic algorithm, and system dynamics approach to develop a spatial dynamic model to capture the various linkages and feedbacks (Li and Lam 2018a).

11.2.4 Project Findings

At the time of writing this chapter (which is close to the project end date of September 30, 2018), our project team has yielded at least 55 refereed articles, two edited journal special issues, and a book in press. Due to space limitations, below we highlight only three of these studies to illustrate the diverse approaches and complexity involved in our project. The first study is an evaluation of land subsidence rates and their implications for land loss in the MRD (Zou et al. 2016). This study is needed to produce a key data layer, the land subsidence rate, because such a data layer did not exist and it is essential to land loss modeling. The second study applies the Resilience Inference Measurement (RIM) model to assess community resilience in the MRD (Cai et al. 2016). Our study provides a methodology for resilience assessment, as well as extracting a list of social-environmental variables that can be used in subsequent dynamic modeling. The third study develops a spatial dynamic model of the system-level coupled natural-human relationships using a raster with a cell size of 3×3 km (Li and Lam 2018a). The study is among the first, if not the only, study to yield an empirical model that captures the CNH system interactions of the MRD.

11.2.4.1 Land Subsidence and Land Loss Evaluation

As shown in Zou et al. (2016), subsidence is defined as the downward shifting of land surface relative to a reference datum. Due to its impacts on the economy, livelihood, and culture, a number of researchers have attempted to evaluate the subsidence rates in coastal Louisiana using different approaches, including analyses based on discrete tide-gauge records (Penland and Ramsey 1990), benchmarks surveys (Shinkle and Dokka 2004), numerical modeling (Meckel 2008), and RADARSAT satellite images (Dixon et al. 2006). However, few investigations examining vertical change in coastal Louisiana have focused on creating an accurate subsidence-rate surface to reveal the spatial patterns and potential impacts on the region's long-term sustainability. This study created a subsidence-rate surface in the study region using the Empirical Bayesian Kriging (EBK) interpolation method. With that surface, we projected future elevation surfaces. Possible land loss impacts caused by subsidence-induced elevation change were also estimated.

The study utilized data from the National Geodetic Survey, which contains vertical change measurements for 2710 discrete benchmarks for the region between 1920 and 1995. Other data including elevation and LULC products were also used. The results show that the subsidence rates in the region ranged from 1.7 to 29 mm/year, with an average rate of 9.4 mm/year. Subsidence rates increased from north to south as the outcome of both regional geophysical conditions and anthropogenic activities. Four areas of high subsidence rates were found, and they are all located in parishes in the South (Orleans, Jefferson, Terrebonne, and Plaquemines). A projection of future landscape loss using the interpolated subsidence rates reveals that areas below zero elevation in the region will increase from 3.86% in 2004 to 19.79% in 2030 and 30.88% in 2050 (Fig. 11.3). This translates to an accelerating increase of areas that are vulnerable to land loss from 44.3 km^2/year to 240.7 km^2/year from 2011 to 2050. Under the same scenario, three parishes in the South (Lafourche, Plaquemines, and Terrebonne) will experience serious loss of wetlands, whereas Orleans and Jefferson parishes (part of the New Orleans Metropolitan Area) will lose significant developed land, and Lafourche parish will endure severe loss of agriculture land.

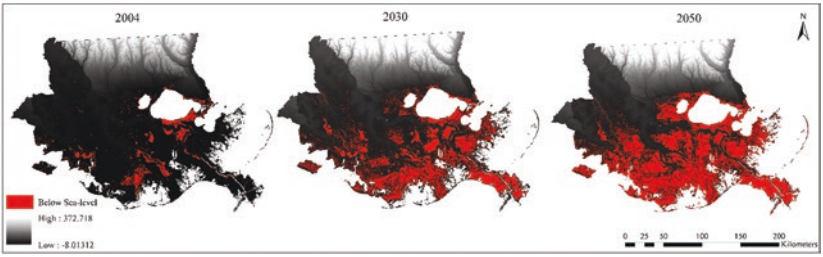


Fig. 11.3 Projected elevation map with areas below sea level shown in red (Zou et al. 2016). Reproduced with permission (Colour figure online)

The significance of this study is that it produced the first subsidence-rate surface for the MRD, which is critical to the overall project goal of modeling land loss. Moreover, the study shows that the subsidence rates are not evenly distributed. Hotspots with high subsidence rates could be associated with human activities, such as frequent pumping of water and withdrawal of underground water, levee constructions, and/or heavy hydrocarbon production (Zou et al. 2016). These various factors will need to be considered in more realistic projections of land subsidence and land loss.

11.2.4.2 Resilience Measurement

A critical challenge in CNH research is how to determine if the system is sustainable in the long term. Linking resilience assessment with CNH modeling remains a major research gap (Lam et al. 2016; Cai et al. 2016). In resilience assessment, despite extensive efforts made in the development of resilience assessment frameworks (NRC 2012; Cutter et al. 2010; Community and Regional Resilience Institute 2013), there is still no commonly adopted metric in the published literature to assess community or system resilience. Lam et al. (2016) identify three main difficulties in resilience assessment. First of all, disagreements among researchers about definitions of key terms have impeded agreement on the quantification of processes and metrics to measure resilience. Second, resilience indices or scores developed in the literature have seldom been validated with empirical outcome data. Most existing indices were developed by aggregating a number of variables with a subjective weighting scheme. Without an objective, empirical outcome validation,

the resultant index values could be easily manipulated by changing the weights of the variables. Third, many resilience assessment methods are often highly context-specific, so indices or indicators derived from one study area cannot be used to estimate the community resilience levels across space and/or over time.

This study applied the RIM model to measure the community resilience of all the 2086 census block-groups in the study region using variables from both the natural and human systems for the period between 2000 and 2010 (Cai et al. 2016). The RIM model, developed previously by our research team (Lam et al. 2016), is designed to overcome the two challenges of resilience assessment: empirical validation of the resultant index and application of the findings to other study areas by inference. Our results show that higher-resilience communities are in the North, whereas lower-resilience communities are those located in the South, in the lower-elevation areas (Fig. 11.4). The study identifies ten statistically significant variables that are associated with the resilience scores. Four of the ten contribute positively to resilience, including percent of housing units with telephone service available, median

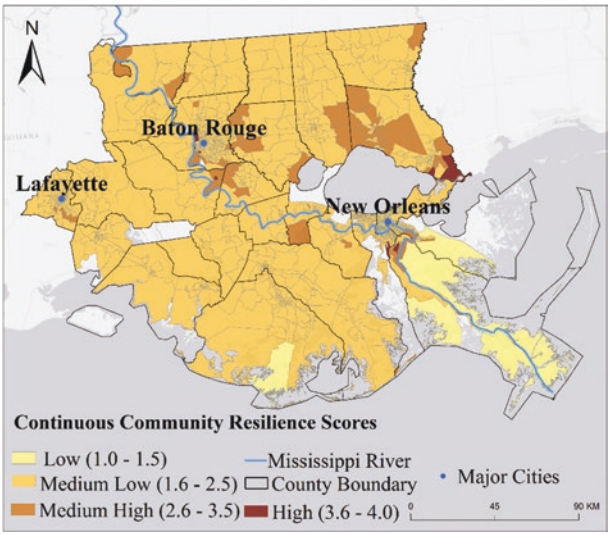


Fig. 11.4 Continuous RIM scores map by block-group; scores ranging from 1–4, the higher the score, the more resilient (Cai et al. 2016). Reproduced with permission

household income, percent of the population employed in construction, transportation, and material moving, and percent of housing built after 2000. The six variables that contribute negatively to resilience are percent female-headed households with children, housing density, road density, percent of the native-born population, and percent of inundation zone. The resilient variables identified to be significant from this study were used to guide the selection of variables to be included in subsequent system-level modeling (Lam, Xu et al. 2018).

11.2.4.3 Dynamic Modeling

We developed a system-level dynamic model to integrate variables from various components (Li and Lam 2018a, b). The study used a total of 35 variables selected from the above studies. These variables were transformed or interpolated into grids with a resolution of 3×3 km^2. This process led to a total of 5980 grid cells in the study region, and they were used as the modeling units. This integrated system-level modeling effort addresses three questions: (1) what are the key socioeconomic factors (i.e., utility) that trigger population change? (2) How important are natural factors (e.g., hazard threat level, elevation, subsidence rate) in affecting population changes in the region? And (3) reciprocally, how do population changes affect local utility and local natural environment.

The study used the Elastic Net regression method to select the most important and noncollinear variables to build the system-level model, and this procedure selected 12 socioeconomic and four environmental variables. The four environmental variables are: property damage from hazards, elevation, subsidence rate, and percent of open water. The 12 socioeconomic variables include: pipeline density, road density, medium housing value, median rent, owner cost as a percentage of household income more than 35%, percent housing units without mortgage, percent housing units with no heating fuel used, percent housing units with no complete kitchen facilities, percent housing units with no complete plumbing facilities, percent units with no telephone, and percent population under five years old.

The system dynamic model is governed by three equations, each specifying a state variable (population count, developed area percentage, and utility) in time $t+1$ as a function of the same variable in time t

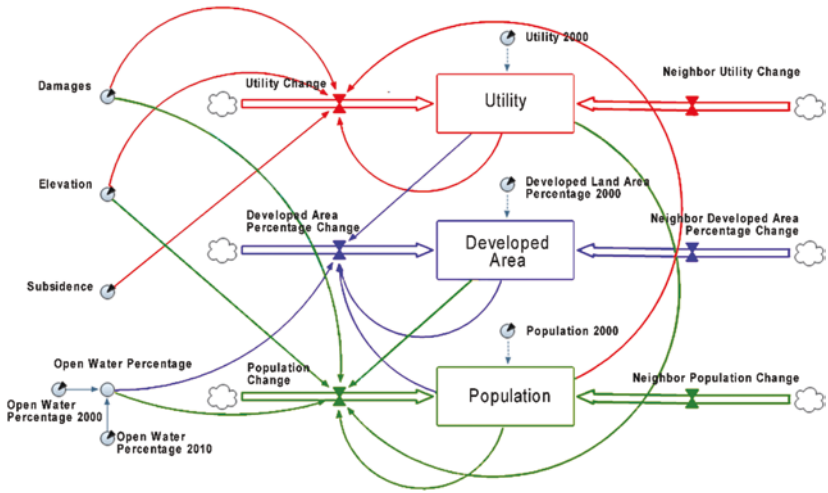


Fig. 11.5 The MRD coupled natural-human (CNH) system dynamic model (Li and Lam 2018a). Reproduced with permission

plus other influencing variables (see Fig. 11.5 in Li and Lam 2018a). The accuracy assessment shows that the model slightly over-predicts the population count and developed land mass in 2010. The largest outliers were found to be mostly in the New Orleans region where population and urban development declined significantly during 2000–2010 after Hurricane Katrina. A simulation of population change from 2010 to 2050 shows that areas in the South continue to suffer population loss whereas areas in the North continue to have steady population growth. In other words, without mitigation and adaptation or any changes in the current condition, the South region will likely be unsustainable.

11.3 Challenges Faced

While pursuing interdisciplinary research on our CNH project, we have encountered a number of issues. Lam, Xu et al. (2018) summarize the technical challenges the project faced and describes the methods used to overcome the challenges. The first and foremost challenge in conducting interdisciplinary CNH research is model integration. Incorporating major components from both the natural and the human systems into a

system-level model is difficult because it requires not only a deep understanding of the underlying processes of both systems, but also an appropriate technical realization of the processes into workable models. This major step in CNH modeling necessitates thorough discussion and collaboration across disciplines to make the integrated model useful. This is not merely a technical question of choosing the best methods, but also a collaborative issue of finding a workable process to identify and then address the issues at hand. Consequently, we discuss five major technical, theoretical, and practical application challenges in CNH modeling research.

First, data incompatibility from various disciplines is a serious technical challenge. The data needed for integrated modeling typically come from different sources; they are collected by various methods and defined at multiple spatial and temporal scales. Integrating disparate types of data into a unified platform for CNH modeling is the most fundamental step that requires accurate methods. Our project uses spatial interpolation methods to harmonize the various types of data. As shown above, we used the EBK method to create a land subsidence-rate surface in pixel form for the study region (Zou et al. 2016), and we used areal interpolation with volume-preserving property to transform socioeconomic data from polygons to pixels so that they can be compatible with the natural data (Li and Lam 2018a). Although these two interpolation methods are considered among the most accurate methods in the literature, errors and uncertainties can occur and are propagated onto model output and thus the findings. Consequently, finding the best way to quantify these errors and uncertainties and understanding how they propagate throughout the modeling system are critical to successful CNH analysis.

Second, on a deeper, theoretical level, there is fundamental incompatibility of the underlying processes and their lagged effects among the various natural and human components. Some processes will take years to observe the difference (e.g., land subsidence and elevation changes), whereas other processes can be measured every minute (e.g., water salinity changes). Some processes are global or regional in nature (e.g., policy changes), while others are local (e.g., land loss probabilities). Modeling the complex linkages among the different processes is a difficult task. For instance, our study on the channel morphology of the final 500 km of the Mississippi River found a continuous riverbed aggradation immediately below the Mississippi avulsion node (Xu and Rosen 2012; Wang and

Xu 2016, 2018), which poses a risk for the river to be completely captured by another river (the Atchafalaya River). If that happens, the MRD would lose the lifeline of freshwater and sediment and the current deltaic system could experience a complete system change. Capturing and modeling these linked effects remain to be extremely difficult in CNH modeling.

Third, it is critical to identify a "common threshold" for studying the resilience of a deltaic system that is highly coupled by natural and human domains (Xu et al. 2018). Such a common threshold could be interpreted as a tipping point, that is, the condition at which a radical change to and/or a collapse of a CNH system occurs if humans cannot or will not want to maintain the system. The "common threshold" also refers to the optimal condition at which a CNH system is considered sustainable by each discipline. However, the thresholds often differ among different stakeholders and/or disciplines, making it difficult to develop an integrated system-level model. Identifying the common threshold through collaboration across disciplines and stakeholders would help guide the modeling process and eventually the assessment of the resilience of a CNH system. In this project, through discussion among team members, we use land loss and population decline as the target variables to evaluate the resilience and sustainability of the system.

The fourth challenge is the scale issue, which often occurs in spatial and ecological studies, especially those involving both human and natural components like our current CNH project. In addition to the theoretical scale mismatch discussed above (where some processes take years to observe the difference while others change every minute), a major scale issue is that relationships among variables change with the scale of the data used, a classic problem also known as the Modifiable Areal Unit Problem (MAUP) (Openshaw 1984). Lam and Quattrochi (1992) describe the four meanings of scale, which include geographical (spatial extent), operational (neighborhood), measurement (pixel size), and cartographic scales (Lam 2012). One of the scale effects is the neighborhood effect, also known as the uncertain geographic context effect (Kwan 2012). For instance, when considering the effects of various variables on land loss, we should not be considering only the effects at individual locations, but also the effects from their neighbors. How best to determine the neighborhood effects becomes a critical step for CNH modeling. Our study on the relationship between landscape fragmentation and land loss

probability in the study region found that the relationship changed with the neighborhood size used to calculate the fragmentation indices (Lam, Cheng et al. 2018). The fragmentation effects were significant and better observed at certain neighborhood scales (i.e., the 71×71, 51×51, and 31×31 pixel neighborhood scales when pixel size is 30 m) but not at larger neighborhood scales (e.g., 101×101 scale). The study confirms that scale matters. It further epitomizes the need for uncertainty analysis of the findings in CNH research (Li and Lam 2018a).

Fifth, linking science to practice poses a great challenge to CNH research (Lam, Xu et al. 2018). Increasingly, researchers are faced with the challenge of making their scientific findings usable in real-world applications. This is especially true for the study of the MRD when land loss and associated population decline are increasingly threatening the existence of this economically, environmentally, and societally highly relevant river delta. Academic publications and project websites are effective means to disseminate the results, but they are not effective in cultivating bidirectional communication. Toward this end, we conducted a full-day workshop on "Knowledge sharing for a delta resilience community of practice" in 2016, in which coastal managers and community stakeholders in the study area were invited to participate. The goal was to cultivate bidirectional communications and information sharing between researchers and stakeholders so that better understanding of the MRD as a CNH system can be obtained. The workshop was found to be stimulating, and more workshops between researchers and stakeholders are called for. Detailed description of the workshop purposes, questionnaires used, and findings are being summarized in another report.

However, the real challenge in linking science with practice remains the translation of theoretically informed research results into practical tools, not just communicating the research results. Our study on resilience assessment (Cai et al. 2016) has demonstrated an effort in translating the RIM resilience measurement results from a less apparent discriminant analysis output (which has three discriminant functions) into a more straightforward regression model while sacrificing a small degree of variance explained. By translating the results into a regression model, we create a statistical tool that is easier to interpret and evaluate the relative importance of the variables. Decision-makers can vary the value of a variable in the regression model to see

how the resultant resilience level changes. In CNH modeling, linking science to practice should be an important goal, and such a goal would be best accomplished by frequent bidirectional communication and close collaboration among researchers and stakeholders.

11.4 Collaboration Across Boundaries

For this chapter, in order to extract our reflections on collaboration more systematically, we conducted a short survey of the team members. The survey included only four open-ended questions. They were designed to help identify the challenges and recommendations in collaboration across boundaries. Results from this survey should provide new insights into the "best practice" of collaboration across boundaries. The four questions are:

1. From your standpoint, what are the top three challenges/difficulties in conducting this large, interdisciplinary project?
2. What are the top three advantages/benefits that you see from participating in this project?
3. What are the top three suggestions to improve research findings and outcome?
4. What are the three suggestions to improve collaboration?

There were 12 responses to the survey. The respondents included senior investigators, postdoctoral researchers, and graduate students. Table 11.1 documents all the answers that are not duplicative. Minor edits were made to either simplify the sentences or make them consistent in format. Also, for Questions 1 and 2, we grouped the responses into two categories, those focusing on the research itself versus those addressing the collaborative aspect.

Regarding Question 1—the top three challenges in conducting this large interdisciplinary project—the dominant responses related to the research category were the difficulties in model integration. As discussed earlier in Sect. 3, issues on how to fit individual models into the system-level model, how to harmonize diverse data types, how to model natural and human processes when they are of different spatial and

Table 11.1 Summary of survey responses on collaboration across boundaries

Question	Summary of responses
Q1: Top 3 challenges	Research: Model integration (how to fit individual models into system-level model); scale issues; model complexity; model uncertainties; difficult to build a seamless model; identify a common threshold from different disciplines; unexpected research results may delay original schedules; different skillsets among team members and students create miscommunication and other issues; avoid digressing from the original big picture and focusing on peripheral projects; not every discipline has the same importance to the final goal, too many viewpoints can reduce coherency Collaboration: Technical communications were challenging at the beginning; data sharing was difficult; difficulties in understanding other perspectives; difficulties in scheduling meetings; maintain smooth workflow with constant turnovers of postdoctoral researchers and graduate students; receive full transparency regarding the updates of other components (e.g., what are the other groups working on and how can I contribute); meet deadlines and follow research schedules when investigators have different priorities
Q2: Top 3 benefits	Research: Acknowledge the need for identifying a common threshold in the research; bring resources together; solve problems that could not be solved by individual expertise; thinking about other people's problem is interesting, which has led to knowledge of different data that can be used in the project Collaboration: Opportunities to learn from others (science vs. social science); valuable information about academic conferences, innovative research ideas, and career development; help me understand where my contribution is; gain experience in working in a multidisciplinary team; get an idea of what CNH and the spatial model is; exposure to big data/big computation; obtain a sense of the need for practical relevance through the stakeholder workshop; more opportunities in research and collaboration in writing; know more people whom we normally would not know, which is especially good for postdocs and students

(continued)

Table 11.1 (continued)

Question	Summary of responses
Q3: Top 3 suggestions to improve research	Have a detailed research timeline and expected results for each group and follow it through; each group presents research progress in every group meeting, at the end of the meeting list the expected results by next meeting; better control of the project direction to help focus; timely and critical review of each component; need explicit manuscript submission goal; the research can be more open for new data, methods, and hypotheses; build smaller modules of models before integrating into the master model; more but narrower scope findings; publications focus on solutions rather than laying out problems; speed up publication of findings and outcomes; enforce the deadlines
	Organize more journal special issues and special sessions in conferences and encourage students to participate; increase communication with stakeholders; encourage; closer collaboration among team members; more group engagement in national meetings; seek more input from students and postdoc
Q4: Top 3 suggestions to improve collaboration	Build a project database and a data management plan for data sharing among team members; more short small group meetings; a cloud-based system or google drive for data sharing; outline a detailed timeline and expected deliverables for each component; more communication through informal meetings and/or mini-group meetings; more discussion and guidance on how results from individual components could be incorporated into the overall model; more interaction among students and postdoc; need an annual full-day workshop brainstorming for integration

temporal scales, how to identify a common threshold of sustainability agreed upon by both natural and social scientists, and how to account for uncertainties are some of the core research issues that faced our research team. Obviously, this challenge is not new, which is why empirical models that incorporate both natural and human components with quantifiable feedbacks and linkages are difficult to find from the literature. This challenge is presumably one of the reasons why the project is funded.

Several quotes from the survey are provided here to illustrate the difficulties in model integration. One team member articulated that it is "challenging to understand and model the complex system across spatial

and temporal scales. A relationship may take effect at a specific scale. However, the whole system is based on numerous relationships at all different scales. Capturing the dominant relationship to guide decision-making at a specific scale is challenging." Another team member suggested that "the main challenge is to identify a 'common threshold' from different disciplines. For instance, the threshold for sustaining a river delta in view of hydrology and sediment transport is different than that …of social science." However, one team member responded that "not every discipline may be as important to the final goal, too many viewpoints can reduce coherency." This is a unique and intriguing viewpoint but is entirely understandable. In the end, when we conduct interdisciplinary research, we may have to recognize that not every discipline has the same degree of importance to the science problem at hand, and that sometimes having too many viewpoints may run the risk of reducing coherency or not achieving a better and more practical solution to the problem.

Regarding the collaborative aspect of Question 1, most team members responded that the main difficulties were not knowing or fully understanding what other groups were working on and how they could contribute to other components. Difficulties in scheduling meetings, not meeting deadlines, and constant turnover of postdoctoral researchers and students were the other concerns. As one respondent elaborated: "Researchers need to understand and respect the insights, background knowledge, and methodology from another discipline. This takes a lot of efforts to overcome these barriers and requires extensive communication among researchers from different components. Researchers need to translate their own perspectives into simple language that researchers from other disciplines could understand." Also, "large projects always involve difficulties in scheduling meetings, dealing with misunderstandings, [and] lack of timely feedback or responses." Although our team values the importance of more communication and more meetings, the difficulties in scheduling meetings and not meeting deadlines were some of the issues that our project had to overcome.

The dominant responses to Question 2—the benefits of participating in this large interdisciplinary project—were the ability to bring resources together, solve problems that could not be solved by

individual expertise, and bring awareness to new data and resources from other team members. A postdoctoral researcher in the team stated: "In this day and age where multidisciplinary collaborations are celebrated and encouraged, I learned a tremendous amount regarding methodologies, hypothesis testing, research questions, and terminologies corresponding to other research groups." Also, finding a common threshold of sustainability among the disciplines helps improve our understanding of the research problem. In terms of the collaborative aspect, respondents suggested many benefits; they are especially useful to the students and postdoctoral researchers. These benefits include: opportunities to learn from others across boundaries, gain experience in working in a multidisciplinary team, obtain a sense of the need to relate research to stakeholders through the day-long workshop, know more people we otherwise would not meet, be exposed to new research ideas and career opportunities, and have more chances for collaboration in writing and publications. As one respondent stated, "the general experience of working with researchers from interrelated yet diverse research areas is a benefit in itself that will help better understand and formulate collaborative research projects in the future."

The main suggestion derived from the responses to Question 3 (top three suggestions for improving research outcomes) is the need to have a detailed research plan with a timeline and expected results for each group and the need to follow the plan through. This would involve timely and critical review of each component, formulating an explicit manuscript publication plan, and enforcing the deadline. To gain better control of the research progress, it was suggested that at the end of every group meeting, there should be a list of expected results by the next group meeting. Other suggestions included organizing more journal special issues and special sessions in conferences, encouraging more students and postdoctoral researchers in participating and seeking their input on the project, and increasing communication with stakeholders.

Regarding suggestions to improve collaboration (Question 4), building a project database and a data management plan for data sharing were thought to be important in improving collaboration. More interactions in the form of informal meetings, mini-group meetings, and more meetings among postdoctoral researchers and students were also

suggested. Finally, an annual full-day meeting of the entire research team devoted to research integration was suggested to be a feasible way to improve collaboration and teamwork.

11.5 Conclusions

Our interdisciplinary project on investigating the sustainability of the MRD using a CNH system approach is a great success. The project so far has produced over 55 refereed publications, 120 presentations, one special journal issue, and a book in press. It has engaged more than 30 faculty and students at different points in time, and has yielded several new collaborative projects including one with researchers at the East China Normal University in Shanghai, China to study the sustainability of the Yangtze River Delta as a CNH system. We are grateful to have the opportunity to work across boundaries on a very important societal problem in this CNH project. We gained new knowledge of the research problem and valuable experience in collaboration. For this chapter, we used the survey method to help organize our reflections on interdisciplinary collaboration based on our experience in working on the project. The survey results provide insights into the development of best practice for collaboration across boundaries.

Two important points on the survey findings are noted here. First, the responses were made in the context of the four questions only, they do not necessarily mean that the items or actions suggested were not carried out in this project. More often, the responses reinforce the importance of certain existing actions that have made the project successful. Second, the responses were based on a project that is supposed to break new ground by dealing with a problem that has seldom been explored. It is a project that develops new knowledge and new methods from messy, disparate data, not a project that follows established guidelines and methods to obtain results. Thus, allowing some deviations from the original plan to develop new ideas and new hypotheses could be valuable.

In summary, the survey results show that a successful interdisciplinary project would require a detailed research plan with clearly defined

timelines and expected results for each disciplinary group, and the plan will need to be followed through. This suggestion would involve timely and critical review of each component, formulating an explicit publication plan, and enforcing the deadline. Finding collaborators who have similar priorities, can deliver the results on time, and continue engagement in the research may be difficult, but the reward in making it happen is gratifying because it will ultimately be beneficial to advancing the science and practice of sustaining complex natural-human systems.

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12

Crossing Boundaries for Collaboration in Comparative Perspective: Key Insights, Lessons Learned, and Recommendations for Future Practice

Stephen G. Perz

12.1 Introduction

The many indications of ongoing degradation and impoverishment in social-ecological systems (SESs) make the goals of sustainability and resilience both daunting and urgent. Several grand ambitions permeate SES science: to integrate various disciplinary perspectives, to make research more relevant to policymakers, practitioners, and stakeholders, and to apply findings to management and governance of SESs around the world. Collaboration across boundaries is thus a central hallmark of the organizational strategy underlying SES science. This, in turn, makes good collaborative practice a fundamental requirement if SES science is to be effective in generating new knowledge and supporting sustainability in SESs.

Spanning divides poses challenges and calls for identification of strategies to make collaborative practice more effective (Perz 2016).

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Every step in the research process—from forming a team to framing the question, defining key terms, delineating the analytical framework, designing the study, sampling, data collection, coding, integration, and analysis—is fraught with perils when crossing boundaries. Strategic practices can be informed by findings from various applied behavioral sciences, as well as hard-won firsthand experience. In this book, the many teams that contributed chapters came to recognize the first by incurring the trials of the second. We now have a body of experiences, in the projects reported here and many others, that offer insights about the practices necessary to support collaboration across boundaries, whether for SES science in the service of sustainability and resilience, or various other goals.

A brief comparative review of the foregoing ten projects permits identification of their similarities and contrasts. All but one were funded by the US NSF's Coupled Natural and Human Systems (CNH) program, and all have as their focus the integrated analysis of SESs to improve understanding and thereby support applications related to sustainable management and governance for resilience. All of the projects crossed disciplinary boundaries, spanning an estimated 4.5 such domains on average, according to how the teams defined disciplines, area studies, and specializations. Similarly, most projects worked with nonacademic stakeholders, with an average of 4.0 constituencies, which can also be defined variously in terms of interest groups, government agencies, and a diversity of NGOs.

There was also diversity in other respects. The type of SES under study varied, from terrestrial ecosystems (Caughlin et al., Fernández-Giménez et al., Perz et al., Smithwick et al.) to watersheds (Caldas et al., Laborde et al., Pischke et al.) to coastal systems (Lam et al., Uchida et al.) to a program that encompassed various kinds of SESs (King and Nibbelink). We could further differentiate these systems, as "coastal" actually encompasses a river delta (Lam et al.) and mangroves (Uchida et al.). In addition, most but not all projects spanned national boundaries: three focused on cases within the United States (Kansas, Louisiana, and Wisconsin), though one involved an indigenous nation (the Menominee). Among the non-US cases, three were in Latin America (Mexico, Panama, and the Amazon), two were in Africa (Cameroon

and Tanzania), one was in Asia (Mongolia), and one involved a training program that encompassed student projects in various countries.

Similarities and contrasts were also manifest in the specific structures and procedures of the teams. One key similarity was that teams divided themselves into sub-teams for operational purposes. A practical consequence of having sub-teams were frequent team meetings for updates and decision-making. Teams varied structurally in other respects. Some teams had a strong PI who fulfilled various leadership functions, while other teams had more distributed leadership structures. Some teams were highly centralized around personnel in the lead institution, while other teams had significant human resources at partner institutions, notably in-country institutions when crossing national boundaries. These differences also led to varying strategies of team management and governance, especially in planning and implementing fieldwork.

These teams constitute serious collaborative efforts in SES science, but they learned valuable lessons in parallel. While there is indeed literature in the applied behavioral sciences on the management of collaboration and crossing boundaries, these teams and other projects still encounter the challenges and learn the requisite skills in large measure by doing. The result is many heroic efforts by smart people trying to figure out known problems as they go. It is obvious enough that teaming is important and necessary in SES science, and that crossing boundaries can cause complications that have to be managed. It is rather less obvious how to anticipate and thus better manage the challenges in order to collaborate more effectively, at least among the non-specialists. Hearing the experiences of other teams can therefore not only be cathartic and validate one's own confusions and frustrations, it can also beget learning about how others have managed many of the same challenges. We all have much to learn, and we can learn from each other. Not every team used the same strategic practices, and not every application of a given practice yielded the same outcome in terms of its effectiveness.

It is thus in the spirit of learning from the experiences of others and reflecting in a comparative perspective that the remainder of this chapter proceeds. I therefore draw on the experiences from the foregoing array of team projects in SES science to offer a comparative analysis of salient issues, which proceeds in several sections. The next section

focuses on key insights from the teams, featuring happy and unhappy realizations during their projects. The intent is to identify issues that go beyond challenges typically listed in previous publications on collaboration and crossing boundaries. The third section turns to shared challenges encountered by the teams. These involve complications that frequently arose, were hard to avoid, and proved particularly enduring or recurrent despite efforts to forestall or mitigate them. Focusing on shared challenges permits comparisons in how they arose on different teams in differing contexts. The fourth section then features some key factors that affect the difficulty of dealing with key challenges. These often involve parameters that teams did not initially regard as important but proved otherwise during their projects. These factors also help account for differences in how serious a challenge was among projects in different contexts. The fifth section discusses key strategies that one or more teams employed to address selected major challenges. This shifts the focus from "lamentations on what can happen" to "enacting agency to get stuff done." I originally conceptualized this section in terms of "unique strategies," as these are strategies I had not practiced or heard about before. Then I realized that there were multiple teams who employed these strategies. But the teams often applied them in different ways and often for distinct purposes, which is instructive. This permits comparisons in terms of those differences as related to their results. The sixth section turns to recommendations with the intent of helping future teams in their collaborative practice. I feature recommendations made by several teams. Teams had much to suggest in light of their experiences, and were intent on conveying what they have learned for the benefit of future teams and their projects. Here again there is some diversity, for teams addressing a specific issue did not always recommend the same thing. My comments therefore seek to contextualize the distinct recommendations so future teams can make their own determinations as to their circumstances and decide which way to go. I conclude the book with some final remarks on the enterprise of collaborating across boundaries. This concluding statement draws on closing reflections by several teams on the endeavor of collaboration across boundaries. I think I speak for the teams who contributed to this book when I say that there may be shared trepidation in preparing for

collaboration across boundaries, but there is also a shared joy in seeing the achievements made possible by following this path. It is our hope that others may benefit from the knowledge gained from the experiences compared here to achieve in joy with less trepidation.

12.2 Key Insights: Revelations and Surprises, Good and Bad

Crossing boundaries for collaboration means learning from many "others," and the teams had no shortage of revelations and surprises. Here I note six on which multiple teams made comments, often in consonance, often in different ways as to how an insight arose.

Teams came to realize that scientists trained in the basic social-behavioral and biophysical sciences are often not prepared to take on complex management tasks like collaboration across boundaries. Team leaders often relied on their personalities and social skills, or their previous cultural experience in another country (often in another capacity, like language study or the Peace Corps). Younger PIs sometimes reported more interdisciplinary experience due to their graduate training, which suggests that we are in the midst of a transition. Most teams placed considerable emphasis on discussing team logistics. Laborde et al. went farther, noting how crucial logistics are under conditions of high uncertainty and having alternative plans at the ready. Smithwick et al. and Fernández-Giménez et al. underscored the importance not only of learning management skills but also the vital role of reflexivity in that process, especially when crossing cultural boundaries. Reflexivity helps incorporate the perspectives of "others" in how one handles a diverse team, especially when it comes to inquiring about assumptions before taking a decision. Reflexivity runs against the grain in academia, where the tendency is to show value by specializing. But on teams spanning boundaries, reflexivity helped build bridges in understanding for joint action. Uchida et al. offer a similar perspective, noting how their team came to rely more and more heavily on in-country partners to not only handle field logistics but also to make crucial in-field management

decisions. Team leaders and in-country partners both offered reflective comments on this shift, noting its importance for effective management. King and Nibbelink provide an extensive discussion of how the core team in their transdisciplinary training program pursued an ongoing learning process as they engaged with various academic departments as well as nonacademic stakeholders, and made adjustments in advisory committees and refined the definitions of committee member roles. In all such cases, there was an emergent recognition that leadership teams needed to be open to the knowledge funds of others and to value and learn from them, even to the point of adjusting how leadership was defined and who had to take key decisions at crucial moments.

Another insight concerns the importance of culture when collaborating across boundaries. Spanning multiple divides means bridging among different kinds of cultures, including disciplinary cultures, organizational cultures, national cultures, and "deep" cultures (such as between western and indigenous cultures). Cultural distinctions matter, but types of cultural distinctions are also important. Fernández-Giménez et al. offer an extensive discussion of national cultural differences, drawing on their experience spanning the United States and Mongolia, countries with totally different histories that exist on opposite sides of the planet. US-based team members had much to learn about Mongolian political history, science, language, and more. Uchida et al. offer similar sentiments about cultural differences across countries, noting that few on their core team had been to Tanzania before they embarked on their project. They employed a suite of strategies to manage deep cultural differences, developing multiple proposals and taking the time to make multiple field visits, as well as intensively partnering with multiple local organizations. In something of a contrast, King and Nibbelink delve into the specialist cultural mentalities among academic departments as they relate to the more metropolitan intellectual culture of an integrative training center. Disciplinary cultures don't just affect research projects but also transdisciplinary training programs, which bears big implications for future SES science. Smithwick et al. offer an excellent discussion that formulates cultures in terms of knowledge systems, which permits some unpacking of how worldviews are constituted in terms of specific terms and beliefs. While they apply the concept of

knowledge systems to deep cultural differences between western and indigenous worldviews, the formulation would seem useful to apply to other types of cultures.

While all teams duly noted that collaboration takes time and often involves frustrations, some teams went farther, noting the personal and emotional tolls of collaboration on the key players. Laborde et al. comment extensively on how crossing boundaries is emotionally taxing, notably due to the uncertainties and risks involved. Scientists are not robots; uncertainty matters, and risks can be consequential, not just for the collection of quality data, but for mental health and even life and limb. Here diversity among team members was extremely valuable, whether among experienced researchers and students or between locals and visitors. In each pairing, the first not only provided guidance to the second, but also emotional support. This was important not only in the specific case of uncertain security situations, but also for the broader task of forging strong connections among collaborators. Uchida et al. encountered risks stemming from a dangerous security situation, which made relations of trust between visitors and locals vitally important for taking decisions about field trips for data collection. The local partners took those decisions, and the US-based visitors wisely respected them. This hindered data collection, but also mitigated stress, and reinforced relations of trust among the partners. Fernández-Giménez et al. underscore the importance of vulnerability and emotion as related to trust-building in collaboration. Making oneself vulnerable, as when crossing boundaries, often involves exposing one's emotions to others, which becomes an opportunity to provide emotional support and thereby build trust. Informal interactions as during field trips provide social spaces wherein collaborators can establish strong personal as well as professional connections. Here it is worth recognizing that gender and other aspects of cultural expectations about vulnerability may affect one's disposition to the forging of strong bonds with collaborators.

A fourth insight came in the dawning recognition by several teams concerning the administrative assets of their home institutions. Many teams felt left to their own devices in managing their projects, but some teams called attention to important moments or longer term shifts that made them appreciate their home administrations more than before.

Whether concerning liability issues, import–export questions, or various other administrative issues, some teams noted that it is good practice to reach out to administrative units for the support and the opportunities for learning. Not only may teams gain insights about project management, this may also prompt universities to build additional capacity to better support science teams in crossing boundaries. Smithwick et al. offer the example of how their project bulked up on computing personnel, who interacted extensively with their home institution's supercomputing services. The team provided code for computing services to test on their high-performance computers, which in turn helped support the team's modeling effort. Perz et al. established a similar relationship with their home institution's supercomputing center, which benefitted both sides. Uchida et al.'s project was crucially assisted early on by a major research center in their home institution, which had established ties to in-country partner organizations and thereby facilitated initial contacts and field visits and introductions to other in-country partners. Those contacts and visits spanned national and organizational divides and established ties to partners who later made the crucial decisions in a dangerous security situation.

Teams spent time discussing the classic challenge of tensions among players when crossing boundaries, but many teams highlighted that points of tension are best viewed not as problems to be solved, but rather issues to be embraced and managed. Caldas et al. report the classic situation: lengthy discussions about definitions of key concepts in order to arrive at decisions about empirical indicators. They achieved perhaps the ideal outcome: the team was able to select key indicators more or less consensually from various possibilities. Fernández-Giménez et al. faced the same challenge, complicated by a significant cultural and linguistic boundary that hindered their ability to adequately translate key terms in order to achieve a consensus on concepts and measures, which resulted in confusion and tensions during discussions. Laborde et al. also encountered difficulties, highlighting how differences among team members in comprehending data needs for specific model components can impede model design. This led to enduring tensions over specific decisions, as well as emotional stress due to the cumulative nature of sequenced decisions in model construction. This prompts

Laborde et al. to focus on Tsing's (2005) use of the term "friction," which characterizes different understandings of a research problem or key process in the study site. Key to their account is their positive characterization of friction as something to be embraced, for upholding differences rather than seeking a watered-down middle ground can build recognition of inter-subjectivities and respect among team members. Laborde et al. recognize that this is likely to require moderated discussions by a network broker to focus the dialogue on communication for improved understanding rather than persuasion. Smithwick et al. make similar noises concerning the profound differences among deep cultural knowledge systems, which also require extensive discussions to strive for mutual comprehension rather than selection of one over the other. The goal is to reach the logical implications of the underlying assumptions of knowledge systems, incommensurate though they may be. Smithwick et al. then observe that this is where the negotiation begins rather than ends, including renegotiation of seemingly inviolable cultural assumptions. They also hold out the notion that to truly meet, cultures have to give up certain commitments. But this need not mean a watered-down meeting-in-the middle; the giving up may well occur by the hegemonic culture with the unsustainable resource management practices. King and Nibbelink offer a distinct perspective on such questions in the context of a cross-boundary training program, in terms of identifying points of overlap and complementarity in disciplinary expertise. Both are important, and the "sweet spot" for collaboration is thus a mix of the two. While the complementarities may turn into tensions, understanding the foundations of the tensions is itself useful and not to be feared or dismissed. Echoing Laborde et al. and Smithwick et al., King and Nibbelink suggest that tensions drive reexaminations of assumptions that can lead to alternative frameworks as innovative paths forward.

Finally, several teams called for reflection on the importance of what motivates collaborators to cross boundaries, despite the extensive toil and travail. Huxham and Vangen (2005) offer the argument of "collaborative advantage", the ability of collaborators to achieve what others going it alone cannot. Teams here however often invoked the other side of the coin: the commitment to a place or a type of SES that justifies

the heroic efforts to collaborate across boundaries. Uchida et al. detail numerous team-building strategies and partnering efforts as they prepared themselves to implement their fieldwork, and those strategies and efforts paid off in big ways, not least because local partners ended up in leadership roles. Similarly, Smithwick et al. pursued a collaboration across a deep cultural boundary characterized by very unequal historical relationships involving colonialism. Their project ran against the grain of a long history of societal domination, and they found productive strategies for engagement precisely by ceding leadership to indigenous partners. In order to study their SES, Caldas et al. embarked on ecological data collection that complemented work with stakeholders with post-truth attitudes toward environmental science. Caldas et al. found ways to engage those stakeholders, even about environmental regulatory policy, by attending their cultural events. In these cases and others, teams assumed commitments to their study regions and SESs, commitments which led to recognized difficulties, but also to surprising strategies to ensure engagement, even by ceding leadership and otherwise bending over backward, so to speak, to make collaborative advantage possible.

12.3 Shared Challenges: Unavoidable, Enduring, and Repetitive Difficulties

Teams reported similar challenges in their SES projects that involved collaboration across boundaries. Many such challenges stem from various forms of power inequalities, whether between team members and their home institutions, among team members in different disciplines, countries and/or organizations, between science teams and nonacademic stakeholders, and other combinations of social actors. Here I offer four (4) key shared challenges that go beyond those often noted in previous statements (cf. Perz 2016).

One shared challenge is that projects are highly dynamic, whether in terms of the theories and methods in use, staffing and collaborative structures, or in the context of the fieldwork. Key changes in projects,

in turn, led to difficult moments when hard decisions had to be made. Smithwick et al. focus extensively on personnel changes on their team before they received funding for their project. Their team was built in part on previous collaborations, so personnel changes are perhaps not surprising. Some cases involved personal issues such as health questions; others were driven by external considerations. Team leadership also reflected on the cast of characters relative to the tasks at hand, which led to adjustments. Asking a team member to leave, they note, was invariably delicate. But staffing changes themselves provided experience in making adjustments that built adaptive capacity on the team. Smithwick et al. were thus well-positioned to manage the growth of their collaborative network over time, including after project funding. Further, they note that the ongoing adjustments provide a foundation for future collaborative activities. Pischke et al. also pay extensive attention to the issue of project staffing. Their team engaged in a multifaceted vetting process that not only considered technical expertise but also behavioral dispositions, notably the willingness to listen and learn from others with differing perspectives. They also experienced team turnover, notably among junior members like graduate students and postdocs, which led to challenges of sustaining team memory. Because grad students and postdocs spent more time with in-country colleagues in the field, turnover posed significant challenges to sustaining international relationships. Uchida et al. used the experience of having an initial proposal declined to make adjustments in their conceptual framework, staffing and design for field data collection. This reshuffled which project components got more staffing and funding, which as with Smithwick et al. was a delicate question. Caldas et al. had a distinct experience, as it was senior team members who took administrative positions at other universities and thus had to leave the team. In their case, the departing members recommended replacements, already with an understanding of the technical and collaborative needs at hand. The challenge in this case was that replacements never perfectly fit the roles of those who had departed, requiring some reconfiguration of responsibilities. Laborde et al. and Perz et al. underscore the importance of bringing in nonacademic partner organizations, though for very different reasons. For Laborde et al. the move resulted from growing security

concerns and the need for more local knowledge of conditions in the field site. But in both cases, the addition of new organizations implied increased team capacity at the cost of organizational diversity and thus the addition of another boundary to be managed.

Another challenge noted by many teams concerned overburdened local partners. Some study regions had few or small partner organizations; in other projects, teams recognized the need to give partners greater responsibilities, but those partners already had many commitments. Fernández-Giménez et al. note that in-country scientists were often the only bilingual collaborators, which meant that they also got translation duties during team meetings. Pischke et al. report multiple challenges concerning overtaxed in-country partners. They note a common lamentation shared by several other teams that local collaborators routinely had to troubleshoot all manner of in-country logistical snafus which in many cases were beyond their control, a thankless task. Pischke et al.'s project took on a significant transdisciplinary dimension as stakeholders increasingly requested outreach activities, which the team's in-country partners then had to organize. The team added new partner institutions and adopted a distributed model of leadership responsibilities to manage the emergent demand. Pischke et al. also note difficulties in seeking to engage government agencies in the context of policy-relevant research. Agency staff were overburdened and had little time for interactions with the science team, even though the topic was of shared interest. Government engagement was also hindered by staff turnover and policy shifts following elections, which necessitated more time for engagement to explain the project again. Uchida et al. pursued a similar strategy of adding more in-country partners to spread responsibilities and manage task burdens. This however created new managerial challenges related to coordination among partners, further complicated by the national boundaries being spanned and sketchy Internet in the field site. The team thus took advantage of communication technologies (tablets, WhatsApp, etc.) to help ensure connectivity for coordination. Nonetheless, at certain moments in the project, in-country organizations were overwhelmed with requests. Uchida et al. note that during planning of the fieldwork logistics, which involved multiple teams, local organizations received multiple requests daily and at the eleventh hour.

Planning needed to be stretched out to better anticipate busy moments of the year for the partners.

A third common challenge concerns universities themselves. As King and Nibbelink note, academic institutions encompass a suite of internal boundaries that go beyond disciplinary divides. King and Nibbelink provide an extended discussion of the implications stemming from their experience in building a transdisciplinary training program, with a detailed examination of a raft of challenges due to the structures and cultures of academia, along with a retinue of strategies to deal with them. King and Nibbelink feature disciplinary as well as administrative issues to consider the implications for faculty–student relationships in a cross-disciplinary training program. They spend substantial time discussing how dissertation committees are structured to support students conducting transdisciplinary projects, noting the key role of the training program representative. For King and Nibbelink, there is much to be negotiated, and the training program representative plays a crucial role for purposes of crossing boundaries and advocating for the value it adds in training. In that light, Caldas et al. provide a useful complementary discussion, observing with others that universities have faculty promotion and reward systems that routinely focus on individual achievement (see also Irwin et al. 2018). As noted above, their team included university administrators, and they explicitly recognize the lack of rewards for collaboration and crossing boundaries. This makes the frustrations of such enterprises look all the riskier in terms of time spent in team meetings as opposed to writing another disciplinary article. Perz et al. and Smithwick et al. call attention to boundaries within academic disciplines, in both instances with regard to integrative modeling. Perz et al. note that modelers may themselves play different roles on a team, as in simulation development and model evaluation. In their case, the first task had to happen before the second, and delays in the first undermined the second, which led to intra-disciplinary tensions. Smithwick et al. describe a similar situation where one model feeds into another, and delays in the first affected the testing of the second.

If there are internal barriers within academic institutions, boundaries are widely recognized between academic and nonacademic organizations. Nearly every team extensively discussed transdisciplinary

challenges in the context of their projects. Caughlin et al. offer extensive comments on how their project became highly transdisciplinarity. Their team's realization of a scale mismatch in their data sources led not only to an interdisciplinary discussion to identify other data sources, but also a recognition of the need to engage stakeholders to confirm their interpretations. They not only turned to high-resolution satellite imagery to provide more information to support their field-based interpretations, they also turned to farmers and participatory workshops to see if their new interpretations were sound. Hence managing scale mismatch in data led from crossing one boundary (between disciplines) to the need to cross another (beyond academia). Caughlin et al. go farther, presenting a game as a participatory platform for engaging nonacademic stakeholders. The game format made exchanges more interactive and enjoyable for nonacademic stakeholders, precisely because it featured and valorized farmer knowledge, while also serving as something of a test of the science team's understanding of land management in the SES under study. Caughlin et al. also offer a discussion of the issue of making data and findings available to nonacademic constituencies. When the data sources (like high-resolution satellite imagery) are expensive, but lend themselves to ready interpretation by stakeholders, it is challenging to bridge the divide. Here partnering with NGOs and keeping an eye out for new data sources can help address the gap.

Smithwick et al. also offer extensive reflections on their engagement with a tribal nation. Because of the deep and complicated historical context, the team and the nation engaged extensively to ensure that the tribal partners had a highly participatory voice in defining the goals of the project. As Smithwick et al. note, this was not only appropriate politically but also scientifically, since a key objective concerned planning for sustainability, and the indigenous nation had deep experience in adaptation for precisely that purpose, based on traditional ecological knowledge of the SES in question. The science team also had valuable contributions on offer, in terms of the conceptual approach of SES science and visualization tools to support planning. While this proved a classic case of complementary capacities and shared interests, this is not to say the process was easy or simple. Smithwick et al. observe that working with tribal stakeholders meant cutting across topical domains

that span many disciplines. The indigenous nation had denominated their own domains for sustainability planning, some of which might sound very broad to specialized academics, like "technology." This required extensive discussion, but led the team to focus on the visualization technology in support of the planning process. As it happened, the science team was well-positioned to respond in a specific, concrete manner, which greatly facilitated project development. As Smithwick et al. observe, transdisciplinarity may drive difficult discussions early on in a project, but those can be beneficial for later stages insofar as stakeholders then have expectations about sharing data and findings.

Several other teams discuss challenges of operating in a transdisciplinary mode. Uchida et al. relied heavily on local partners who were largely nonacademic organizations, ranging from local NGOs, comanagement authorities, governmental agencies, and communities. In some cases, establishing a relationship with one stakeholder was necessary to reach others, as with NGOs who provided introductions to government agencies, and comanagement authorities who reached out to communities. Multiple steps were thus required but there were no guarantees of success all the way. Further, because data collection requirements on some field teams were more onerous than others, leadership had to devote considerable effort to managing relationships as well as monitor data quality during field campaigns, a delicate balancing act. Pischke et al. encountered a distinct challenge, involving incorporation of stakeholders in data collection in the mode of citizen science. This is easier said than done due to the range of stakeholder interests and their acquaintance with systematic data collection. Timeframes for data collection and accrual of benefits (and the kinds of benefits, monetary and otherwise) became important questions as to their alignment between the academics and the stakeholders. This project focused on a payments for ecosystem services (PES) program, which explicitly invokes economic exchange, which complicated relations between the science team and stakeholders. Project leadership thus had to manage understandings of stakeholders about benefits from the project, lest stakeholders assume there would be economic payments from data collection, find there were not, and discontinue participation. Perz et al. also sought stakeholder participation, but for values of model parameters. This led

to a similar challenge of managing stakeholder expectations as concerned deliverables from the modeling effort. When it came time for outreach workshops to return findings, it was sometimes surprising which stakeholders actually appeared, perhaps a manifestation of who was interested in the findings and not something else. Caldas et al. also sought to engage stakeholders for data collection, but this was complicated by post-truth attitudes among some groups. What is more, the team focused on environmental change, notably climate change, an especially sensitive and contentious issue. As if that weren't sufficiently complicated, they sought stakeholder input about support of environmental regulatory policies, which was to be explicitly incorporated into the model. As we will see below, this was not an easy challenge to meet, but they did.

12.4 Factors Affecting the Challenges of Collaboration Across Boundaries

Teams also commented on certain challenges that were particularly thorny or surprisingly tractable compared to previous accounts (e.g., Perz 2016). Comparisons among the projects revealed some commonalities in the factors affecting the difficulties posed by key challenges to collaboration across boundaries. Below I discuss three (3) such parameters.

The ambitions behind the framing of research questions and subsequent project development emerged as one such factor. Several teams took note of how initial framings and other early decisions greatly influenced the many subsequent steps in the research process, including the staffing and the organization of teams, design and site selection, sampling and data collection, and especially data integration for modeling. Framings early on also influenced the ability of teams to incorporate add-on or spin-off components to their projects. More ambitious initial frames led to significant complications in terms of the viability of comparisons, the scales for sampling, and eventual integration of project components. Figuring out how to fit the project as conceived to staffing

capabilities and budgets to ensure on-time deliverables was in some cases greatly hampered by complications at many steps in the research process. Fernández-Giménez et al. devote substantial space to discussing data issues as they sought to tie project conception to design and analysis, as well as downstream and spin-off activities. For their team as for others, there were major implications for data integration later on. Indeed, each step along the way, methodologically speaking, bore implications for both team cohesion and integration for analysis. For Pischke et al. a key early decision was to add a second study site to scale up and permit comparisons. That however required tradeoffs of breadth for depth of detail in data collection in each site, as well as the allocation of human resources among sites, including among collaborators. Pischke et al. underscore that the site decision was only taken after discussion by the whole team, so everybody knew what they would be in for. Another adjustment made later on was to differentiate a model integration component in recognition of the complications involved in that crucial step of the project. On that note, Pischke et al. further reflect that their team would have benefited from a data integration plan formulated right up front. Such a plan would have forced early discussions of sampling design, replications and other details as explicitly related to data integration. This would also have eased the incorporation of new team members in mid-stream. Uchida et al. had a similar experience: project conception quickly led to discussions of design, and the ambitions of a comparative design posed complications when the team tried to relate sampling to data integration for analysis. Even with the early recognition of the design and scaling issues, it took the team substantial time and effort to develop the analytical framework in order to sort out questions of site selection and sampling. Uchida et al. reflect that having their initial proposal declined for funding was something of a blessing in disguise, as revisions in the proposal led to discussions of the assumptions behind question framing and the many ramifications for design, sampling and other methodological decisions as they bore implications for the analysis. Nonetheless, Pischke et al. and Uchida et al. report difficulties with data integration for modeling. Perz et al. note their own travails in data integration: some data simply took longer to acquire, clean and otherwise prepare for analysis. Even setting aside issues of

design and scale, simply having multiple components of data collection led to timing mismatches that impeded full data integration for modeling. This slowed development of the simulation model and thus downstream steps in model evaluation. Further, because modeling and model evaluation involved the newest collaborators to the network, discussions of the data integration issues took more time as team members also had to gain familiarity with each other and their respective tasks and expertise. As something of a contrary case, Caughlin et al. focus squarely on scale mismatch issues in their data, but devote considerable time to offering a means of addressing it, which in turn provided an avenue for managing the exigencies of data integration.

A second factor that can increase the challenges of collaboration across boundaries concerns the depth of cultural divides. Whereas Perz (2016) notes that the number of boundaries being spanned increases the complications to collaboration, several teams report that the profundity of cultural differences is particularly important. More profound divides imply greater investments of time and effort for effective crossings. Several teams called attention to deep cultural divides across countries. Laborde et al. note that team members viewed their study site, the Logone floodplain, in fundamentally different terms, whether as an SES of significant scientific and biophysical value, or as home. This and language differences greatly influenced priorities in studying and approaches to managing the system among team members. Fernández-Giménez et al. offer similar comments on their collaboration in Mongolia, noting deep cultural differences, language barriers and contrasting histories that informed divergent understandings of science and practices of research. This entrained significant needs for translation, knowledge exchange, and training of Mongolian participants in order to facilitate their full participation in the research process, including data analysis, interpretation, and publication. Uchida et al. share many of these observations, as they also worked across countries that had relatively few established ties. The deep cultural differences between the United States and Tanzania is what motivated carefully planned scoping visits, facilitated by organizations on both sides, in order to permit bridging. Pischke et al. offer something of a contrasting case from a project in two different countries that share a common border: the

United States and Mexico. It was precisely that shared border, and thus a history with many cultural tensions, that made specific practices like language selection for meetings very important. Despite highly integrated relations between the countries, language differences required language selection, and speaking a language not everyone understood, especially in the country where the meeting took place, risked alienating significant numbers of team members. Smithwick et al. offer similar comments on another case of two contrasting cultures with a shared history that also involves considerable historical tensions, US society and the Menominee Nation. Managing deep cultural divides required careful attention to values transparency and extensive dialogues about worldviews, knowledge funds, cultural practices, and more. Some of these same teams also highlighted how not all disciplinary divides are equal. Laborde et al. note the contrast between ecosystems sciences and humanistic social sciences such as anthropology in their accounting for differing perspectives on the Logone floodplain. Uchida et al. include social and biological scientists, but encompassed numerous sampling units, including people, wells, soils, plants, and fish. They also incorporated stable isotope analysis (SIA), which broadened the array of technical procedures, equipment requirements, and import–export protocols on the project. Smithwick et al. however offer a contrary case of sorts, in that they incorporated a significant humanities component in their SES project in a way that helped their team. While adding philosophy broadened the disciplinary range in a direction not often seen in SES science projects, it facilitated the spanning of the deep divides among knowledge systems in western and indigenous cultures.

A final parameter affecting the difficulty of challenges in crossing boundaries for collaboration concerned a key transdisciplinary issue, namely the policy importance of the research. Policy-relevant research imposes additional time constraints since governments and other stakeholders may want answers on their schedules (cf. Angelstam et al. 2013). This is especially the case if the policies are new, economically important, and/or controversial. Policy relevance also exposes teams to potential public criticism and various forms of political pressure if the findings are seen as consequential for and/or critical of vested interests. Pischke et al. focused their project on the evaluation of a PES program

involving hydrological services. Their case in Mexico involved established PES programs, but there remained a need for more robust analyses to improve their effectiveness and breadth of adoption. Difficulties arose however in effectively engaging governments and other nonacademic organizations. Complications in those organizations hindered the establishment of baselines and systematic data collection necessary for robust policy evaluation, introducing confounding factors that threatened to obscure the conclusions. An uncertain political environment, due to periodic elections and consequent staffing and policy shifts, also undermined collaboration. Caldas et al. offer a more hopeful example. They took on the issue of climate change in the central United States, where climate science is controversial. A key element of their modeling effort was to go beyond the usual approach of incorporating state policies as exogenous factors in their land use model. Understanding that policy implementation depended on policy support, they modeled policy implementation itself. That however required sampling stakeholder constituencies, some of whom held post-truth attitudes about climate change and environmental regulation, about their support for various environmental policies. This complicated their research effort, but the complications seemed worthwhile, for the findings from the models indicated that stakeholder support for environmental regulations was in turn dependent on extreme climatic events. Bringing the politics of policies into the model not only showed a key relationship from natural to human systems, it also made the model an important tool not only for policy evaluation but for timing policy promulgation.

12.5 Heroic Strategies: Efforts That Facilitated Collaboration Across Boundaries

The foregoing sections emphasized challenges and complications and thus issued various lamentations, though I also often noted how teams handled their difficulties. This section turns the focus squarely on some remarkable strategies that multiple teams employed to address one or more of the challenges noted above. Many teams took proactive steps

to help anticipate the vagaries of collaboration across boundaries. There were innovative strategies pursued to build and strengthen ties among team members, among sub-teams, with partners, and with stakeholders. Several teams were highly reflective in their collaborative practice. Some teams used the opportunity to contribute to this book to collect data on their reflections about their collaborative experiences. This section features four (4) strategies that facilitated collaboration across boundaries and reflects on their benefits.

Several teams underscored the importance of building long-term relationships that spanned multiple projects, and in some instances involved nonscientific collaborative activities. Building relationships over many years encompasses numerous shared experiences so collaborators get to see how each other operates in a range of situations. All this builds trust, a crucial quality in strengthening ties across boundaries, particularly if they constitute deep divides. Where such relationships do not already exist, building ties with the intent of sustaining them for the long haul pairs well with commitments to improving SESs over the long term. Strong commitments to partners often makes them more disposed to facilitate access to local organizations, possible field sites, and so on. Fernández-Giménez et al. underscore the importance of long-term ties between the US PI and her Mongolian counterpart, who had previously worked together for many years on various research projects. They had thus built significant personal trust, mutual understanding, and respect across their cultural differences. This relationship served as a model for others on the team, and anchored the team across a profound national and cultural boundary between the United States and Mongolia. Pischke et al. similarly note that several US and Mexican counterparts already knew each other before the project they report, which facilitated their ability to identify other collaborators, students, and stakeholder participants. The strong foundation of trust was especially important for the selection of field sites, all the more so since those sites were also tied to public policies being evaluated by the project. For both Fernández-Giménez et al. and Pischke et al., established relationships among key counterparts also helped manage language differences among other team members. Having counterparts with previous experience communicating in multiple languages

was very important for building trust, since language renders other cultures communicable and reveals much about collaborator assumptions and perspectives. Previous investments in building relationships via language and communication thus fostered shared understandings across national cultural divides, which in turn facilitated project planning. Laborde et al. observe the importance of anthropologists on their team, who had previously established personal relationships with counterparts by spending time on site, acquiring the language and immersing themselves in the regional culture. This not only forged key network ties, but also helped build bridges to facilitate linguistic as well as conceptual translations among team members who saw the study region in very different terms. Smithwick et al. offer a distinct experience, where the time frame for building relationships was rather shorter (two years) but involved an intense period of institutional courtship with a series of meetings, conferences, and declined proposals. All of these activities amounted to shared experiences across a deep cultural divide, experiences that occurred before collaboration officially began under the aegis of a funded project. The period of collaborative courtship was however crucial for the reasons already noted: counterparts came to understand and trust each other, which constituted a crucial basis for the collaboration that followed. Hence "long-term" in building relationships need not mean decades but just a few years even for spanning deep divides, if the shared activities are frequent and carefully thought-out.

A second strategy employed by multiple teams was to embed social scientists in teams to facilitate team reflections about their collaborative practice. Different teams invoked distinct paradigms for engaging in this reflexive practice, such as via the mode of participatory action research. Laborde et al. offer the most extensive account, as the first author led the effort to observe the team in action, thus constituting a highly reflexive team structure. They invoke the term "co-presence" to describe the role of researcher-as-observer. As Laborde et al. note, co-presence amounts to behaviors that express care and concern via investments in listening to dialogues. Other teams also underscored the crucial role of listening (and not just communicating) in dialogues among team members crossing boundaries. But Laborde et al. take this farther, emphasizing how listening itself shows care and concern among

team members, a deeper appreciation of personal relationships on teams than more general expressions of openness to other perspectives. In the process, they are able to unpack the multiple social aspects of collaboration from a firsthand orientation, which permits highly reflexive practice and thus ongoing diagnosis of tensions as they emerge. Co-presence thus takes very seriously the need to maintain a watch on how teams respond to challenges and manage themselves, seriously enough to dedicate staff to the practice of reflexivity. Fernández-Giménez et al. pursued a similar investment, by embedding a "team science" scientist on their team. They frame this practice in terms of a "reflexive adaptive process", which involved regular team reflections on their collaborative practice, led by the team science scientist. In that regard, team members all took on dual roles of researchers and participant observers. Regular reflections, in turn, inculcated a "communication climate" that encompassed not only meetings but also reflective essays by team members. Those essays were analyzed by graduate students and the team science scientist, who summarized the main themes and presented them back to the team as part of the reflective discussions she facilitated. The chapter by Fernández-Giménez et al. thus provided their team an opportunity to further record their insights, as in their inset boxes.

A third strategy to proactively manage challenges on teams crossing boundaries involved conducting surveys, focus groups and other research on team members. Such methods offer a somewhat more structured approach to inquiry, which can be important if the team is facing particularly difficult challenges. Laborde et al. employed surveys and other forms of structured data collection throughout their project in order to actively monitor changes in researcher perceptions and understandings of their collaborative practice. They conducted regular surveys after weekly meetings over a period of more than a year, providing extraordinarily detailed documentation of the team's practice and progress. Particularly intriguing was the feedback obtained during the process of building the integrated model, which went well beyond what team members had time to share during meetings. Given the especially complicated and potentially contentious process of data integration for modeling noted above, Laborde's practice here of using surveys proved particularly valuable. Lam et al. similarly conducted a survey in the later

stages of their project, which also provided insightful information about how the team viewed their collaborative experience.

A final initiative employed by several teams to support their collaboration across boundaries involved shared trips to field sites. Such trips offered the experience of physically crossing deep cultural boundaries together, and thus experiencing the exigencies of traveling, eating and lodging together. While it is of course necessary to make such visits, different teams planned their trips with distinct wrinkles in the logistics and activities, and those plans proved enormously valuable in preparing teams to face similar challenges later on. Uchida et al. offer an especially prominent account. Few on their team had previously visited the study region on the Tanzanian coast, and they relied on institutions at both ends with established ties to facilitate the initial field trip. They therefore carefully planned the trip specifically to build the team in several respects simultaneously. Not only would the team get to know the in-country partners and see potential field sites, but the visitors would also get to know each other better by going thru the rigors of the trip together. The visit thus made manifest the strong commitment by the team to potential partner organizations, which facilitated the institutional courtship among counterparts. As Uchida et al. note, the visit permitted "proper introductions". Backed by supporting institutions, this helped create personal and professional goodwill that was important for partners to feel confident in making further introductions to other local organizations. What is more, the itinerary and activities of the trip specifically called for cross-training of visitors across disciplinary boundaries. Uchida et al. went beyond just having the team visit the same places and eat the same food. They also instituted activities designed to move the key players out of their disciplinary comfort zones, and specifically to push them in the direction of the work of their colleagues. It was a stroke of genius to have the ecologist sit down and listen to local peoples talk about their fishing practices, and to have economists wade around in mangroves in tidal basins to examine sediments. By requiring everybody to do what another discipline would do on the project being planned, everyone got the firsthand experience of crossing disciplinary boundaries, gaining a concrete appreciation of the research concerns and exigencies of other disciplines. No team meeting in a seminar

room could match this experience. Coming as it did in the middle of a trip to another country to meet with largely nonacademic organizations, the trip activities thus managed to cross three major boundaries all at once, an invaluable package of joint learning experiences that built considerable respect and mutual understanding on the team. Later on, when in-country partners were overwhelmed with requests, a security situation arose, and other challenges appeared, Uchida et al. were well-prepared in the sense of having collectively met the partners in their context, and having jointly experienced the exigencies of the fieldwork to be conducted. Smithwick et al. also report extensive visits to establish and strengthen ties with leaders of the Menominee nation. They participated in a tribal summit and other activities. Salient in their account is how the meetings featured indigenous perspectives on relationships with forests and the question of adaptation to climate change. Following an initial visit by co-PIs, subsequent visits included the broader team of project staff. Also hosted by the Menominee, the visitors thus received cultural education as a shared learning experience. As Smithwick et al. emphasize, it was very important that the team gain a shared understanding of Menominee knowledge systems as a means of learning how to communicate across a deep cultural divide. Crucially, the team had ample time for reflection on this cultural education during long car rides and other collective activities. The visits thus provided vital opportunities for the team to gain a shared understanding of Menominee culture and each other. Caldas et al. also made field trips, and they are very explicit in emphasizing the importance of those trips for building an *esprit de corps* on their team. They point out how trips permitted socialization among team members outside of work, getting senior team members away from their offices. Trips in turn afforded team members the opportunity to exchange ideas at field sites, where the research issues were no longer abstractions. Joint trips also occurred later in the project, when the natural and social scientists jointly participated in a stakeholder survey. That, in turn, was possible among initially suspicious stakeholders, because the team used earlier visits to attend cultural events held by those same stakeholders, like county fairs. The sequence of shared trips thus helped integrate the team across disciplines, while also giving the team a positive identity before various

groups of stakeholders, which in turn, was crucial for data collection to permit integration of key data into their model.

12.6 Emergent Recommendations

Out of the insights, challenges, conditioning factors, and strategies in the foregoing sections, teams all offered recommendations for improving collaborative practice when crossing boundaries in SES science projects. Perhaps a global recommendation stemming from the conjuncture of experiences reported in the foregoing chapters is to adopt an adaptive management model of collaborative practice. Figure 12.1 offers a basic rendition of what such an adaptive model might look like. The basic adaptive cycle would run from (1) investment in management skills, and continue to (2) engagement of management skills in practice, which leads to (3) reflection on outcomes and shared learning from collaborative experiences, resulting in (4) adjustments and improvements of practice based on lessons learned, plus (5) identification of specialists

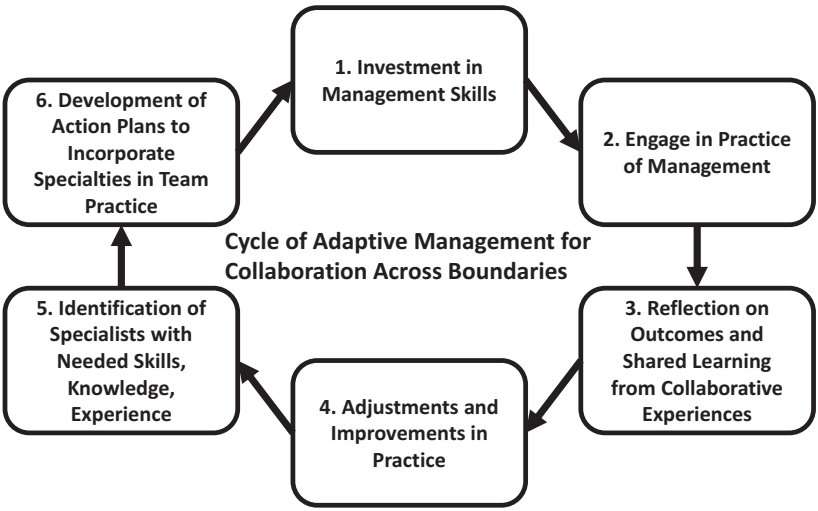

Fig. 12.1 The cycle of adaptive management for collaboration across boundaries (*Source* Figure created by the author)

with needed skill sets, experiences and knowledge, to support (6) development of action plans to incorporate those specialties in team practice. The cycle then repeats, hopefully with improved team performance as to their processes and outcomes.

I suggest this cycle because it seems to apply well to each of five (5) key recommendations made by multiple teams: (1) engage in extensive efforts to build relationships and plan joint actions, (2) pursue staffing for nonscientific functions that support both collaboration and crossing boundaries, (3) develop transdisciplinary action plans for nonacademic engagement, (4) build teams based on shared experiences, and (5) address tensions not to resolve or deny them, but to manage them as a means of compelling learning and thereby driving innovation. In each case, the recommendations feature practices that require investments, implementation, learning, and adjustments, many involving staffing and planning.

Teams routinely observed that pre-project investments in building relationships and engaging in up-front planning were extremely valuable, as well as flexibility and adaptation when they discovered that early preparations proved inadequate. King and Nibbelink underscored these issues in the context of a transdisciplinary training program, where the formation of ties to departments and individuals was crucial, and the core team had to make adjustments as they went. The authors note that departmental courtships with potential participating units permitted dialogues to figure out which of various modes of collaboration across boundaries would be most fruitful in practice. They also emphasize that routine meetings were vital to manage challenges and surprises, though this does not mean that meeting format need always be the same: there were dialogues, role plays, games and various other platforms to help players examine assumptions and improve communication. Pischke et al. underscore the importance of up-front planning, especially in the face of uncertainties. Explicit recognition of challenges and unknowns helped leadership identify issues and think about contingency plans. This affected all manner of decisions about the organization of subteams, matching counterparts, site selection, sampling, and a suite of other elements that greatly affected data collection and thus integration for modeling, as well as outreach and collaboration with nonacademic

stakeholders. For Pischke et al. the sooner the onset of operational thinking about task allocation, coordination, and integration, the better. They also argue that up-front operational planning also fosters clarification of a vision for how the team will function, which leads to expectations about behavioral dispositions of team members. This, in turn, eases the process of incorporating newcomers. Shared vision also helps manage the organization of sub-teams; a key step in their project was to create an integration sub-team out of shared recognition of its necessity. Smithwick et al. provide a detailed backstory to their project to make the point that building on past collaborative efforts and careful networking permitted consolidation of several networks among key players, on which they could then build to formalize cross-cultural ties as well as delineate specific sub-teams. The planning of project structure was thus based on investments in network ties. Network brokers became PIs and their counterparts, "sub-networks" became sub-teams, and other important nodes in networks took on key functional roles on the project. Like other teams, Smithwick et al. experienced changes in personnel and collaborative structures over time, as part of the proposal preparation process as well as during the project. Ongoing discussions helped to foster clarity about goals and thus enact shifts in the focus of shared activities; doing this during the preliminaries was more efficient than in mid-project, which motivates their recommendation to plan early and extensively. Even so, personnel changes occurred during the project, often by including nonscientists, whether academics in the humanities or specialists with other functions. Caughlin et al. had the experience that can result from a surprise at the outset of a project: a dispute stemming from contrasting interpretations of SES change because collaborators were looking at different data sources, which called into question assumptions about the data and the validity of interpretations therefrom. Fortunately, the team managed the dispute without conflict. This was possible in large measure by adding new specialists in high-resolution remote sensing, the key missing piece to address the interdisciplinary puzzle, along with incorporation of farmers in stakeholder workshops, to help validate interpretations of the new data. Perz et al. found it necessary to incorporate NGO partners to increase sampling density in their botanical data. Laborde et al. also sought out NGO

partners to help in managing an uncertain security situation. Caldas et al. also incurred staffing changes. They offer extensive reflections on their experience, noting how departing collaborators recommended others as substitutes. This reflected a shared team spirit and an important practice of adaptive management in the recruitment of human resources on teams. Caldas et al. also emphasize that they engaged in extensive vetting of potential collaborators, not only by reviewing their technical competence but also their behavioral dispositions to listen, consider other perspectives, and learn. This stemmed from careful planning in the early phases of the project, not only about defining key concepts but also in prioritizing behavioral expectations of team members for *esprit de corps*. Caldas et al. thus offer recommendations not only about up-front meetings to plan the science, but also about planning and building teams, which in turn support modifications in team lineups to sustain team functions and spirit later on.

Several teams made recommendations featuring the need to increase staffing for nonscientific team functions, notably for field coordination. Uchida et al. observe that their team had several network brokers on their team and among their in-country partners, a fortunate circumstance that facilitated recruitment of additional team members. They emphasize that network brokers are crucial when additional staffing needs become apparent. Fernández-Giménez et al. offer a more specific reflection, observing that several key functions that were not obvious at the outset became vital during the project, such as the need for translators. Key personnel such as graduate students and postdocs had to dedicate considerable time to that function, which hindered their focus on the science. Fernández-Giménez et al. would thus budget for professional translators for written technical translations, but would also prioritize bilingual team members to facilitate cross-cultural communication within the team. Pischke et al. encountered emergent demand for creation of new sub-teams for various functions, both scientific and nonacademic. In the case of the latter, they received requests to form more transdisciplinary relationships. The requests brought the opportunity to favorably influence public opinion about the PES program being evaluated. They realized that this required a plan rather than ad hoc decision-making. They conclude with the recommendation that teams

hire a project manager (and an assistant manager, too) to ensure effective coordination between scientists and stakeholders. Caldas et al. provide a similar recommendation, arguing for staffing to support a team communication strategy. They outline various approaches and platforms for outreach, organized around communication specialists to oversee a strategy for communicating effectively with a portfolio of diverse stakeholders, especially those who may be indisposed to hear politically unpopular scientific findings vis-à-vis their cultural beliefs or economic interests. Science communication is not trivial, especially in light of SES science projects on high-profile topics with urgent need for improved management and governance. Laborde et al. however note that some staffing for functions that complement research can still come from university administrative units. Such "satellite team members" can provide important functions such as risk analysis. This takes advantage of the many boundaries within universities, which can obscure university assets in support of projects with important non-research needs.

Closely related to staffing for nonscientific functions is the frequent recommendation to invest in planning for transdisciplinary tasks like stakeholder outreach. Not only can planning for outreach increase the scale of project impact among stakeholders, it can also positively affect career trajectories of team members, especially junior team members interested in nonacademic jobs after projects or graduation. Laborde et al. combined workshops for in-country partners on SES research with outreach workshops with local peoples. Perz et al. employed the "knowledge exchange train" model to scale up outreach across a tri-national frontier. In this case, the scale of the enterprise necessitated several months of planning. But the planning was for strategic purposes; the knowledge exchange train also provided a platform for planning downstream collaborative activities with various nonacademic stakeholders. Pischke et al. did not have an outreach plan per se due to uncertainties tied to government decisions and staffing changes. Instead, they worked to take advantage of opportunities as they arose, which then led to other opportunities, including collaboration with government. Their strategy was to respond to stakeholder expressions of interest by modifying the team's structure via the addition of an outreach sub-team. Outreach activities by the sub-team helped the team

leverage one alliance with an impact into another, as they reached different constituencies with findings about the benefits of the PES policies. The result was to increase the scope of the publics the team could reach, which in turn called the attention of government decision makers. King and Nibbelink offer the most developed platform for transdisciplinary engagement, though their case of a training program helps explain the highly structured approach to outreach. Preparation of students to engage nonacademic stakeholders took multiple forms during their training: a literature review on communication strategies, practice via communication exercises, internships, and strategic communication practices with stakeholders. All of these measures could be adapted to projects, as via the inclusion of outreach or communication specialists. Scientists crossing boundaries without training in communicative practice with nonacademic audiences would do well to pursue that preparation or find partners who have it.

A fourth recommendation stems from the design and implementation of intentional shared on-site field experiences to form and strengthen bonds among team members. Virtual meetings are useful, but traveling to the field site to meet partners, attend cultural events of stakeholders, and engage in cross-training among team members all serve to quickly and robustly build understanding among team members along multiple dimensions. Uchida et al. as well as Fernández-Giménez et al., Smithwick et al., and Caldas et al. offer salutary models of field visits that were strategically programmed with regard to crossing multiple boundaries to facilitate the constitution of effective collaborative teams. In each case, field visits went well beyond a meeting or two, and in each case, the visits built strategic collaborative capacities on which teams relied heavily in their projects to better manage key challenges. Through visits, Uchida et al. forged strong ties with in-country partners that proved crucial later when those partners had to take on greater responsibilities. Through attendance at cultural events, Caldas et al. created the foundations for cross-sub-team collaboration that facilitated stakeholder interviews on the policy component in their model.

A final recommendation from multiple teams concerns the fundamental issue of how to manage disagreements, tensions and conflicts within teams, understanding that crossing boundaries involves

various power inequalities. While teams often strove for consensus, and a few teams achieved it, many teams explicitly recognize that neither consensus nor voting (win-lose) nor middle-ground approaches are necessarily preferable. This reflects other observations about management of "essential tensions" when crossing boundaries in SES research (cf. Turner et al. 2015). Caldas et al. admit to some long discussions before reaching consensus, and they underscore the importance of having previously established shared goals to help push discussions toward consensus, at least for the case of defining and operationalizing key terms. For Caughlin et al., an initial dispute over interpretations of data proved manageable, because it led to a more interesting question, as well as a methodology to span a scale mismatch. This case also illustrates the perils in seeking consensus: many stars had to align, as the dispute had a technical solution with positive social and ecological implications. Were we all so fortunate. In contrast, Laborde et al. offer an extended discussion of frictions as useful for impelling intentional collective action that fostered learning. They highlight how frictions might at first glance seem threatening or frustrating, but they in fact constitute opportunities for learning that can beget new insights and thus innovation. Other teams express similar sentiments. Uchida et al. note that junior and mid-level faculty actually led discussions to figure out how to manage data integration. This stemmed from the fact that junior colleagues led the modeling effort. Using the model as a framework, it became easier to discuss data integration. That led to realizations about the implications for data collection, which imposed constraints on the field campaign. Perz et al. report a similar circumstance that arose due to their modeling effort, but after the field data collection had concluded. This time, it was a junior ecologist who pointed out some implications in the field data for modeling, which drove data exchanges to increase sampling density to permit parameter estimation. In turn, negotiations over the ecological data delayed model development, which led to tensions among the modelers. But because the modelers knew each other well, the tensions running from data integration to model development and then evaluation were kept in bounds. That permitted sustained work on model development and improvement. In the process, the ecological data were compiled and integrated. This amounted to a

good collaborative relationship, where trust despite problems yielded dialogue, learning, and progress. Smithwick et al. make a stronger statement out of their experience with the encounter of deep differences between western and indigenous cultures. They underline how a respectful cultural dialogue required an iterative process that recognized the deep differences but then evolved toward mutual understanding across knowledge systems. The evolution occurred through learning the cultural differences, which built respect that permitted joint action. Cross-cultural learning thus facilitated exchanges of knowledge systems and sustainability planning practices, which drove innovation by affording identification of creative uses of visualization technologies. In the examples from Uchida et al. to Smithwick et al. it was not consensus, win-lose votes or middle-ground proposals that impelled progress on collaborative teams when they crossed boundaries, but instead the recognition and management of tensions as a means of encouraging dialogues that fueled the search for, and identification of, novel solution pathways.

12.7 Final Remarks

I close with a final observation about the endeavor of collaboration across boundaries which also stems from comments from multiple teams. The preparatory labors necessary for effectively collaborating across boundaries are exertions not for a single project, but instead constitute a strategic move to build long-term relationships. This correlates with earlier comments that collaboration across boundaries is a strategic commitment, just as the study of SESs to improve the sustainability of their governance and management requires a long-term obligation. To fully realize collaborative advantage means pursuing collaboration as an overall strategy, and thus maintaining relationships after a particular project concludes. The enterprise is not the project, but the larger goals a project seeks to serve. Collaboration across boundaries is thus a strategy that fits the grand challenges of sustainability and resilience of SESs. On an individual level, the investments required can change career trajectories by producing professionals as likely to go into academia as

government or the third sector, precisely because they gained cutting edge technical knowledge as well as experience working with diverse constituencies, granting them a broader vision of science and action with regard to SESs, and sustainability itself. On the project level, as multiple teams noted, one initiative often led to demand for others. King and Nibbelink speak from experience in running a transdisciplinary training program, noting that many graduates enter government or join or found NGOs, a reflecting of a broader shift in the jobs taken by transdisciplinary graduates. Fernández-Giménez et al. report similar employment trajectories from graduate participants in their project. Pischke et al. address the larger issue of strategic commitments, weighing the challenges of new needs identified by stakeholders and whether those lead to "mission creep" on a project versus the opportunities that open to increase impact and leverage downstream activities. Smithwick et al. further address the commitment issue with a surprising reflection on the endeavor of collaboration across boundaries: "we are enjoying it." If scientists work hard in order to learn, and if transdisciplinarity affords more numerous and deeper learning opportunities, what scientist wouldn't want to partake? Uchida et al. offer very similar reflections from end-of-day meetings during their planning trips. In that context, the "enjoyment" sentiment supported their enormous motivation to go to all the effort to build a team, establish ties with partners, and so on, because of the learning opportunities, instrumental for the scientific contributions that stood to be made, and the relevance of the knowledge gained for improving management of the mangroves and the lives of the people who depend on them. Uchida et al. provide quotes from their Tanzanian partners that underscore the long-term importance of the collaboration. The work required was formidable, but the benefits exceeded expectations in terms of contributing to long-term shared goals, which prompted reflections about future collaborations. If wicked problems like sustainable management of SESs are to be addressed, the experiences of these many teams indicate that collaboration across boundaries offers an effective strategy for the path forward.

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Index

A

Adaptive governance. *See* Adaptive management
Adaptive management 3, 16, 190, 250, 355, 420, 423. *See also* Leadership, governance and management in collaboration
Agent-based models (ABM) 96, 118, 132, 136, 277, 303
Agile scientists 228, 235–237, 255, 258, 261
Agriculture. *See* Land use
Amazon, southwestern 22, 24, 330–333, 335, 337–339, 346
Applied behavioral sciences 3, 4, 396, 397

B

Benefits in collaboration. *See* Expectations and benefits in collaboration
Biodiversity 37, 40, 46, 51, 63, 81, 82, 85, 87, 89, 122, 160, 161, 267, 268, 273–275, 277, 281, 285, 295, 297, 332, 337
Boundaries. *See* Interdisciplinarity; International Cooperation; Transdisciplinarity

C

Cameroon. *See* Logone floodplain, Cameroon

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Capacity building 2, 96, 146, 187, 195, 212. *See also* Transdisciplinarity
Carbon storage 116, 118, 119, 121, 124, 133, 297, 311
Central Great Plains (CGP) 24, 267, 270, 271, 274
Citizen science 39–41, 55, 61, 409
Climate change 7, 8, 24, 154, 156–160, 167, 180, 187, 190, 192, 202, 267, 268, 274–276, 337, 362, 370, 374, 410, 414, 419
Coastal ecosystems 7, 129. *See also* Mangroves
Collaboration, challenges in 4, 5, 9, 10, 15, 17, 19, 20, 80, 97, 110, 134, 147, 154, 156, 177, 187, 198, 199, 205, 209, 217, 220, 228, 229, 240, 247, 254, 256, 260, 304, 343, 352, 363, 380, 383, 398, 404, 410, 412, 413
Collaboration, commitment to 14, 109, 165, 192, 240, 403, 404, 427
Collaboration, field visits for 166, 177, 400, 425
Collaboration, issues 3–5, 9, 10, 14–17, 19, 134, 162, 188, 192, 199, 256, 380, 385, 387, 398, 412, 421, 428. *See also* Common interests and complementary capacities; Expectations and benefits; Goals and objectives; Introductions and communication; Leadership, governance and management; Politics and inequalities; Surprise and uncertainty
Collaboration, lessons learned. *See* Collaboration, recommendations
Collaboration, recommendations 25, 156, 178, 198, 216, 282, 287–290, 352, 383, 398, 420, 421, 425
Collaboration, staffing for 404, 405, 414, 421, 424
Collaboration, strategic practices 9–12, 15–18, 21, 25, 118, 331, 343, 352, 396, 397
Collaborative advantage 4, 10–12, 17, 20, 137, 247, 403, 404, 427
Collaborative inertia 4
Collective action 3, 426
Common interests and complementary capacities in collaboration 10, 12, 134, 257, 353
Communication in collaboration. *See* Introductions and communication
Community-based monitoring. *See* Citizen science
Comparative analysis of projects 397
Complementary capacities. *See* Common interests and complementary capacities
Consensus building 53, 66, 107, 109, 174, 177, 199, 251, 285, 286, 305, 402, 426, 427
Co-presence 105, 106, 110, 416, 417
Coupled Human and Natural Systems (CHANS). *See* Social-ecological systems (SES)

Coupled Natural and Human Systems (CNH). *See* Social-ecological systems (SES)
Coupled Natural-Human (CNH) systems program, National Science Foundation 40, 42, 49, 53, 64, 317, 361, 374, 381, 388
Critical thresholds 6, 7
Crossing boundaries 1–6, 9, 10, 17, 21–23, 105, 130, 177, 260, 312, 352, 355, 396–399, 401, 402, 407, 413, 416, 417, 420, 425. *See also* Interdisciplinarity; International cooperation; Transdisciplinarity
  culture and 2, 130, 177, 401, 407, 413
  models of 23, 352, 355, 407, 420

D

Data integration. *See* Integration, of data and models
Disciplines. *See* Interdisciplinarity
Distributed leadership 15, 397

E

Ecosystem services 23, 35, 40, 42, 46–48, 51, 53, 62, 64–66, 116–119, 121, 122, 124, 126, 129, 130, 133, 136, 140, 144, 158, 234, 275, 302, 368
  hydrological 36, 37, 39, 40, 46, 48, 80, 84, 276
Emotional challenges in collaboration. *See* Collaboration, challenges in
Epistemological challenges. *See* Collaboration, challenges in; Interdisciplinarity
Esprit de corps 287, 419, 423
Expectations and benefits in collaboration 10, 15, 16, 172, 243, 251, 258, 260, 355, 428

F

Feedbacks, social-ecological 5, 6, 83–85, 192, 201, 234, 313, 339
Field logistics 67, 135, 195, 399
Field visits. *See* Collaboration, field visits for
Fish. *See* Fisheries
Fisheries 7, 117, 119, 125, 126, 130, 133, 138, 142
Fishing. *See* Fisheries
Forests 24, 38, 45, 46, 48, 65, 116
Forest ecosystems 8, 24, 40, 43, 46, 48, 116–118, 121, 133, 140, 176, 303
Friction, relational 105, 107

G

Games, for interdisciplinary training 154, 243, 244, 247, 258, 279
Goals and objectives in collaboration 10, 13, 14, 247, 257, 354
Governance. *See* Governance, environmental; or Leadership, governance and management in collaboration
Governance, environmental 1, 8, 60
Governance, in collaboration. *See* Leadership, governance and management in collaboration

Graduate students 54, 58, 86, 93, 94, 96, 117, 127, 133, 137, 164, 165, 168, 191, 194, 197, 198, 206, 210, 212, 218, 228, 244, 286, 339, 340, 366, 383, 384, 405, 417, 423
Graduate training 24, 228, 229, 232, 233, 235, 238, 239, 251, 254, 255, 257, 260, 399. *See also* Capacity building
Grassland ecosystems 188

I

Inequalities in collaboration. *See* Politics and inequalities
Integration, of data and models 23, 24, 49, 51, 53, 54, 60, 66, 69, 102, 108, 136, 140, 174, 202, 219, 233, 269, 281, 353, 380, 383, 385, 411, 417, 420, 421, 426
Integration, of personnel across boundaries 24, 140, 144, 396, 410, 412, 421
Integrative Conservation (ICON) Training Program 228, 229, 232, 235, 236, 238–241, 243, 249–256, 258, 260, 261
Interdisciplinarity 1, 2, 4, 5, 17, 18, 22, 23, 41, 48, 49, 54, 56, 57, 59, 60, 62, 66, 79, 80, 93, 96, 97, 99, 100, 102, 104, 105, 107–110, 117, 134, 136–138, 164, 176, 177, 179, 181, 194, 195, 198, 204, 216, 218–220, 228, 229, 231–234, 236, 238, 240, 245, 247, 252, 256, 268, 269, 273, 274, 282, 284–286, 288–290, 297, 304, 305, 307, 315, 317, 335, 361, 363, 379, 383, 386, 388, 399, 408, 422. *See also* Collaboration, challenges in
International cooperation 4, 5, 17, 21, 22. *See also* Collaboration, challenges in
Inter-organizational collaboration. *See* Transdisciplinarity
Introductions and communication in collaboration 10, 11, 131, 240, 255, 256

K

Knowledge systems 154, 156, 158, 162, 177, 178, 180, 181, 400, 403, 413, 419, 427

L

Land use 8, 24, 36, 40, 41, 43, 45, 46, 51, 64, 120, 266, 268, 270, 271, 274, 275, 277, 280, 296, 298, 304, 312, 338, 367, 371–373, 375, 414
Languages 1, 20, 56, 62, 67, 69, 93–95, 102, 103, 106, 110, 169, 177, 199, 203–207, 217, 220, 349, 399, 400, 412, 413, 415. *See also* Collaboration, challenges in
Leadership, governance and management in collaboration 9, 10, 14, 15, 162, 258, 354, 395–397, 427

Logone floodplain, Cameroon 23, 80, 85, 86, 88–91, 93, 94, 100, 106, 111, 412, 413
Los Santos Province, Panama 301, 303, 305, 309

M
Management, environmental. *See* Governance, environmental
Management in collaboration. *See* Leadership, governance and management in collaboration
Mangroves 115–122, 124, 126, 130–133, 135, 136, 140–143, 396, 418, 428
MAP Frontier. *See* Amazon, southwestern
Menominee Nation 24, 156, 159, 162, 165, 167, 177, 413, 419
Mexico. *See* Veracruz, Mexico
Miscommunication. *See* Introductions and communication in collaboration
Mississippi River Delta (MRD) 24, 362, 388
Model evaluation 330, 355, 407, 412
Mongolia 24, 186, 188, 191, 192, 194, 197, 198, 202, 204, 205, 207, 210–218, 220, 397, 400, 412, 415
Muddling through in collaboration 16, 355

N
Network brokers 11, 12, 105, 106, 110, 137, 145, 146, 163, 164, 177, 258, 260, 403, 422, 423
Non-linear dynamics 5, 6, 45, 83–85, 339

O
Objectives in collaboration. *See* Goals and objectives

P
Panama. *See* Los Santos Province, Panama
Pastoralism 87, 96, 185, 188
Payments for ecosystem services (PES) programs 409, 413, 423, 425
Payments for hydrological services (PHS) programs 35–49, 51, 53, 56, 57, 59–65, 68, 70, 71
Policy acceptance 279
Politics and inequalities in collaboration 10, 12, 17, 21, 243, 256, 352
Post-truth attitudes 279, 290, 404, 410, 414
Poverty traps 24, 115, 117, 118, 121, 122, 132, 135, 144

R
REDD+. *See* Payments for ecosystem services (PES) programs
Reflection. *See* Collaboration, strategic practices
Reflexive practice. *See* Collaboration, strategic practices
Reforestation 46, 121, 295–305, 311, 313, 317
Regime shift, complex systems. *See* Critical thresholds; Non-linear

dynamics; Social-ecological systems (SES)
Resilience. *See* Governance, environmental
Roads 25, 60, 327–329, 331–333, 335, 336, 338–340, 367, 378

S

Satellite imagery, high resolution 24, 161, 296, 301, 305–307, 408
Scale mismatch 24, 297, 303, 312, 317, 381, 408, 412, 426
Scenario planning 16, 197, 203, 214, 219, 355
Science, Engineering, and Education for Sustainability (SEES) program 303
Science of teams. *See* Team science
Secondary forests. *See* Forests
Security situations in field 401, 402, 419, 423. *See also* Surprise and uncertainty
Sensitivity analysis, global. *See* Model evaluation
Servant leadership 15
Shared leadership. *See* Distributed leadership
Smoky Hill River Watershed 270
Social-ecological systems (SES) 5, 7, 8, 10, 16, 18, 22, 24, 80–85, 88, 108, 188, 234, 290, 328–331, 335, 339–341, 347, 352, 395, 396, 403, 404, 408, 413, 422, 424, 426
Social-ecological systems (SES) science 5–9, 11–13, 16, 17, 22–25, 351, 354, 355, 395–397, 400, 413, 420, 424
Stakeholder engagement. *See* Collaboration, challenges in; International cooperation; Transdisciplinarity
Stakeholders. *See* Transdisciplinarity
Sub-teams in collaboration 49, 54–56, 60–62, 66–71, 94, 117, 134, 135, 139–141, 194, 201, 202, 204, 397, 415, 421–423
Surprises and uncertainty in collaboration 16, 17, 253, 259
Surveys 49, 50, 61, 69, 97–99, 108, 110, 111, 125–129, 141–143, 193, 196, 201, 203, 204, 236, 275, 276, 281, 288, 291, 299, 302, 317, 363, 365, 372, 375, 383–385, 388, 417, 419
Sustainability. *See* Governance, environmental

T

Tanzania 23, 117, 118, 120, 122–126, 128–131, 133, 134, 138, 139, 142, 143, 145–147, 397, 400. *See also* Mangroves
Team dynamics. *See* Collaboration, staffing for; Integration, of personnel acrossboundaries; Leadership, governance and management in collaboration
Team formation. *See* Leadership, governance and management in collaboration
Team learning. *See* Introductions and communication in collaboration
Team meetings 58, 60, 97, 99, 101, 102, 111, 139, 196, 197, 204,

218, 286, 367, 397, 406, 407, 418
Team science 22, 134, 145, 187, 191, 215, 218, 238, 240, 417
Telecouplings 6, 8
Tenure, university faculty 105, 144
Thresholds. *See* Critical thresholds
Tipping points. *See* Critical thresholds
Traditional knowledge. *See* Culture; Knowledge systems
Transdisciplinarity 14, 19, 154, 156, 171, 175, 180, 181, 237, 238, 247–249, 257, 290, 408, 409, 428. *See also* Collaboration, challenges in
Transparency in collaboration. *See* Expectations and benefits in collaboration; Introductions and communication

U
Uncertainty in collaboration. *See* Surprises and uncertainty in collaboration
Uncertainty in modeling 355

V
Values-beliefs-norms (VBN) framework 4, 276–278. *See also* Culture
Veracruz, Mexico 40–45, 48

W
Watersheds 7, 8, 36, 38–44, 46, 48–56, 61, 62, 65, 66, 80, 159, 167, 270, 271, 273, 275, 277–280, 297, 302, 396
Wicked problems 1–4, 428
Workshops. *See* Capacity building