Collaboration Across Boundaries for Social-Ecological Systems Science

Experiences Around the World

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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

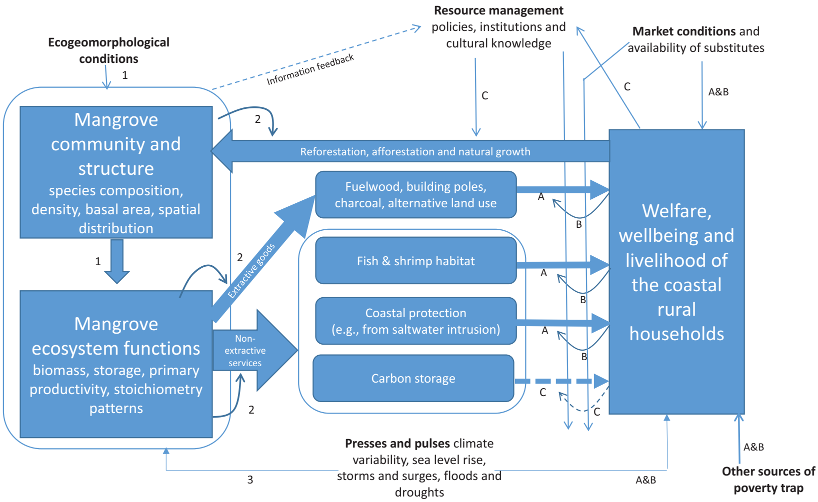

Fig. 4.1 Mangrove ecosystem services and poverty traps framework. In this diagram, stock is represented by rectangles and flows by thick arrows and rounded rectangles indicating ecosystem services. Curved arrows represent feedback loops while thin straight arrows show conditioning factors and drivers. 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

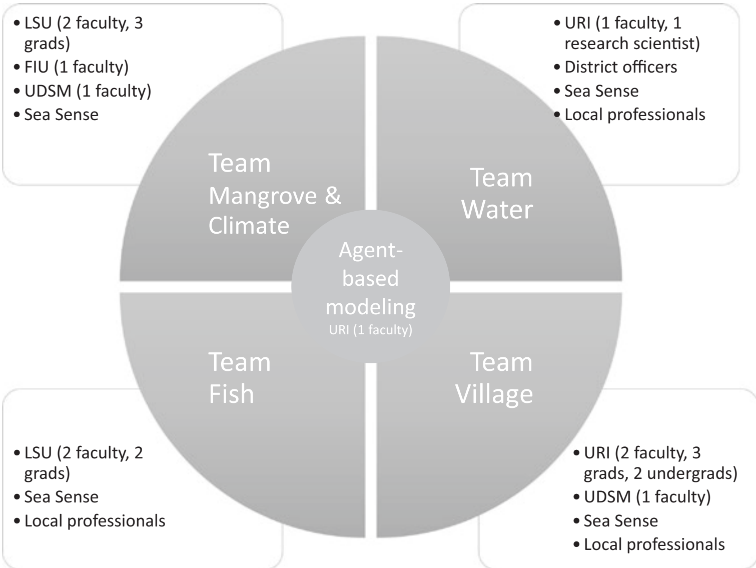

Fig. 4.2 Research team structure (*Source* Figure created by the authors)

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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