Chapter 12

Lessons Learned

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As it evolved over fifteen years, our research effort in the Yaqui Valley grappled with a range of issues related to land and water management, from the policy environment to constraints on resources to consequences for local people and ecosystems. The preceding chapters of this volume illustrate crucial interactions within the human-environment systems of this valley, across agricultural, water, coastal and urban, and natural ecosystems, and across space and time scales. The research suggests that management issues must be studied with these connections in mind, and that systems perspectives are key to developing solutions that make sense for both people and the environment.

In the process of our research, and in attempting to link our research with decision making, we learned a number of lessons. Some of these lessons are apparent in the earlier chapters; we use this final chapter as an opportunity to highlight the most important ones. We believe that many of our conclusions can be generalized beyond the Yaqui Valley to other regions where resource sustainability and economic sustainability are the emerging bywords of the day, and to other research groups that are trying to mobilize a sustainability transition. The next two sections of this chapter address lessons about improving understanding and translating knowledge into action.

For academic researchers, our reflections on research approaches, training students, and institutional organization may be of interest. In the

P.A. Matson (ed.), *Seeds of Sustainability: Lessons form the Birthplace of the Green Revolution in Agriculture*, DOI 10.5822/978-1-61091-177-1_12, © 2012 Island Press

latter half of this chapter, we discuss the experience of doing this work and its impact on sponsoring institutions. Other experiments like this one are playing out around the world, and we hope our ideas contribute to a growing understanding of what is needed to engage academic researchers in sustainability science—the broad field that focuses on interactions within human-environment systems, and on the knowledge, tools, technologies, and approaches needed to meet sustainability goals (Kates et al. 2001).

Lessons for Sustainability Transitions in the Yaqui Valley and Beyond

Sustainability is an ongoing process; research and management capacities are needed to continuously advance sustainability goals.

Seeds of a sustainability transition in the Yaqui Valley can be seen in efforts to (1) increase agronomic yields and profitability through modern agricultural technology and knowledge-intensive management approaches, (2) increase nitrogen use efficiencies and reduce nitrogen and other pollutant losses, (3) increase the sustainability of water resources through management approaches across a range of scales, and (4) identify and reduce vulnerabilities to changes, including climate changes. However, much more remains to be done in these areas, and in some ways our work has just skimmed the surface. Efforts in other sustainability pathways—such as diversification to different, more site-optimum crops; landscape-scale management that maximizes ecosystem services by matching crop and soil types and by embedding conservation strategies in the agricultural landscape; the development of sustainable livestock management approaches; or the development of alternatives to agriculture altogether—have received very little attention but could be part of the sustainability transition in this place. One could argue, in fact, that our research effort, which focused on the dominant current practices and led to evolutionary, incremental, near-term improvements, should instead have been focused on the longer-term, more significant, more revolutionary and game-changing alternatives. This was a trade-off that we contemplated and discussed, but we never seriously considered shifting our focus. As researchers and educators who wished to make a difference, we traded off the longer-term and potentially more optimal, but much less certain, solutions for the ones that we thought we could deliver, even knowing they were only first steps. At the same time, our near-term efforts changed the vocabulary and the agenda of the valley to one that included the idea of sustainability; that change may be the most critical foundation for the larger, longer-term efforts that need to come.

One of the benefits and also one of the drawbacks of working in one place for an extended period is recognizing all that *could* be done, if there was only enough time, people, expertise, and money. Perhaps that is one of the lessons of a sustainability transition: it is never done. Based on our experience, it is about moving one step at a time, hopefully more forward than backward, learning as we go. The research needed is not a one-shot deal. This perspective speaks strongly for building capacity for research in a place, and luckily, the Yaqui Valley has a strong local base of scientists and managers who are engaged in the transition.

One of the most critical barriers to sustainability transitions in the Yaqui Valley is the same challenge that faces all of agricultural decision makers: the need for decision making under uncertainty.

Farmers in the valley face heterogeneity, variability, volatility, and uncertainty in soil, pests, insects and diseases, climate conditions, water resources, national policies (applied to the country as a whole, despite vast differences between the subsistence-scale and high-productivity systems in Mexico's dual agricultural sector), international policies, international markets and contracts, commodity and input prices, access to credit and inputs, environmental awareness, social contexts, and information. Unlike most other sectors of the economy, agriculture has a unique temporal dimension; farmers make most of their key decisions before or at the time of planting, prior to the emergence of biotic and abiotic stresses and often months before the crop goes to market. Part of the problem is incomplete knowledge, and part of it is simply that some of these things are inherently variable. Our work suggests that adding new goals—and new ways of doing things—to this complicated and uncertain world can be very difficult and even risky.

On the other hand, to the extent that research can focus on new approaches that help decisions makers deal with uncertainty, sustainability goals can benefit along with others. For example, our work on water and nitrogen-use efficiency approaches that use real-time information represent *no-regrets* actions that can be taken at little cost and that will be beneficial for society and the environment regardless of how climate change, policy changes, or other stresses unfold. Indeed, while our team did not specifically address the concept of *adaptive risk management* (briefly described in box 12.1, adapted from NRC 2010b), some of our approaches can be

BOX 12.1

COMPONENTS OF ADAPTIVE RISK MANAGEMENT (ADAPTED FROM NRC 2010).

Risk identification, assessment, and evaluation. Risks need to be evaluated by a range of affected stakeholders (who typically have different values and preferences) and by considering a range of factors. These include the impacts of allowing risks to go unmitigated, the costs of different risk management strategies, public perceptions and acceptability of risks and/or responses to them, as well as broader societal values that tend to favor certain general approaches to managing risk over others (e.g., a precautionary approach versus a cost-benefit or risk-benefit approach).

Iterative decision making and deliberate learning. Because many decisions will have to be made with incomplete information, and new information can be expected to become available over time (including information about the effectiveness of actions taken), decisions should be revisited, reassessed, and improved over time. This will require deliberate planning and processes for "learning by doing," as well as ongoing monitoring and assessment to evaluate both evolving risks and the effectiveness of responses.

Maximizing flexibility. Whenever decisions with long-term implications can be made incrementally (i.e., in small steps rather than all at once), the risk of making the "wrong" decision now can be reduced by keeping as many future options open as possible.

Maximizing robustness. When decisions have to be made all at once (for example, to build a piece of infrastructure or not), the risk of making the wrong decision can be reduced by selecting robust options—that is, options that maximize the probability of meeting identified goals and desirable outcomes while minimizing the probability of undesirable outcomes under a wide range of plausible future conditions.

Ensuring durability. Many policies need to remain in place, albeit in modified form, for many decades, in order to achieve their intended goals. This requires mechanisms that can ensure the long-term durability of policies and provide stability for investors and society while allowing for adaptive adjustments over time to take advantage of new information—a significant challenge for policy and institutional design.

A portfolio of approaches. In the face of complex problems, where surprises are expected and much is at stake, it would be unwise to rely on only one or a small number of actions to "solve" the problem without major side effects. A more robust approach would be to employ a portfolio of actions to increase the chance that at least one will succeed in reducing risk and to provide more options for future decision makers.

Effective communication. An essential component of effective risk management is the communication of risks, including the risks associated with different responses, to all involved stakeholders, including public, private, and civic sector stakeholders, as well as expert and lay individuals familiar with, or potentially affected by, the risks at hand.

Inclusive process. Since climate-related risks affect different regions, communities, and stakeholders in different ways and to different degrees, stakeholders should be included in significant roles throughout the process of identifying risks and response options, determining and evaluating what risks and responses are "acceptable" and "unacceptable," as well as in the communication and management of the risks themselves.

useful components of risk management under uncertainty. We believe this should be an operating principle of many agricultural systems in a world of change.

Changing the "agenda" to one that embraces sustainability objectives requires more than near-term economic incentives; voices that speak for an expanded set of interests must be heard.

While we did not study the psychology of decision making by growers in the valley, we did take away a sense that there are real barriers, at least for some decision makers, associated with the *idea* of change—whether it is toward the diversification of crops, more efficient fertilizer practice, changes in the overall level of government assistance, or recognition of environmental consequences. Economics is not all that matters; history, social relationships, and personal values all matter, and that means that change can be slow even under reasonable economic incentives. Through our knowledge system research, we became deeply aware of how challenging it is to change the agenda of a place, especially a place that is so subject to external forces. In the Yaqui Valley, we watched as the agenda shifted from one born in the *green revolution*—the encouragement of high yields and ever increasing inputs—to one that more closely resembles a sustainability agenda, in which increasing profits and reduction of negative externalities are both items of concern. Agendas are slow to change because they are set by those in power, those at the decision-making table. Agendas are reinforced because those decision makers determine what gets attention, and in some cases, what kind of research gets done. Voices change, and new voices are heard, but only slowly. Our voices, through our research funded by organizations inside and outside the region, mingled with others to influence the agenda of the Yaqui Valley to one that includes concern for off-site environmental and human health issues.

Knowledge matters, but so does connecting knowledge with action.

Sustainability approaches are often *knowledge intensive*, and when we could engage our research team in the development and application of knowledge for decision making, we usually made at least a small difference. But the range of questions was enormous, and new questions continuously emerged as we worked together. There were many, many areas in which we lacked the right expertise, or enough time and money, to be helpful (some of these are discussed later). For many of these questions, our team was insufficient, and other experts were hard to find or to coax into joining us. However, it was not just research expertise that we lacked—we sometimes lacked the time and mechanisms to connect what we were learning to decision making. We were extremely fortunate to have highly respected scientists (in agronomy and in water-resource management) on our team who worked directly with producers and other stakeholders to incorporate sustainability goals—they were boundary individuals, with one foot in the research world and one foot in the management world. To them we owe thanks for making sure that our research was relevant, useful, and actually used. However, we lacked people who could play that role at a different level—for example, to provide policy options to decision makers in Hermosillo (the state capital) and in Mexico City, and to help outline the types of incentives needed to diversify and stimulate agriculture wisely in the Yaqui Valley. We also lacked the time and expertise to fully engage and partner with relevant decision makers, and to make sure that we were communicating quickly and clearly what we had learned. All too often we found that we had engendered great interest in the results of our work but lacked the infrastructure to provide that knowledge in an ongoing way. Clearly, we needed additional partners at the table to help us do that, but in some areas in which we worked, such partners did not exist.

Finally, we learned that the links between researchers and decision makers are always changing—the knowledge system is dynamic. Relevant partners in linking knowledge to action changed over the time of our team effort (see chap. 5), and sometimes we were unaware of the ongoing changes. This point may be a crucial lesson for any attempt to construct mechanisms for linking knowledge and action, or for any research team that wishes to engage in that activity. We learned the drawbacks of making assumptions about the identity of our most critical actors or decision makers in the knowledge system; we learned not to assume, but to study and understand the players in the knowledge system, early and often, and actively identify key points where the knowledge to action links can most effectively take place.

Critical Missing Pieces in Studies of the Yaqui Valley Human-Environment Systems

As noted, our years of research raised as many questions that went unanswered as were addressed. We wished we could dedicate research effort to better understand, for example, knowledge barriers to diversification; the social consequences of constitutional reform for *ejido* communities' and Yaqui Amerindians' livelihoods, health, and welfare; the extent and ecosystems consequences of downwind transfers of pollutants from agriculture; the public health consequences of agriculture; the ecosystem services being provided by the streams and channels linking land to the oceans; the changing opportunities for marketing of commodities; the implications of future climate change, and many others. To address these critical questions about the human-environment system, we would have needed, along with more people and more expertise, a dramatic increase in information about population dynamics in the region, and additional and longer-term data bases on a range of critical measures and metrics. In the following paragraphs, we reflect on these two critical and understudied areas, with the hope that other research efforts, in the Yaqui Valley or elsewhere, will prioritize and incorporate them.

Population Dynamics in the Yaqui Valley

As our work evolved, it became increasingly clear that we needed an explicit focus on population dynamics if we were to succeed in understanding the social and human dynamics associated with land- and water-use decisions in this region.[1] We incorporated population data through two sources: census data and household surveys. Although census data provide general information such as age structure, gender, and household size, they lack detailed, household-level information about income, migration, and health of the population. Nonetheless, the census data show that urban populations are increasing and rural populations are remaining relatively stable at the municipality level. Moreover, throughout the Yaqui Valley, larger towns are growing faster than smaller ones, and in many cases, smaller localities are disappearing. We lack a nuanced understanding of why these changes are occurring and their direct role in land-use changes in the Yaqui Valley. Our household surveys provided detailed information about household characteristics, but those surveys were designed to collect information about different sectors of the population (e.g., aquaculture households, farmers), and not of the entire population. Accordingly, we were unable to extrapolate our survey data to characterize household dynamics for the entire region.

We also failed to spatially disaggregate data on migration. Such data can be obtained through household surveys or estimated via the *residual method*, whereby the rate of natural increase is estimated (births minus deaths) and then deducted from the total population increase. We hypothesized that many of the population changes have occurred within the region as a response to exogenous shocks. For example, it is likely that purposeful economic and technological development of the region during the early years of the green revolution encouraged in-migration. Over time, however, improving mechanization and increasing sizes of lands being managed by single owners may have resulted in surplus agricultural workers. A failure to diversify the Yaqui agriculture resulted in an increase in the area of grain crops such as wheat that are highly mechanized with a low labor requirement, as opposed to vegetable or fruit crops that require more labor. Whether these workers migrated out of the region or were absorbed by local urban or rural economies is unclear from the available census data. Ciudad Obregón and Navojoa experienced significant economic and urban growth over the last three decades, but population data aggregated at the city level make it difficult to answer questions about inter- and intracity socioeconomic differentiation and income and welfare dynamics. Furthermore, the census data classifies population based on residence; a household is labeled rural if the home structure is located in a nonurban place. As it becomes more common for rural residents to work in the city, this urban-rural dichotomy may not be sufficient for fully describing the demographic characteristics of the area nor for accounting the role of population on land-use change. How significant is rural nonfarm employment and incomes to rural households, and how has this contributed to out-migration? Likewise, have changes in Article 27 that allow *ejido* land to be rented and sold resulted in significant alteration of ownership patterns and out-migration, and if so, what are the consequences for land uses? And did these changes have indirect impacts on the Yaqui Amerindian communities, farming practices, or livelihoods? None of these questions were adequately answered in our study, but all would have improved our understanding and provided important insights into change in the valley.

Information on population and household dynamics are likewise important in the study of vulnerability. Our conceptual vulnerability framework (chap. 6) directs us to examine the access of individuals and groups to human and social resources as well as biophysical capital. We know that access to credit and information varies among communities and individuals, but we can only surmise that differential access is influenced by population characteristics and dynamics. Are different components of the population differentially at risk under external pressures resulting from policy changes or climate change? As the land tenure law changes lead to changes in ownership, will it decrease, or increase, the vulnerability of the *ejido* populations? Does the level of education, household size, age structure, or other population variables influence the ability of people to respond to external stresses? How have neighborhoods and place-based community ties influenced information sharing and risk management? While it is easy to state such questions, access to, and development of, appropriate data that allow their answers is more difficult and would have required focused, on-the-ground research at a level that our team was not able to engage in, because of lack of engaged expertise and lack of funding.

Adequate Temporal Databases

For a great many of the questions we asked, we needed long-term or at least multiyear data.[2] Very few research projects are sufficiently supported to collect and manage long-term monitoring data—ours certainly was not—yet such data are crucial to understanding change and influencing transitions. To meet some of our data needs, we took advantage of the years of work done at the International Maize and Wheat Improvement Center (CIMMYT) and other local research institutions. Data at the field and farm level on yields and inputs, farm budgets, and farmer perspectives were available for decades, and in comprehensive form since 1980, thanks to the work of CIMMYT. Soil maps and climate data were available from the National Institute of Forestry, Agriculture, and Livestock Research (INIFAP), National Water Commission (CNA), and Agricultural Research and Experimentation Board of the State of Sonora (PIEAES). Data on land and ocean characteristics were also available from remote sensing data from Thematic Mapper, SeaWiFS, AVHRR, and other sensors. As part of our projects, we obtained and compiled remote sensing databases going back several decades, and also obtained current data. We also used socioeconomic data from the National Institute of Statistics and Geography (INEGI) to provide a regular snapshot of demographic and economic trends. INEGI is an organization of the federal government of Mexico that is responsible for the collection of data on national accounts, prices, socioeconomics, and geography. Like most other government statistical bureaus, INEGI collects detailed census statistics every ten years, and at higher temporal frequency for select data. These data are available at multiple spatial scales, subdivided along administrative units (e.g., state, municipality, and locality). However, while these data provide information for a large area over a long time period, they are not available with enough temporal frequency to present a detailed picture of the dynamics of the system. Finally, we compiled and used water-resource databases, including input and outputs from reservoirs and spatially and temporally defined irrigation allocation values that had been collected by CNA. Beyond these, we had to collect our own data.

Over the course of our project we carried out several farm-level surveys on general agricultural conditions, with each survey focused on a particular topic: nitrogen fertilizer applications (1994, 1996, 2001, 2003), farm management practices (1996, 2001, 2003), and land ownership and rental agreements (1999, 2001, 2003). These surveys became part of a longer-run survey effort by CIMMYT to document the uptake of agricultural technology, resource management, and socioeconomic change in the Yaqui Valley. Using structured and in-depth interviews, we developed a rich dataset on farm characteristics, with much less information at the household level. The principal advantage with conducting surveys is the ability to acquire exact (or proxy) variables of interest (e.g., farm profits, household income, management practices). However, surveys are time and labor intensive, and their temporal and spatial extents are limited to the duration and budget, respectively, of the project. If the sample size is large or the distances between samples great, a survey can quickly become cost prohibitive.

In the course of our projects, we also collected biogeochemical and hydrologic data from field plants and soil, drainage canals, estuaries, groundwater wells, and air; these data were complemented by the longer-term measurements of climate variables and water use in the valley, but, for many of the questions that we wished to ask, these databases were insufficient. For example, we struggled to calculate valleywide nitrogen budgets, depending on our own several years of sampling of streams and canals, when what was required was a longer-term, more spatially complete, record of water flows and chemistry. Such data are often collected in the United

States and other parts of the world but were missing here. Likewise, understanding the downwind consequences of nitrogen oxide emissions from agriculture required good information on air quality in Ciudad Obregón and downwind deposition monitoring sites. These measurements, too, were not available and their absence made it impossible to characterize the full implications of overfertilization in the region, although back-of-the-envelope calculations suggested they could be large. Even for the sampling that we carried out ourselves, there were significant challenges and difficulties related to collecting the biophysical data, setting up and maintaining analytical instrumentation, transporting samples across international borders, and managing tremendous amounts of data being collected at fine temporal resolution and analyzed at different places.

Our surveys suggest that public health concerns may prove to be a stronger driving force in agricultural management and policy decisions than are environmental concerns. Researchers are beginning to link the burning of crop residues and emissions of nitrogen oxides to respiratory disease and other negative health impacts with heavy pesticide, herbicide, and fungicide exposure. Such health impacts of exposure are common in intensive agricultural farming communities throughout the developing world. In interviews, residents of the valley broadly claimed that the region suffers from high rates of leukemia and other cancers, but this effect has not been documented in peer-reviewed literature. Without good information documenting disease trends and monitoring pollutants from agriculture and other sources, it is difficult for health and environmental institutions to influence the agenda of the valley and to require changes in agriculture on behalf of those who may suffer from its impacts.

Reflections on Research Organization and Participation

As we carried out our research, we increasingly recognized that we were actors in a broader knowledge system for agriculture, water resources, and sustainable development. Many of our research team—students, academics, and research scientists from national and international research and management organizations—wanted to make their science useful to decision makers and thus intentionally engaged the valley's knowledge systems, which we purposely studied and participated in. At the same time, while many of us were fascinated by exploration and discovery in our own disciplinary areas, we were also engaged in the challenges of learning new disciplines and integrating them with our own. It was a complicated research environment. The experiences of the researchers, the challenges we faced, the way we organized, and the lessons we learned are explored in the following paragraphs.

In organizing our research, we started small and simple, and built to more complicated research networks over the years. Our early interactions were primarily among only three investigators—Matson (biogeochemist/environmental scientist), Naylor (economist), and Ortiz-Monasterio (agronomist)—and our research groups. Our research interests were driven by broader issues related to food security and global environmental change (see chap. 3); our research funding was from the USDA, Ford Foundation, the Pew Charitable Trusts, and Matson's MacArthur Fellowship. All three investigators were in it from the start, and the process of bringing our perspectives and research teams together to develop the research design was built on mutual respect and the lack of dominance of any one discipline over the others. A key element of our approach was to work with and for each other on the ground; for example, Naylor spent time in the lab and field learning firsthand about the biogeochemistry instrumentation and measurement, Matson went to the field with Ortiz-Monasterio and Naylor to understand the agronomic and economic questions being tested, and Ortiz-Monasterio became involved with all dimensions of field and lab work. It took time to learn and understand one another's perspectives and knowledge base, but the result was well worth it: *It is fair to say that the kinds of questions that we ultimately asked together, and the combination of experiments, measurements, and analyses that we made were different than any one of us would have made working alone.* This first project, motivated by a simple but nonetheless integrative interest, was the most easily funded piece of Yaqui Valley research. It probably would not have worked so well had we attempted to tackle something more complex.

It was impossible, however, to work in the Yaqui region and not notice the broader and more complex set of issues that were influencing decision makers—changing resource availability, information availability, global markets, national and international agricultural policy changes, and so on. Questions about water resources, climate change, macroeconomic upheaval, and national and international policy changes raised concerns about vulnerability. Rapid aquaculture and livestock expansion were hard to ignore and raised more questions about economics and environment. Changes in land tenure laws opened new questions about land-use patterns and population dynamics. Farmer associations and credit unions began to take on new roles. As new issues emerged, those of us who were in a position to notice them began a dialogue about what research could or should be done to address them, and what or who would be needed to do so. At our monthly or bimonthly team meetings (typically held at Stanford University, with members calling in where necessary) or annual all-hands meetings (typically held in the Yaqui Valley), we invited new investigators (both established and student investigators) with particular knowledge about the issues that were just coming onto our radar screen—agricultural and development policy experts, hydrologists, geographers, climate scientists, mathematical modelers, remote sensing experts, conservation scientists, sociologists, physical and biological oceanographers, and so on—and sometimes they chose to join in. With their engagement, we identified potential funding sources and wrote proposals, many of which did not succeed. We had big, integrative, multidisciplinary research ideas, and in the mid- to late 1990s there were not yet federal funding sources for them, nor were many reviewers willing to bet on our ability to work together in this way.[3] Typically, our research had to be funded in pieces, with each discipline bringing their own sources to the table, although seed money from Stanford's Institute of International Studies Bechtel Initiative funds, and later, a large grant from the Packard Foundation, helped us build the matrix into which all these pieces fit. As new funding could be patched together (and sometimes even without such support), new members were added to the whole. As our group and resources grew, we also increased our connections with regional NGOs and other researchers working in the broader Gulf of California area. Over time, influenced by our interactions with the international global change research programs and the nascent international sustainability science community, we began collaborations with separate interdisciplinary teams and comparisons with other places, using the Yaqui Valley as a case study for comparative analyses (see, for example, chaps. 5 and 6). While it would be ridiculous to say that we planned this long-term project, we did indeed do careful planning to bring each new piece into the whole.

In most of our research, our intent was to aid decision making in the Yaqui Valley, but also to address issues that were both scientifically interesting and useful in many other places around the world. Some of us came originally from a research world where rewards focus on the discovery of new knowledge; others were employed and rewarded for providing science in support of decision making. The Yaqui Valley allowed us to work in both these areas, often at the same time. In the midst of research on fertilizer management, for example, we discovered more about the role of nitrification in controlling the emission of nitrous oxide—a mechanism that had been recognized from the laboratory but not measured in the field, and that remained unaccounted for in greenhouse gas emissions models and reduction strategies. Likewise, the role of climate in wheat yield variation had never before been so clearly and forcefully shown as with our remote sensing–based time series analyses. Our in situ studies provided a textbook illustration of thermodynamic controls on trace gases from water systems, and synoptic, remotely sensed measures demonstrated relationships between phytoplankton dynamics in the ocean and activities on land for the first time. Concepts and analytical frameworks for vulnerability analysis emerged in part from our understanding of the situation in the valley, and hypotheses about the functioning of knowledge systems for sustainability were tested in our sites. And finally, the effects of major macroeconomic change (e.g., a sudden devaluation of the Mexican peso and sharply escalating interest rates that dominated farm production costs in the early to mid-1990s) provided a clear picture of how and why macro- and microeconomic evaluation should be integrated into any study of agricultural development. Our findings were presented in scientific journals and as invited and contributed presentations at many scientific meetings.

Much of what we learned was shared with decision makers, including farmers, credit union and farmer association leaders, civic leaders, water resource managers, and so on. As noted in chapters 3, 5, and 9, decision-maker participation in the research was a crucial form of shared learning, and on-farm trials of alternative management practices and new tools were important. Workshops, farm days, and other more formal communications were also used to engage decision makers in what was being learned and recommended. Research findings were published in a variety of CIMMYT and CNA white papers and handout materials. Remotely sensed images of crop yields, phytoplankton blooms in the Gulf of California, and aquaculture change were also shared and served as excellent boundary objects that engaged the research and decision-making communities together.

While overwhelmingly positive, this merging of science that could push the boundaries of knowledge and discovery with science in support of real-time decision making at times raised career concerns for members of the team. For example, in asking agronomic or water resource researchers to walk the fine line between developing and recommending new, innovative approaches versus providing dependable, low-risk (and often conservative) advice, were we exposing our colleagues to potential failure? By engendering interest in new approaches and tools, were we risking their ability to meet an ever-growing demand for the new information by their constituencies; were we promising more than we could deliver? And, as noted below, were we risking our student and junior faculty team members' academic research careers by engaging them in near-term problem solving research? Over time, we learned to walk that fine line together.

Much that we learned in the Yaqui Valley is transportable. At times we worried that our deep focus in this one place would help that one place, but not others. Indeed, one of the more common criticisms of our case study was that so much effort was being spent on one small place, when so much of the world needed similar kinds of work. With that concern in mind, we explicitly built or tested approaches, tools, metrics, and models that can be applied in other places. Moreover, many of our researchers are in positions that expect and even require them to carry the knowledge and perspectives to other regions of the world. Finally, we selected the Yaqui Valley in part because it is home to a major international research organization, CIMMYT, and regularly receives scientist and manager visitors from many other regions of the developing world. What we learned there had the potential of being shared more widely, and indeed, has been or is being transferred into policy and practice in Mexico and in other developing countries.

Perhaps as important, the Yaqui Project helped launched a new generation of researchers who understand what it means to be multi- or interdisciplinary in their perspectives or approaches, and who are committed to research for the welfare of people and the environment and resources on which they depend. This younger generation included both disciplinary scientists (e.g., biogeochemists, economists) as well as interdisciplinary scientists (e.g., those combining remote sensing and GIS-based analyses of land-use change with policy analysis), but all of them had the opportunity to gain multidisciplinary perspectives and engage with the larger group in asking interdisciplinary questions—questions that could not be asked by any one discipline working alone. Responsibility for the intellectual development and career paths of these young people sometimes weighed heavily on the older members, especially early in the project. Was this a fantastic opportunity or a career risk? Would this take too much time (given that interdisciplinary projects, in our experience, often take more time and effort than disciplinary ones, as do efforts that include linking knowledge with decision making)? Would they get jobs after this? With the passing of time, the proof was in the careers of these young scientists themselves, all of whom have gone on to other positions of their choice—in academia, consulting groups, government, foundations, and other nongovernmental organizations. For many of our students, the interactions and participation in the multidisciplinary team left a lasting mark that will influence their research and training in years to come.

Reflections on Impacts in Academic and Research Institutions

The Yaqui Project represented, for many of us, a first-time experience of working with researchers in disciplines or academic fields far from our own. Many of us had experience working in multidisciplinary teams, but those were by and large *near-field* multidisciplinary interactions; in the Yaqui Project, we were forced to deal with ideas, methods, and approaches very different than those we grew up with in science. We discovered the fun and exhilaration of working in this way, and also the frustrations and extra time taken in doing so. As noted earlier, some of us also experienced for the first time the challenges of linking what we were learning with decision making. As it turned out, the experimenting that we were doing as we progressed in our research programs yielded good things, not only in terms of contributions to science and to the Yaqui Valley and to other decision makers, but also to the development of interdisciplinary sustainability research at our home institutions. Moreover, the experience and learning within the Yaqui Project and through interactions across our many other research connections helped us articulate lessons that are relevant to research institutions more broadly.

Impacts in Our Home Institutions

At Stanford, our team's original home base was in the Institute for International Studies (now the Freeman Spogli Institute for International Studies [FSI]), an interdisciplinary policy institute led by team member Wally Falcon throughout the 1990s. The institute provided seed funding at critical times, and encouraged the merging of science and policy analyses that was the early hallmark of the Yaqui Project. Within several years after the launch of the project, and in part because of our team members' efforts, the interdisciplinary Center for Environmental Science and Policy was created within the institute; by the early 2000s, that center morphed into a much larger endeavor, now called the Woods Institute for the Environment, that brought together researchers from all seven schools of the university, explicitly encouraged a focus on interdisciplinary sustainability research, and explicitly incorporated the goal of linking knowledge to action. Seed funds launched a number of new interdisciplinary projects, and the institute fostered and supported the efforts of research teams to communicate and connect with decision makers. The Yaqui project was an early example of the kinds of research now engaged in widely at Stanford.

Among the most exciting of those projects is the Food Security and Environment (FSE) Program, a joint program of the FSI and Woods Institute. Team member Roz Naylor leads the interdisciplinary effort, engaging a new generation of students and many new faculty in efforts at the interface between food, hunger, and environment. FSE focuses on research in China, Indonesia, India, Brazil, Chile, and several countries in Sub-Saharan Africa—all of which play significant roles in the world food economy and are challenged by food security and environmental issues related to agriculture. The Yaqui Valley project illustrates the type of research conducted by FSE, with a focus on crops, livestock, aquaculture, biofuels, climate, water, and policy. Several of the researchers engaged in the Yaqui Project now work on other projects at FSE in different parts of the world.

The kinds of graduate students we were training, and the interdisciplinary nature of some of their research, also provided an early model for interdisciplinary graduate education at Stanford. While all of our students engaged in multidisciplinary interactions, a few of our graduate students learned and brought together multiple disciplines in their own research—they became true interdisciplinarians. Those who did so did it more or less in spite of their departmental degree programs, sometimes with their advisors running interference for them. The experiences of these students and their advisors contributed to the broader call for an interdisciplinary graduate program that crossed fields and departments. In 2000, our team members and other Stanford faculty developed a proposal for an interdisciplinary graduate program in environment and resources; within the proposal were several worked examples of the kinds of students, education, and research that would be expected within this program—and Yaqui Project students were the models. The Emmett Interdisciplinary Program in Environment and Resources (E-IPER) now is home to PhD students as well as MS students who are jointly obtaining JDs, MBAs, MDs or other graduate degrees. Many of them are carrying out research as part of interdisciplinary teams under the auspices of the Institute for the Environment.

Our experience with research and education for sustainability in the Yaqui Valley also became one proof-of-concept for Stanford's twenty-first-century initiatives to help solve problems and train leaders who are prepared to address the complex problems of the century (http://multi.stanford.edu/). Initiatives on environment and sustainability, human health, K–12 education, arts and creativity, and international democracy and development were all launched in the mid-2000s and are meant to foster the kinds of interdisciplinary interactions that the Yaqui Valley project illustrated. Indeed, the Yaqui Project was discussed and presented to illustrate what we *could* do if we decided to work together to address real-world problems.

Would these research and educational changes have occurred at Stanford without the Yaqui Project's experience? Probably so, but perhaps not so early or easily. The Yaqui Project provided evidence that this kind of research and education could be done well, could engage faculty and students alike, and could contribute both to improved understanding about how the world works and to problem solving.

At CIMMYT, our research brought greater awareness in the institution about the importance of considering and measuring the environmental impact of agronomic practices. In the area of fertilizer management, our evidence that improved management practices could lead to win-wins for farmers and the environment has led to similar efforts in other regions. In other areas of agronomic research at CIMMYT, including research on conservation agriculture, our work encouraged a stronger focus on the potential consequences of technology changes on resources and the environment. Measurement of environmental impacts from agricultural practices and technologies has become a part of CIMMYT's efforts in other areas in and outside Mexico, as has an interest in vulnerability and response to climate change. However, expanding research to include, for example, measurements of environmental impacts like greenhouse gas emissions, poses an important challenge in terms of logistics, equipment, and trained scientific staff in many developing countries, reinforcing the benefits of and need for interdisciplinary collaborations to work toward sustainability goals in other regions of Mexico and the world.

Lessons for Mobilizing Science and Technology for Sustainability

These reflections, and our experience with other groups trying to engage their research communities in sustainability science, suggest a number of things that are needed within institutions (especially academic institutions).[4] First, academic institutions need to find ways to facilitate interdisciplinary efforts that draw on the strengths of many different disciplines, allowing researchers to combine and integrate their knowledge around specific sustainability challenges. Working across disciplines takes time, respect, and openness to new ideas and new people; no one discipline can dominate. Working on sustainability challenges takes humbleness and openness to the knowledge and knowhow of people outside academia. Researchers working as part of interdisciplinary approaches to sustainability challenges often characterize this kind of research as the most fun thing they do, but it is often done outside the traditional research expectations of the university. Like Stanford, a number of universities now are engaged in experiments around the theme of encouraging such interactions. Some have identified new schools or colleges within the university with the explicit role of interdisciplinary problem solving. Others have developed umbrella institutions that are meant to harness the dispersed disciplinary and interdisciplinary strengths of the university and facilitate and incentivize research interactions that integrate them. Still others have instituted freestanding centers that operate more or less independently from the academic portions of the university. Some also provide seed money and incentive grants to entice and assist people as they work together for the first time. And some have employed more than one approach. We should actively learn from these experiments.

Recognition of interdisciplinary work is also key—both to successful scientific careers and to raising awareness of academic roles in the field. Having *Science*, *Nature*, or *Proceedings of the National Academy of Sciences* publish the science outcomes of this kind of effort raises recognition of both the field and the researchers (Clark 2007). Within universities and professional organizations, high-level attention to, and recognition of, researchers and their work (by university leaders, university press and outreach venues, and through professional awards, for example) are also very helpful.

Universities are also starting up programs for training students who understand and work within the broad context of sustainability, who sometimes carry the strengths of more than one discipline, and who can combine multiple disciplines, either themselves or through team efforts, to address questions that most of us more traditionally trained disciplinarians are challenged to do. Demand for such interdisciplinary programs is rapidly growing.

Much of sustainability science is fundamental research, but it is also use inspired and oriented toward decision making. Just as in the agricultural and medical fields, science-public interactions, outreach, and knowledge sharing are crucial aspects of sustainability science, yet most universities do not have well-honed mechanisms for the kind of dialogue, multidirectional information flow, and partnerships that are needed for sustainability science to be actually useful and used in decision making. Again, experiments are taking place with new kinds of research partnerships between academic, NGO, corporate, governmental, or community groups; dialogues and workshops with multiple stakeholders; communication strategies, and the development of in-house or external boundary organizations that purposefully link researchers and decision makers. Such efforts are exceptionally challenging, especially to universities, because they represent costs for which there are very few traditional sources of funds. Ultimately, the development of regional or local entities—sustainability resource and research centers—may help to provide integration and connection among research communities and local actors.

Finally, a sustainability transition will require changes in state, federal, and international research and development efforts, with more focused and coordinated approaches to fund both parts of the knowledge-to-action effort—both fundamental research and links to decision making. Institutional change is hard, but it is needed today at all levels if we are to successfully engage the science and technology community in a transition to sustainability.

Concluding Thoughts

The Yaqui Valley intensive agricultural region was born in the green revolution but is now evolving, ever so slowly, toward sustainable resource use and the *doubly green revolution*. Our study has been useful in terms of understanding the dynamics of human-environment systems in this place and time, and also in helping the region transition to sustainability. For all of us, the Yaqui Valley provided a real-life laboratory that allowed us to make serious contributions to scientific knowledge—and to problem solving. While this particular team effort is over, the research continues, and for the researchers who remain or will join in, there are many exciting challenges ahead.

Quite obviously, there's no one magic solution, no all-encompassing, win-win opportunity in agriculture, nor are there in water, energy, health, or other areas of sustainable development. But we can engage researchers and decision makers together in developing the knowledge, tools, and approaches that will allow agriculture and our other life-supporting endeavors to become more sustainable, and we can encourage governing institutions to support such changes. Large changes are needed, but small steps can make a difference in fostering a transition to sustainability, especially if they help shift the conversation and agenda toward the goals of sustainability.