People, Land Use, and Environment in the Yaqui Valley, Sonora, Mexico

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This paper describes on-going research that integrates social and natural science approaches to the study of interactions between development and environment in the Yaqui Valley region of southern Sonora, Mexico. While the focus of this project has evolved over the past 10 years, much of our research addresses three broad questions: 1) what drives land-use and land-management decisions? 2) what are the implications of these decisions for the people and ecosystems in the region, and for the regional and global environment? and 3) what alternatives are available to the people of the region in order to harmonize development and environment? Our analysis draws from various disciplines including, agronomy, biogeochemistry, ecology, economics, geography, hydrology, international policy analysis, remote sensing science, and water resources engineering to address these questions at multiple points across the landscape.

In this paper, we first present an introduction to the Yaqui Valley study region. We then outline several of the conceptual themes or frameworks that we have used to organize our study of the Yaqui system, all of which focus on the interaction of social and biophysical factors in the human-environment system. We briefly describe three broad studies – on agriculture-environment interactions; land use dynamics at the regional scale; and vulnerability – discussing the motivation for and results of the work as well as the multiple data sources and analytical techniques used in each. We include at the end of this section a brief discussion of the potential insights that could be gained when we include a more specific and focused analysis of human population dynamics. Finally, we discuss the lessons that we have learned about integrative studies of the human-environment systems.

The Yaqui Valley Case Study

The Yaqui Valley is located on the northwest coast of mainland Mexico in the state of Sonora (Figure 1). Situated on a coastal strip along the Gulf of California, the Valley consists of an intensively managed agricultural region amidst a desert scrub forest and is bordered by estuarine ecosystems that provide critical habitat for migratory and resident water birds, marine mammals, fish and shellfish populations (Flores-Verdugo et al. 1992). These coastal waters have long been an important center for both subsistence and the export fishing industry.

The Yaqui Valley region is of vital economic importance to Mexico both in terms of its agricultural production and fish production. Today the Yaqui Valley consists of 225,000 ha of irrigated wheat-based agriculture, and is one of the country's most productive breadbaskets (Naylor et al. 2001). Using a combination of irrigation, high fertilizer rates and modern cultivars (Matson et al. 1998), Valley farmers produce some of the highest wheat yields in the world (FAO 1997). The region also maintains the most productive fisheries in Mexico with sardines and shrimp being among the most important species (CONAPESCA 2002). In recent years the region has also developed the second largest shrimp aquaculture industries in Mexico (CONAPESCA 2002). However, in a world of globalized markets, reduced subsidies and price supports, drought, hurricanes and other forces, many farmers and fishers in the region are concerned about maintaining production and household incomes.

Like many developing regions, the Yaqui Valley is undergoing rapid socioeconomic and ecological changes. Population growth, urbanization, agricultural intensification, expanded livestock operations, and coastal aquaculture development are just some of the major developments in the area.

People and Land: A Brief History

In the early 1900s the land in the Yaqui Valley was primarily under the control of large landholders (Lewis 2002). However, the land tenure in the region began to change in the aftermath of the 1910 Mexican Revolution when Article 27 of the Mexican Constitution established the *ejido* land reform program and declared all land ultimately the property of the nation. While private property was allowed in principle under the new *ejido* system, Article 27 established a legal limit on private land holdings of 100 irrigated hectares or the "non-irrigated equivalent."[1] Furthermore, Article 27 mandated that the state reserved the right to expropriate private land holdings when they exceeded the legal limit and to reclaim *ejido* lands when they were improperly managed.

The first major land distribution in southern Sonora was in the 1930s under President Lazaro Cardenas. The Cardenas administration expropriated nearly 120,000 ha and distributed it to over 5,000 *ejidatario*s (collectives of peasants) (Hernandez et al. 1981). The vast majority of the re-distributed land was managed collectively for grazing and rain-fed agriculture (Dabdoub 1980). However, by the mid-1900s, land use and management began to rapidly change.

The Agriculture System. In the mid-twentieth century, the Mexican government and the international development community identified the Yaqui Valley as an appropriate center for agricultural development. In 1943, Normal Borlag, working for the Mexican government and the Rockefeller Foundation, launched a wheat research program that was the forerunner of the International Maize and Wheat Improvement Center (CIMMYT) that remains in the region today (Naylor et al. 2001). Later, a national agricultural experiment center (CIANO) was also established in the Valley. Because the region is agro-climatically representative of 40% of the developing world wheat growing areas, it was selected as an ideal place for the early wheat improvement program.

The climate of the region is semi-arid, with variable precipitation rates averaging 317mm yr-1, which made the development of irrigation reservoirs essential for agricultural intensification. By 1963, three dams had been constructed supplying irrigation water to 233,000 ha (Naylor et al. 2001). However, the construction of these reservoirs did not eliminate the region's sensitivity to climatic extremes. Prolonged droughts, such as the one that has persisted in the region since 1994, have lead to dramatic declines in total reservoir volume, increases in well pumping, and reduced water allocations to farmers resulting in less

[1] Article 27 defines "non-irrigated equivalent" as follows: One hectare of irrigated land is assumed equal to

than 50,000 ha in production in 2003. Meanwhile, recent studies have pointed to the concerns that increasing temperatures resulting from global warming may lead to decreased wheat yields (e.g. Lobell et al. 2002).

The use of fertilizer N has increased markedly in the past three decades; between 1968 and 1995 fertilizer application rates for wheat production increased from 80 to 250 kg N ha^{-1}. Today the most common agronomic practice for wheat production in the Valley is a pre-planting broadcast application of urea or injection of anhydrous ammonium (at the rate of 150-200 kg N ha^{-1}), followed by irrigation (the pre-planting irrigation is intended to aid in weed control by causing germination of weeds that can then be plowed under prior to planting). As we discuss later, the causes and consequences of these management approaches have been one focus of our studies in the region.

As agricultural development and intensification have proceeded, concerns about the quality of agricultural soils have increased. Approximately one third of the soils of the Valley are thought to be vulnerable to salinization. Today, approximately 19,000 ha have salinity levels high enough to reduce productivity. Management approaches that reduce groundwater tables and improve drainage, along with the use of large amounts of relatively low-salt freshwater in irrigation, prevent much broader salinization problems. However, as the availability of high quality fresh water from the reservoirs has declined drastically due to long-term drought, dependence on ground water from wells has increased. In areas where high salinity well water is present, vulnerability to salinization will increase.

Although agricultural management practices have changed during the past three decades, wheat has remained the dominant crop. Harvested winter wheat averaged 130,000 ha in the late 1970s, ranging up to 190,000 ha currently. Other crops, however, have increased or decreased in area planted over the same time frame. Planted hectares of cotton have declined since the 1950s, while alfalfa, garbanzo beans, vegetables and fruit crops have increased (Naylor et al. 2001). The proportion of vegetables planted has increased 8-fold since the early 1980s, while the proportion of fruit trees has quadrupled in the past 10 years.

This growth in agriculture was accompanied by an increase in population in the region, at an annual rate of seven percent between 1950 and 1960. Most of the growth in population in the region in recent years has occurred in the two major population centers, Ciudad Obregon

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two hectares of rain-fed agricultural land, four hectares of pasture land and eight hectares of grazing land.

(pop: ca 250,000) and Navajoa (pop: ca 100,000). While high growth in these urban centers continues, over the last two decades the populations in the rural areas have remained remarkably stable (Figure 2). We currently have very little information on the source of the increase, whether it is from immigration or internal growth. Nor can we say with complete certainty that the increase is a result of the government's purposeful development of agriculture in the region (to be discussed later). It seems likely, however, that the development of the irrigation district, which provides water to both agricultural and non-agricultural (urban) users, and influx of technological assistance in the form of national and international agricultural experiment stations allowed the support of many more people than the arid region was earlier able to support.

Coastal Zone. Between 1940 and 1970s, during the peak of agricultural intensification and expansion, land re-distributions to *ejidos* were minimal, as government support moved away from the *ejido* sector toward the private sector. Finally, in 1976, in response to continued peasant rebellions demanding land, the Luis Echeverria administration re-distributed almost 100,000 ha to local peasants and formed 62 new *ejidos* in the region (Cristiani 1984). Only about one third of these lands were irrigated and most of the other two-thirds were made up of near coastal lands that were seen to have little or no productive use at the time (Dabdoub 1980). However, by the early to mid-1990s with the rise of shrimp farming in the region, these coastal lands that were once seen as wastelands began to be perceived as potential goldmines.

Shrimp farming (part of the Blue Revolution), similar to the Green Revolution, was first introduced to the region as a government supported program. In the late-1980s, the Administration of president Carlos Salinas distributed over 5,000 ha of non-arable coastal lands in southern Sonora to approximately 2,000 new *ejidatarios* as part of a state program that provided technical and financial assistance to the *ejido* sector for shrimp farm development. Despite these initial efforts, the industry did not begin to grow rapidly until almost a decade later when a series of policy reforms opened the region to private investors (Luers 2003).

Recent Policy Changes. During the 1990s the use and management of lands in both the upland and coastal region began to rapidly change as did the individuals who operated the lands (as noted below, one important result has been the transfer of lands from the *ejido* to private sector). These changes were driven in large part by a series of legal, economic, and institutional reforms promulgated in the 1980s and 1990s by the Mexican government to integrate rural Mexico into the global economy. The most important of these policy reforms included: 1) the development of a 15 year program of direct income payments to farmers (PROCAMPO), linked to the abolition of input subsidies and price supports; 2) the reduction in the government's institutional involvement in agriculture, including privatizing the Mexican Fertilizer Company (FERTIMEX) and the reduction in government credit subsidies (BANRURAL); 3) the decentralization of operating authority and funding responsibilities for irrigation systems to local water user groups via the Water Laws of 1992 and 1994; 4) the amendment of Article 27 of the Constitution of Mexico, which made possible the legal sale, rental and mortgage of previously inalienable *ejido* land (the amendment created a process which provided *ejidos* for the first time transferable titles to their land); 5) the adoption of the North American Free Trade Agreement (NAFTA), which led to large changes in prices of many agricultural inputs and outputs; 6) modifications to the Fisheries Law which legalized the direct private investment in the shrimp industry and removed longstanding rules that restricted the capture and cultivation of shrimp to the *ejido* and cooperative sectors; and 7) modifications to the Foreign Investment Laws which allowed up to 100% of foreign ownership of industries in Mexico. Many of these political-economic liberalization policies parallel those in Vietnam and China with similar impacts on land use (Seto 2004).

Prior to these changes, the government was the primary investor in the nascent shrimp farming industry. In addition, government involvement in the Mexican agricultural sector provided price supports for agricultural products, and input subsidies on water, credit, and fertilizer that by 1990 represented about 13% of the Mexican Federal budget (Naylor et al. 2001). The planned reforms replaced these policies, and in effect shifted responsibility for agriculture and aquaculture from government to the private and *ejido* sectors leading to many changes regarding how and by whom land and water resources are being used. Prior to the reforms, in the Yaqui Valley region, 56% of the total agricultural area and 72% of producers were *ejidatarios* (Puente-Gonzalez 1999, CNA 1998), while 40% of the total aquaculture area was controlled by *ejidos* (Luers 2003); however, changes in the *ejido* land-reform program has lead to the transfer of both ownership and management of lands throughout the region from *ejido* back to the private sector (Lewis 2002, Luers 2003).

A focus of our research has been to understand how these and other policy reforms coupled with biophysical variability and change have influenced land-use decisions, environmental conditions, and the sustainability and vulnerability of people and ecosystems in the region.

Conceptual Themes and Research Frameworks

Our research on the drivers and consequences of changes in land use and resource use has followed several related themes. In a sense, these themes track the evolutionary thinking and perspectives that our team experienced during the ten years of research in the Valley. Indeed, the conceptual framework that we are applying now in most of our studies (described in the upcoming vulnerability section) is a product of our prior experience in the Valley, as well as the experiences of our collaborators in other places. All of these themes deal with sustainability issues in one form or another; all of them address interactions within human-environment systems, although population dynamics have been very inadequately evaluated. In the following sections, we discuss research questions and results; research participants; approaches, methods and data sources; and plans for continued research on 1) integrating ecological and economic perspectives in agriculture; 2) land-use change and interactions on the landscape; and 3) vulnerability and resilience. While work is on-going in all three areas, we present them in the chronological order in which they were initiated. We conclude this section with a short discussion of critical aspects of these themes related to population dynamics, some of which we are currently exploring in our research.

Linking Ecological and Economic Perspectives in Intensive Agriculture

Beginning in 1993, we evaluated questions about nitrogen (N) fertilizer use and efficiency in the Yaqui Valley, asking how farmers managed fertilizer and why, what the consequences of their fertilizer practices were for crop yields and also for environmentally-important losses of nitrate and trace gases, and what alternatives were available to them to reduce fertilizer losses to the environment. Our research was driven by broader issues related to agriculture and global environmental change, but also by concerns about plant nutrient use efficiency and farmer economic well-being. Three Principal Investigators (PIs) – an economist, an agronomist, and a biogeochemist/ecologist – initiated the project.

Worldwide, inputs of N in agriculture have been increasing rapidly and represent an enormous change in the global nitrogen cycle (Vitousek and Matson 1993, Vitousek et al. 1997). Production of fertilizer N and the planting of legume crops together fix more N annually than is fixed by biological nitrogen fixation in all natural terrestrial ecosystems. These enhanced inputs of N are critical to crop yield, but they also affect losses of N from soils to freshwater and marine systems and greenhouse gases and air pollutants to the atmosphere. When we began our study, the consequences of fertilizer management for emission of trace gases and nitrate losses in developing world agricultural systems had not yet been evaluated and was one of several outstanding questions related to global atmospheric change as defined by the international global change research community (the International Geosphere-Biosphere Program (Matson and Ojima 1990). Had only a biogeochemist been involved in this work, the analysis might have stopped there. However, we also were motivated by the growing dialogue focused on reconciling the needs for food with the needs of the environment (Naylor and Matson 1993, Conway 1997), and importantly, we were concerned about the welfare of the farmers and their crops in the Yaqui Valley. Ultimately, we wanted to understand how and why farmers made their fertilizer management decisions, and to evaluate management alternatives in terms of their ability to reduce N losses and yet to be agronomically feasible and economically attractive, and the combination of researchers allowed this integrated concern to be addressed.

Using daily to weekly sampling frequencies during the six month wheat season in two consecutive years, we measured changes in soil nutrients, soil gas fluxes, and nitrate leaching prior to and following fertilizer additions in farmers' fields and also in experimental plots (in a randomized block design with four block replicates), where fertilizer additions simulated farmer practice in comparison to alternatives. This biogeochemical research involved the use of gas chromatography, chemoluminescence detection, lysimetry, isotopic labeling and many other lab and field analytical approaches, and ultimately resulted in the analysis of more than ten thousand gas and soil samples. In sites using the farmer practice, gas fluxes were among the highest ever reported (Matson et al. 1998). We concluded that, if fluxes of N_2O and NO in other developing-world intensive agricultural systems are similarly high, agriculture is likely to be a more important source of atmosphere change than currently thought, and it will become even more critical in the future. We evaluated several alternative management practices that added less N fertilizer and/or added it later in the crop cycle, in closer synchrony with plant uptake. While all of our alternatives resulted in some reduction in losses, the "best" alternative, which applied 20% less N per ha and applied during and after planting, lost less trace N gas over the entire cycle than the simulated farmer's treatment lost in just the first month.

Fertilizer use and loss are but one component of farm budgets, and farmers typically focus not just on costs, but also on the balance between costs and expected income under some degree of price and production uncertainty. For wheat farmers in the Yaqui Valley, yield of good quality wheat provides the essential income. In our integrated analysis, we measured yields and grain quality in the experimental plots and farmers' fields using standard agronomic measurement approaches, and found that the more nitrogen-conserving alternatives were not significantly different from the farmer practice.

We carried out an economic analysis of farmers' costs and returns for both 1994/95 and 1995/96 wheat seasons, using farm-based socioeconomic survey techniques. The surveys were conducted in person by our team members as well as by Mexican collaborators who had long histories of research with farmers in the Valley. Our surveys consisted of a random sample of 58 farmers in 1994/1995 and 31 farmers in 1995/1996, stratified by farm operating size and land tenure (private versus collective landholders). Farm owners or managers relied on recorded input, yield, and price data to answer questions. The survey results indicated that fertilization was the highest direct production cost in the Yaqui Valley farm budgets and the single most important cost component in the entire budget. Given the importance of fertilizer in the Valley farm budgets, we evaluated the extent to which savings in terms of increased fertilizer efficiency represented a significant budgetary savings to the farmers. In contrasting the farmer practice with our "best" alternative in terms of reduced trace gas losses and total N losses, we found that the alternative resulted in a savings equivalent to 12-17% savings of after-tax profits from wheat farming in the Valley.

We are currently working on social and private profitability in the Valley, especially critical in the current policy and global market environment, and conducting similar farm-based surveys. This earlier work also lead to a series of studies by Ortiz-Monasterio, in his role as an agronomist at the International Maize and Wheat Improvement Center (CIMMYT), located in Ciudad Obregon, on reliable nitrogen diagnostics tests and other metrics that provide information to farmers that they can use to reduce over-fertilization; and studies by David Lobell and Greg Asner (a Stanford Ph.D. student and research scientist at the Carnegie Institution, respectively) on new remote sensing-based techniques to estimate yield and the factors that regulate variation in yields over space and time at the regional scale. One PhD thesis (Avalos 1997) and one undergraduate honors thesis (Harris 1996) at Stanford originated from this area of research.

Land-Use Decisions and the Provision of Ecosystem Services

Our early work on agriculture and environment in the Yaqui region demonstrated to us some of the tight linkages between the agricultural sector and other components of resource use and development in the Valley. For example, it became clear that agricultural land use and management decisions were highly related to the availability of water as well as input subsidies, and that policy changes that affected both needed to be evaluated. Likewise, we realized that fertilizer management decisions were likely to influence the marine systems adjacent to the Valley. Starting in 1996, with an expanded team that included remote sensing scientists, geographers, and hydrologists as well as ecologists, economists and agronomists, we evaluated the causes and consequences of land-use change and land-management decisions across the Valley. Land use issues had become a central focus for many disciplines within the global change and geography research communities, and the mid-1990s was a period of intense analysis on drivers and consequences (for people and environment) of land use change (see Lambin et al. 2003 for a review). In our analysis of land use changes in the Yaqui Valley, we contributed to the body of research attempting to draw general understanding about land use dynamics. In doing so, we also joined the discussion and debate around the topic of agricultural intensification and its role in "sparing land for nature" (Waggoner 1994). We hypothesized that intensification of agriculture over the decades of the Green Revolution in the Yaqui Valley would be related to many off-site consequences, including those related to urbanization, nutrient transfers down-wind and down-stream, and extensive land-use changes in surrounding areas.

Much of this NASA-funded research utilized time-series remote-sensing data to examine land-cover changes inside and outside the intensive irrigation district. We accumulated information on such things as the Valley-wide irrigation systems, land ownership, and population using municipal, state and national data bases, and we utilized a data base of farm-scale and *ejido*-scale socioeconomic survey information from our own work (see earlier section for details on typical survey sampling) and from the long-term CIMMYT surveys to track changes in agricultural yields, varieties, and fertilizer use over the past 40 years.

We found that intensive, irrigated agriculture increased in area by only 6.5% over the last 30 years, but that dramatic increases in wheat yields and fertilizer use, as well as rapid adoption of new varieties of wheat, characterized a rapidly changing agricultural region. During this time period, land owners diversified by changing summer crops and increasing tree crops. In addition, during the decades of the 80s, there was an estimated 15-fold increase in pigs and poultry in the Valley. By 1996 production was approximately 350,000 head and 6 million birds (Naylor et al. 2001).

Some of these changes can be explained by policies put in place by the Mexican national government. In the 1970s and 80s, a set of domestic policies that included price supports, input subsidies and consumer subsidies, adding up to 18% of federal budget, supported intensification and livestock diversification (Naylor et al. 2001). Based on our analysis, approximately 33% of gross farm income came from subsidies in the 1980s and encouraged continued increase in inputs. During the 1990s, these and other subsidies changed with the suite of liberalization policies (see above). In 2000, price supports for wheat were reintroduced due to falling farm incomes and heightened competition from the U.S. where farm supports are much higher. We are still trying to understand the consequences of these earlier and more recent and dramatic policy changes.

Other dramatic changes in cropping systems occurred during this time frame as well, not because of planned policy changes but due to unplanned shocks. Until 1993, the most consistent cropping pattern in the Valley was wheat as the winter crop and soybeans as the summer crop. Between 1993 and 1996, white fly outbreaks decreased soybean area from 69,000 ha in 1991 to 0 ha in 1996. One response of farmers was to increase the area of sorghum and summer maize, both of which receive much more nitrogen fertilizer than the previous soybean crops. As noted later, this unplanned change has consequences for off-site effects.

While the land area under intensive agriculture remained constant over our study period, intensification in the form of increasing fertilizer inputs influenced off-site ecosystems through their effects on nutrient use and loss. We estimated nitrogen loss from current fertilization practices in comparison with earlier practices (using our NLoSS simulation model developed by Bill Riley as part of our earlier project – Riley et al. 2000), and found that the typical farmer practice results in very large losses of N relative to losses of just 10 years ago. These losses influence the functioning of both the surface water systems draining the Valley as well as the coastal ecosystems of the Sea of Cortez. Two Ph.D. dissertations in terrestrial (Harrison 2002, Harrison et al. in press) and marine biogeochemistry (Beman et al. submitted) and one undergraduate honors thesis (Rice 1995) have focused on the processing of agricultural and urban effluents in the surface waters and coastal marine system adjacent to the Valley. In addition, Esther Cruz from the Center for Conservation and Use of Natural Resources (CECARENA) in Guaymas, Mexico and several Stanford professors in engineering and earth sciences, have begun a focused study of estuarine and open ocean circulation, ultimately to be tied to ocean biogeochemical processes that link to activities on land.

Water resource issues related to the intensive and non-efficient use of water in irrigation also characterized the period of study. Although we have not examined the off-site consequences of water diversions from the Yaqui and other rivers, we recently have examined the components of decision making in the irrigation district that have lead to severe over-draw of reservoir water during the recent five years of drought. An additional Ph.D. dissertation in water resource engineering and policy modeling (Addams 2004), plus considerable research by collaborator Jose Luis Minjares in the CNA (Mexican National Water Commission) have detailed the structure, function and constraints in the water sector, and have led to policy changes in the way water allocation decisions are made.

In addition to the off-site biogeochemical and hydrologic consequences, we evaluated the extent to which land-use changes in the surrounding natural coastal lands accompanied and could be related to intensification in the irrigation district. Our assessment of coastal land-use dynamics was based on the analysis of satellite time series data, and formal interviews with *ejido* households and shrimp farm managers. Using a combination of supervised and unsupervised maximum likelihood classification, we produced thematic land-use and land-cover maps of subscenes from two mosaicked Landsat images from 1973 (MSS), 1992 (MSS), and 2001 (ETM), for change detection and modeling. In addition, we conducted 131 formal household interviews with 41 different coastal *ejidos* (controlling approximately 70% of coastal *ejido* land) and 88 formal interviews with private and *ejido* shrimp farms. We set out to conduct interviews in all the coastal *ejidos* and operating shrimp farms within our study region. However, we had to reduce the sample size slightly due to difficulties with locating households of members for several *ejidos* and making successful contacts with a few *ejido* farms. We conducted 2-5 household interviews in each *ejido* we included. One interview was with a member of the *ejido* governing committee and the others were randomly selected. Our results indicated a very rapid and relatively recent expansion of land-use changes in the coastal zone, with coastal wetlands and mudflats being converted to aquaculture ponds at an increasing rate (Luers 2003 Ph.D. dissertation). Our analyses suggest that this expansion has been facilitated by reforms in the Fisheries and Foreign Investment Laws, changes in the rural credit system, and the constitutional reform of land tenure laws (Article 27), which allows *ejidos* for the first time to rent and sell their land (a significant share of which is coastal land) (Naylor et al. 2001, Lewis, 2002, Luers 2003). These policy reforms and their impacts on coastal aquaculture development mirror similar processes and land-use changes in the Red River Delta in Vietnam, discussed in this volume (Seto 2004). surveys further suggest that a large part of the private shrimp farm development has been carried out by private agricultural farmers from the irrigation district who have had the capital or access to credit to allow them to diversify their production activities. Thus, agricultural intensification in the irrigation district and the expansion of aquaculture appear to be directly linked. Our findings highlight the importance of looking beyond simplistic single-cause explanations of land use/cover dynamics and towards explanations that incorporate both endogenous and exogenous factors that lead to different opportunities and constraints on land-use/cover changes (Lambin et al. 2003).

Taken together, our analyses suggest managed and natural ecosystems in the Yaqui region are linked biogeochemically, hydrologically, ecologically, and economically (Matson al in preparation). Decisions made in the intensive agricultural area affect off-site areas in a number of ways, many of which may negatively affect natural ecosystems and the services (clean water, healthy fisheries, conservation of species) that they provide.

Vulnerability and Resilience

As we studied a place undergoing rapid change through changes in national and international policies, globalization of markets, and variations in climate (drought), we identified dramatic differences in the way individuals could respond. This concern about vulnerability and response has likewise become a focal point in the international realm. As policy-makers shift their attention from broad assessments of potential global change impacts to specific preventative and mitigative action, the global change research community is increasingly focusing on questions about the vulnerability and resilience of people and ecosystems to environmental change (Liverman, 1994, Dow 1992, Cutter 1996, Kelly and Adger 2000, Bohle 2001). This focus on vulnerability is particularly evident in the climate change assessments. The latest publications of the Intergovernmental Panel on Climate Change (IPCC) are dedicated to questions of vulnerability, which they define as "the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes."

Much of the vulnerability literature focuses on either the biophysical hazards or social aspects of vulnerability separately. However, in recent years there have been efforts to integrate these approaches (Folke et al. 2002, Downing et al. 2000, Turner et al. 2003a). Members of the Yaqui Valley research team, working in collaboration with scientists from Clark University, Harvard University, and Stockholm Environmental Institute (SEI), developed a conceptual framework for integrating social and biophysical processes to address questions of vulnerability (Turner et al. 2003 a,b). We extended this work to explore quantitative approaches of analyzing vulnerability in the Yaqui Valley region of Mexico (Luers et al. 2003).

In our multi-dimensional framework, vulnerability, defined as a function of exposure, sensitivity and adaptive capacity, is manifested within the interactions of social and ecological systems (Figure 3). In our analysis of the agricultural region of the Yaqui Valley, we used this framework to identify the critical interactions and feedbacks that mediate the responses of both social and biophysical parts of the system to external and internal stresses and shocks.

In the Valley, the changes in the suite of national policies in the 1990s related to farm and fishing commodities (see above) are external forces that have removed significant financial support and exposed land owners and managers to the vagaries of the international market. Biological shocks such as whitefly invasion continue to force farmers to respond through changes in management and in production patterns. Climate shocks and the on-going drought are forcing farmers to consider alternate crops and changes in irrigation management, at the same time that policy changes with respect to water resource allocation are potentially opening new opportunities for efficient use of water. And on top of these changes themselves, the uncertainties associated with some of them (e.g., drought, commodity prices, exchange rates) have made planning and decision making very difficult (Naylor et al. 2001). The ability of farmers to respond to these and other stresses is likely to depend on both their social and biophysical resources, and how those resources are changing in response to the stresses. If so, vulnerability of farmers in the Valley may be very heterogeneous, potentially leading to winners and losers. We have begun to explore these issues using various analytical techniques.

One approach we have taken is to estimate vulnerability of selected outcome variables of concern (e.g. agricultural yield) to identified stresses (e.g. climate change) as a function of the state of the variables of concern relative to a threshold of damage, the sensitivity of the variables to the stresses, and the magnitude and frequency of the stressors to which the system is exposed. Our proposed metric of vulnerability is distinct from many previous efforts to quantify vulnerability that have focused more generally on identifying sets of proxy vulnerability indicators for a place or population of interest (Downing et al. 2000).

We used this metric of vulnerability to begin to evaluate the relative vulnerability of wheat yields to temperature variability and change, and market fluctuations. The data on wheat yields for this analysis were based on yield estimates derived from Landsat TM and ETM+ data for four years, 1994, 2000, 2001, and 2002, as described in detail by Lobell et al. (2003). Building on Lobell et al.'s analysis, we developed a linear least-squares regression model of yield with average night-time temperature for January-April (Luers et al. 2003) to define the sensitivity. We then calculated the vulnerability using a threshold value of four tons/ha, which is the approximate average minimum yield required for farmers to "break-even" (i.e. zero net profit) based on the average management practices.

Our analysis suggests a skewed distribution of vulnerability to temperature variability and change within the study region, with most farmers exhibiting low vulnerabilities and a few farmers with high vulnerability. In addition, our method revealed that Valley farmers, without adaptations, are on average more vulnerable to a 10% decrease in wheat prices than a 1 degree (C) increase in average minimum temperature. Finally, we found that soils and management both contributed to relative vulnerabilities in the region, however, it appears that the some constraints imposed by poor soil types can be overcome by improved management practices.

A recent focus of our work in the Valley has been to examine relative vulnerability of farmers and their agricultural ecosystems to long-term drought. As noted earlier, Yaqui Valley agriculture relies on irrigation, with the water largely derived from surface reservoirs draining the Yaqui watershed, and with an additional small contribution pumped from private and public wells in the Valley. Now in its 9th year of drought, reservoir levels are at less than a third their long-term values and water allocations have been reduced throughout the Valley resulting in less than 20 percent of the Valley's agricultural area in production. Our research team is exploring the social and biophysical factors that created the current crisis and the alternatives and constraints that the Valley farmers face today.

Switching crops from wheat to less water intensive crops like garbanzo and safflower is one alternative being considered (Naylor et al. 2001), although such changes are highly influenced by global markets and the skewed subsidy/price support environment that the farmers find themselves in, with wheat being more strongly supported than other crops. In addition, crop choice is influenced by the emergence of new diseases in the alternatives. An additional option that farmers are considering is increasing the pumping of water from aquifers. However, aquifer water is often too saline to apply directly to fields. Most wells pump water directly to canals such that mixing with the less-saline surface water reduces the salinity to acceptable levels. In the most recent 2003-2004 crop cycle, most farmers did not have access to reservoir water and the very limited planted area received water directly from the wells to fields. If water from the reservoir continues to be limited, this practice will create salinity problems for at least some of the Valley's soils. On the other hand, analyses by team members suggest that the energy-related costs of pumping are themselves prohibitive, and thus ground water, whatever its salinity, is not a profitable approach at this time (Addams 2004).

Our analysis of the region's vulnerability to drought draws on a combination of hydrologic modeling, remote sensing analysis and household surveys. Lee Addams and Jose Luis Minjares from our team have developed a model of the water basin and water distribution system that we are using to assess alternative management plans. Meanwhile, David Lobell and Greg Asner are using Landsat TM and MODIS satellite images to assess the effect of water stress on yield for different crops under different management regimes. Farmers' responses to the drought and reservoir draw-down are also being analyzed in a masters thesis (McCulloch, in prep). These studies are being coordinated with household interviews that focus on management practices, risk perception, and responses to the drought crisis. Of particular interest is how the prolonged drought will influence the re-location of people and resources in the region.

Population Dynamics in the Yaqui Valley: Critical Missing Pieces in the Analyses

As our work evolved over the past decade, 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 use in this region. We began to incorporate population data through two sources: census data and household surveys. Although the census data provide general information such as age structure, gender, and household size, it lacks detailed household-level information about income, migration, and health of the population. What we do know from the census data is that urban populations are increasing and rural populations are remaining relatively stable at the municipality level. For example, the population of the municipality of Cajeme has increased by nearly seven-fold since 1950. Most of this increase has occurred in the city of Obregon, where the official population has increased from 31,000 in 1950 to 251,000 in 2000.

One of the current research activities is to examine demographic dynamics at the locality level by combining data from demographic surveys and census into a spatial context using a GIS. Our preliminary results indicate that there are huge variations in population structure and growth rates over space and time. Of the thirty-one localities in Cajeme for which we have a comprehensive dataset spanning 1950 to 2000, twelve have experienced a decline in population since 1950. In the most extreme case, the locality of Daniel Leyva Higuera has seen a decline in population from 299 in 1950 to 6 in 2000. Yet this pattern of population decline is not limited to localities in Cajeme. Other municipalities such as Guaymas, Etchojoa, and Navajoa also have localities with shrinking populations. Thus, throughout the Yaqui, larger towns are growing faster than smaller ones, and in many cases, smaller localities are disappearing. We lack an 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 the surveys were designed to collect information about different sectors of the population (e.g. aquaculture households, farmers), and not of the entire population. As such, we were unable to extrapolate our survey data to characterize household dynamics for the entire region.

A second missing piece of information that is critical to analyses of land use change is spatially disaggregated data on migration. These 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. The result is then attributed to migration or immigration. We hypothesize 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. Whether these workers migrated out of the region or were absorbed by local urban or rural economies is unclear from the available census data. Cuidad Obregon and Navajoa 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 intra-city 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 non-urban 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 non-farm 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?

Information on population and household dynamics are even more important in the study of vulnerability. Our conceptual vulnerability framework 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 (Naylor et al. 2001), but we can only surmise that differential access is influenced by population 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* population? 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. As we discuss later, such information is surprisingly unavailable at desired scales of analysis. Thus, it is apparent that addressing them will require focused on-the-ground research at a level that our team has not yet engaged in.

Lessons Learned: Challenges for Integrating Natural and Social Sciences

Our work in the Yaqui Valley incorporates multiple data sources and types, including social surveys, annual compendium, archival maps, remote sensing imagery, administrative boundaries, and soil, water and plant data collected *in situ* and analyzed at multiple institutions. From our efforts to integrate these data emerged a number of challenges related to the scale, availability, compatibility, and integration of biophysical and social data. Likewise, our research integrates the perspectives and knowledge of many disciplines, and ranges across a knowledge-action continuum. These interactions have resulted in significant complexities in collaboration and funding issues. In the following sections, we will discuss some of those challenges and how we addressed them.

Scale Issues

We encountered two specific scale-related issues related to the unit of analysis and temporal dynamics. One of the objectives of the Yaqui project as it has evolved today is to make the research results available to farmers and policymakers in order to influence and assist in decision making. Toward this end, our analysis must be conducted at a unit that is policy relevant. Where we have integrated remote sensing with household level data, we have defined the 'farm unit' as a Landsat TM pixel. Although the pixel does not correspond with either the operational or the management unit, it is the smallest observational scale, and thus could be aggregated to correspond with the decision-making unit. Alternatively, the analysis could be conducted at the management unit and resampled to be consistent with the scale of the imagery. Which unit of analysis is most appropriate and how should the data be integrated?

In addition, we are studying farm management and land-use change at the sub-state level, when most policy decisions are made at the federal or state level. Do environmental changes at the local level warrant policy action at the federal level? Similarly, are incentive structures set by federal and state policy compatible with the constraints and development goals of the southern Sonoran region? Scale issues in the policy domain pose particularly difficult problems in analyzing sustainability challenges.

A related issue is that of temporal dynamics. In a rapidly changing region like the Yaqui Valley, what is the temporal scale (study period) and temporal resolution (frequency of observation) required to capture land-system dynamics? Data acquired in decadal cycles may not provide a complete picture of the fluctuations and inter-annual variability of the coupled human-environment system.

Availability of Biophysical Data

We have used a suite of field methods to monitor ecosystem dynamics and their responses to multiple external forcings. In part due to the composition of our research team and in part due to our research questions, one of the strengths of this project is the wealth of biophysical data collected over the life of the project. There have been significant challenges and difficulties with collecting biophysical data, including 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. The collaboration with CIMMYT researchers, and the use of the CIMMYT labs in Ciudad Obregon, considerably reduced these difficulties. Such research would not have been possible without a well-established and well-protected laboratory *in situ*, and without the relationships between PI Ortiz-Monasterio and the local farmers that allowed us access to their fields.

Availability of Social Data

Social scientists have a long tradition of studying human behavior with the use of data on the individual or some aggregation thereof (e.g., household, administrative units, firms).

Two methods to obtain these data include conducting a survey designed for the research project or using figures published by the government statistics bureau. We used both approaches in Yaqui and encountered different challenges in each case.

Over the course of our project we carried out three 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) (Naylor et al. 2001, Lewis 2002, Lobell et al. 2004). Using structured and in-depth interviews, we developed a rich data set on farm characteristics, with much less information at the household level. A 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. We greatly benefited from the longer-term set of survey data acquired by economists at CIMMYT, in which they carried out Valley-wide surveys of farmer practice and budgets starting in 1981.

We also used socioeconomic data from INEGI (Instituto Nacional de Estadística Geografía e Informática or the National Institute of Statistics, Geography, and Informatics) 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 10 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.

Compatibility and Integration of Biophysical and Social Data

Our experience in the Yaqui Valley has shown that both social and biophysical data need to be collected via fieldwork, and that only limited information about demographic dynamics can be obtained from sources such as statistical bureaus. Critical social data have been difficult to obtain because we rely on the availability of such data from INEGI. For example, human migration patterns at a fine spatially disaggregated level are wholly absent from their database. In order to collect these data, we will have to embark on extensive household surveys. However, integrating the socioeconomic and biophysical data will be challenging due to inconsistent data and a mismatch of temporal and spatial scales. While conceptually simple, the incompatibility of data makes integration a methodological challenge.

Understanding How the World Works Versus Solution-oriented Research: Project Evolution

The long-term nature of this project allows us to think about project evolution and issues related to knowledge production and use. Our early interactions were among only three investigators -- Matson (ecologist), Naylor (economist), and Ortiz-Monasterio (agronomist) -- and their research groups. Our research was driven by broader issues related to agriculture and environmental change; our funding for the scientific work was from the USDA, and for the economic analysis from the Ford Foundation and the Pew Charitable Trusts. The process of bringing our perspectives together in our research design was enlightening – and it is fair to say that the kinds of questions that we ultimately asked together, and the kinds of measurements that we made, were different than any one of us would have made alone. In this first study, we did not involve stakeholders, although Ortiz-Monasterio's close connection with farmers of the Yaqui Valley provided considerable real-life perspective to our work. Ultimately, that project expressed our desire to help farmers as well as the environment, and luckily our results indicated that win-win opportunities were possible with respect to fertilizer use. Even with win-win outcomes, however, adoption of new practices is not necessarily widespread (Manning 2002). This first project, motivated by a simple but none-the-less integrative interest, was to date the most easily funded piece of Yaqui Valley research.

The perspective of concern for people and environment established in this first study laid the groundwork for all research to follow. It was impossible to work in the Yaqui region and ignore the broader set of issues that were influencing farmer decision making – resource availability, information availability, global markets, national and international agricultural policies, etc. Likewise, it was impossible to overlook the strong possibility that decisions made in isolation by farmers were not only influencing farmer well-being, but were in fact influencing people and ecosystems far away, as well as the long-term sustainability of agriculture itself. We began to think of the Yaqui Valley as a microcosm for the developing world, and began to use it as a place to pursue questions about land-use change, and the responses of human-environment systems to interacting local, regional, and global forcings.

Not surprisingly, these new perspectives attracted and demanded new kinds of participants with different expertise. Moreover, the work from the first Yaqui studies provided a base from which graduate students and undergraduate honors students could launch their research; while some of these students remained quite disciplinary in their approach to their research, others completed truly interdisciplinary research and training and have carried that perspective and knowledge base to their subsequent positions. With the support of Stanford University seed money (from the Institute of International Studies Bechtel Initiative funds) and relatively small amounts from the Packard and MacArthur Foundations, our research group rapidly grew to include agricultural policy, international development policy, mathematical modeling (engineering), and remote sensing along with economics, agronomy, and biogeochemistry. With a grant from the NASA Land Use/Land Cover Change program, we focused on the history of land use in the area, and the consequences of land-use decisions for the broader region. As our group and resources grew, we also increased our connections with regional NGOs and other researchers working in the broader Sea of Cortez area. Over time, influenced by PI interactions with the international global change research programs and the nascent international sustainability science community, we began to think about what it would take for this place to move toward sustainable resource use. With a grant from the Packard Foundation providing "matrix money" that allowed the coming together of many more researchers in the region, we expanded our project to include water resources, conservation, and marine researchers from Mexico. Importantly, we began to identify ways in which local stakeholders (including local farmers and the local research community) could be included, and we confirmed our role as one of information providers to the people of the area, as well as international researchers striving to identify generalizations in research tools and approaches that could be useful well-beyond the Yaqui Valley.

The Yaqui Valley case study has been useful in terms of identifying the dynamics of change in human-environment systems, and providing tools and approaches that can help the people of the Yaqui Valley in decision making for human and environmental well-being. We did not intentionally design it to be thus, at least not in its early years. Had we done so, we probably would have included additional members of the research team, and certainly more local stakeholders. On the other hand, thanks to the involvement of PIs who have practical, place-based interests, the research is probably more directly useful than many such studies by academic researchers might be. Our additional intent, however, is to contribute information and knowledge that is useful beyond the Valley, in terms both of understanding global changes and developing sustainability approaches. Our best hopes for more general learning are through a comparative approach with other such case studies, and through the development of tools and metrics, many of which use remote sensing and modeling, that can be applied in many places.

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Figure Legends

Figure 1. Map and location of the Yaqui Valley in the state of Sonora, Mexico.

Figure 2. Population changes in the urban and rural sectors in the Yaqui region.

Figure 3. A framework for evaluating vulnerability to multiple and interacting changes.