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Review

# Science and socio-ecological resilience: examples from the Arizona-Sonora Border

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ABSTRACT

The Greater Sonoran Ecoregion (GSE), spanning the U.S.-Mexico border between Arizona and Sonora, faces myriad biophysical and social challenges to maintaining long-term socio-ecological resilience. Concepts of socio-ecological resilience and transformability provide a foundation for examining interactions between society and nature, and between society and science. An analysis of three case studies reveals that the GSE is becoming ever more vulnerable to systemic changes that will have serious consequences for the environment and society alike. While much more knowledge needs to be developed in both the biophysical and social sciences, there is an equally pressing need to bring social values and practices more closely into alignment with the resources and limitations of the coupled system itself. Improvements in science–society interactions are also needed. Threats to the GSE can only be addressed through long-term programs having the ultimate goal of preserving the system's human and ecological integrity.



## 1. Introduction

Where political boundaries bisect deep social, economic, cultural, and legal differences (Varady and Morehouse, 2003), finding common ground on defining resilience and achieving socio-ecological sustainability constitutes a major challenge. So too does foreseeing the long-term implications of the dramatic social and biophysical changes already underway. These problems are particularly acute in the Greater Sonoran Ecoregion (GSE) (Fig. 1), which spans the U.S.-Mexico border between Arizona and Sonora. One of the most diverse and scenic areas of the border region, the GSE faces multiple pressures emanating from human population growth and patterns of concentration, economic development activities and related infrastructure construction, growing traffic across backcountry lands, expanding demand for water in a water-limited landscape, militarization of the border zone, and stresses arising from contradictory institutions and conflicting value systems.

Intersecting these multiple social pressures are serious stresses posed by global to local scale hydroclimatological variability and change, and related environmental

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**Fig. 1 – The Greater Sonoran ecoregion.**

variability and change (Alley et al., 2003; IPCC, 2001a, 2007a). Climate change, in interaction with changes in patterns of variability occurring within larger-scale global warming, is altering ecosystem dynamics and composition, hydrologic processes, and human systems. These changes are already affecting real people in real places (IPCC, 2001b, 2007b); the number and intensity of impacts are highly likely to increase as warming accelerates and thresholds bounding the current limits of tolerance to variability and change are crossed. These dynamics raise fundamental questions about the current and future prospects for socio-ecological sustainability of the GSE, and the potential for influencing the course of events in the region through science–society collaboration.

In this paper, we partition the GSE into three social–ecological systems (SES's), all located on the U.S.-Mexico border, in order to articulate important contextual factors, the nature and dynamics of change, the institutional influences on those dynamics, and potential policy alternatives for addressing stresses to the system. Our work follows on concepts of social–ecological resilience, vulnerability, and transformation developed by Berkes and Folke (1998), Holling and Gunderson (2002), Berkes et al. (2003), and Chapin et al. (2006). In our analysis, we pose the following research questions: (a) What is the context within which each of these systems operates? (b) What are the nature and dynamics of change in each system? (c) What is the primary institutional driver within each system? (d) What policies hold most promise for current and future management of each SES and of the GSE more broadly? and (e) Is good science sufficient to address the problems that exist in each SES and in the GSE more broadly? We explore these questions by applying our conceptual framework to a structured review and synthesis of research previously published on each of these systems.

Our inquiry focuses specifically on the Colorado River Delta, the Organ Pipe Cactus and Pinacate protected areas, and the Upper San Pedro River. We find that each of these areas is currently experiencing environmental stresses; long-term commitment to improving institutional capacity is required to address current and future challenges to social–ecological resilience. We also find that scientific knowledge is an important element in this effort but by itself is insufficient for ensuring a more sustainable GSE. Also needed are new paradigms for science–society interactions, ones that do not rely on one-way delivery of information from science to society, but rather that encourage mutual sharing of knowledge and experience and work from common goals (Lemos and Morehouse, 2005; Warner and Havens, 1968). We suggest that one way to achieve these ends in the GSE is through creation of a binational center for science–society collaboration (Ferguson et al., 2006).

## 2. The Greater Sonoran ecoregion

For purposes of this analysis, we define the greater Sonoran ecoregion as including the Sonoran Desert terrestrial ecoregion defined by Ricketts et al. (1999), the sky islands (Whittaker and Niering, 1965) located therein, and the San Pedro River basin located on the eastern edge of the region (Fig. 1). The lowlands of the GSE are generally semiarid to arid, but support an unusually high diversity of plant and animal species, many of which are endemic to the area. Rather than the barren desert often conjured by the popular imagination, the GSE is in fact one of the most diverse regions on the planet, with almost all of the world's biomes occurring here (Dimmit, 2000:3; Nabhan, 2000; Whittaker and Niering, 1965).

The GSE has supported human life for millennia (Carpenter and Sanchez, 1997; Fish et al., 1992; Reid and Whittlesey, 1997). Past and contemporary imprints of the area's original inhabitants exist throughout the region in the form of villages, irrigation networks, and artifacts reflecting activities ranging from horticulture to religious rituals. Indigenous peoples who today constitute a significant presence in the GSE include the Cocopah, Cucapá, Yaqui, and Tohono O'odham. Of these groups, the Tohono O'odham have the largest officially designated territory, with land holdings on the Arizona side of the border constituting an area about the size of the U.S. state of Connecticut. The O'odham also occupy remnants of their prior lands on the Mexican side of the international boundary.

Beginning in the late 19th century and continuing today, commercial farming, ranching, mining, tree-cutting for fuel, industrialization and, above all, urban growth have accelerated the rate and intensity of both ecological and societal change in the region. Today large cities in the region include Phoenix and Tucson, Arizona; Hermosillo and Nogales, Sonora; and Mexicali, Baja California Norte. Urban population growth on both sides of the border is driving unprecedented levels of urban, suburban, and exurban development. This in turn is inducing profound changes in the biophysical landscape such as those described in this paper. Studies in the Gulf of California region have highlighted some of the environmental implications arising from economic change and restructuring, as well as the rise in the levels of vulnerability (Wong-González, 2006, 2007).

These changes are occurring in the context of a regional climate regime that has exhibited a long history of high variability across time and space (Sheppard et al., 2002), but that is now on the brink of more profound and long-term alteration (Seager et al., 2007). Recent evidence suggests there is a strong probability that GSE landscapes will change substantially in response to changes in the intensity and periodicity of climatic variability as well as to the intensity and periodicity of extreme events such as droughts, floods, and fires (Seager et al., 2007; Westerling et al., 2006; Diffenbaugh et al., 2005). Already, winter and spring minimum temperatures are rising and freeze events are occurring less frequently (Weiss and Overpeck, 2005), and projections for the area's future climate indicate more changes are in store (Seager et al., 2007). At the same time, invasive species such as buffelgrass, tamarisk, and cowbirds, all introduced as a result of human activity, are challenging the survival of native species throughout the region (Tellman, 2002; Marshall et al., 2000).

Added to the stresses posed by population increases, urban expansion, climate variability, and climate change are pressures arising directly from the movement of goods and people, and indirectly by policies on both sides of the border that are fueling these movements. The international boundary itself serves as a focal area for policies aimed at increasing binational economic activity. From the bracero program (a guest worker program existing from 1942 to 1964 that encouraged temporary migration of Mexican laborers into the U.S. to fill essential but low-level jobs such as harvesting farm crops), to the subsequent Border Industrialization Program and emergence of maquiladora (manufacturing and assembly) operations in Mexico during the 1960s, the United States and Mexico have sought to link the manpower needs of U.S. agriculture and industry with the manpower surplus in Mexico (see, e.g., Kopinak, 2004). Since the middle of the 1980s, policies aimed at opening the Mexican economy have prompted the location of capital-intensive operations with high-technology segments, such as the automotive industry, in Mexico's northern border states (Wong-González, 1992; Sandoval and Wong-González, 2005). The impacts of these programs are evident on the landscape, affecting the structures, flows, and processes of the region's ecosystems. As discussed in more detail below, the border is also being profoundly affected by narcotrafficking activities, as well as by unauthorized migration of Mexicans, Central Americans, and others into the United States.

The U.S.-Mexico boundary itself is among the strongest obstacles to social, political, economic, and ecological sustainability in the GSE. The boundary, for example, bifurcates what are otherwise unitary ecological systems. More broadly, the boundary constitutes a powerful delineation between two national governments and serves as a reminder that decision-making power resides in sovereignty that is reinforced in the two national capitals, both of which are distant from local processes and concerns (Ingram et al., 1994; Ingram et al., 1995). The boundary also demarcates a pronounced transition between an advanced economy and a developing economy attempting to increase its participation in global flows of goods and capital while at the same time maintaining stability in a society sharply split between great wealth and great poverty. In Mexico, resources and capital have shifted northward, making the country's border states among its wealthiest. Partly for this reason, the region also is the heartland of the conservative Partido Acción Nacional (PAN) political party (OCDE, 1998; Wong-González, 2001; EIU, 2006). By contrast, communities on the U.S. side of the border contain some of the nation's poorest and most politically marginalized areas. Importantly, despite such differences, strong transboundary ties exist among local communities and families.

In this arid to semiarid region, local and regional resilience is closely associated with availability of water resources. Three rivers flow across the border within the GSE; from east to west they are the San Pedro, the Santa Cruz, and the Colorado (Fig. 1). The water available in these rivers, however, is insufficient to meet the needs of the region, a deficit that is overcome by exploitation of groundwater, most of which was deposited thousands of years ago and is being replenished very slowly if at all. Low average precipitation and limited availability of water in the region, combined with the dependence of all living organisms on this resource, underpins an ongoing series of binational disputes regarding the quality and quantity of the surface and groundwater resources available in the three watersheds (Browning-Aiken et al., 2004; Varady et al., 2001; Brusca and Bryner, 2004; Getches, 2003; Pitt et al., 2000; Morehouse et al., 2000, 2002; Ingram et al., 1995). Natural landscapes and ecosystems have been profoundly altered by development of these water resources; recurrent drought further strains these systems (Seager et al., 2007).

## 3. Resilience and complexity as conceptual integrators

In this paper we focus on subsystems of the greater Sonoran ecoregion as complex social–ecological systems (SES) (Berkes and Folke, 1998; Berkes et al., 2003). The SES concept places humans within nature and focuses on the way in which interconnections between people and their biophysical contexts produce complex adaptive systems (Davidson-Hunt and Berkes, 2003; Levin, 1999; Holland, 1995, 2006; Berkes et al., 2003; Kay et al., 1999). The GSE constitutes a series of such complex adaptive systems, in each case integrating, across time and space, hydroclimatological, ecological, and social dynamics. Complex adaptive systems, such as those of the GSE, are nonlinear, meaning that a given cause – often resulting from a complex chain of biophysical and human interactions – can produce a disproportionate effect (Holland, 1995, 2006; Levin, 1999; Folke et al., 2005). The nonlinearity of complex system processes makes predicting the outcomes of reorganization difficult from both scientific and decision-making points of view. These systems adapt to change; whether or not the adaptation is amenable to the biota or humans in the region is often a matter of chance (Levin, 1999, p. 12; Chapin et al., 2006).

SES theory suggests that human decisions and behaviors, in interaction with biophysical influences, have the potential to ripple through parts or all of the system and thus generate impacts at different temporal and spatial scales (Folke et al., 2005; Low et al., 2003, p. 96; Kay et al., 1999, p. 723; Levin, 2006, p. 328). In decision processes people tend to discount the future heavily and to invest in actions that have shorter-term impacts (Ostrom, 1990, pp. 34–35); likewise, they tend to focus on the geographical scale that is most pertinent to their shorter-term interests. Nevertheless, human impacts can have very long-term consequences on SES's. Biophysical processes also operate on both short and long time scales. Indeed, under stress, biophysical changes can in fact occur quite rapidly. Contradictions between processes occurring on different human and biophysical time scales can produce serious problems (Folke et al., 2005).

The concept of resilience has emerged over the past decade as a means of framing human–environment relations (see, e.g., the Resilience Alliance website, www.resalliance.org). For our purposes, resilience, defined as ''the magnitude of disturbance that can be absorbed before the system redefines its structure by changing the variables and processes that control behavior'' (Gunderson, 2003, p. 34), offers a foundation for examining socio–ecological dynamics in the GSE. Using this definition, sustainability, defined as addressing the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987), becomes a subset within the larger concept of socio-ecological resilience. We note, however, that sustaining resilience may not always be desirable (as in the case of systems dominated by invasive species) and in fact may be detrimental to healthy SES dynamics (Chapin et al., 2006, p. 16641). Indeed, no single approach can address all socio-ecological problems (e.g., Gregory et al., 2006; Lamont, 2006; Berkes, 2004).

One promising concept for assessing system resilience is system memory, defined as ''the accumulated experience and history of the system ... [that] provides the sources for self organization and resilience'' (Berkes et al., 2003, p. 20). Socio-ecological systems have both ecological and social memory; this embedded information provides important feedbacks that allow recovery after disruption. It is possible that changing climate and/or increasing land use and land cover change will push systems like the GSE into states that are outside existing system memory. However, to the extent that current system memory is understood, it may be mobilized to reduce existing pressures and delay ecological state transition to undesirable conditions.

Theories of adaptive management, the primary principle of which is to manage natural resources in a way that is flexible, experimental, and open to subsequent modification, offer an avenue for introducing resilience into socio-ecological systems. However, adaptive management, while embraced in a variety of SES arenas, has proven to be easier said than done (e.g., Gregory et al., 2006; Lee, 1999; McLain and Lee, 1996).

We frame our analysis based on the paradigm, set out in Chapin et al. (2006), that assesses case studies based on three factors: dominant external driver, likely (or current) system trajectory, and policy alternatives. We apply this frame to each of the SES's in our study (see Table 1). We begin by drawing on the existing literature to depict the current circumstance of each SES and the nature and dynamics of change occurring in that system. Then, drawing on Chapin et al. (2006) and Ostrom

**Table 1 – Primary driver, current trajectory, and policy priority for each of the social-ecological systems considered**

| | Colorado River Delta | Organ Pipe-Pinacate protected areas | Upper San Pedro River Basin |
|---|---|---|---|
| Dominant External Driver | Resource harvesting institutions | Externality-producing institutions | Resource conservation institutions |
| Likely outcome (current trajectory of system) | Passive degradation to less favorable state | Passive degradation to less desirable state | Active transformation to potentially more desirable state |
| Policy priority | Increase resilience of system | Facilitate transformation to potentially more desirable state | Increase resilience of the system and promote long-term adaptive capacity |

(2005), we identify the institutional context, characterizing each area in terms of its dominant institutional structure (resource-harvesting, resource-conserving, or externality-producing). We next assess each SES in terms of its prospects for continued vitality. Reflecting Chapin et al. (2006, p. 16640), we analyze the likely trajectory of each system in terms of (a) its persistence of the fundamental properties of the current system; (b) its active transformation to a potentially desirable state; or (c) its passive degradation to a less favorable state. Finally, in keeping with the four policy strategies outlined in Chapin, we suggest what is likely to be the most effective policy alternative for each SES: (a) fostering human adaptability (ability to respond effectively to variability and change), (b) enhancing socio-ecological resilience (ability to absorb shocks while retaining fundamental features of structure, identity, and feedbacks), (c) reducing vulnerability (likelihood of experiencing harm from exposure to a stressor or hazard), or (d) – where desirable – enhancing transformability (the capacity of a system to reorganize into a new state having different characteristics). Throughout our analysis, we include consideration of system memory, the influence of climate change on socio-ecological processes, and the role of collaborative science.

The first case study, of the Colorado River Delta, represents a system that has experienced reorganization and collapse and where only recently have environmental advocates begun voicing strong concern about socio-ecological resilience. The second case study, of the Organ Pipe Cactus-Pinacate protected areas, represents an area where social processes have recently begun generating profound damage in what was previously a relatively pristine system. The third case study examines the Upper San Pedro River Basin, an SES that remains largely intact but is facing the prospect of changes that could lead to system collapse and reorganization.

## 4. The Colorado River Delta: resource harvest institutions

### 4.1. *Context and conditions*

The Colorado River (Fig. 1) is one of largest and most heavily tapped rivers in the United States. Originating in the mountains of the interior West and flowing south-southwest to the Sea of Cortez, seven states and Mexico have institutionalized rights to Colorado River water. A complex series of laws, treaties, and policies, collectively called the Law of the River, govern use of the river and its water. While ostensibly partitioning water based on availability, these institutions allocate more water than actually flows in the river during most years (Pitt et al., 2000, p. 833).

At the end of the river lies the Colorado River Delta, a historically rich reservoir of biodiversity. The Delta is located entirely within Mexico (Pitt et al., 2000, p. 824) yet has experienced serious impacts from U.S. federal and state policies. For many years after the completion of a series of large dams, little or no water reached the Delta, leading to severe ecological damage. Nowhere in the Law of the River is water specifically allocated for in-stream or other ecological uses (Pitt et al., 2000, p. 834; Glenn et al., 1996, p. 1175; Varady et al., 2001), although the United States and Mexico made a small movement toward rectifying this problem in adopting Minute 306, an addendum to the Law of the River that calls for joint study of the issue (Getches, 2003, p. 187).

### 4.2. *Nature and dynamics of change*

The Delta, once a vast assemblage of diverse wetlands covering several million hectares, has shrunk by approximately 80% over the last century (Valdés-Casillas et al., 1998 cited in Hinojosa-Huerta et al., 2005, p. 637), largely due to construction of a series of large dams on the river. By the late 1960s, measurements of Colorado River flows at the southernmost gauging station were actually discontinued because there was no flow to measure (Brusca and Bryner, 2004, p. 23). The loss of freshwater produced widespread changes in the upper Sea of Cortez and lower reaches of the river, including extensive loss of wetland, increased salinity in the upper Sea of Cortez, and a substantial loss of sediments and nutrients throughout the lower Colorado River and the Delta. These changes cascaded through the system, affecting plant and animal communities, soil and water composition, fisheries, agriculture, and the hydrography of the upper Sea of Cortez (Glenn et al., 2006, 2001; Schöne et al., 2003; Pitt, 2001; LavÍn and Sánchez, 1999).

Historical neglect of the riparian areas along the Lower Colorado River rendered the Delta vulnerable to biophysical shocks such as prolonged drought. The remnants of the historical Delta that still support biodiversity and other ecosystem services are especially vulnerable to both human and biophysical pressures and require proactive management for their survival (Brusca and Bryner, 2004; Getches, 2003; Pitt, 2001). Studies have suggested that a relatively small flow of water, as low as 32,000 acre-ft per year, with periodic flows of around 260,000 acre-ft, would be sufficient for survival of the Delta's ecology (Sprouse, 2005, p. 23; Pitt et al., 2000, p. 831). Yet given the demands of the farmers, fishermen, commercial and industrial enterprises, urban dwellers, and indigenous peoples, obtaining water for ecological uses remains a fraught political issue. Of importance to our analysis, recent changes have led to revival of portions of the historical wetlands and the rise of intense policy debates.

In the 1980s and 1990s, freshwater flowing from agricultural run-off, precipitation generated by a particularly strong El Niño-Southern Oscillation climate cycle (Zamora-Arroyo et al., 2001, p. 50), and related higher-than-average flows in the river itself combined to revitalize parts of the Delta. Today, the upper reaches of the Sea of Cortez include vibrant freshwater riparian areas and wetlands as well as brackish marshes and tidal flats. The riparian corridor south of Morelos Dam, as well as the Cienega de Santa Clara, the Rio Hardy and its associated wetlands, and the Mesa Andrade wetlands have also gained new life. Constituting only a small portion of the historical wetland area, these revitalized areas have subsequently been maintained by human-generated water flows, including agricultural return flows and, during dry years, groundwater (Cortez-Lara and García-Acevedo, 2000; Glenn et al., 1996, 1992; Zamora-Arroyo et al., 2005, p. 27).

The ability of the Colorado River Delta to rebound, given optimal circumstances, highlights an important lesson about large socio-ecological systems: when the human systems and the biophysical systems are ill-coordinated over time and space, the overall system becomes less resilient and therefore less sustainable. In the case of the Colorado River Delta, the overwhelmingly dominant institutional driver over the last century has been the suite of resource harvesting institutions along the course of the river that have allowed rapid human development throughout the West, largely at the expense of the Delta ecosystem. Although the Delta is still not considered to be a completely healthy ecosystem, it nevertheless constitutes the largest wetland system in the southwestern United States (Pitt et al., 2000, p. 821). The wetlands support a relatively high level of resident and migratory bird biodiversity (Hinojosa-Huerta et al., 2005, pp. 638–639; Zamora-Arroyo et al., 2005; Bergman, 2002; Glenn et al., 1996, p. 1182). The marine estuary provides habitat for saltwater animals and is an important livelihood resource for local fishermen. The Upper Sea of Cortez is home to several endangered species (Zamora-Arroyo et al., 2005, p. 13). Desire to preserve delta biodiversity has prompted sustained contests between supporters of the traditional resource-harvesting institutions associated with water allocations under the Law of the River and advocates urging a shift to resource-conserving institutions designed to protect the Delta's wetlands.

The renewal of the Delta wetlands testifies to a living reservoir of ecological system memory that has been sufficiently robust to produce reorganization into an ecological state similar to that which existed before the dams were constructed. This occurred even though there had been no major change in the resource-harvesting institutions that had led to degradation in the first place. The socio-ecological system, however, remains very fragile, and lacks the institutional support required for long-term resilience. Studies based on instrumental and tree-ring records reveal that deeper and more severe droughts than those traditionally assumed by water managers have occurred in the past and confirm that the original estimates of available water had been made based on a period of anomalously high flow (Tipton, 1965; Stockton and Jacoby, 1976, p. 38; Fulp, 2005). Management of the river continues to be predicated to some extent on these erroneous assumptions (Fulp, 2005), though projections of likely climate change impacts, recent serious drought conditions, and other scientific advances (e.g., Cintra-Buenrostro et al., 2005; Dettman et al., 2004) have prompted efforts among managers and scientists to improve climate-based inputs to river management policy.

The greatest and most immediate threat to the Delta today is a plan to desalinate water flowing through the Wellton-Mohawk Canal, and to redirect the treated water into the Colorado River for delivery to Mexico (Dibble, 2007). The project is viewed by water managers as a way to help meet the U.S. treaty obligation to furnish designated amounts of water to Mexico annually. The 100,000 acre-ft of water that flows through the canal each year is the largest source of supply to the Cienega de Santa Clara and is vital to the survival of that wetland. Alternatives exist that would not deprive the cienega of water. For example, desalinated groundwater from the Yuma area could be directed into the city's potable water supply or could be used to augment water supplies in Mexican communities (Dibble, 2007; McKinnon, 2007). Either of these would help meet the obligation to Mexico while preserving flows to the wetland through the Wellton-Mohawk Canal. The apparent lack of long-term political commitment to preserving the ecological integrity of the wetland, however, reveals the staying power of the existing institutional framework. Resolution of the problem, ultimately, requires political and societal will to experiment with alternative adaptation strategies. Absent willingness to change direction and in the face of substantial climate change impacts, it is unlikely that the wetlands will survive over the long term; nor is it likely that ecological memory can be preserved. Due to lack of political will to assure that the Delta continues to receive sufficient water to support its ecosystem, the entire Delta SES is on a trajectory of degradation toward to a less desirable state.

### 4.3. *Potential policy alternatives*

In the past, the Delta has exhibited robustness in the face of dramatic change. Therefore, policies aimed at increasing resilience in the system through fostering reemergence of system memory may help stem current degradation trends (Table 1). Adaptive management and adaptive governance offer a framework for experimenting with alternative management practices and institutional designs that may improve the Delta's socio-ecological resilience. For example, experiments to determine how best to integrate a permanent allocation of water for ecosystem functions into existing laws, plans, and operating procedures could be done. Well-designed policies (Ostrom, 1990; Ostrom et al., 2003) would take into account the latest scientific knowledge about climatic conditions such as extended drought and prolonged wet cycles. Policies could also be designed to balance societal and ecological needs for water. Policies that achieve such balance would need to recognize the value of preserving and expanding long-term socio-ecological memory and be flexible enough to respond to unanticipated surprises and nonlinear dynamics. To assure adequate warning that the system is approaching critical threshold conditions, policy frameworks should also formalize opportunities for collaborations among scientists, stakeholders, managers, and decision makers.

Today, decision makers seldom know whether the conditions they are observing are anomalous in the context of history or are within the bounds of a steady state of long duration (Jacobs and Morehouse, 2005). At the same time, science is providing abundant evidence that existing institutions cannot be sustained much longer. This is especially worrisome given current estimates of climate change impacts in terms of reductions in average river flow. In the context of fundamental climate regime change, the need to reduce water demand and reallocate water based on societally agreed-upon values is clearly becoming ever more imperative. Hoerling (2007, p. 35), for example, warns that "The Southwest is likely past the peak water experienced in the 20th century preceding the signing of the 1922 Colorado River Compact: a decline in Lees Ferry flow will reduce water availability below current consumptive demands within a mere 20 years." Coping with this very serious threat requires, among other things, ongoing commitment to providing the resources needed to support long-term biophysical and social monitoring, scientific analysis of data generated by such monitoring activities, and experiments aimed at managing threats to the vitality of the coupled system. It also requires deep-seated recognition that management based on outdated knowledge and practices are no longer sufficient to address the challenges of the future.

## 5. Organ Pipe Cactus and Pinacate Biosphere Reserves: externality-producing institutions

### 5.1. *Context and conditions*

Organ Pipe Cactus National Monument, in southwestern Arizona, and the Pinacate y Gran Desierto de Altar Biosphere Reserve, in northwestern Sonora (Fig. 1), are among the most spectacular desert landscapes in North America; they are also the driest and warmest landscapes on the continent. Temperatures can exceed 50 °C in the summer and in winter snow sometimes falls in the mountains. Precipitation varies from 0 to 100 mm per year at low elevations to 100–400 mm in the mountains (Mendoza, 1989). The area is home to many unique species, some endangered; all are finely adapted to their extreme environment. The Rio Sonoyta, a small intermittent stream that drains 3360 $km^2$ of land, constitutes the only surface flow of note. More generally, high evapotranspiration rates severely limit the amount of water available throughout the area for ecological or human uses, although a few small basins of perennial flow support native species such as the endangered desert pupfish (Anderson et al., 1989). Extended droughts and related overexploitation of groundwater pose serious threats to ecological resilience as well.

The Pinacate Biosphere Reserve is famous for its 600 sq mi of volcanic landscape, large expanses of desert pavement (Hayden, 1989), active sand dunes, and unique life forms. Tinajas, scoured-out cavities in the lava that capture rainwater, provide the only sources of water across much of the preserve (Hayden, 1989, p. 52). Traces of human habitation date back at least 20,000–40,000 years. Today, members of the Hia Ced O'odham, a subgroup within the larger O'odham culture – whose traditional lands stretch across large areas on both sides of the border – regard this area as their aboriginal homeland and spiritual center (Joaquin, 1989, p. 13; Chester, 2006, p. 61).

Organ Pipe Cactus National Monument on the Arizona side of the border features a rugged landscape punctuated by dense stands of the signature organ pipe cactus and ecological niches supporting many other unique, desert-adapted plant and animal species. The preserve, carved from lands traditionally occupied by the Tohono O'odham, has been characterized as "the only place [along the U.S.-Mexico border] where three nations – the United States, Mexico, and the Tohono O'odham – meet" (Chester, 2006, p. 56).

### 5.2. *Nature and dynamics of change*

Thirty miles of international boundary separate the two preserves. Previously remote and largely inaccessible, these areas are experiencing major impacts from externality-producing economic institutions that are propelling huge waves of migrants seeking higher-paying jobs in the U.S. Paved roads now provide relatively easy access to the area, while tourism and expansion of nearby towns are enlarging the human footprint on the landscape. Unauthorized migration and illegal narcotics traffic from Mexico into the United States, however, is creating a much larger footprint, one that is fragmenting ecological continuity. Border Patrol and military surveillance practices, and related law enforcement activities, funnel heavy traffic and ecological damage to sensitive desert areas (Tobin, 2002; GNEB, 2004). Extreme weather conditions, the harsh terrain, and lack of water sources take a high annual toll of lives among unauthorized migrants (see, e.g., Rubio-Goldsmith et al., 2006), while crime associated with narco-trafficking poses a serious danger to everyone in the area (see, e.g., Erfani and Murphy, 2007).

The huge upsurge in traffic across this remote and harsh desert landscape began in the 1990s when the U.S. federal government sealed off most of the urban border crossing areas in Texas, Arizona, and California to unauthorized and illegal cross-border movements, thus funneling traffickers of people, narcotics, and weapons into more difficult, remote, and less-monitored terrain (Rubio-Goldsmith et al., 2006). The backcountry of Arizona became a prime route for unauthorized traffic. Sensors placed recently on known migrant pathways in Cabeza Prieta National Wildlife Refuge have recorded as many as 4000–6000 crossings per month during the peak months of April, May, and June each year (Erfani and Murphy, 2007). Nevertheless, proposals to build a high boundary fence, which would control human traffic in the area but would also impede essential ecological flows, have thus far been successfully opposed in favor of an extensive, but wildlife-friendly, vehicle barrier, completed in 2006. The Organ Pipe-Pinacate SES is being extensively altered by ecological externality-producing institutions, which Chapin et al. (2006, p. 16639) defined as "a heterogeneous suite of rule sets that, in the process of pursuing social and economic development goals, have unintended side effects on ecosystems, creating externalities". Climate variability and longer-term climate change, particularly the impact of rising temperatures on availability of already scarce water (Garfin and Lenart, 2007), compound these pressures, as does erosion in areas denuded of stabilizing vegetation.

### 5.3. *Potential policy alternatives*

Currently, serious institutional conflicts exist in the area. On the one side are value-driven resource-conservation institutions such as national park rules aimed at preserving the existing environment in a state of quasi-stationarity. On the other side are externality-producing political and economic institutions, such as both national governments' tolerance of wage-driven migration from Mexico to the U.S. Militarization of more populous border crossings has forced unauthorized migrants to cross the very same fragile desert landscapes that another arm of government in each country (the Department of the Interior and SEMARNAT) is trying to protect. Conflicts also exist between federal laws restricting cross-border travel and the need of the O'odham to freely cross in order to maintain their cultural heritage and social cohesiveness. The best scientific evidence available is insufficient by itself to address these issues. However, through working closely with knowledgeable residents and experts, science can make valuable and useful contributions to the development of policies that explicitly protect socio-ecological resilience. Among the most promising policy remedies is development of structures that generate decent jobs and wages for Mexicans living in Mexico. Another proposed remedy calls for the U.S. to rationalize its immigration policy and to support enforcement of laws governing employment of unauthorized migrants. Most important, in terms of human welfare, the U.S. needs to work actively to redirect migrant streams to safer, more populated, and less ecologically fragile areas.

Adding to the pressures the SES currently faces is climate change, which seems likely to spur transformation of the GSE's ecosystems from a cactus-dominated landscape to one dominated by woody species. Given this insight and the intensity of the biophysical and societal pressures on the system, policies and practices designed to preserve resilience in the existing system may be counter-productive over the long term. Instead, a substantial portion of social and economic capital might be better invested in identifying critical thresholds in the system, monitoring indicators that would signal that such thresholds are being reached, and exploring policy options to cope with and adapt to potential socio-ecological transformation and reorganization. One such policy might reserve property outside preserve boundaries that would accommodate ecological shifts occurring in response to climate change or other impacts in core areas of biodiversity. Existing resources could also be employed to much greater benefit, including local and traditional knowledge, scientific knowledge developed over many decades of research in the area, and knowledge developed by environmental advocates about the role and influence of value systems.

While it is unclear whether sufficient biophysical memory still exists to support socio-ecological resilience, the reservoir of social and scientific memory may provide indispensable insights for optimizing decisions and management actions that can help to facilitate an ecological transformation to a potentially more desirable state (Table 1). Commitment to sustaining science–society collaborations as well as long-term monitoring of societal and biophysical trends is essential to developing a more complete understanding of this complex system and how to live in it.

## 6. The Upper San Pedro River Riparian area: resource-conservation institutions

### 6.1. *Context and conditions*

The Upper San Pedro River lies at the far southeastern edge of the GSE (Fig. 1). The river basin originates in northeastern Sonora and flows northward across the international border to eventual confluence with the Gila River, a tributary of the Colorado River. The watershed encompasses approximately 7600 km$^2$ (5800 km$^2$ in Arizona and 1800 km$^2$ in Sonora, Kepner et al., 2004, p. 117). The river, characterized by low average flows and occasional flood events, is rich in biodiversity. Water sources for surface flow include rain, subsurface flows, and groundwater inflows. One of the few remaining unimpounded rivers in the U.S., and the last in Arizona, the river is internationally famous for its resident and migratory bird populations. The river corridor itself serves as a major flyway for migratory birds in the western hemisphere. More broadly, the river is historically, culturally, and ecologically important to the region (Varady et al., 2000).

### 6.2. *Nature and dynamics of change*

Population growth and development constitute the primary drivers of ecological stress on the river. Some 115,000 people now live in the area (Browning-Aiken et al., 2004, p. 358). The Arizona portion of the watershed in particular continues to experience rapid growth, which in turn is exacerbating pressures on water resources. The U.S. Army's Fort Huachuca, the largest water user in the U.S. portion of the basin, employs approximately 40% of Sierra Vista's population and adds some $1.5 billion annually to Arizona's economy (Sprouse, 2005, p. 11; Browning-Aiken et al., 2003; Varady et al., 2000).

Most people living on the Sonora side of the border reside in the city of Cananea, home to one of the largest open pit copper mines in the world (McSherry et al., 2006, p. 82). The mine, which employs 70% of Cananea's residents, controls water use at the San Pedro's headwaters (Sprouse, 2005, p. 12), and represents the single largest water user in the entire watershed (Sprouse, 2005, p. 12; Browning-Aiken et al., 2003; Varady et al., 2000; Browning-Aiken et al., 2004, p. 358).

While today groundwater provides all municipal water and most irrigation water throughout the Upper San Pedro region (Kepner et al., 2004, p. 117), research indicates that groundwater pumping in recent years, particularly from the floodplain aquifer, has reduced stream flow and has probably transformed much of the San Pedro from a mostly perennial to a primarily ephemeral stream (Arias, 2000, p. 209; Steinitz et al., 2005, p. 60; Stromberg et al., 2006, p. 167; Goodrich et al., 2000). A comparison of total demand to average supply shows that withdrawals already exceed recharge by approximately 6–12 million m$^3$ per year (Browning-Aiken et al., 2004, p. 359), posing a major threat to the ecological viability of the river. Population growth will certainly exacerbate this stress. Establishment of the San Pedro Riparian National Conservation Area (SPRNCA) in 1988 introduced an important new water demand: in-stream flows to support the SPRNCA riparian area. The creation of the SPRNCA represents a concerted effort to shift the major institutional driver from resource harvesting institutions toward resource conservation institutions.

Creation of the SPRNCA, especially a BLM decision to bar farmers and ranchers from using the riparian area for cultivation or grazing, generated hostilities that have not entirely abated (Varady et al., 2000, p. 230). Although the Commission for Environmental Cooperation has proposed conservation solutions for the area (Varady et al., 2000, p. 232), people on both sides of the border remain wary of entering into agreements out of fear that each is simply trying to gain access to more water (Browning-Aiken et al., 2003, p. 618). The issues are further complicated by significant differences in concerns among residents on the Mexican side of the border. Here, the focus is largely on much more basic issues of water quality and delivery for municipal and industrial purposes, rather than on conserving water for ecosystem maintenance (Varady et al., 2000, p. 232).

The relative ineffectiveness of existing resource-conservation institutions devised to protect the riparian corridor in the

Upper San Pedro basin (USPB) reveal the inherent problem of focusing on a single component of a complex social–ecological system. Clearly, the riparian area is ecologically important for the entire San Pedro basin and beyond. However, waters that recharge the San Pedro are equally critical to supporting regional socio-economic dynamics, reflecting the continued strong influence of resource-harvesting institutions. Science continues to contribute knowledge about the ways in which water moves through the system and this knowledge continues to reinforce the finiteness of the water resources available within the system. What even the best science cannot determine, however, are the best management decisions, for "the issue of desired conditions is a subjective one that varies with the range of stakeholder values" (Stromberg et al., 2006, p. 168).

### 6.3. Potential policy alternatives

USPB researchers, decision makers, and stakeholders are currently pursuing an effort to integrate scientific knowledge with water policy (USPP, 2006), with the goal of assuring system resilience under conditions of continued growth and biophysical processes of variability and long-term change. The Upper San Pedro Partnership offers a promising model for sustaining socio-ecological memory through maintaining flexibility, accommodating input from various entities, and emphasizing collaboration. Nevertheless, given the nature of the multiple stresses and demands, water issues in the USPB are likely to persist indefinitely, perhaps only dissolving if/when the ribbon of green that marks the riparian corridor disappears. Establishment of SPRNCA has forced decision makers to consider the value of a resilient, healthy riparian area; yet institutional recognition by itself by no means guarantees a dependable and adequate amount of water for ecological functions, especially given persistent high levels of high socio-ecological change.

The impacts of such changes on the system remain somewhat weakly understood, implying a need to blend resilience-enhancing institutions with policies that promote long-term adaptive capacity (Table 1). Recent events suggest that beneficial changes might be in store. In March 2007, Arizona lawmakers agreed to allow voters living in the San Pedro watershed to decide, in the November 2008 election, whether to approve creation of a special district charged with finding ways to add more water to the system. A related measure would allow the Cochise County Board of Supervisors to let voters decide whether to approve a fifty-cent tax on themselves for every thousand gallons of water they use; the funds would be spent on water augmentation projects. Further, a bill passed by the Arizona House of Representatives could have the effect of limiting new construction in areas unable to demonstrate access to an adequate supply of water (Fischer, 2007). While all of these measures – if ultimately enacted – are designed to allow the area to continue growing, they also demonstrate recognition of the need to balance supply with demand and, in the process, to reduce threats to the river and its riparian area. Perhaps most crucially needed, though, are binational processes aimed at mobilizing science, policy, and human values in a coordinated, long-term campaign to manage the river from its headwaters in Sonora to its confluence with the Gila River in Arizona.

## 7. Conclusions

The case studies presented above provide insight into how to come to grips with the complexities of understanding a large social–ecological system such as the Greater Sonoran Ecoregion (GSE). Combining theories of resilience, transformability, adaptation, and vulnerability in analysis of the case studies offers a valuable framework for assessing social–ecological systems and the contributions of good science to addressing problems in social–ecological systems. We recognize that, while providing a useful framework for assessing the status of the SES's examined in this study, the framework devised by Chapin et al. (2006) may produce different or contradictory outcomes when applied to larger or finer scales. For example, vulnerability at the finer scale of the Delta SES, produced by withdrawal of water for other uses, helps contribute to resilience at the larger scale of the Lower Colorado River Basin. This constitutes a conflict among social forces favoring resource conservation institutions versus those favoring resource-harvesting institutions.

It is this kind of conflict that sharply foregrounds why good science by itself is not sufficient either to understand or address the complex challenges facing socio-ecological systems such as those of the GSE. In addition, the practices of science itself may contribute to its insufficiencies for addressing such problems. Such practices are typically rooted in academic institutions and practices that reward production of science for its own sake and for the reinforcement of the scientific establishment, rather than science expressly undertaken in collaboration with society to solve real-world problems (Warner and Havens, 1968; Jasanoff and Wynne, 1998). The disconnect between science and societally defined problems can be further exacerbated by a lack of social and institutional capacity to integrate scientific knowledge easily into policy making, decision processes, and everyday practices (Rayner et al., 2005; Lemos and Dilling, 2007; Ingram and Fraser, 2006).

In the case of the Colorado River Delta, the revitalized wetlands are seriously vulnerable to human decisions and actions aimed at coping with drought impacts and related obligations to deliver a specified amount of water to Mexico through redirecting the waters now feeding the wetlands to the mainstem of the Colorado River. In the absence of fundamental changes in socio-ecological worldviews, rules, management practices, and ability to integrate scientific knowledge effectively, the most likely outcome will be destruction of the wetlands once again. Given the anticipated impacts of climate change and current lack of effort to expand adaptation efforts to include ecological viability, socio-ecological transformation is likely to be permanent this time.

For the Organ Pipe-Pinacate preserves, the future socio-ecological resilience of the system hinges most directly on political will and capacity to alter federal laws and policies in a manner that recognizes the overriding importance of preserving the area's environmental values. Such changes would include binational efforts to revise migration and job-creation policies, demilitarization of the border so as to redirect migrants to safer and less ecologically sensitive crossing points, and commitment of much higher levels of support for scientific monitoring, public environmental education, and maintenance/restoration of the area's sensitive natural landscapes.

The Upper San Pedro River watershed, which lies at the far eastern edge of the GSE, may today be the least vulnerable of our three case studies. Here, experiments in adaptive management on the U.S. side of the border hold promise for demonstrating how socio-ecological resilience may be maintained through multifaceted science–society collaborations. Yet serious threats to the system lurk in the shadows. The most serious vulnerabilities stem from interactions between rapid military and urban expansion and climate-related stresses, notably sustained drought and longer-term temperature increases associated with climate change. The combined demand and supply pressures forebode deep reductions in – or elimination of – water available to support in-stream and riparian habitat needs. The cultural and ecological impacts of loss of this, the last of the free-flowing waterways in Arizona, would be profound. Upstream, on the Mexican side of the border, improving people's fundamental access to water for everyday needs, and balancing the water demands of the mine in Cananea with urban water needs, the needs of downstream farmers, and the instream and riparian ecological demands add complexity and immediacy to the challenges facing scientists and citizens alike. As in the other two case studies, intensive commitment is required in terms of innovative thinking, adaptive experimentation, long-term monitoring, political support, and public willingness to embody their environmental values in everyday actions.

Moving beyond notions of stability as the norm to recognition of variability and change as the more usual condition of life requires significant changes in values, institutions, and behaviors and understanding that, in the context of ever-changing complex systems, sustainability will be a moving target. These shifting sands require greater commitment to the kind of collaborative, interdisciplinary science that integrates social, physical, and ecological knowledge and public activism at landscape scales. Also required is transformation of scientific knowledge into useful, usable, salient, and credible (Cash et al., 2003) information and products that promote resilience and avert untimely systemic collapse and reorganization or that promote either orderly transformation to a more desirable state or efficient reorganization in the wake of systemic collapse.

In this latter context, good science is essential to expanding knowledge and understanding about socio-ecological systems and their components at all scales from nano to global, as well as how elements interact across both temporal and spatial scales. The project requires integration among many different kinds of expertise and knowledge, as well as commitment to understanding socio-ecological systems in all their untidy complexity. Developing a deep understanding of the nature of system memory and its influence on sustainability, defined in terms of resilience, is essential, as is understanding the processes by which complex socio-ecological systems generate and absorb shocks, collapse, and reorganize (Holling and Gunderson, 2002). Likewise, strengthening the ability of society to pursue adaptive management of a region's socio-ecological systems is a critical factor in achieving genuinely sustainable development. Such ability resides in regional actors, social networks, and institutions (Lebel et al., 2006). This work, in particular, requires collaboration among scientists, decision makers (see, e.g., Lemos and Morehouse, 2005), and holders of local knowledge and tradition, in order to monitor conditions and to anticipate the emergence of serious systemic stresses, including the unintended consequences of prior socio-ecological interactions. Above all, the task requires combining the best available science with mature socio-ecological citizenship. The task is huge, but so are the stakes.

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