Southwestern Desert Resources

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Edited by William Halvorson, Cecil Schwalbe, and Charles van Riper III

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This book brings together peer-reviewed research from two interagency projects that focused on Southwestern Desert ecosystems and resources. The first is a series of biennial conferences that were held from 1996 through 2006. These were guided and managed by a committee representing Arizona Game and Fish Department, National Park Service, The Nature Conservancy, Sky Island Alliance, Sonoran Institute, Universidad de Sonora, University of Arizona School of Natural Resources, USDA Agricultural Research Service, USDA Natural Resources Conservation Service, U.S. Forest Service, and U.S. Geological Survey. The second is an interagency project that took place from 2000 through 2008. This inventory of the National Park Service units in southern Arizona and eastern New Mexico was a coordinated effort of the National Park Service, U.S. Geological Survey, and the University of Arizona, School of Natural Resources.

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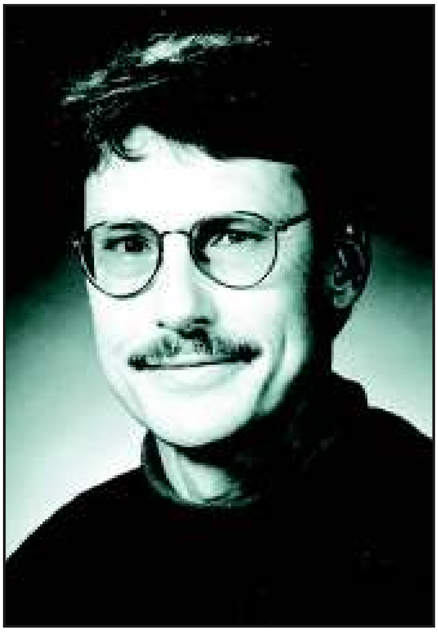
SOCIAL AND CULTURAL ISSUES

DEDICATION — DR. DEAN A. MARTENS

Dean A. Martens was born in Fort Dodge, Iowa to Verona and Gern Martens on June 22, 1954. He received his B.S., M.S., and Ph.D in agronomy from Iowa State University. Dean was involved extensively with soils and agricultural water contaminant problems in California becoming a soil scientist at the National Soil Tilth Laboratory in Ames, Iowa. There he investigated erosion, soil stability, and carbon and nitrogen cycling dynamics in agricultural soils. He was transferred to Tucson, AZ in 2000 where he worked as a soil scientist with USDA-ARS at the Southwest Watershed Research Center.

His research efforts were directed to investigations of land use changes in semiarid rangelands on the cycling of carbon and nitrogen and its impact on potential climate change. These land-use changes involved the impacts of man and vegetation changes on biogeochemical changes in riparian zones, grasslands, and mountainous woodlands. He was also an Associate Adjunct Professor in the Department of Soil, Water, and Environmental Sciences at the University of Arizona. He was an active and supporting member of the Committee that organized the 2002 and 2004 Conferences on Research and Resource Management in the Southwestern Deserts. While the Conference Committee was preparing for its sixth conference, Dean passed away after a brief battle with cancer on November 15, 2005.

Dr. Martens was known for his intense scientific curiosity and boundless energy regarding the preservation of natural resources. He was a 24-year member of both the American Society of Agronomy and the Soil Science Society of America. At the time of his death, he was serving as the Division S-3 Associate Editor for the Soil Science Society of America Journal. His scientific legacy will live on. His publications have been cited in over 300 studies around the world.



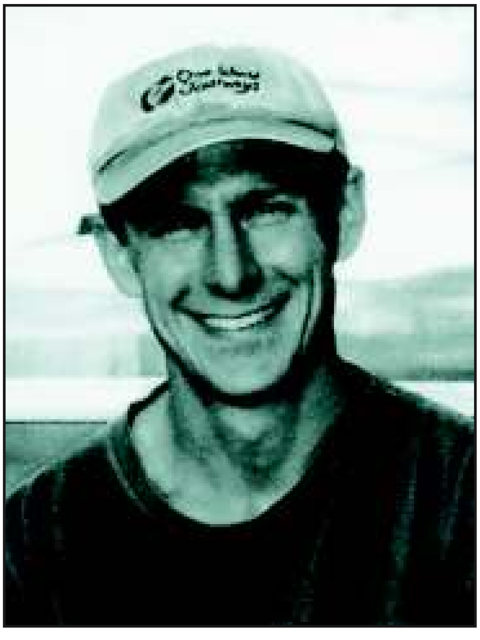
He is survived by his wife Ursula and daughter Sophie.

DEDICATION — ERIC W. ALBRECHT

Eric Wells Albrecht was born September 6, l970 in Eugene, Oregon to Robert and Llewellyn Wells Albrecht. After graduating from Lane Community College, he moved to Seattle for two years before attending The Evergreen State College in Olympia, where he received a Bachelor's degree specializing in Natural History in 1992. He developed a particular interest in ornithology, volunteering on a project to band raptors in the Sawtooth Mountain range in Idaho. He also worked as a guide at Denali National Park in Alaska.

In 1998, Eric began his career in natural resources after moving to Tucson, Arizona. There he assisted his close friend and wildlife graduate student, Brian Powell, in his thesis research on songbirds in the Sonoran Desert. Eric also assisted other graduate students with research on hawks and the interactions between vegetation, insects, and fire. In 2000, Eric began his own graduate work at the University of Arizona where his research in the Huachuca Mountains focused on fire as a tool to restore populations of grassland birds. On September 20, 2004, at age 34, Eric died unexpectedly of an acute brain infection. He received his Masters of Science in Wildlife Conservation and Management posthumously.

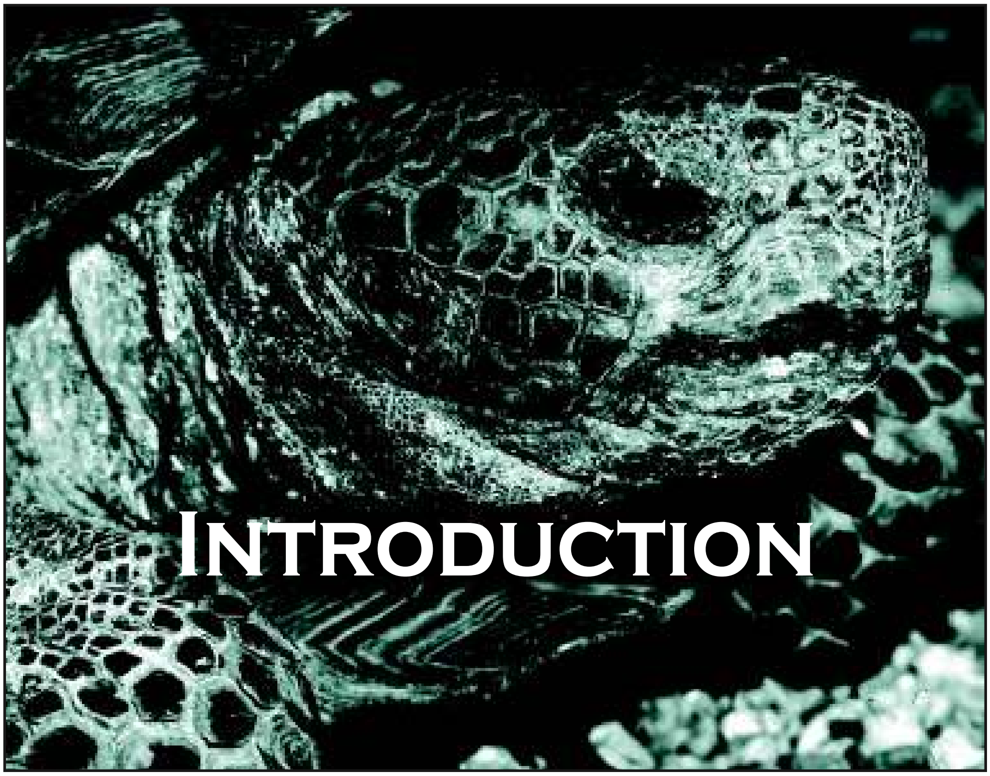
From 2002 until his death, Eric was the co-coordinator of the University of Arizona Biological Inventory and Monitoring program. His work involved the development of monitoring protocols for the National Park Service Units in the Sonoran Desert Network. His work aided in the completion of 12 Open-file Reports for the U. S. Geological Survey's Southwest Biological Science Center.



He was devoted to his family and community, active in his neighborhood association in spearheading a community garden project. Eric was a passionate conservationist and ecologist, and avid outdoorsman and nature photographer. His scientific curiosity was always with him, so much so that he had a rule when attending presentations: he always asked a question of the presenter.

Eric is survived by his partner of eight years, Kathy Moore, and their two children Elizabeth and Zachary.

Southwestern Desert Resources



Introduction

INTRODUCTION

William L. Halvorson

Over the last few decades, management of natural and cultural resources has evolved from managing from a position of beliefs to managing from a basis of knowledge[1]. Those of us who had responsibilities in federal, state, local and private land management areas once did not have much of a response when asked, "How can you manage your land and ecosystems without knowing what's there?" Overcoming the information gap has come about through programs like the National Park Service's Inventory and Monitoring Program (http://science.nature.nps.gov/im/index.cfm) and added emphasis on research on the part of resource managers, along with national and regional conferences directed at bringing researchers, managers, and interpreters together for exchanging knowledge, ideas, questions, successes, and failures.

This book brings together peer-reviewed research from two interagency projects that focused on Southwestern Desert ecosystems and resources. The first is a series of biennial conferences that were held from 1996 through 2006. These were guided and managed by a committee representing Arizona Game and Fish Department, National Park Service, The Nature Conservancy, Sky Island Alliance, Sonoran Institute, Universidad de Sonora, University of Arizona School of Natural Resources, USDA Agricultural Research Service, USDA Natural Resources Conservation Service, U.S. Forest Service, and U.S. Geological Survey. The coordination of scientists within these federal and state agencies and non-government organizations furthered the research and conservation of Southwestern desert resources much more than could be accomplished without this cooperation. The second is an interagency project that took place from 2000 through 2008. This inventory of the National Park Service units in southern Arizona and eastern New Mexico was a coordinated effort of the National Park Service, U.S. Geological Survey and the University of Arizona School of Natural Resources.

The Southwestern Deserts stretch from southeastern California to west Texas and then south to central Mexico. The landscape of this region is known as basin and range topography with many hills and mountains rising above desert valleys. Where there are well-developed mountains, they are often referred to as sky islands; forested islands in a sea of desert. This provides for a uniquely interesting and complex ecology. Another issue that this region deals with is the international border that stretches for hundreds of miles from the coast of California, through Arizona and New Mexico, east to the Gulf Coast of Texas. In dealing with people moving across this border, governments have also caused difficulties for many animal populations. This book spotlights individual research projects that increase our understanding of forces acting on the biological and cultural resources of this vast region so that those resources can be managed as effectively and efficiently as possible. Our intent is to show that collaborative efforts among federal and state agency, university, and private sector researchers working with land managers provide better science and better management than scientists and land managers working independently.

The first part of the book highlights studies aimed at inventories to discover what species and communities are associated with specific land management units. It is surprising to most that complete inventories of plants, animals, and communities do not exist for most of the federal and state land management units. In many, only the most obvious species are on any given area's species list. Even for those National Park Service units at which this major project was aimed, major groups like insects are completely missing. Going beyond a list of species to detail community structure and function is likewise missing for many areas. The inventories accomplished for the National Park Service was the first step in a long-term monitoring program. Once the inventories were completed and the NPS knew what resources were found in each management area, the steps of describing a conceptual model, listing key abiotic and biotic factors in that model, and noting key vital signs that should be monitored could take place. Based on those steps and understanding the costs involved in long-term monitoring, a program was developed for tracking changes and reporting the status of resources over time. This information can then be provided to managers for their decision-making about what changes need to be made.

The second and largest segment of the book reports on the status of biological resources of the Southwest Desert Region without regard to management areas. We leave it up to the managers as to how this information can best be used within their area of concern. It is important to keep in mind that the diversity of this region is great because the basin and range topography supports ecosystems from hot, lowland deserts to montane coniferous forests. Elevations range from sea level to over 3,261 meters (10,700 ft). Resources addressed in this section range from termites to pronghorn, from animals living at sea level to those that inhabit the tallest mountains. Issues dealt with include the implications of human border crossers, adaptive management of desert grasslands, conservation plans for the lower Colorado River, and how best to advance the recovery of endangered species and other large mammals in the borderland desert regions. Mammals whose status is discussed include bats, small mammals in ironwood forests, black bear, pronghorn antelope, and mountain lions. There are chapters on conservation of the Sonoyta Valley, monitoring mammals at Coronado National Memorial, the status of turtles and frogs in Mexico, conservation of amphibians and reptiles, and termite activity on live saguaro cacti.

The final chapters of the book address social and cultural themes: a technique that towns can use to protect open space, dust patterns across the southwestern U.S. and northwestern Mexico, and historic transportation corridors.

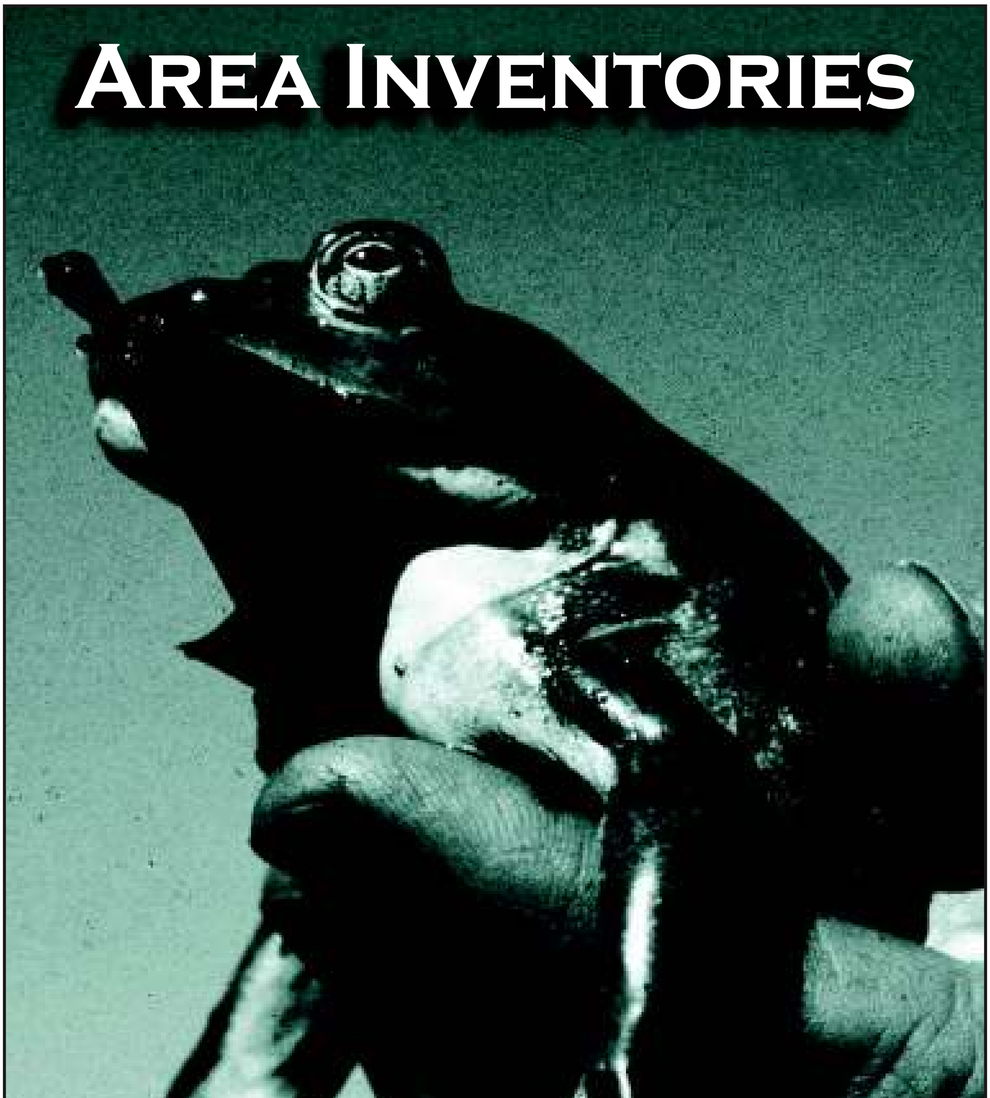
Southwestern Desert Resources is for researchers, resource managers, and land managers, as it shares the similarities in climate and topography across the region, helps all to understand the status and distribution of species, and discusses many of the issues that make management of resources difficult. All of this information, when shared between all the individuals and groups working in the region will increase our collective understanding and help inform our everyday management decisions. This volume can serve as a quick guide, a stepping stone if you will, to the types of research and management projects that we need to undertake next[2].

We are doing a much better job than we did even twenty years ago. As we look to the future we are beginning to understand that we will need to be managing landscapes that integrate human communities with natural protected areas and that provide high quality sustainable habitats for both humans and natural plants and animals.

A work of this nature always involves a large number of people, the names that are directly seen in the book are the tip of the iceberg. The editors give our thanks and appreciation to all those for which this book is but a small portion of all the work being done in managing the desert's natural resources every day. A special thanks goes to the conference committee for putting on the conferences on research and resource management in the Southwestern deserts: Acasia Berry, Alejandro Castellanos, Nina Chambers, Doug Duncan, Peter Ffolliott, Brooke Gebow, Jerry Gottfried, David Hodges, Andy Hubbard, Sue Kozacek, Larry Laing, Dean Martens, Joan Scott, Frank Toupal, and Dale Turner. We want to thank all of the natural area managers who gave their support and time for the studies represented in this volume, especially Brian Carey and Alan Whalon of Chiricahua National Monument and Kathy Davis of Tuzigoot and Montezuma Castle National Monuments. We also appreciate the work of the cadre of reviewers who took on the task so that every chapter in the book had at least two peer reviews: Mike Barna, Kevin Bonine, T. J. Fontaine, Andy Hubbard, Tom Jones, Jeff Lovich, Larry Laing, Bruce Nash, Larry Norris, Carrie Dennett, Mike Sredl, Eric Stitt, Marty Tuegel, and Sandy Wolf.

[1]Halvorson, W.L. and G.E. Davis. 1996. Science and Ecosystem Management in the National Parks. The University of Arizona Press, Tucson

[2]No endorsement is implied by the mention of commercial products in any of the book's chapters.


Area Inventories

VASCULAR PLANT AND VERTEBRATE INVENTORY OF CASA GRANDE RUINS NATIONAL MONUMENT

Brian F. Powell, Eric W. Albrecht, Cecilia A. Schmidt, Pamela Anning, Kathleen Docherty

In 2001 and 2002 we surveyed for vascular plants and vertebrates (amphibians, reptiles, birds, and mammals) at Casa Grande Ruins National Monument (NM) to document the presence and in some cases relative abundance of these species. This was the first comprehensive biological inventory of the monument. By using repeatable study designs and standardized field techniques, which included quantified survey effort, we produced inventories that can serve as the basis for a biological monitoring program.

Of the National Park Service units in the region, no other has experienced as much recent ecological change as Casa Grande Ruins NM. Once situated near a large and biologically diverse mesquite *bosque* (forest) associated with the perennially flowing Gila River, the monument is now a patch of sparse desert vegetation surrounded by agriculture and by urban and commercial development which is rapidly replacing the agricultural fields as the dominant land use in the area. Roads, highways, and canals directly surround the monument. Development, and its associated impacts, has important implications for the plants and animals that live in the monument. The plant species list is small and the distribution and number of non-native plants appears to be increasing. Terrestrial vertebrates are also being impacted by the changing landscape, which is increasing the isolation of these populations from nearby natural areas and thereby reducing the number of species at the monument. These observations are alarming and are based on our review of previous studies, our research in the monument, and our knowledge of the biogeography and ecology of the Sonoran Desert. Together, these data suggest that the monument has lost a significant portion of its historic complement of species and these changes will likely intensify as urbanization continues.

Despite isolation of the monument from nearby natural areas, we recorded noteworthy species or observations for all taxonomic groups:

- Plants: night-blooming cereus
- Amphibians: high abundance of Couch's spadefoot toads
- Reptiles: high abundance of long-nosed snakes
- Birds: 10 species of diurnal raptors including 4 species of falcons
- Mammals: American badger

This study was a first step in the process of compiling information about the biological resources of Casa Grande Ruins NM and surrounding areas. For complete details of the Casa Grande Ruins NM study see Powell et al. (2006) [http://sbsc.wr.usgs.gov/products/ ofr/]. Scientific and common names used throughout this chapter are current according to accepted authorities for each taxonomic group: Integrated Taxonomic Information System (ITIS 2001) and the PLANTS Database (USDA 2001) for plants, Stebbins (2003) for amphibians and reptiles; American Ornithologist Union (AOU; 1998, 2003) for birds; and Baker et al. (2003) for mammals.

MONUMENT OVERVIEW

Monument Area and History

Casa Grande Ruins NM is located in Coolidge, Arizona, approximately 70 km southeast of Phoenix (Figure 1). The monument currently encompasses 191 contiguous ha and managers are proposing to increase the size of the monument by approximately 105 ha (including 32 ha adjacent to the current site; NPS 2003a).

Casa Grande Ruins NM was created to protect the Casa Grande, a four-story adobe structure that was built by the Hohokam between AD 1200 and 1450 (Clemensen 1992). The Hohokam had a sophisticated culture—they built extensive canals to irrigate crops and provide water to large communities in the vicinity of the Casa Grande. After the mysterious departure of the Hohokam in approximately 1450, the Casa Grande stood abandoned for over 440 years until, in 1892, the structure and the land surrounding it became the first U.S. prehistoric cultural site to receive federal protection (Clemensen 1992). In 1918, Casa Grande Ruins became part of the National Park Service system.

Physiography, Geology, and Soils

The monument is located approximately 1 km south of the Gila River, which now only flows seasonally. The Pima Lateral canal runs parallel to (and a few meters from) the southern boundary of the monument and a smaller irrigation ditch parallels the west boundary (Figure 2). State Highway 87 runs along the east and north boundaries of the monument.

The monument is situated at approximately 430 m above sea level in the Basin and Range Physiographic Province, which is characterized by gently sloping valley floors surrounded by mountain ranges. The monument is characterized by Quaternary and Tertiary alluvial deposits (fluvial and lacustrine) from the surrounding mountain ranges: San Tan Mountains (6 km north), Sacaton (16 km west), Picacho (30 km southeast), and Casa Grande (30 km southwest). The mountains bordering the valley floor are composed of non-waterbearing Precambrian granite, gneiss, and schist (Van Pelt 1998). All mountain ranges are currently isolated from each other by agriculture and development. Soil at the monument is Coolidge sandy loam, with caliche two to four feet below the surface.

Hydrology

The Gila River is the main water body in the region, but impoundments upstream from the monument cause the river bed to be dry for most of the year in the reach to the north of the monument. Irrigation canals carry water for crops, while water for developments comes from groundwater pumping (Sprouse et al. 2002).

Climate

Casa Grande Ruins NM is located in the subtropical desert climatic zone of southern Arizona which is characterized by heavy summer (monsoon) storms brought about by moisture coming from the Gulf of Mexico and less intense, frontal storms from the Pacific Ocean in the winter. The monument receives an average of 228 mm of precipitation annually. Summers in the area are hot; daily maximum temperatures from June through September often exceed 40° C. Winters are mild and temperatures rarely drop below freezing (WRCC 2004).

Average annual precipitation totals during the course of our study were slightly above the long-term mean of 228 mm in 2001 (247 mm) but considerably lower than average in 2002 (122 mm), one of the driest years on record (WRRC 2004). In the fall of 2000 rainfall was above average; this rain may have increased winter annual plant seed germination and growth prior to our 2001 spring plant surveys. Average annual temperatures during both years of our study were 0.9° C above the long-term mean of 20.8° C.

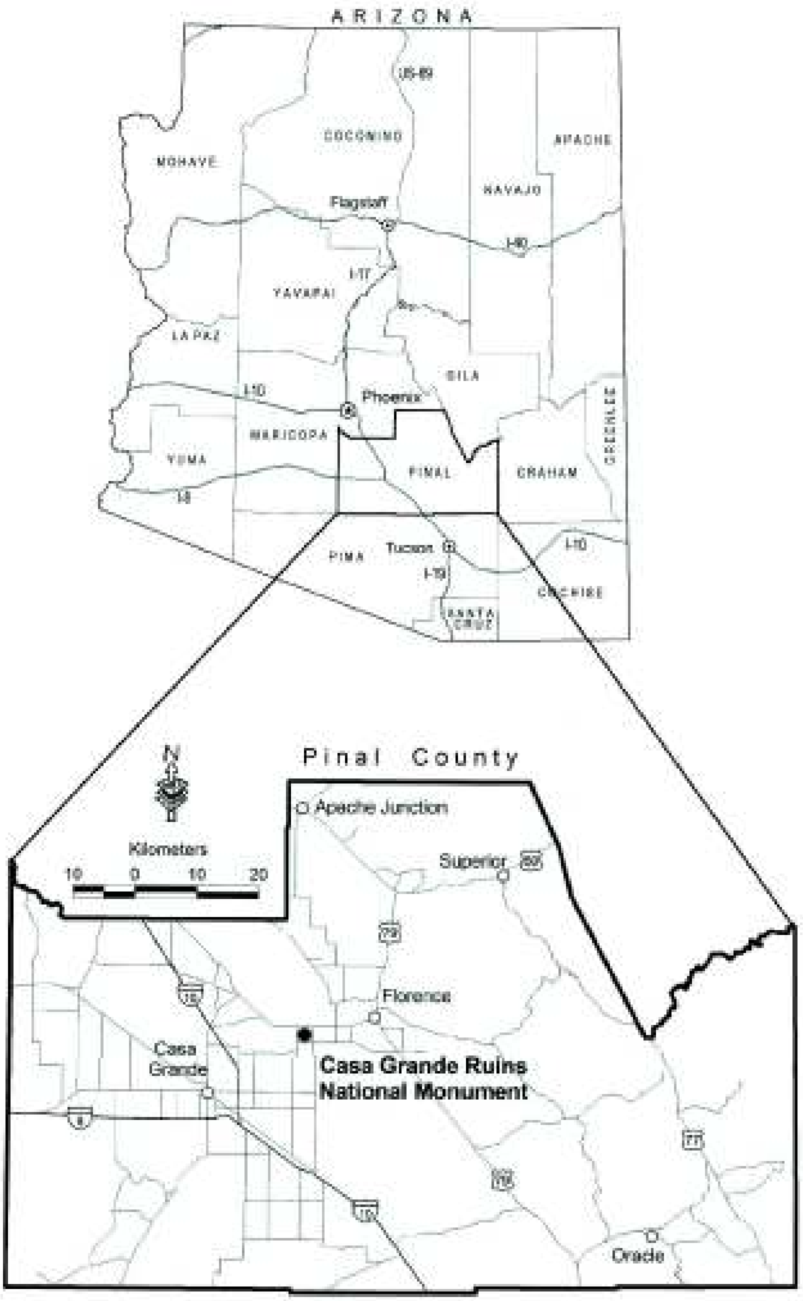


Figure 1. Location of Casa Grande Ruins National Monument, Arizona.

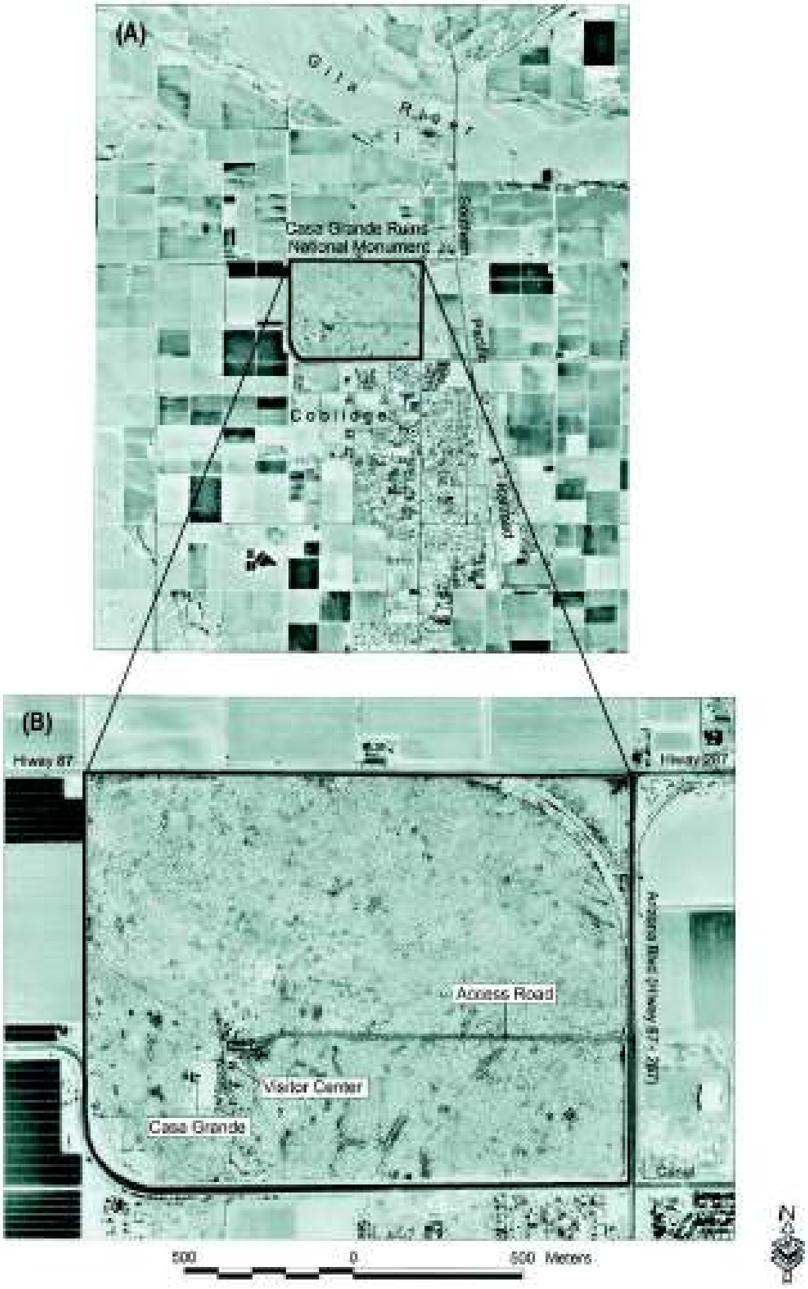


Figure 2. Aerial photograph of Casa Grande Ruins NM showing it in a patchwork of commercial and residential development and agricultural fields (A) and a more detailed image of the monument's major features (B).

Vegetation

The relatively homogenous vegetation community at Casa Grande Ruins NM is characterized as Sonoran desertscrub dominated by creosote with scattered velvet mesquite, saltbush and annual grasses and forbs (Reichhardt 1992). Shrubs and trees in the vicinity of the visitor center are irrigated, and the many standing dead velvet mesquite trees in other areas of the monument reference a change from historic conditions.

Because the area in and around the monument has been intensely used for hundreds of years, it is difficult to determine the "natural" vegetation community of the area. Given the monument's close proximity to the Gila River, coupled with the topographic and soil conditions of the site, it is likely that the general area was once more fully covered with large areas of mesquite, especially before colonization by the Hohokam. Even since the abandonment of the area by the Hohokam, many large mesquite trees dominated the area, as noted by late 19th century visitors (Clemensen 1992). Subsequent cattle grazing probably enabled the increase in woody shrubs such as creosote, catclaw acacia, and saltbush. However, in the mid to late 1930s, the large mesquites at the monument began to die off, apparently due to a drop in the groundwater related to pumping for agricultural irrigation (Judd et al. 1971; Clemensen 1992; Nickens 1996; Van Pelt 1998). The lowering of the water table also likely changed the soil conditions enough that a shift took place from salt bush and catclaw acacia to a proliferation of creosote, which now dominates at the monument.

Historical Land Use of the Monument and Surrounding Areas

Clemensen (1992) compiled a detailed history of Casa Grande Ruins NM and the following information comes from his work. Beginning in the 1870s, settlers began grazing cattle in the area because of the abundant forage. Grazing continued until 1934 when the monument was fenced to exclude cattle. But it was agriculture that would become the dominant land use of the area outside the monument, and beginning in the 1880s settlers began in earnest to clear land in the vicinity of the monument. Water for irrigating crops (fruit trees, grapes, cereal grains, cotton, lettuce, and alfalfa) came first from direct diversion of flow from the Gila River, and later from above-ground storage with the construction of nearby Coolidge Dam in the mid 1920s and groundwater accessed by pumping. In 1925 the town of Coolidge was created and by 1932 the monument was surrounded by agricultural fields. However, by 1947, agricultural fields were being abandoned because of drought and a lowered water table, due in large part to pumping of water in excess of recharge rates. Depth-to-water rebounded somewhat by the late 1990s, in part because of reduced groundwater pumping (Sprouse et al. 2002).

Natural Resource Management Issues

Casa Grande Ruins NM is an isolated patch of desert vegetation surrounded by intensively altered land; uses include agriculture, residential and commercial development, and roads. Although it is difficult to quantify the effect of these land uses, these (and other) influences inevitably affect the structure and composition of plant and animal communities of the monument.

Agriculture

Agricultural fields bordering the monument to the west and north are typical of the dominant land use in the surrounding area. These areas provide disturbed soils and only marginal space for other plants to grow, space that is typically occupied by non-native "weedy" plants including redstem stork's bill, red brome, Russian thistle, and Johnsongrass. In addition, the canals that border the monument are periodically dredged and the sediment (likely rich in non-native plant seed) is deposited along the edge of the monument boundary (Hubbard et al. 2003).

Residential and Commercial Development
Casa Grande Ruins NM is located within the City of Coolidge. The city's population (7,786 inhabitants in 2000) is increasing rapidly, leading to increased residential and commercial development (NPS 2003a, 2003b). Large-scale commercial developments (e.g., Wal-Mart®) have been built along Highway 87 across from the monument. Residential development abuts the south boundary and is planned along the west boundary should the proposed monument boundary expansion not be approved. Impacts of these developments on the monument's natural resources may include: (1) an increase in non-native plants, for example the first sighting of a common plant used in landscaping, crimson fountaingrass, was reported by Halvorson and Guertin (2003); (2) increased trash and run-off of sediment and toxins from vehicles; (3) disruption of animal movement patterns; and (4) increased harassment and mortality of native animals by free-roaming feral pets (Clarke and Pacin 2002).

Roads
Casa Grande Ruins NM is completely encircled by roads, most notably Highway 87 (Figure 2), the primary highway in the area. Roads act as dispersal corridors for non-native plant species, which often thrive in the adjacent disturbed soils. Roads surrounding the monument likely act as barriers to the flow of terrestrial wildlife because of direct mortality and modification of behavior (Trombulak and Frissell 2000; Clark et al. 2001; Tigas et al. 2002; Cain et al. 2003).

Groundwater Pumping
The continued pumping of groundwater for agricultural, residential, and commercial use may threaten existing mesquites on the monument despite the recent (and likely temporary) rise in the level of the groundwater (Sprouse et al. 2002). Groundwater pumping can also lead to subsidence that threatens the Casa Grande structure (NPS 1998; Richardson 2002; Hubbard et al. 2003).

Non-native and Pest Species
Awareness of non-native species as a management issue has increased in recent years; ecologists have ranked this issue as one of the most significant causes of species endangerment (Brooks and Pyke 2001). Non-native plant species are a significant management issue at the monument because it is surrounded by roads, agricultural fields, and development, which generally provide ideal conditions for the dispersal and establishment of some non-native plants. Non-native plants are known to alter ecosystem function and processes (Naeem et al. 1996; D'Antonio and Vitousek 1992) and reduce abundance of native species, creating potentially permanent changes in species diversity and community composition (Bock et al. 1986; D'Antonio and Vitousek 1992; OTA 1993). The Casa Grande and associated structures provide habitat for many non-native birds such as house sparrow and European starling, and the adjacent developments provide a source for free-roaming and feral cats and dogs.

In its Integrated Pest Management Plan (IPM; NPS 1997), monument personnel identified a number of wildlife species that are causing significant damage to the archaeological ruins in the monument. The IPM plan, along with that by Swann et al. (1994) identified round-tailed ground squirrel, rock pigeon, and house finch as the most important pest species.

METHODS

Plants

Previous inventories
The earliest collecting effort at the monument was from 1939 to 1942 when Natt Dodge, the regional naturalist, and Francis Elmore, a park ranger, collected plants from throughout the monument. These specimens (43 species) are at the University of Arizona Herbarium. Reichhardt (1992) conducted an inventory of plants at the monument in 1987. This work included a list of plants that she collected, classification of vegetation communities in the monument, creation of a checklist of non-ornamental plants, establish-

ment of vegetation plots, mapping of mesquite trees, and establishment of photo points for use in describing qualitative changes in the vegetation community. Halvorson and Guertin (2003) mapped the distribution of select non-native plant species in the monument from the fall of 1999 to the spring of 2001. Collections of plants from the monument made by additional observers have been accessioned to the herbarium at the University of Arizona and to the Western Archaeological Conservation Center in Tucson. The excellent work that preceded our effort reduced the field work required for the inventory. Below-average monsoon rains in 2002 further limited our efforts because most of the species that we hoped to record are annuals that germinate following rains.

This inventory

In March 2001 and again in September 2004 we conducted 6 person-day "general botanizing" surveys at the monument, during which observers walked throughout the monument and opportunistically collected and recorded plants. In addition to our own results, we present here the first synthesis of findings from past studies and collections. For simplicity, we refer to all subspecies and varieties ($n = 5$) as species.

Amphibians and Reptiles

Previous inventories

To our knowledge, there has been no inventory and there is scant research related to amphibians and reptiles at Casa Grande Ruins NM, though we located three specimens collected from the monument and know of several others collected in the area or region. Charles Conner, a biologist at Organ Pipe Cactus National Monument, has surveyed diurnal lizard populations at the monument for several years, but to date only a species list has been produced.

This inventory

We surveyed for herpetofauna using four methods representing plot-based and more flexible non-plot-based methods. Plot-based methods are constrained by time and area, and thus provide data for estimates of relative abundance that should be unbiased by these factors. Random location of these surveys also allows inference out to the current monument boundaries.

Non-plot-based surveys (Crump and Scott 1964) allow observers more flexibility in adjusting their search time, intensity, and location, and this flexibility is important for detecting rare, elusive, or ephemeral species more likely to be missed using plot-based surveys. We used both diurnal and nocturnal surveys in an effort to detect species with restricted periods of activity (Ivanyi et al. 2000, Stebbins 2003). We also used pitfall traps (Corn 1994; Gibbons and Semlitsch 1981), road surveys (Rosen and Lowe 1994), cover boards (Fellers and Drost 1994), and incidental observations to add species that were otherwise difficult to observe because they are very rare, have limited periods of activity, or inconspicuous behavior (Powell et al. 2006).

Birds

Previous inventories

To our knowledge, scant bird research has taken place at Casa Grande Ruins NM since a limited-scope banding study in the 1930s (Fast 1936). Barry (1987) created a checklist for the monument, but no source material exists and so we do not consider it here. There are two Breeding Bird Survey routes located approximately 5 and 10 km west of the monument (Sauer et al. 2004): "Cactus Forest" transect was surveyed in 1991, 1993, and 1996–2002; "Coolidge" was surveyed from 1974 to 1985. We found no records of specimens collected from the monument.

This inventory

We used four field methods: variable circular-plot counts for diurnal breeding birds (Reynolds et al. 1980; Ralph et al. 1995; Buckland et al. 2001), nocturnal surveys for owls and nightjars (Colver et al. 1999; Bibby et al. 2002), line transects for over-wintering birds (Bibby et al. 2002), and incidental observations for all birds in all seasons. We concentrated our primary survey effort during the breeding season because bird distribution is relatively uniform at this time (Bibby et al. 2002). Our survey period included peak spring migration times for most species, which added many migratory species to our list.

We also sampled vegetation around variable circular-plot (VCP) survey stations. Vegetation structure and plant species composition are important predictors of bird species richness or the presence of particular species (MacArthur and MacArthur 1961; Rice et al. 1984; Strong and Bock 1990; Powell and Steidl 2000). We visited all 12 VCP stations four times each in 2001. In 2002 we reduced the number of stations to 8 (station numbers 1, 2, and 6–11) and surveyed each of them four times. Each station was visited for 8 minutes.

We used a modified line-transect method (Bibby et al. 2002) to survey for birds from October to December 2002. Line transects differ from station transects (such as those used in our VCP surveys) in that an observer records birds seen or heard while the observer walks a line, rather than stands at a series of stations. The transect method is more effective during the non-breeding season because bird vocalizations are less conspicuous and frequent, and therefore birds tend to be more difficult to detect (Bibby et al. 2002). We established one transect at the monument, broken into 12 sections. Each section was approximately 250 m in length. We visited all 12 sections four times in 2002: 24 October, 8 and 25 November, and 19 December. The total time spent on each section was 10 minutes.

To survey for owls we broadcasted commercially available vocalizations (Colver et al. 1999) using a compact disc player and broadcaster (Bibby et al. 2002), and recorded other nocturnal species (nighthawks and poorwills) when observed. We established one nocturnal survey transect that bisected the monument along the main entrance road. The transect had four stations that were a minimum of 300 m apart. As with other survey methods, we varied observers and direction of travel along transects and did not survey during periods of excessive rain or wind to reduce bias. We began surveys approximately 45 minutes after sunset. We visited each of the four nocturnal survey stations three times each in 2001 and twice each in 2002.

When we were not conducting formal surveys and encountered a rare species, a species in an unusual location, or an individual engaged in a breeding behavior, we recorded UTM coordinates, time of detection, and (if known) the sex and age class of the bird. We recorded all breeding behavior observations using the standardized classification system (developed by the North American Ornithological Atlas Committee; NAOAC 1990). This system classifies breeding behavior into one of nine categories: adult carrying nesting material, nest building, adult performing distraction display, used nest, fledged young, occupied nest, adult carrying food, adult feeding young, or adult carrying a fecal sac. We made breeding observations during both standardized surveys and incidental observations.

Mammals

Previous inventories

We know of no earlier inventory work done for mammals. Only two research projects have been conducted at the monument, one on ground squirrels (Koprowski and Monroe 2003) and one on damage to cultural resources (Swann et al. 1994). We located only three mammal specimens previously collected from the monument.

This inventory

We surveyed for mammals using three field methods: live-trapping for rodents and ground squirrels (primarily nocturnal; herein referred to collectively as small mammals), infrared-triggered photography for medium and large mammals, and incidental observations for all mammals. We also located three mammal specimens collected from the monument. With no standing water available, we did not net for bats as it would likely not have been productive.

We selectively placed 8 small-mammal trapping sites in areas of the monument that we felt represented slight variations in vegetation community and structure. We avoided the vicinity of the picnic grounds because of the high density of round-tailed ground squirrels in that area and we prioritized the likelihood of documenting additional species in other areas. We used infrared-triggered cameras (Trailmaster) to record the presence of medium and large mammals. Trailmaster cameras have been proven to be the most cost-effective method for recording the presence of medium and large mammal species (Kucera and Barrett 1993; Cutler and Swann 1999; Swann et al. 2004). We placed cameras in two areas of the monument that we thought would record the highest number of species; typically these were in areas of dense vegetation. We baited camera sites with a commercial scent lure or canned cat food.

We recorded UTM coordinates of incidental observations made by any of the inventory crew members or the monument staff. Finally, we repeatedly checked the Casa Grande and its roof structure for bats.

RESULTS AND DISCUSSION

Plants

We recorded 60 species during our study, including 21 species that had not been previously documented in the monument. Combining data from all studies (Reichhardt 1992; Halvorson and Guertin 2003), including our own and from relevant records in the collections of two herbaria (University of Arizona and Western Archaeological Conservation Center), there have been 127 species of plants recorded on or adjacent to the monument. This number includes cultivated trees, but not cultivated shrubs and succulents (e.g., ocotillo) around the visitor center (see Reichhardt 1992 for an explanation). There have been 31 species of non-native plants observed or documented at the monument (24% of total flora), and of these, nearly 40% (*n* = 12) are grasses. The combined results of our inventory effort and the surveys of Halvorson and Guertin (2003) recorded 37 previously unrecorded species, 12 of which are non-native). These additional species may indicate a change in the plant community that appears to have occurred over the last 15 years. Indeed, of the 22 non-native species that Halvorson and Guertin mapped, 16 were found only along roads and/or the irrigation canal just outside the boundary, and an additional three species were found primarily along the monument's roads. New species were detected throughout their study. There were 52 species, including six non-natives, found by prior studies but not by our crews or by Halvorson and Guertin, further suggesting a shift in vegetation composition and increased non-native occurrence during the last 60 years. The list of plants that have not been found since 1942 includes three species of shrubs (Alkali goldenbush, fairyduster, and eastern Mojave buckwheat).

We believe that the combined effort of our study and previous studies and collections have recorded virtually all of the perennial plant species that occur at Casa Grande Ruins NM (excluding ornamentals around the visitor center). The list of annuals, however, is incomplete, due in part to the increasing number of non-native plants that are becoming established in the monument (Halvorson and Guertin 2003). Each study at the monument, including ours, has recorded from 11 to 21 species that were not reported by any other efforts. Because most of the new species for the monument are annual forbs and grasses, these numbers highlight the importance of surveying following periods of above- normal precipitation (as we did in 2001) and to survey repeatedly.

Amphibians and Reptiles

We recorded three amphibian and 11 reptile species at Casa Grande Ruins NM. Common side-blotched and western whiptail lizard were the two most abundant species and together they represented > 75% of all detections across all survey methods. We added one new species (Great Plains toad) to the monument list with

Table 1. Summary results of the vascular plant and vertebrate inventories at Casa Grande Ruins NM, 2001 and 2002.

Taxonomic group	Number of species recorded	Number of non-native species	Number of new species added to monument list[a]
Plants	60	12	21
Amphibians and reptiles	14	0	13
Birds	82	3	70
Mammals	13	2	7
Totals	169	17	111

[a] Species that had not been observed or documented by previous studies.

the road survey method; in fact we observed all three of the amphibian species recorded by our inventory during one night of road survey in 2002. Although the pitfall trap did not contribute additional species to our monument list, results from the trap were consistent with other methods and suggest that common side-blotched and western whiptails are among the most common lizards at the monument. Incidental detections did not add any species to our lists, but this method did add records for species that were seldom detected by other methods, notably Couch's spadefoot, coachwhip, and common kingsnake. We found no animals underneath coverboards.

It is seems unlikely that we missed several conspicuous species that we would expect to find at the monument: zebra-tailed lizard, desert iguana, long-nosed leopard lizard, and sidewinder. Species likely present in the monument that we did not detect include snakes that are nocturnal and inconspicuous such as: western blind snake, spotted leaf-nosed snake, saddled leaf-nosed snake, glossy snake, western ground snake, western shovel-nosed snake, and night snake (Stebbins 2003). We believe that our inventory detected fewer than 90% of the amphibians and reptiles present simply because the list has so few names on it that even adding one is a significant percentage.

The amphibian and reptile communities at Casa Grande Ruins NM comprise relatively few species in comparison to what was likely present historically or in comparison to what has been documented in the course of other recent herpetofauna inventories in management units of similar size in southern Arizona (Rosen and Mauz 2001; Powell et al. 2002; Powell et al. 2003; Powell et al. 2006). This low species richness likely results from the land uses in the vicinity of the monument and degradation of the nearby Gila River (i.e., loss of aquatic and riparian resources; McNamee 1994; Ingram 2000).

Birds

We recorded 82 bird species during the two years of the study. Seventy-one percent (n = 58) of the species that we observed were neotropical migrants. We observed a number of species of conservation concern: loggerhead shrike, burrowing owl, peregrine falcon, and ferruginous hawk, all of which are considered "Species of Concern" by the U.S. Fish and Wildlife Service. Of the 82 bird species on the monument's list, only three (3.7%) are non-native: rock pigeon, European starling, and house sparrow.

We recorded 63 species during VCP surveys at the monument. The mourning dove, Gambel's quail, and house sparrow were the most abundant species during this portion of the study. We observed 32 species during four surveys of line transects in the fall of 2002. The mourning dove and great-tailed grackle were the most frequently detected species. We recorded four species during nocturnal surveys: lesser nighthawk, great horned owl, burrowing owl, and barn owl. Thirty-six species were recorded outside of formal surveys, including eight observations for species that we did not find with any other survey type.

All of the most abundant species at Casa Grande Ruins NM are considered human-adapted generalist species in southern Arizona. These species reach high densities in human-dominated landscapes (Mills et al. 1989; Germaine et al. 1998): mourning dove, rock pigeon, Gila woodpecker, cliff swallow, European starling, red-winged blackbird, great-tailed grackle, house finch, and house sparrow. Rock pigeon, house finch, and house sparrow regularly use the Casa Grande structure and therefore cause damage through roosting and nesting (Swann et al. 1994; NPS 1997). Based on our complete coverage of the monument for two breeding seasons, we believe that we recorded all of the species that permanently resided or bred in the monument. However, a species-accumulation curve suggests that we would record additional migrant species with further effort.

Mammals

The current list of mammals for Casa Grande NM consists of 13 species, 7 small mammals and 6 medium-sized mammals; 2 species (domestic dog and cat) are non-native. This study added 7 species to the monument's official list. Using the live-traps, we recorded all seven species of small mammals. Merriam's kangaroo rat and the Sonoran Desert pocket mouse were found to be the most widespread and abundant small mammals.

With the Trailmaster cameras we recorded 3 species. The most photographed species was the cottontail. These animals were most likely desert cottontails; eastern cottontail is difficult to differentiate in photographs, but is unlikely to be present in the area near the monument (Hoffmeister 1986). Other mammal species detected with cameras were black-tailed jackrabbits and the western white-throated woodrat.

University of Arizona personnel made incidental observations of 5 species during the course of the study. Monument personnel reported regular observations of feral cats. No bats were observed in any part of the monument. We collected two skulls during the course of the study, a domestic cat and an American badger.

The majority of our mammal survey effort targeted small mammals. Based on a species accumulation curve, it appears that we trapped most of the species that occurred on the monument during the time of the study. A number of species could be present or may historically have been present at the monument, based on range maps and published habitat associations, including: little pocket mouse, Bailey's pocket mouse, cactus mouse, Arizona cotton rat, and the non-native house mouse (Hoffmeister 1986). It is quite likely that these species, particularly cactus mouse and house mouse, would be captured with additional survey effort. Also, there are a few species that are within range but would require higher density of vegetation (particularly dense grasses and forbs): Botta's pocket gopher, silky pocket mouse, banner-tailed kangaroo rat, western harvest mouse, and hispid cotton rat (Hoffmeister 1986). Based on the description of the vegetation at the monument prior to cattle grazing and mesquite die-off (Clemensen 1992), it is likely that these species were once common residents of the monument. Also, Merriam's mouse, probably once common at the monument before the die-off of the large mesquite forest, is very restricted to that vegetation component and therefore unlikely to be present now.

We found no large mammals (e.g., mountain lion, deer, or bear) during our surveys and no large mammals have been reported for decades (Clemensen 1992; CGRNM Staff, pers. comm.). Clemensen (1992) also reports that fox and bobcat have been seen at the monument. We observed or documented some medium-size mammals such as badger (skull), striped skunk (sighting), and feral cats and dogs. Coyotes have been reported in the monument both historically (Clemensen 1992) and recently (CGRNM Staff, pers. comm.).

One particularly striking change in the mammal community has been the use of the Casa Grande by Brazilian ("Mexican") free-tailed bats. In 1944, monument personnel counted over 5,000 bats exiting the ruins, but by 1956 bats no longer lived on the monument (Clemensen 1992). This time period coincided with the increased use of insecticides, including DDT. More recently, Swann et al. (1994) did not find any bats or sign of bats on their inspection of the Casa Grande in the late summer and fall of 1993 nor did we find any bats during our surveys. Although free-tailed bats have a large foraging range (Best and Geluso 2003), the combination of pesticide use, subsequent lack of insects in areas adjacent to the monument, and regional-scale population changes all work to keep the bats from returning.

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VASCULAR PLANT AND VERTEBRATE INVENTORY OF TUMACÁCORI NATIONAL HISTORIC PARK

Brian F. Powell, Eric W. Albrecht, Cecilia A. Schmidt, Pamela Anning, Kathleen Docherty

From 2000 to 2003 we surveyed for vascular plants and vertebrates (fish, amphibians, reptiles, birds, and mammals) at Tumacácori National Historical Park (NHP) to document presence of species within the administrative boundaries of the park's three units. Because we used repeatable study designs and standardized field techniques, these inventories serve as the first step in a long-term monitoring program. We recorded 591 species at Tumacácori NHP, significantly increasing the number of known species for the park. Species of note in each taxonomic group include:

- Plants: Second record in Arizona of muster John Henry, a non-native species that is ranked a "Class A noxious weed" in California;
- Amphibian: Great Plains narrow-mouthed toad;
- Reptiles: Eastern fence lizard and Sonoran mud turtle;
- Birds: Yellow-billed cuckoo, green kingfisher, and one observation of the endangered southwestern willow flycatcher;
- Fishes: Four native species including an important population of the endangered Gila topminnow in the Tumacácori Channel;
- Mammals: Black bear and all four species of skunk known to occur in Arizona.

We recorded 79 non-native species, many of which are of management concern, including: Bermudagrass, tamarisk, western mosquitofish, largemouth bass, bluegill, sunfish, American bullfrog, feral cats and dogs, and cattle. We also noted an abundance of crayfish (a non-native invertebrate). We review some of the important non-native species and make recommendations to remove them or to minimize their impacts on the native biota of the park.

Tumacácori NHP possesses high biological diversity of plants, fish, and birds for a park of its size. This richness is due in part to the ecotone between ecological provinces (Madrean and Sonoran), the geographic distribution of the three units (23 km separates the most distant units), and their close proximity to the Santa Cruz River. The mesic life zone along the river, including cottonwood/willow forests and adjacent mesquite bosque at the Tumacácori unit, is representative of areas that have been destroyed or degraded in many other locations in the region. Additional elements such as the semi-desert grassland vegetation community are also related to high species richness for some taxonomic groups.

For complete details of the Tumacácori NHP study see Powell et al. (2005) [http://sbsc.wr.usgs.gov/products/ofr/]. Scientific and common names used throughout this chapter are current according to accepted authorities for each taxonomic group: Integrated Taxonomic Information System (ITIS 2001) and the PLANTS Database (USDA

2004) for plants; Stebbins (2003) for amphibians and reptiles; American Ornithologist Union (AOU; 1998, 2003) for birds; and Baker et al. (2003) for mammals.

PARK OVERVIEW

Park Area and History

Tumacácori NHP contains three small units: Calabazas, Guevavi and Tumacácori. Tumacácori, the main administrative unit, is located on 258 hectares at the town of Tumacácori, Arizona. The Calabazas (9 ha) and Guevavi (3 ha) units are 15 km and 23 km SSE of Tumacácori, respectively (Figure 1). The units of the park lie along the Santa Cruz River; the river is perennial at Tumacácori and Guevavi.

Tumacácori NHP preserves the remnants of three Spanish colonial missions located along the upper Santa Cruz River in southern Arizona. Originally established in 1908 as a monument under the Antiquities Act, the park protected the San Jose de Tumacácori (Tumacácori unit), a Spanish mission founded in 1691. In 1990, the area was designated a National Historical Park with the inclusion of Los Santos Angeles de Guevavi mission (Guevavi unit; founded in 1691) and San Cayetano de Calabazas mission (Calabazas unit; founded in 1756).

Physiography and Geology

The Upper Santa Cruz River Valley is located in the southern Basin and Range Province of southeastern Arizona and northern Sonora. This terrain of alternating, fault-bounded, linear mountain ranges and sediment-filled basins began to form in southeastern Arizona as the result of dominantly east-northeast/west-southwest-directed crustal extension. The mountain ranges to the east of the park (Santa Rita, San Cayetano, and Patagonia) consist of a variety of rocks, including igneous, metamorphic, volcanic, and sedimentary, ranging in age from Precambrian to Miocene. The Tumacácori and Atascosa Mountains west of the park are composed chiefly of Tertiary volcanic rocks with the exception of a Jurassic granitic pluton south of Sopori Wash at the northern end of the Tumacácori Mountains. The Pajarito Mountains at the southern end of the valley, west of Nogales, are composed of Cretaceous volcanics.

Hydrology and Soils

The three units of Tumacácori NHP are associated with distinct pockets of reliable water, resulting from basin-fill sediments over relatively shallow aquifers that fill quickly after precipitation (Sprouse et al. 2002). Perennial flow at the Tumacácori unit is augmented by treated wastewater discharges from the Nogales International Wastewater Treatment Plant. Basin-fill sediments along the Santa Cruz River, north of the City of Nogales to Amado, form three aquifer units: Nogales Formation, Older Alluvium, and Younger Alluvium (ADWR 1999). In the vicinity of all the park units the soils are typical of floodplains, alluvial fans, and valley slopes of this semi-desert region; they are deep and well drained, with a high water-holding capacity (NPS 1996).

Climate

Tumacácori NHP is located within the semi-desert climatic zone of southern Arizona, which is characterized by heavy summer (monsoon) storms brought about by moisture coming from the Gulf of Mexico and less intense, frontal storms from the Pacific Ocean in the winter. Approximately half of the annual precipitation falls from July to September (WRCC 2004). The area's hot season occurs from April through October; maximum temperatures in July often exceed 40° C. Intense surface heating during the day and active radiant cooling at night can result in daily temperature ranges of 17° to 22° C. Winter temperatures are mild. Prevailing winds tend to follow the Santa Cruz Valley, blowing downslope (from the south) during the night and early morning, and upslope (from the north) during the day.

Weather during the three years of this study was highly variable and atypical. Annual total precipitation ranged from slightly greater than

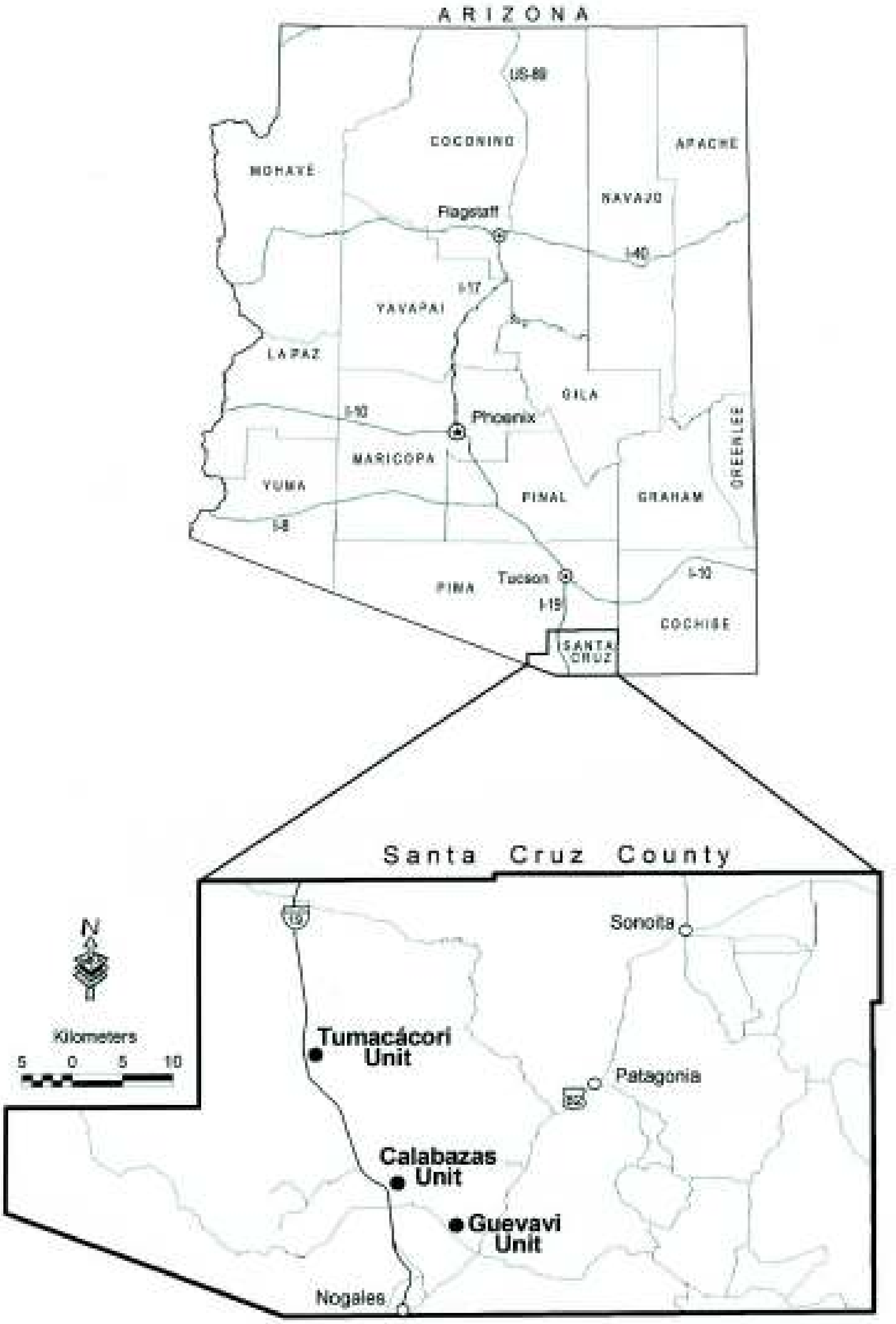

Figure 1. Locations of the three units of Tumacácori NHP in southern Arizona.

average (340 mm) in 2000 (488 mm) and 2001 (422 mm) to one of the driest years on record in 2002 (236 mm). Annual mean temperatures were above the long-term mean (17.7° C) in 2000 and 2002 (18.0° C in both years) and below it in 2001 (17.4° C) (WRCC 2004).

Vegetation

All three units have vegetation typical of the semi-desert grassland association (Brown et al. 1979; Brown and Lowe 1980). Common species include velvet mesquite, foothills palo verde and species of acacia, wolfberry, and greythorn, as well as annual and perennial grasses, and forbs (NPS 1996). At the Tumacácori unit, in particular, there are dense stands of mesquite bosque and gallery riparian vegetation. Velvet mesquite, netleaf hackberry, and Mexican elderberry are common in the mesquite bosque areas, whereas in the mesic riparian areas, Fremont cottonwood, Goodding's willow, tamarisk, and Arizona walnut form dense and structurally diverse stands of vegetation, particularly adjacent to surface water.

Natural Resource Management Issues

Because of its location along a river corridor, its proximity to the border with Mexico, and its diversity of biotic communities, Tumacácori NHP has many natural resource management issues that deserve attention.

Adjacent Development

The boundaries of the Tumacácori unit are near the town of Tubac (to the north) and the Rio Rico development (to the south). Much of the remaining undeveloped land adjacent to the park is currently used for irrigated agriculture or livestock grazing, but the population of Rio Rico is expected to increase three-fold by 2025 (ADWR 1999) and Tubac is rapidly expanding as well. Similarly, increased residential development is taking place near the Calabazas unit, which is close to ex-urban sprawl from the City of Nogales, Arizona. Potential impacts of residential development include an increase in the number and extent of non-native plants, increased runoff of toxins and sediment, disruption of animal movement patterns, habitat loss and fragmentation, and increased harassment and mortality of native animals by free roaming pets, feral dogs and feral cats (Mills et al. 1989; Theobald et al. 1997; Riley et al. 2003).

Water Quality

Given the park's location along the Santa Cruz River, the quantity and quality of surface water are important concerns at the park (Sprouse et al. 2002; King et al. 1999). Effluent from the Nogales International Wastewater Treatment Plant (NIWTP), located 14 km upstream from the Tumacácori unit and across the river from the Calabazas unit, has a significant impact on both water quality and quantity. Treated effluent provides perennial surface flow for more than 15 km of the Santa Cruz River in an area that would otherwise be dry much of the year.

Countering the benefits from the presence of the effluent are a number of water quality problems that affect park resources. Water samples from the Calabazas Road Bridge (located between the Tumacácori and Calabazas units) have included twenty-two groups of parameters that exceeded National Park Service Water Resources Division screening criteria (NPS 2001). In addition, dissolved oxygen, pH, chlorine, cyanide, cadmium, copper, lead, mercury, selenium, silver, and zinc exceeded respective U.S. Environmental Protection Agency (USEPA) criteria for the protection of freshwater aquatic life (ADEQ 2000; USEPA 2001). Nitrate, arsenic, barium, cadmium and chromium exceeded USEPA drinking water criteria (ADEQ 2000; USEPA 2001), fecal-indicator bacteria concentrations (total coliform and fecal coliform) exceeded Water Resources Division screening limits for freshwater bathing, and turbidity measurements exceeded Water Resources Division limits deemed safe for aquatic life (ADEQ 2000; NPS 2001). The ADEQ has categorized the water in the Santa Cruz River as "impaired" due to turbidity at the Guevavi unit and impaired due to fecal-indicator bacteria concentrations along stretches adjacent to both the Calabazas and Tumacácori units (ADEQ 2000).

Although levels of ammonia decreased with distance from the treatment plant, the toxicity of water upstream of the Tumacácori unit may dramatically reduce the likelihood that additional native aquatic or semi-aquatic animals will colonize that area from upstream locations. Indeed, in an earlier study, researchers noted that despite presence of five species of amphibian upstream from the treatment plant, "… no amphibians are found along the river from the waste water outfall downstream for several kilometers" (Drost 1998). Upgrades to the treatment plant scheduled in 2009 will significantly improve the water quality in the effluent-dominated reach of the river.

Riparian Plant Communities

Riparian plant communities in the southwestern United States account for less than 1% of the landscape cover (Skagen et al. 1998), yet it is estimated that greater than 50% of southwestern bird species (Knopf and Samson 1994) and up to 80% of all wildlife species in the southwest are dependent on riparian areas (Chaney et al. 1990). Riparian areas in arid regions support high bird species diversity due to their structural and floristic diversity, giving rise to abundant insects for foraging and large trees for nesting (Thomas et al. 1979; Lee et al. 1989; Strong and Bock 1990; Powell and Steidl 2000). Riparian vegetation, such as cottonwood, willow, and ash have been found to decrease levels of heavy metals in water and soil in addition to decreasing water temperatures, providing a source of organic matter, and stabilizing stream banks (Osborne and Kovacic 1993; Karpiscak et al. 1996; Karpiscak et al. 2001). The Bureau of Land Management estimates that less than 20% of the western United States' potential riparian vegetation remains to perform these vital services (BLM 1994). Such loss highlights the importance of maintaining these rare riparian plant communities along the Santa Cruz River.

Non-native Species

Awareness of non-native species as a management issue has risen dramatically in recent years and ecologists have ranked it as one of the most significant causes of species endangerment (Brooks and Pyke 2001). Non-native plant species are a significant management issue at the park, particularly at the Tumacácori unit, where invasives such as tamarisk, Bermudagrass, and Russian thistle are well established. Non-native plants are known to alter ecosystem function and processes (Naeem et al. 1996; D'Antonio and Vitousek 1992) and reduce the abundance of native species, potentially permanently changing diversity and species composition (Bock et al. 1986; D'Antonio and Vitousek 1992; OTA 1993). The Tumacácori unit provides habitat for non-native vertebrates as well, including western mosquitofish, largemouth bass, bluegill, sunfish, American bullfrog, house sparrow, European starling, cattle, and feral cats and dogs.

Impacts from Undocumented Immigrants

The proximity of the park to the U.S.-Mexico border results in a number of unique management issues. The Santa Cruz River provides a well-known and well-used corridor for undocumented immigrants traveling north from Mexico, and much of this traffic passes through the Tumacácori unit (NPS 2003). Although visitor safety concerns have not yet become a significant issue, reported impacts to the park include erosion, compacted soils, and vandalism (NPS 1996). Other national parks in the border region have reported fire hazards, theft and destruction of historic resources, disruption of wildlife movements (including reduced access to water sources), reduced water quality, and closure of park attractions due to safety concerns (NPS 2003). To our knowledge only one (recently initiated) study is aimed at quantifying the effects of immigrants on animal communities in southern Arizona (O'Dell 2003; McIntyre and Weeks 2002).

Trash Flows

During heavy flooding events in the Santa Cruz River watershed, a large quantity of trash washes downstream, primarily from the Nogales (Portrero) Wash that originates in Sonora, Mexico. This trash often becomes trapped in a few locations, leading to large accumulations. Trash is principally plastics, such as water bottles, but also includes batteries and tires. Park personnel and volunteers have done an excellent job of cleaning up a number of these sites in recent years, but the problem will likely continue.

METHODS

Plants

Previous inventories

There were two previous plant inventories at the Tumacácori unit. Mouat et al. (1977) recorded 130 species during seven survey days in the spring and summer of 1977. A less complete and poorly documented survey was conducted at the Tumacácori unit in the 1980s or 1990s (Bennett, year unknown). There are also 50 specimens from the park at the University of Arizona (UA) Herbarium. To our knowledge, there were no prior plant inventories at either the Calabazas or Guevavi units.

This inventory

Our surveys included both qualitative and quantitative methods: qualitative "general botanizing" surveys in which we opportunistically collected and recorded plants, and quantitative plot-based sampling which included three complementary methods to estimate abundance, percent cover by species, and species composition of all plants in a small area.

General botanizing surveys encompassed most areas within the park during most visits. For modular plots we used a simple random sampling design (Thompson 1992) to locate 17 plots. We also subjectively placed three plots in community types that we felt were not represented by the 17 other plots: one each in an agricultural field, in dense mesquite bosque, and in dense mesic riparian vegetation.

We made 29 general botanizing visits (typically one observer for one-half day) within the Tumacácori unit and 14 and 15 visits to the Calabazas and Guevavi units, respectively. Whenever possible we collected one representative specimen (with reproductive structures) for each plant species in each park unit. We also maintained a list of species observed but not collected within each unit. We accessioned mounted specimens into the UA herbarium. Four observers measured vegetation on 20 plots at the Tumacácori unit during ten field days from 2 to 17 November 2002. Nineteen plots had four modules in a 20 x 20 m arrangement and one plot had two modules in a 20 x 10 m arrangement (78 modules).

Fish

Previous inventories

Arizona Game and Fish Department personnel completed periodic surveys of the Santa Cruz River, in or near Tumacácori NHP, between 1998 and 2001, in 2003, and one survey in the Tumacácori Channel in 1999 (Voeltz and Bettaso 2003).

This inventory

We surveyed for fish at two sites at the Tumacácori unit: the Santa Cruz River and the Tumacácori Channel. The channel is an abandoned meander that is watered by groundwater seepage, maintaining a downstream connection with the river. We captured fish using two methods: (1) electrofishing (Dauble and Gray 1980) with a Smith-Root backpack unit in both areas (12-B POW set to DC pulse width of 60 Hz, frequency of 6 ms, voltage of 300 V; Smith-Root, Inc., Vancouver, WA); and (2) dipnetting (long-handled dip nets with 4 mm mesh; Dauble and Gray 1980) in shallow-water areas of the channel. Three to four field personnel surveyed the channel and river on four sampling periods; once each in the spring and fall of 2001 and 2002.

Amphibians and Reptiles

Previous inventories

To our knowledge there were no inventories nor any research related to amphibians and reptiles at Tumacácori NHP prior to this study.

This inventory

We surveyed for herpetofauna in 2001 and 2002 using four methods. We used both diurnal and nocturnal surveys in an effort to detect species with restricted periods of activity (Ivanyi et al. 2000).

For all methods except intensive surveys, we surveyed for herpetofauna in non-random sites because we wanted to detect as many species as possible. To determine locations for intensive survey plots we used a modified simple-random sampling design (Thompson 1992) whereby we used ArcView GIS software to select points (15) at random in each park unit to serve as the southwest corner of each plot. We then post-stratified plots (Thompson 1992) by vegetation type; in lieu of a vegetation map for the park we used aerial photographs to estimate vegetation types and moved the location of some plots that appeared to cover more than one vegetation type into the type representing the majority of the area.

In 2001 we used searches constrained by both time and area to provide a standardized survey method. These surveys are similar to visual encounter surveys (Crump and Scott 1994), but were confined to a 1 ha (100 x 100 m) plot. Due to the heterogeneity of vegetation types at the Tumacácori unit, our random locations resulted in plots representing each of the dominant community types in the park: riparian, mesquite bosque, semi-desert grassland, and agricultural land. We visited all plots on 24–27 April and most plots again on 9–10 September, 2001. We began all 35 surveys (one person-hour each) between 7:30a.m. and 12:30p.m. In 2002 we chose not to continue intensive surveys because of the relatively low number of species and individuals recorded, and instead focused our efforts on other methods.

We used the extensive survey method for both diurnal and nocturnal surveys. To increase the odds of finding rare animals, we placed 20 cover boards (Fellers and Drost 1994) around the festival grounds area at the Tumacácori unit, and checked these opportunistically by turning the boards. We recorded UTM coordinates to define the boundaries of our search area or the path we followed during our surveys.

We spent 168 hours on 52 extensive surveys between 24 April and 24 September 2001, and between 11 July and 25 August 2002. Almost 90% of the surveys (n = 46) were initiated during the cooler evening, night-time, or morning hours (5p.m. to 9a.m.). We operated one pitfall trap array (with four pitfall traps and six funnel traps) near the bank of the Santa Cruz for a total of 672 hours between 11 July and 24 September 2001 and between 10 July and 26 September 2002 (Gibbons and Semlitsch 1981; Corn 1994).

When we encountered uncommon amphibians and reptiles outside of formal surveys, we recorded the species, sex and age class (if known), time of observation, UTM coordinates, and route we were following. Incidental detections recorded by other survey crews (e.g., bird crew) were not accompanied by route descriptions. We collected incidental observations between 25 April and 24 September 2001, and between 15 May and 25 August 2002.

Birds

Previous inventories

Previous bird research at Tumacácori NHP focused on the yellow-billed cuckoo (Powell 2000) and on mist-netting passerines and hummingbirds from 1997 to 2004 (Turner 2003).

This inventory

We surveyed for birds at the Tumacácori unit in 2001 and at all three units in 2002 and 2003. We used four field methods: variable circular-plot (VCP) counts for diurnal breeding-season birds, nocturnal surveys for owls and nightjars during the breeding season, line-transects for fall and winter-season birds, and incidental observations for all birds in all seasons. We concentrated most of our survey effort during the breeding season because bird distribution is relatively uniform during the breeding season due to territoriality among birds (Bibby et al. 2000). This survey timing increases our precision in estimating relative abundance and enabled us to document breeding activity. Our survey period included peak spring migration times for most species, which added many migratory species to our list (Reynolds et al. 1980; Buckland et al. 1993; Ralph et. al 1995; McGarigal et al. 2000)

We used a modified line-transect method (Bibby et al. 2000) to survey for birds in all units from November 2002 to January 2003. Line transects differ from station transects (such as those used in our VCP surveys) in that an observer records birds seen or heard while the observer walks an envisioned transect line, rather than by standing at a series of stations. The transect method is more effective during the non-breeding season because bird vocalizations are less conspicuous and frequent, and therefore birds tend to be less visible (Bibby et al. 2000).

To survey for owls we broadcasted commercially available vocalizations (Colver et al. 1999) using a compact disc player and broadcaster (Bibby et al. 2000), and recorded other nocturnal species (nighthawks and poorwills) when heard. We established one nocturnal survey transect along a road or trail in each park unit. The number of stations varied from one to three per transect and stations were a minimum of 300 m apart. As with other survey methods, we varied observers and direction of travel along transects and did not survey during periods of excessive rain or wind. We began surveys approximately 45 minutes after sunset (Fuller and Mosher 1987). We did not specifically survey for any species listed as threatened or endangered — e.g., the cactus ferruginous pygmy-owl (*Glaucidium brasilianum cactorum*) because such species require specific protocols for surveying.

When we were not conducting formal surveys and we encountered a species of interest, a species in an unusual location, or an individual displaying breeding behavior, we recorded UTM coordinates, time of detection, and (if known) the sex and age class of the bird. We noted all breeding-behavior observations using a standardized classification system (NAOAC 1990).

Mammals

Previous inventories

To our knowledge, there has been no previous mammal research at Tumacácori NHP, and though some mammal specimens have been collected from the park, there have been no comprehensive mammal inventories.

This inventory

We surveyed for mammals using four field methods: trapping for small mammals, infrared- triggered photography for medium and large mammals, investigation of roost sites for bats, and incidental observations for all mammals.

We trapped small mammals at all three units in 2000 and 2001. We used Sherman® live traps (large, folding aluminum or steel, 3 x 3.5 x 9"; H. B. Sherman, Inc., Tallahassee, FL) set in grids (White et al. 1983), with 10 m spacing among traps arranged in configurations of five rows and five columns (Calabazas and Guevavi units) or 10 rows and five columns (Tumacácori unit).

We used Trailmaster® cameras (model 1500, Goodman and Associates, Inc., Lenexa, KS; Kucera and Barrett 1993) to record the presence of medium and large mammals at the Tumacácori unit only.

As with other taxa, we recorded UTM coordinates of incidental mammal sightings. Observers from all field crews (e.g., bird crew as well as mammal crew) recorded mammal sightings and signs such as identifiable tracks or scat, and we took photo vouchers when the sign alone was definitive.

We visited the Tumacácori unit once, on 2 October 2001, to search for bats in and around the Mission structure. We did not mist net bats at the Santa Cruz River because netting is most efficient when areas of open water are limited, thereby concentrating foraging bats into a small area.

RESULTS AND DISCUSSION

Plants

We recorded 378 species during general botanizing and modular plot surveys in 2000 to 2003 (Table 1). We recorded the most species at the Tumacácori unit (293). We recorded fewer species at the Calabazas (175) and Guevavi units (151). The most common families were composites (Asteraceae), grasses (Poaceae) and legumes (Fabaceae). More than 82% of the remaining families were represented by three or fewer species, a pattern consistent with floras of nearby areas (McLaughlin et al. 2001). We included all subspecies and/or varieties in our summary statistics of the number of "species" recorded.

We recorded 67 non-native species in all units combined. Excluding ornamentals, the percentage of non-native species was 18% at the Tumacácori unit (52), 11% at the Guevavi unit (17), and 9% at the Calabazas unit (16). Considering all units, the grass family (Poaceae) had the highest percentage (33) of non-native species. Perhaps the most notable non-native species we documented was the muster John Henry (at the Tumacácori unit); this was the second documentation of its occurrence in Arizona.

We searched for two endangered species thought to be in the area: Pima pineapple cactus (*Coryphantha scheeri* var. *robustispina*) and Huachuca water umbel *(Lilaeopsis schaffneriana* var. *recurva*), but did not find either.

Other researchers listed 46 species at the Tumacácori unit that we did not find. While these may still be present and we missed them, alternative explanations include misidentification (many previous records were not documented), local extirpation, and use of different field methods. Judging from the presence of conspicuous perennial species at both the Calabazas and Guevavi units but not Tumacácori unit (e.g., whitethorn acacia), some local extirpation may have occurred. Three factors likely contributed to our finding twice the number of species reported by previous studies (Mouat et al. 1977; Bennett year unknown): (1) our field effort was more than twice that of previous studies, (2) our survey area was larger, and (3) we likely benefited from a winter (2000) that had more precipitation than average, resulting in higher species richness of annuals during our fieldwork than during sampling by Mouat et al. (1977).

Once well established, a number of non-native species pose a significant management problem. Prominent species include tamarisk, Bermudagrass, Lehmann lovegrass, Johnsongrass, Russian thistle, London rocket, and yellow sweet clover. Bermudagrass, in particular, is difficult to control and was recorded in 85% of the modular plots. A complete description of these non-native species as well as their life history, threat to native species, and eradication method(s) can be obtained from Halvorson and Guertin (2003).

Additional general botanizing surveys, carried out during wet summers in the expansion area of the Tumacácori unit, should increase the species list for annual plants. A diligent effort to seek out species that have previously been reported (Moatt et al. 1977; Bennett, year unknown) but not found during our surveys, would help confirm possible changes to the flora. Additional modular plots, especially in the under-sampled mesquite bosque and dense cottonwood/willow forests, would be an effective tool for long-term monitoring of vegetation changes.

Fish

We recorded eight species (four native, four non-native) and one hybrid (green sunfish/bluegill) at Tumacácori NHP (Table 1). We recorded all eight species on the first sampling event in the channel, and Gila topminnow, longfin dace, and western mosquitofish in both sites on all sampling events.

Table 1. Summary results of vascular plant and vertebrate inventories at Tumacácori NHP, 2000–2003.

Taxonomic group	Number of species recorded	Number of non-native species	Number of new species added to park list[a]
Plants	378	67	168
Fish	8	4	3
Amphibians and Reptiles	24	1	22
Birds	146	3	40
Mammals	35	4	33
Totals	591	79	266

[a] Species that had not been observed or documented by previous studies.

Species richness in the channel was higher than in the river on all but the last sampling event.

Based on distribution records (Minckley 1973) and our experience, we documented all species that are thought to occur in the park. The apparent persistence of the federally endangered Gila topminnow in the Tumacácori Channel is perhaps the most important finding of our inventory effort. We found Gila topminnow in all sampling periods and they were likely present in the channel during the extreme drought of the late spring/early summer of 2002 when no surface water was present at the river site. It appears that the channel serves as a refugium during extreme drought events.

The other native species documented were longfin dace, Sonora sucker and desert sucker. The presence of Sonora and desert suckers for the first three sampling events in the Tumacácori Channel is significant because both species are rare in southern Arizona (Recon 2004). There was at least one prior sighting of the desert sucker in the channel in June 1999 (Voeltz and Bettaso 2003). However, we did not find either species during our fourth sampling period in the fall of 2002. The possible loss of these species from the park is particularly troubling given that movement back to the park may take considerable time or may not happen at all.

Once introduced throughout the western U.S. to control mosquito populations, the western mosquitofish is thought to be one of the major reasons for population declines of the Gila topminnow (and other small native fishes in the southwest) through predation, harassment, and competition (Meffe 1985; Courtenay and Meffe 1989). The persistence of the Gila topminnow in the presence of western mosquitofish is notable. In addition to large numbers of western mosquitofish, we recorded three other non-native sport-fish species: largemouth bass, bluegill, and green sunfish.

During most of our surveys, we observed crayfish (*Orconectes virilis*), an important non-native invertebrate, especially in the channel. Crayfish are one of the most serious threats to native aquatic biota because they effectively compete with aquatic herbivores, prey on aquatic invertebrates and vertebrates, disrupt normal nutrient cycling, and decrease aquatic macroinvertebrate diversity (Creed 1994; Fernandez and Rosen 1996). A program to eliminate these crayfish would be beneficial to the native biota of the Santa Cruz River and the Tumacácori Channel, but would be logistically difficult.

Amphibians and Reptiles

Using intensive surveys, we recorded seven amphibian and 17 reptile species at Tumacácori NHP in 2001 and 2002 (Table 1). We recorded the most species (n = 22) at the Tumacácori unit and the fewest (n = 9) at the

Guevavi unit. A single Woodhouse's toad was heard calling on 24 July 2001; otherwise the only amphibians heard vocalizing were American bullfrogs.

We recorded the most species ($n = 7$) in the semi-desert grassland community type and the fewest ($n = 2$) in the mesquite bosque community type. Clark's spiny lizard was the most widespread species (recorded at least once in all park units and community types), the Sonoran spotted whiptail was the most abundant reptile on plots in all community types except in the mesquite bosque where it was not recorded. The common lesser earless lizard, Clark's spiny lizard, and regal horned lizard were most abundant in the semi-desert grassland community type; the eastern fence lizard and the two whiptails were most abundant in riparian areas; and the ornate tree lizard and gophersnake were most abundant in the cleared mesquite bosque area.

Relative abundance of all reptiles in the riparian community type was more than 30% higher than in any other community type, yet species richness in the riparian community type (6 species) was equal to that of the semi-desert grassland community type at the Calabazas unit and only slightly greater than richness in the cleared mesquite bosque community type (5 species). The eastern fence lizard and the regal horned lizard were the only species that we found in only one community type, riparian and semi-desert grassland, respectively.

We added one new species to the park list by using incidental observations (western box turtle) and another using the pitfall array (Great Plains narrow-mouthed toad).

Species accumulation curves for amphibian surveys indicate that we recorded most of the species likely to be observed with these methods, at least under the environmental conditions we experienced during our study. In contrast, our reptile list for the park is likely far from complete. Based on range maps, known habitat requirements, historic records, and results of a nearby study, an additional 32 species may be present, may have been historically present, or might pass through the park in the course of movement from nearby areas.

We found American bullfrogs in the Tumacácori Channel during both herpetological and fish surveys. The American bullfrog is native to eastern North America but has been introduced throughout the western U.S. for food production and sport (Stebbins 2003). The American bullfrog is a species of management concern at Tumacácori NHP because both adults and tadpoles are voracious predators (Kiesecker and Blaustein 1997) and are thought to be partially responsible for the decline of many native fish species (Minckley and Deacon 1991), reptiles (Schwalbe and Rosen 1988), and amphibians (particularly other Ranid frogs; Hayes and Jennings 1986; Lawler et al. 1999) in the southwest.

Birds

We recorded 146 species during the two years of the study. Although comparisons among units may be biased by unequal survey effort, species richness was highest at the Tumacácori unit ($n = 129$), lower at the Calabazas unit ($n = 80$), and lowest at the Guevavi unit ($n = 74$). We recorded 50 species at all three units and 59 species at only one of the three units. All three non-native species that we found during this study (rock pigeon, European starling, and house sparrow) were recorded at the Tumacácori unit, whereas only one (European starling) was recorded at the Calabazas unit and no non-natives were recorded at the Guevavi unit. Neotropical migrant species made up 71% (103) of all species recorded.

We recorded 104 species during VCP surveys in 2001 and 2002. Species richness was 57–71 among community types. We found 34 species that were unique to a single community type while an equal number of species were recorded in all community types. The number of species unique to a community type was highest for semi-desert grasslands (14) and fewest for the developed area (4). House sparrows were most abundant and were recorded predominantly in the developed area.

Other abundant species in the developed area were the vermilion flycatcher and phainopepla. In the mesquite bosque, the yellow-breasted chat, Bell's vireo, and Lucy's warbler were most abundant, in the adjacent riparian area, the yellow-breasted chat, Bewick's wren, and song sparrow were the most abundant. At the Calabazas and Guevavi units, representing the semi-desert grassland community, the Lucy's warbler and Bewick's wren were the most abundant.

We recorded 56 species during line-transect surveys in the three park units. Species richness was 21–23 among the community types. The most abundant species in each community type were: the chipping and white-crowned sparrows in the mesquite bosque, the European starling and white-crowned sparrow in the developed area, the yellow-rumped warbler and chipping sparrow in the riparian area, and the chipping sparrow and mourning dove in the semi-desert grassland.

During nocturnal surveys, we recorded three species of owls (barn owl, western screech owl, elf owl) and one common poorwill. We recorded incidental observations of 121 species; 41 species that were not recorded during another survey type. Based on the species accumulation curve, we believe that we have recorded at least 90% of the species that breed in and around the park or that stopover for a significant amount of time during the time of the VCP surveys. However, based on the high bird species richness and the diversity of vegetation at the park, we believe that the bird inventory is not complete and is likely missing spring and fall migrants and winter residents. There are at least 40 species that were not recorded by us, MAPS personnel, or other researchers or observers, but which are likely to be recorded at Tumacácori NHP with additional survey effort.

Two rare species in particular are noteworthy: yellow-billed cuckoo and southwestern willow flycatcher. These are found in the riparian area at the Tumacácori unit. This area has been reported to have one of the highest densities of yellow-billed cuckoos in the western U.S. (Powell 2000).

There are two species that are troublesome: house sparrows and brown-headed cowbirds. House sparrows in the developed area around the Tumacácori Mission can be a problem for other native bird species and cultural resources. House sparrows nest in cavities or on ledges (Erlich et al. 1988), and are known to be aggressive toward other cavity-nesting species. At Tumacácori NHP these sparrows may displace cavity-nesters such as the Bewick's wren and Lucy's warblers, can damage cultural resources by enlarging existing cracks, and certainly create a nuisance and distraction via excessive nest material and defecation. Brown-headed cowbirds pose a threat to many native birds outside of the developed area because they are brood parasites and reduce the productivity of host species. Species particularly susceptible to brown-headed cowbird parasitism include four abundant Neotropical migrants at Tumacácori NHP: Bell's vireo, song sparrow, yellow-breasted chat, and yellow warbler (Schwietzer et al. 1998; Averill-Murray et al. 1999; Powell and Steidl 2000).

Mammals

We trapped 16 species of small mammals in our trap grids. Species richness was highest at Calabazas ($n = 12$), slightly less at Tumacácori ($n = 11$), and lowest at Guevavi ($n = 9$). However, the Guevavi unit had the most number of species ($n = 3$) not recorded at other units (brush mouse, northern pygmy mouse, and northern grasshopper mouse) although just one individual represented each of these species. The desert pocket mouse was the most abundant rodent at both the Calabazas and Guevavi units and the second most abundant at the Tumacácori unit, where the cactus mouse was the most abundant. The high species richness of small mammal communities at the smaller Calabazas and Guevavi units is consistent with known patterns of small mammal species richness in southern Arizona; true semidesert grasslands contain the highest species richness of any vegetation community in southern Arizona (Price 1978; Stamp and Ohmart 1979; Hoffmeister 1986; Sureda and Morrison 1999).

Seventy Trailmaster photographs were good enough that we could identify an animal to genus or species. From these we identified 10 species. Eight of 10 species photographed were represented by five or fewer photographs. The Virginia opossum was the most frequently photographed species. We photographed all four species of skunks that occur in Arizona. Only one species of bat was recorded by the study and one large mammal, a black bear, was documented at the park by photographing definitive tracks adjacent to the Santa Cruz River.

We believe that our mammal inventory was most successful in documenting the list of small mammals. We estimate that we documented at least 90% of the rodent species likely to occur at the park based on the species accumulation curve; we did not detect any new species in the last 10 sampling periods. However, for other groups of mammals, the picture is quite different. Based on a comparison of the species we recorded to a list of "possible" species at the park, we believe that we recorded approximately 41% of the species. Bats make up the bulk of the species we did not find; there are a possible 24 in addition to the one that we recorded. It should be noted, however, that not all of the mammal species would use the building structures or vegetation for any significant amount of time. Most may simply fly over (bats) or pass through (e.g., jaguar) the park en route to habitat elsewhere. Large mammals that we would expect to find include: gray fox, kit fox, mountain lion, and ringtail (Hoffmeister 1986).

The only non-native rodent, the house mouse, was recorded twice at the Calabazas unit, not at all at the Guevavi unit, and 56 times at the Tumacácori unit. By using Trailmaster photographs and incidental sightings, we documented or observed the non-native domestic cat, domestic dog, and cow. Domestic cats can pose a serious problem for native vertebrates, especially rodents, reptiles and birds, through harassment and predation of nests and individuals (Clarke and Pacin 2002). We documented the Virginia opossum in 37% of our infrared photographs at the Tumacácori unit. It is likely that opossums are relatively new to the area (Hoffmeister 1986) and may have several impacts, including predation of bird nests (Peterson et al. 2004), competition with other medium-sized, omnivorous mammals such as the raccoon (Ginger et al. 2003) and transmission of tuberculosis (*Mycobacterium bovis*) to both wildlife and livestock (Fitzgerald et al. 2003).

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PLANT AND VERTEBRATE INVENTORY OF ORGAN PIPE CACTUS NATIONAL MONUMENT

Cecilia A. Schmidt and Brian F. Powell

One of the goals of the National Park Service (NPS) Inventory and Monitoring Program is producing up-to-date species lists for plants and vertebrates in all natural areas managed by the NPS. In contrast to our work in other parks in the Sonoran Desert Network (e.g., Powell et al. 2005, 2007a), we were able to rely on the field work done by others to produce the species lists for Organ Pipe Cactus National Monument (NM). Few natural areas in southern Arizona have received as much ecological research as Organ Pipe Cactus NM. Bennett et al. (1990) provide an excellent review of research related to cultural and natural resources of the monument and surrounding areas prior to 1981.

The designation of the monument as a United Nations Biosphere Reserve in 1976 provided important early initiative to scientists interested in studying the Sonoran Desert. Biosphere reserves are designated because they are thought to represent the most outstanding examples of selected ecosystems. Organ Pipe Cactus National Monument's isolation and geographic location at the center of the Sonoran Desert provided an excellent laboratory for research and education. One of the first initiatives after the monument's designation as a Biosphere Reserve was the compilation of all known information on the natural and cultural history of the monument.

In 1986, monument staff gathered regional experts to help create the first inventory and monitoring program in the region. Modeled after the Channel Islands' Inventory & Monitoring Initiative (Davis and Halvorson 1988), the monument's Sensitive Ecosystems Program (SEP) was designed to determine: (1) the condition of the monument's ecosystems, (2) alternatives available for ecosystem management, and (3) the effectiveness of implemented action programs. Initially, the SEP program included a broad range of natural resource studies at the monument, specifically baseline inventories of plants, songbirds, and nocturnal rodents (Bennett and Kunzman 1987). The program was expanded in 1991 to implement some of the recommended long-term monitoring protocols. Finally, in 1994, the title of the program changed to the Ecological Monitoring Program (EMP) to reflect a change from the historic focus on sensitive monument areas to a broader look at the ecosystem's many components (NBS 1995). Prior to the initiation of the NPS Inventory and Monitoring Program (NPS 1992; of which the Sonoran Desert Network is one program), the Organ Pipe Cactus NM EMP program was one of the most extensive ecological research and inventorying and monitoring programs in the National Park Service. Because of early interest in the monument by ecologists, the monument had a fairly complete list of plants and vertebrate species, well ahead of other park units in southern Arizona.

For complete details of the Organ Pipe Cactus NM study see Schmidt et al. (2007). Scientific and common names used throughout this chapter are current according to accepted authorities for each taxonomic group: Stebbins

(2003) for amphibians and reptiles; American Ornithologist Union (AOU; 1998, 2003) for birds; Baker et al. (2003) for mammals; and Rutman (2005) for plants.

MONUMENT OVERVIEW

Monument Area and History

Organ Pipe Cactus NM is located near the center of the Sonoran Desert, in southwestern Arizona on the border with Mexico (Figure 1). The monument was established in 1937 to preserve the largest portion of desert in the United States with the park's namesake, the organ pipe cactus. Ninety-six percent of the monument is designated wilderness. The monument was designated as a Biosphere Reserve in 1976 by the United Nations Educational, Scientific and Cultural Organization (UNESCO). This designation signifies that the monument contains an outstanding, internationally significant ecosystem. The UNESCO designation prompted the NPS to interpret the management objectives for the monument as preserving the monument as a representative example of the natural and cultural resources of the Sonoran Desert and serving as a natural laboratory for understanding and managing Sonoran Desert ecosystems (NPS 1994a).

At 133,830 ha, it is the largest park unit in the Sonoran Desert Network, yet it is dwarfed by the major land management units surrounding it: Cabeza Prieta National Wildlife Refuge to the west and north, the Tohono O'odham Indian Reservation to the east, and Bureau of Land Management land to the north (Figure 1). In Mexico, El Pinacate y Gran Desierto de Altar (also a designated UNESCO Biosphere Reserve) borders the monument to the south.

Archaeological evidence suggests that humans occupied the monument as far back as 12,000 years ago (Rankin 1991). Quitobaquito Springs has been an active site for settlement in recent history, and it was an important source of water for Spanish explorers and migrants attempting to cross the Sonoran Desert (Bennett and Kunzman 1989). Today, there are a number of sites at the monument that are sacred to the Tohono O'odham. Livestock grazing was the livelihood for a number of families who lived in the area, but was discontinued in 1976 (NPS 1997). Prior to the creation of the monument there were numerous active mining claims.

Physiography, Geology and Soils

Organ Pipe Cactus NM is located in the Basin and Range Physiographic Province and its topography varies from deep alluvial valleys to steep, rugged mountain ranges. Elevation at the monument is as low as 305 m in the west and extends to 1,465 m at its eastern boundary atop the Ajo Mountains. Geology of the mountains is the result of volcanic flows during the Cretaceous, Tertiary and Plio-Pleistocene periods. The valleys of the monument are formed of alluvial material originating in the mountains and transported down via streams and sheet-flow (Warren et al. 1981). Soils at the monument are all classified as aridisols (Chamberlin 1972).

Hydrology

There are no perennial rivers or streams within the monument, though there are 11 springs, four with perennial flow. The most prominent spring, Quitobaquito, feeds a large human-made pond. Two of the other perennial springs and five of the intermittent springs occur near the Quitobaquito area. There are 60 tinajas (natural depressions in bedrock that hold water) throughout the monument and they are the most widespread source of seasonal water.

Climate

Organ Pipe Cactus NM experiences an annual bimodal pattern of precipitation which is characterized by heavy summer (monsoon) storms brought about by moisture coming from the Gulf of Mexico, and less intense frontal systems coming from the Pacific Ocean in the winter. On average, approximately one-half of the annual precipitation falls from July through September (WRCC 2005). The area's hot season occurs from May through September; maximum temperatures in July can exceed

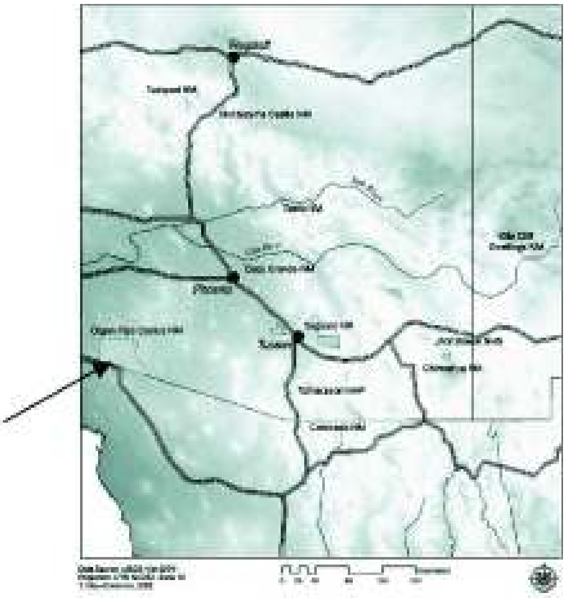

Figure 1. Location of Organ Pipe Cactus NM in relation to other parks in the Sonoran Desert Network of parks.

40° C. Winter temperatures rarely dip below freezing. Average annual precipitation for the monument is 243 mm.

Vegetation

According to Warren et al. (1981), the monument has six plant community types:

- Great Basin conifer woodland containing oneseed juniper–Arizona rosewood mixed shrub association;
- Madrean evergreen forest and woodland containing Ajo Mountain scrub oak mixed shrub association;
- Sonoran riparian woodland containing honey mesquite riparian woodland association;
- Interior chaparral containing rock gooseberry–common hoptree mixed scrub association;
- Sonoran desertscrub containing 23 associations dominated by creosote bush, burrobush, ragweed, ocotillo, palo verde, jojoba, ironwood, acacia, organ pipe cactus, and saltbush;
- Sonoran interior marshland containing southern cattail–chairmaker's bulrush association and inland saltgrass–rush association.

Natural Resource Management Issues

Border Crossings

Fifteen years ago, the trespass of drug smugglers and undocumented immigrants (border crossers) across the U.S./Mexico border was not considered a natural resource management issue (NPS 1994a). Today, this issue is one of the greater challenges to the ecological integrity of the monument. It is estimated that 500 border crossers enter the U.S. through the monument each day and approximately 700,000 pounds of drugs are brought through the monument each year (NPS 2003a). Border crossers pose a serious threat to visitors, employees, and personal property at the monument. They also create a network of trails, leave trash, and damage soils and vegetation.

There is concern that excessive use of the major springs and water has led to water contamination (Sprouse et al. 2002).

The movement of illegal vehicles crossing into the monument and subsequent border patrol vehicle pursuits has caused severe damage to fragile desert resources. Responding to this threat, the NPS constructed a vehicle barrier across most of the monument's border with Mexico. The barrier will likely prevent some animal movement, but the anticipated drop in off-road vehicle traffic and associated impacts is expected to allow improvements in soil stability and habitat for plants and animals (NPS 2003b).

Vertebrate Mortality along Arizona Highway Route 85 which runs north/ south and dissects the monument

Roads are a common source of vertebrate mortality and they act as barriers to the dispersal of small mammals creating subpopulations; deter, disturb and alter movement patterns of songbirds and medium and large mammals near roads; and pollute soil and water via runoff. Roads may also attract many vertebrates, ultimately leading to them being killed by vehicles. Herbaceous plant species thriving along roadsides from runoff attract granivorus birds and small mammals and road surfaces provide warmth to ectothermic reptiles and amphibians (Oxley et al. 1974; Adams and Geis 1983; Forman and Alexander 1998; Trombulak and Frissell 2000; Rosen and Lowe 1994, 1996).

Animal Poaching and Collection

Organ Pipe Cactus NM has several species of plants and vertebrates that are of interest to illegal collectors and poachers. Many plants are of value for landscape purposes and many woody plant species are scavenged by border crossers for fire and shelter (NPS 2003a). Many species of reptiles, such as the rosy boa, Gila monster, chuckwalla, sidewinder, tiger rattlesnake, and desert tortoise found in the monument are collected for personal collections or for the pet trade (Rosen and Lowe 1996).

Aircraft Noise

Low-flying military aircraft from Luke Air Force Base, law enforcement aircraft from the U.S. Border Patrol, and private aircraft pass over the monument often (NPS 1994b). Both vibrations and noise generated by these aircraft affect the natural quiet of the monument and may also affect wildlife in the area. Aircraft overflights can produce changes in the physiology and behavior of some wildlife species (Luz and Smith 1976; Weisenberger et al. 1996).

METHODS

Plants

The monument's plant list is the most complete of any large natural area in the desert southwest and is the result of many studies. The first known species list for the monument was created by McDougall (1945) and was based on his collections and those of A. A. Nichols from 1939 (Rutman 2005). Other early collections were made by Ora Clark, a science teacher in Ajo during the late 1930s and early 1940s. Specimens from these collections still remain at the monument and/or at the University of Arizona Herbarium. There were three subsequent, unpublished lists for the monument (reviewed in Pinkava et al. 1992) but Bowers (1980) produced the first annotated list. She reported 518 species. Other additions to the flora included Pinkava et al. (1992) and Felger et al. (1992). Principle works on the non-native plants of the monument include Felger (1990) who reviewed plant specimens from four herbaria and his own field observations and Halvorson and Guertin (2003) who provided location information for 17 species of non-native plants. Ruffner Associates (1995) identified 44 species of plants that were in need of monitoring because of "sensitivity to disturbance" or because they were deemed to be indicators of change.

There have been a number of vegetation studies in the monument. Steenberg and

Warren (1977) constructed exclosures at four sites to determine the impacts of grazing on plant community structure and composition. These exclosures were resurveyed by Warren and Anderson (1995). Warren et al. (1981) classified and mapped dominant (perennial) vegetation at the monument. Bowers (1990) reviewed past studies from the region, provided a historical context for vegetation changes, and used repeat photography to illustrate some important changes. Brown and Warren (1986) plotted the location and calculated density of riparian vegetation in and around Quitobaquito Springs and Pond. Parker (1991) established vegetation and environmental relationships at 100 sites throughout the monument. Lowe et al. (1995) designed the vegetation monitoring protocol for the EMP.

Rutman (2005) compiled a list of specimens in herbaria, at the monument, Arizona State University (ASU), and the University of Arizona (UA). All specimens were reviewed by experts and those excluded from the monument's official list were species that were obviously transitory as no reproducing populations were established. The current list is the result of dozens of collectors working over approximately 75 years and represents one of the most complete plant lists of any area in the region.

Rutman (2005) primarily used Flora of North America (FNA 1993) as a taxonomic references for her list, but also used W3Tropicos (MGB 2004), the PLANTS Database (USDA 2004), and individual publications.

Fish

The Quitobaquito pupfish (*Cyprinodon eremus*) is the only species of fish at the monument and it occurs only at Quitobaquito Springs and Pond and a few sites outside of the monument (Hendrickson and Romero 1989). Listed as endangered in 1986 under the Endangered Species Act, the Quitobaquito pupfish is one of several species of pupfish that were once found throughout the Gila River drainage, lower Colorado River and Delta, and the Imperial Valley in California (Miller 1990). Most of these populations are now extinct, presumably because of habitat destruction (Pearson and Conner 2000).

Monument personnel monitor population size annually at Quitobaquito Springs and Pond as part of the monitoring program (NPS 1998a, 1998b; Tibbitts 1999; Pearson and Conner 2000). The pupfish appears to be doing well at Quitobaquito; in the last 25 years the population has never dipped below 1,800 individuals (Pearson and Conner 2000) and is currently thought to consist of approximately 8,000 to 10,000 individuals (Douglas et al. 2001). A concern to the long-term persistence of the Quitobaquito pupfish is the potential introduction of non-native fish and other vertebrates, invertebrates, and plants (Pearson and Conner 2000).

Amphibians and Reptiles

Lowe (1990) provides an excellent summary of early amphibians and reptile studies and collections at Organ Pipe Cactus NM. More recently, Rosen and Lowe (1996) conducted an inventory and established a long-term monitoring program. In this inventory, they have created the most definitive, up-to-date species list for the monument. We base our amphibian and reptile species list on this list and on a study of museum specimens (Schmidt et al. 2007). The list by Rosen and Lowe (1996) was created using many of the previous lists, studies, and collections, and over 600 field days of their own research. Most of the species on the list are backed by voucher specimens located at the monument and the UA Amphibian and Reptile Collection. Although this is a very complete list, Rosen and Lowe (1996) believe that other species may be found in the monument with additional work.

The monument has likely experienced loss of species in the last few decades. Two native species, the Mexican spadefoot and yellow mud turtle were previously documented in the monument but are believed to no longer be present (Rosen and Lowe 1996). Four non-native species — tiger salamander, American bullfrog, painted turtle, and pond slider — have also been documented at the monument but no longer occur there.

Birds

Steenbergh and Hoy (1963) created the first species list for the monument; it summarized observations made by researchers and the general public from 1939 to 1963. Subsequent lists included: Cunningham (1969, 1971), the first annotated list by Wilt (1976), and Brown et al. (1985). The most comprehensive annotated list was by Groschupf et al. (1988) and later revised by Tibbitts and Dickson (2005). We based our bird species list on these lists, on a study of museum specimens (Schmidt et al. 2007), and on the report by Benson et al. (2001). This list represents one of the most thoroughly documented bird species lists of any in the region. Like the lists for plants and herpetofauna, the bird list is an outstanding example of one built on past efforts with periodic updates.

The bird list is one of the most complete lists of its kind in the region. In the 17 years since the excellent work by Groschupf et al. (1988), only 11 species were added to the list (Tibbitts and Dickson 2005). This indicates that the bird species list is nearly complete. However, because birds are highly mobile animals, it is difficult to compile a truly complete list, especially for Organ Pipe Cactus NM, which is well known for species that seldom enter the U.S. from Mexico. Also, it is likely that even more birds requiring open water will be found at Quitobaquito Pond because of its proximity to the Gulf of California.

Mammals

Mearns (1907) was the first collector at the monument. He and others collected vertebrates at Quitobaquito and others areas around Sonoyta, Mexico in 1894. Huey (1942) was the first to report on the mammals from throughout the monument and to document a species list. Steenberg and Warren (1977) quantified vegetation characteristics and trapped small mammals in grazed and ungrazed areas of the monument to establish the effects of livestock. Other rodent-trapping efforts included establishment of trapping grids as part of the monitoring program (Petryszyn 1995; NPS 1998a, 1998b; Petterson 1999) and associated programs (Rosen 2000). Bats are also well surveyed at the monument. Cockrum (1981) trapped bats in 1979 and 1980 and reviewed past information to create a species list of bats for the monument. Petryszyn and Cockrum (1990) trapped at Quitobaquito Pond in 1981 and 1982 and created a species list of other mammals they found there.

The list of the monument's mammals is based on Cockrum and Petryszyn (1986), with additions from the inventory and monitoring program (NPS 1998a, 1998b; Pate 1999). Based on the list of species and the many years of mammal surveys, most of the mammal species that occur at the monument have been recorded. There is one species, the feral burro (*Equus asinus*), which occurred at the monument in the recent past but is no longer present.

RESULTS AND DISCUSSION

Plants

There have been 642 species of plants found at the monument (Table 1), of which 55 (9%) are non-native. Compared to other NPS areas in southern Arizona, the monument's flora is not particularly species rich (Bowers 1980). For example, Powell et al. (2007b) found almost the same number of species (638) at Fort Bowie National Historic Site in southeastern Arizona, an area < 0.5% the size of Organ Pipe Cactus NM. Bowers (1980) provides similar comparisons to other flora in southern Arizona. However, within the monument there are areas of high species richness, most notably Quitobaquito Springs and Pond and the Ajo Mountains. Bowers (1980) found 163 species only in the Ajo Mountains, which comprise about 10% of the area of the monument. This high species richness is primarily due to topographic relief, soil-texture changes and gradients in temperature and rainfall (Bowers 1980; Parker 1991). In addition, a number of species reach the westernmost limit

Table 1. Summary results of the vascular plant and vertebrate inventories at Casa Grande Ruins NM.

Taxonomic group	Number of species	Non-native species
Plants	642	55
Fish	1	0
Amphibians and reptiles	49	0
Birds	285	3
Mammals	54	1
Totals	1,031	59

of their geographic ranges in the Ajo Mountains, including some with distinctly Madrean affinities (Bowers 1980).

The number of non-native plant species recorded in the monument (*n* = 55, 9% of all species) is low, although slightly higher than Saguaro National Park (approximately 7%; Powell, et al. 2006, 2007a), which has the lowest percent of non-native species in the Sonoran Desert Network. Non-native plants are a management concern because they alter ecosystem function and processes (Naeem et al. 1996; D'Antonio and Vitousek 1992), reduce abundance of native species, and cause potentially permanent changes in diversity and species composition (Bock et al. 1986; D'Antonio and Vitousek 1992; OTA 1993). However, some species have stronger impacts on the ecological community than others. In assessing the potential threat posed by non-native species, it is important to consider the spatial extent of species, particularly those species that have been identified as "invasive" or of management concern. Felger (1990) found 14 species, including red brome and buffelgrass, to be "thoroughly" invasive and an additional 10 species, including smooth barley, crimson fountaingrass, and common sowthistle, that have become established on disturbed sites.

Amphibians and Reptiles.

There are 49 species of amphibians and reptiles that are known to occur at the monument: five toads, two turtles, 16 lizards, and 26 snakes. There were no non-native herpetofauna species found to breed at the monument. Unlike plants, there is a high diversity of herpetofauna at the monument, related to its relatively large size and biophysical variety. Reptiles are well represented at the monument, particularly lizards and snakes. Rosen and Lowe (1996) assert that dominant physical features of the monument's geology and soils separate the lizards and snakes into three communities: (1) rock piles, (2) bajadas, and (3) valley-bottom fills. Two "true" desert species inhabit only rock piles: common chuckwalla and speckled rattlesnake. By contrast, six species (including: desert horned lizard, western shovel-nosed snake, and sidewinder) inhabit the valley-bottom fills (containing fine-textured soils) where the vegetation is dominated by creosote bush. Finally, the bajadas contain some species associated with Arizona Upland Sonoran Desertscrub: tree lizard, regal horned lizard, and Sonoran shovel-nosed snake (Rosen and Lowe 1996). Another important community within the monument is xeroriparian desertscub along washes, which hosts a number of species such as the western coral-snake, and common kingsnake. Rosen and Lowe (1996) noted that washes become particularly important during droughts when species from adjacent areas use the washes more than in times of normal rainfall.

Rosen and Lowe (1996) created a list of

species that they considered threatened because of (1) range-wide or local population decline, (2) potential for poaching, and/or (3) susceptibility to mortality on Arizona Highway Route 85. This list includes the desert tortoise (a federal Species of Concern and an Arizona state Wildlife Species of Concern) and tiger rattlesnake, species that are targeted by collectors. The rosy boa (a federal Species of Concern and a Sensitive species according to BLM) and the Sonoran shovel-nosed snake (a Sensitive species according to the USFS) both are also targeted by collectors and are often killed on roadways. The Sonoran mud turtle is probably undergoing a population decline and it is restricted only to Quitobaquito Pond. The canyon spotted whiptail, a federal Species of Concern, has its largest known population in the Ajo Mountains, which are only partially within the protective borders of the monument. The following species have restricted distributions, isolated populations, population centers off the monument, or are uncommon: Sonoran green toad, longtailed brush lizard, desert horned lizard, black-necked garter snake, southwestern black-headed snake, speckled rattlesnake, Sonoran whipsnake, and western shovel-nosed snake. The one additional species not listed by Rosen and Lowe (1996) that is federally listed as a Species of Concern is the common chuckwalla. They foresaw no immediate threat to this species.

Birds

There have been 285 species of birds recorded at the monument. Of these only three are non-native. Organ Pipe Cactus NM has the highest bird diversity of any unit in the Sonoran Desert Network. This diversity results from three main factors. First, the monument has had extensive surveys and observations over the past century, which has enabled the monument to have a near complete species list. The second factor is that many species have their northernmost distribution at the monument (i.e., crested caracara). The third factor determining the diversity of birds at the monument is the variety of biophysical situations within the monument, from mixed Sonoran desertscrub in the western flatlands to the juniper-oak woodland/mixed mountainscrub in the eastern highlands to marsh and open water (Rosenberg et al. 1991).

Quitobaquito provides an oasis of open water and marsh in an area otherwise devoid of surface water. This important resource attracts birds requiring open water and also hosts many migrants en route to more northern or southern wintering or summering areas. Seventy-three have been documented at Quitobaquito Pond: 21 species of ducks and geese, four species of grebe, seven species of heron and egret, five species of rail, 19 species of shorebirds, nine species of gulls, and eight other species. Several species that use this open water and marsh are federally listed as Endangered or Species of Concern including the wood stork, brown pelican and white-faced ibis. Although extremely rare at the monument, they have been found at Quitobaquito Pond.

Another important resource for birds are the xeroriparian areas along washes such as Alamo Canyon and Growler Wash. Hardy et al. (2004) surveyed ecologically similar areas north of the monument and found that most of the spring passage migrant species preferentially selected dry washes, and many species used them exclusively. Also, many of the species that breed at the monument prefer the xeroriparian washes compared to upland sites, presumably because washes provide cooler microsites and protection from predators (Parker 1986).

Mammals

The current list of mammals for Organ Pipe Cactus NM consists of 54 species: 14 bats, 20 small, terrestrial mammals (principally rodents) and 20 medium to large mammals. Also included in this list is one non-native species, the feral dog. Quitobaquito plays an important role in the high mammal diversity at the monument by providing the largest source of perennial water in the region. Quitobaquito is an important resource for bats that use open water to hunt for insects and is the only site in the monument were the desert shrew is located

(Cockrum and Petryszyn 1986). Other important resources are the night-blooming cacti, including organ pipe and saguaro, which provide nectar for the endangered southern (lesser) long-nosed bat.

There are two large mammals that are found at the monument which are uncommon in Arizona: the Sonoran pronghorn and desert bighorn sheep. The pronghorn is believed to be an occasional visitor to the monument and the desert bighorn sheep is found in very small numbers in the Diablo, Puerto Blanco and Ajo mountains. Both species may occasionally be found at Quitobaquito.

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VASCULAR PLANT AND VERTEBRATE INVENTORY OF SAGUARO NATIONAL PARK, RINCON MOUNTAIN DISTRICT

Brian F. Powell and Cecilia A. Schmidt

From 2001 to 2003 we surveyed for vascular plants and vertebrates (amphibians, reptiles, birds, and mammals) at the Rincon Mountain District of Saguaro National Park to document the presence of species within its boundaries. Park staff also surveyed for medium and large mammals using infrared-triggered cameras from 1999 to 2005. Our spatial sampling design was ambitious and was one of the first of its kind in the region to co-locate study sites for vegetation and vertebrates using a stratified random design. We also chose the location of some study sites non-randomly in areas that we thought would have the highest species richness. Because we used repeatable study designs and standardized field methods, these inventories serve as the first step in a long-term, biological monitoring program for the district.

With the exception of plants, our survey effort was the most comprehensive ever undertaken in the Rincon Mountains. We recorded a total of 801 plant and vertebrate species, including 50 species not previously found in the district, of which five (all plants) are non-native species. Based on a review of our inventory and past research at the district, there have been a total of 1,479 species of plants and vertebrates found there. We believe inventories for all taxonomic groups are nearly complete. In particular, the plant, amphibian and reptile, and mammal species lists are the most complete of any comparably large natural area of the "sky island" region of southern Arizona and adjacent Mexico.

For all groups except medium and large mammals, the low elevation stratum (< 1219 m or 4,000 ft) contained the highest species richness, after accounting for differences in survey effort among strata. This is consistent with known patterns of species richness in the sky island mountain ranges.

Our review of species lists and park records reveals that the district has lost species, particularly plants and mammals, in the past few decades. Because of the district's close proximity to the rapidly growing city of Tucson, there are a number of development-related threats that could cause additional loss or decline in abundance of some species. In particular, the increasing groundwater pumping near Rincon Creek, the most species-rich area in the park, is likely to impact the unique riparian vegetation and animals of that area.

See Powell, et al. (2006) for complete details of the study of Saguaro National Park, Rincon District [http://sbsc.wr.usgs. gov/products/ofr/]. Scientific and common names used thoroughout this chapter are current according to accepted authorities for each taxonomic group: Taxonomic Information System (ITIS 2001) and the PLANTS Database (USDA 2004) for plants, Stebbins (2003) for amphibians and reptiles, American Ornithologist Union (AOU; 1998, 2003) for birds, and Baker, et al. (2003) for mammals.

PARK OVERVIEW

Park Area and History

Saguaro National Park is located in eastern Pima County adjacent to Tucson, Arizona (Figure 1). Originally designated as a national monument, the park was created in 1933 to preserve the "exceptional growth" of the saguaro cactus (NPS 1992). In 1961, the park was expanded to include over 9,000 ha (22,239 ac) of the Tucson Mountains (known as the Tucson Mountain District). The Rincon Mountain District is the subject of this report. It is 27,233 ha (67,294 ac) in size and is bounded by U.S. Forest Service land to the east; Forest Service and private land to the north; Forest Service, private and state land to the south; and private land to the west (Figure 2). Although created to preserve natural resources, the park is also home to native American campsites and petroglyphs and contains remnants of early ranching and mining (NPS 1992). Annual visitation to both districts of the park averages approximately 700,000 (NPS 2005).

Physiography and Geology

Saguaro National Park is located within the Basin and Range Physiographic Province. The district encompasses most of the Rincon Mountains, one of the region's prominent "sky island" mountain ranges. Topography at the district varies from low-elevation desert flats to steep rocky canyons and high-elevation coniferous forest and meadows. Elevation ranges from 814 m (2,670 ft) in the northwestern corner of the district to 2,641 m (8,665 ft) at Mica Mountain. The Rincon Mountains are primarily metamorphic in origin, with rocks of the Santa Catalina Group, a mixture of Pinal Schist, Continental Granodiorite, and Wrong Mountain Quartz Monzonite (McColly 1961; Drewes 1977). All components are of Precambrian rock parentage, subsequently deformed and recrystalized. Sedimentary rocks in the vicinity are largely Permian limestones of Earp and Horquilla formations (Drewes 1977).

Hydrology

The Rincon Mountain District has several sources of perennial water: Chimenea, Madrona, Rincon, and Wild Horse Creeks; and Deer Head, Spud Rock, Italian, and Manning Camp Springs. The most prominent hydrologic feature is Rincon Creek, which drains approximately one-half of the district (Sprouse et al. 2002).

Climate

Saguaro National Park experiences an annual bimodal pattern of precipitation which is characterized by heavy summer (monsoon) storms brought about by moisture coming from the Gulf of Mexico, and less intense winter frontal systems coming from the Pacific Ocean. On average, approximately one-half of the annual precipitation falls from July through September (WRCC 2005; PCFCD 2005). The area's hot season occurs from April through October; daily maximum temperatures exceed 40° C (104° F) at lower elevations and 30° C (86° F) at high elevations. Winter temperatures dip below freezing and snow is common at high elevations.

From 2001 to 2003, during the time of most of our inventory effort, annual precipitation totals for the high elevation areas were below the long-term mean of 69.1 cm (27.2 in). Annual temperatures for high elevations ranged from slightly below to slightly above the long-term mean of 8.5° C (47.3° F; PCFCD 2005). Annual precipitation totals for low elevations ranged from slightly to substantially below the long-term mean of 28.6 cm (11.3 in). Annual temperatures for low elevations from 2001 to 2003 were above the long-term mean of 21.3° C (70.3° F; WRCC 2005).

Vegetation and Biotic Communities

The Rincon Mountains are one of the "sky island" mountain ranges of southeast Arizona and northern Mexico. Sky islands, so called because the mountains are isolated by "seas" of desert and semi-desert grasslands, are areas of remarkable biological diversity as a result

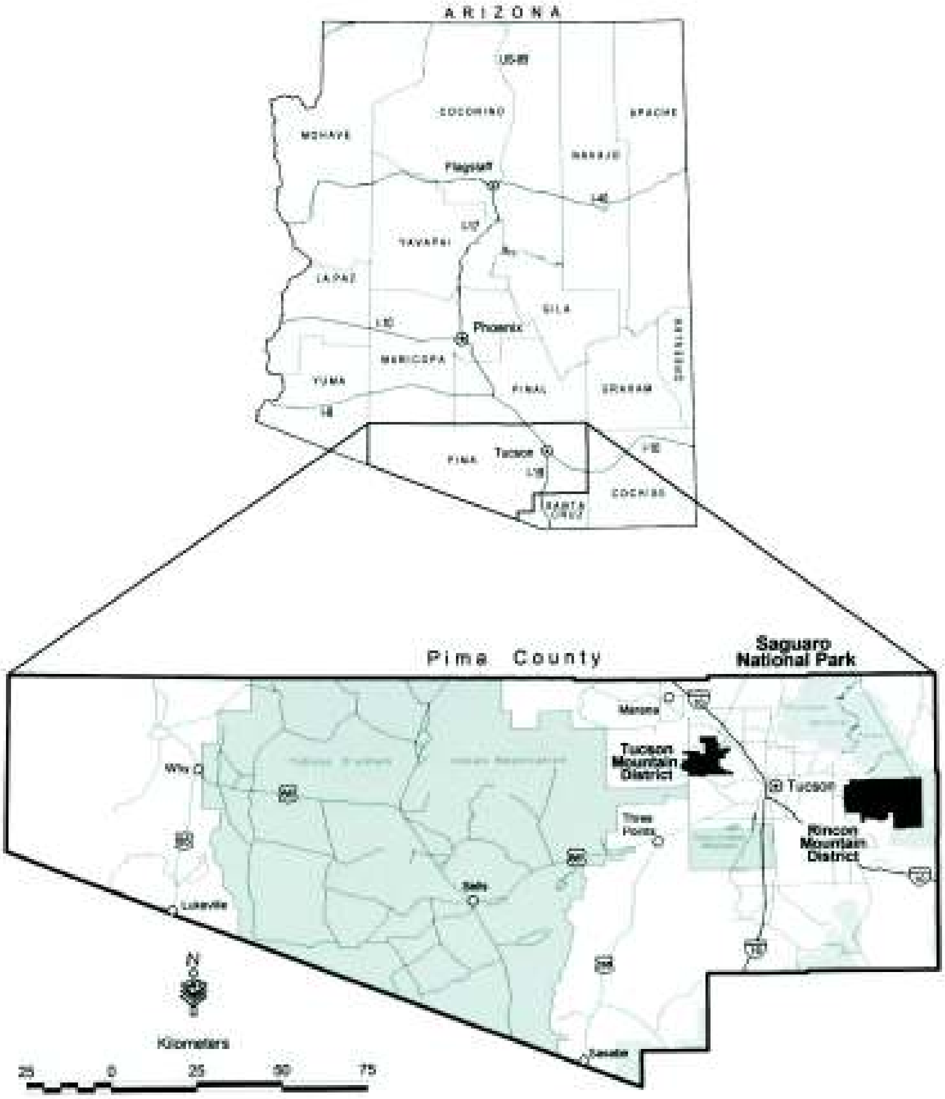

Figure 1. Location of the two districts of Saguaro National Park in southern Arizona.

of elevational gradients and subsequent differences in precipitation and temperature. These mountain ranges extend from subtropical to temperate latitudes, hosting species whose core distributions are from the Sierra Madre of Mexico and the Rocky Mountains of the United States and Canada (Warshall 1994). In southern Arizona, the sky island mountain ranges all have similar biotic communities from low-elevation Sonoran desertscrub to high-elevation conifer forests (Whittaker and Niering 1965).

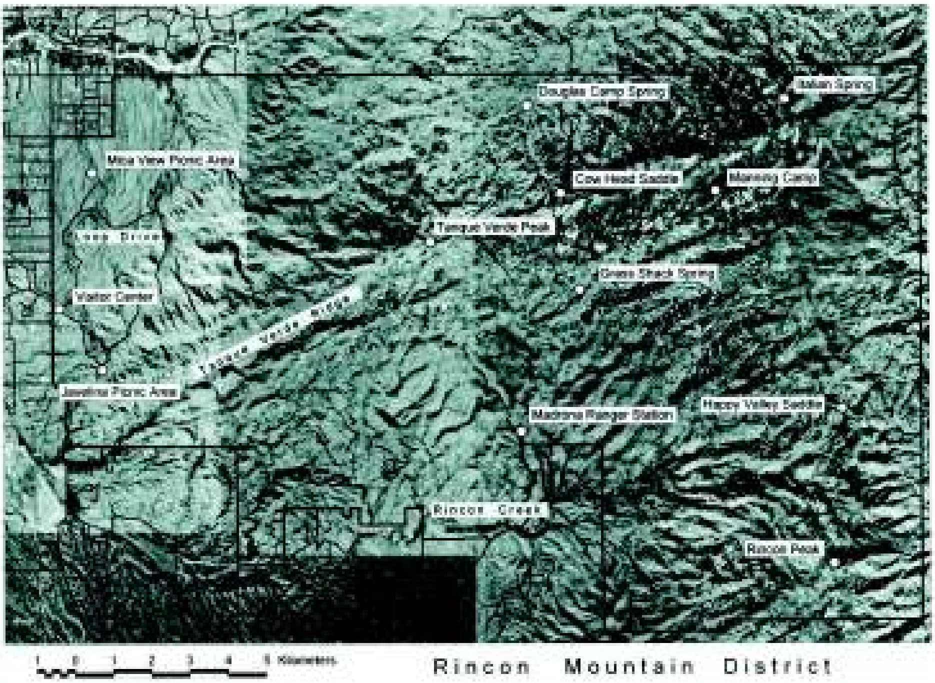

Figure 2. Aerial photograph showing major features of Saguaro National Park, Rincon Mountain District.

Sonoran Desertscrub

Sonoran Desertscrub is found at the lowest elevations and driest areas of the district, on its west and southern boundaries. The dominant shrubs are velvet mesquite, acacias, palo verdes, and creosote bush. Succulents are ubiquitous and include: saguaro, agave, yucca, barrel cactus, pincushion cactus, prickly pear, and cholla. Warm- and cool-season annuals, both native (e.g., woolly plantain) and introduced (e.g., red brome) are common following rainfall.

Southwestern Deciduous Riparian Forest

These forests are found along low-elevation washes and creeks and are among the most biologically unique communities in the Sonoran Desert. At the district they are found along Rincon Creek and to a lesser extent along its tributaries. The dominant tree species are Fremont cottonwood, Arizona sycamore, velvet ash, willow, and netleaf hackberry. In the Rincon Mountain District, Sonoran Desertscrub bounds these zones.

Semi-desert Grassland

Semi-desert grasslands occur in some middle elevation areas of the district, primarily along the northern boundary of the district and on a few areas of Tanque Verde Ridge. The community is composed of perennial short- and mid-grass species, with most areas invaded by velvet mesquite.

Oak Savannah

The oak savannah community is found at higher elevations than the semi-desert grassland community and lower elevations than the pine-oak woodland, and it contains elements of both communities. It is ecologically similar to the chaparral communities of central Arizona. In this community there are dense stands of manzanita and oak, with a variety of annual and perennial grasses.

Pine-oak Forest and Woodland

Pine-oak forest and woodland is ubiquitous at mid-elevations throughout the Apache Highlands (Bailey 1998; McPherson 1993). Madrean evergreen woodland is characterized by evergreen oaks with thick sclerophyllous leaves, such as Emory oak, Arizona white oak, and Mexican blue oak. Mexican pinyon pine and alligator juniper are the common gymnosperms. Understory grasses are usually abundant. At the higher elevations and in drainages, there is also ponderosa pine.

Coniferous Forest

Dominated by gymnosperms such as pines and firs, coniferous forests represent the cold-hardiest biotic community in the district. In these communities, ponderosa pine and Douglas fir dominate, with some temperate deciduous plants intermixing, primarily on the north-facing slopes: Gambel oak, quaking aspen, maples, and boxelder. Conifer forests are fire-adapted ecosystems, with natural low-intensity fires occurring every 6 to 15 years (Baisan and Swetnam 1990; Dimmitt 2000).

Natural Resource Management Issues

Adjacent Land Development

Increased housing development along the western and southern boundaries has become the most pressing natural resource issue for the district. Sandwiched between both districts of the park, the greater Tucson metropolitan area is one of the fastest growing in the United States. The area currently has an estimated population of 800,000, a 44% increase over the last two decades (PAG 2005). The increase in human residents brings with it a variety of natural resource-related problems including harassment and predation of native species by feral animals, increased traffic leading to altered animal movement patterns and mortality, the spread of non-native species, illegal collections of animals, vandalism, increased water demands, air pollution from vehicle emissions, and visual intrusions to the natural landscape (Briggs et al. 1996).

Of immediate concern is the depletion of groundwater and its effects on the ecologically valuable Rincon Creek (Baird et al. 2000). There are numerous single-family housing units being constructed (or planned) directly adjacent to the district. The proposed Rocking K Ranch development anticipates 9,000 residents and has been granted a permit by the Arizona Department of Water Resources to withdraw 4,400 acre feet of water per year from the underlying aquifer (Mott 1997). Rincon Creek has the most well-developed stretch of southwestern deciduous riparian forest in the district and it will likely be negatively impacted by drawdown of the aquifer. Groundwater drawdown at Tanque Verde Wash has already affected the riparian community there (Mott 1997).

Non-native Species and Changes to Vegetation

Buffelgrass, Lehmann lovegrass, red brome and other non-native grasses, have increased in the last ten years (Funicelli et al. 2001). The spread of some non-native plants used for landscaping, such as crimson fountaingrass, from development bordering the district is also a concern. The invasion of non-native grasses has led to structural changes in vegetation, from areas that supported mostly sparse bunchgrasses to areas of uniform grass. This change in species composition and structure alters the fire regime of the area by supporting larger fires and higher fire frequencies, thereby leading to other changes in vegetation composition and structure (Anable et al. 1992). Nowhere are these effects more evident than in the Sonoran Desertscrub community, which rarely burned historically (Steenbergh and Lowe 1977). Many native plant species, especially succulents, are not adapted to short duration, high-intensity fires and therefore die (Schwalbe et al. 1999; Dimmitt 2000).

Wildland Fire

Since the park began keeping records in 1937, there have been 572 fires in the district (Swantek, et al. 1999; NPS Files), and since 1984, park personnel have burned approximately 1,450 ha (3,583 ac) through their active fire management program. Fires play a crucial role in the middle and high-elevation semi-desert grasslands and forests by depleting dense understory vegetation and downed-woody debris. Even in these fire-adapted ecosystems, however, fire can be devastating, particularly after decades of suppression and subsequent buildup of fuel loads. In addition to fire-caused loss of species, a number of large fires in the last few decades have led to massive runoff of sediment and ash, filling down-stream perennial pools, and destroying habitat of leopard frogs and other aquatic species. Despite such problems, the NPS is committed to returning natural fire cycles to the park's biotic communities

METHODS

Focal Points

We used a process in our design that allowed for all inventories to be conducted partially at the same locations so that analyses could be made about communities at specific spots on the landscape. These co-located sites were defined using a randomization technique and resulted in the creation of 17 focal points that were available for use by all inventory crews (Powell et al. 2006).

Plants

We located specimens representing 883 species at the University of Arizona herbarium. Many of these specimens were collected or reported in Bowers and McLaughlin (1987). Their treatise is the most comprehensive annotated flora for the Rincon Mountains, though species have been added to the list since its publication. Bowers and McLaughlin (1987) also provide an excellent overview of previous research and collecting from the range, the plant communities present, species richness gradients, and a list of species extirpated from the range. The Bowers and McLaughlin list was compiled from work by Bowers (1984) above 1,371 m (4,500 ft) elevation and by Carole Jenkins who collected from 1978 to 1982 below 1,371 m. The list was updated in 1996 to include the addition of 34 species and the subtraction of four species due to incorrect identifications (Fishbein and Bowers 1996). There were floras developed for four designated natural areas of the district: Wildhorse Canyon (Rondeau and Van Devender 1992), Chimenea Canyon (Fishbein et al. 1994a), Box Canyon (Fishbein et al. 1994b), and Madrona Canyon (Fishbein 1995). Halvorson and Gebow (2000) compiled these works into a single volume. Halvorson and Guertin (2003) mapped locations of 27 species of non-native plants.

We collected species opportunistically and when we thought we had found a species not on the district list. We collected specimens during 38 days of fieldwork between 10 April and 24 September 2001 and 4 and 5 May 2002. We collected specimens from 41 locations throughout the district and many of the collections were made in the course of traveling to and from focal points. We used modified-Whittaker plots to characterize plant communities at the inventory focal points. Each plot was 20 x 50 m (1000 m^2) and contained 13 subplots of three different sizes (Stohlgren et al. 1995). We used the point-intercept method (Bonham 1989) to sample vegetation along 50-m transects located at 13 focal points.

Amphibians and Reptiles

Previous inventories

Prior to this study several species lists had been developed (Black 1982; Doll et al. 1989; Lowe and Holm 1991; Swann 2004). Goode et al. (1998) inventoried the district's Expansion Area in Rincon Valley and Murray (1996) and Swann (1999) inventoried both the Expansion Area and the nearby Rocking K Ranch and provided detailed information for these areas. Most recently, Bonine and Schwalbe (2003) inventoried the Madrona Pools of Chimenea

Creek; their effort was limited to five days in May.

This inventory

We surveyed herpetofauna in 2001 and 2002 using four field methods: plot-based intensive surveys, non-plot based extensive surveys, road surveys, and incidental observations. We used multiple methods to ensure coverage across a broad range of environmental features and to facilitate complete species lists and estimates of relative abundance (Powell et al. 2006).

Intensive Surveys

At focal points in 2001, we completed 131 surveys at 51 subplots located along 17 focal-point transects. In 2002 we discontinued intensive surveys because of the relatively low number of species detected.

Extensive Surveys

Non-plot based extensive surveys facilitated sampling in areas where we expected high species richness, abundance, or species not previously detected. Typically, we selected areas for extensive surveys in canyons or riparian areas, and also included ridgelines, cliffs, rock piles, bajadas, summits, or other physiographic features. We surveyed in spring (4 April to 24 May) and summer (25 June to 20 September) of 2001 and 2002. One, two, or three observers searched 85 areas. Total duration of surveys among all observers ranged from 1.2 to 20.4 hours. Survey effort was roughly three times greater than for other methods and focused mainly during daylight except at lower elevations where we also surveyed during late evenings and nights.

Road Surveys

We focused mainly on the Cactus Forest Loop Drive and also drove Speedway Boulevard from Douglas Spring Trailhead to the intersection with Tanque Verde Loop Road and Camino Loma Alta from the trailhead to Old Spanish Trail. We recorded each individual detected by species and whether animals were dead or alive. We surveyed between 29 April and 18 August 2001 and between 9 to 14 July 2002 during nights and occasionally during evenings. We conducted 55 road surveys totaling 46.3 hours of effort.

Incidental Observations

Incidental detections were often recorded before or after more formal surveys and we used these sightings to determine species presence and richness. We also included incidental sightings from other field crews (e.g., birds).

Birds

Previous inventories

There has been considerable bird research at the Rincon Mountain District, but no comprehensive and well-documented inventory has been completed. Monson and Smith (1985) compiled a checklist for both districts of the park, but there is no documentation of the data used to create that list. The park has contracted for periodic raptor surveys (Felley and Corman 1993; Berner and Mannan 1992; Bailey 1994; Griscom 2000). Park personnel surveyed three Breeding Bird Atlas blocks within the district (Short 1996) and those results are reported in Corman and Wise-Guervais (2005). The Tucson Bird Count includes three low-elevation sites in the park, including Rincon Creek (TBC 2005).

This inventory

We surveyed for birds at the Rincon Mountain District from 2001 to 2003. We used four field methods: variable circular-plot (VCP) counts for diurnal breeding and spring migrant birds, nocturnal surveys for owls and nightjars (breeding season), line transects for diurnal birds in the non-breeding season, and incidental observations for all birds in all seasons. We concentrated our primary survey effort in the breeding season (Bibby et al. 2002) which included the peak spring migration times for most species, thus adding many migratory species to our list.

VCP Surveys

In 2001, we spent more effort surveying at focal-point stations (n = 272) than at non-random stations (n = 160). In 2002 we surveyed exclusively at non-random stations, both repeat-visit (n = 130) and reconnaissance (n = 107).

Line-transect Surveys

We used a modified line-transect method (Bibby et al. 2002) to survey for birds from November 2002 to February 2003. We established three line transects in the district and surveyed each transect four times in the winter of 2002 and 2003.

Nocturnal Surveys

To survey for owls we broadcast commercially available vocalizations (Colver et al. 1999) using a compact disc player and broadcaster (Bibby et al. 2002) and recorded other nocturnal species (nighthawks and poorwills) when observed. We established nine transects. We broadcasted vocalizations of species that we suspected, based on habitat and range information, might be present:

- Low elevation: elf, western screech, burrowing, and barn owls;
- Middle elevation: elf, northern pygmy, flammulated, and whiskered screech owls;
- High elevation: northern pygmy, flammulated, northern saw-whet, and whiskered screech owls.

Although we had the most transects in the high elevation stratum, we had most (56%) of our survey effort in the low elevation stratum because of greater ease of accessing stations.

Incidental and Breeding Observations

When we were not conducting formal surveys and we encountered a rare species, a species in an unusual location, or an individual engaged in breeding behavior, we recorded it. We recorded all breeding observations using the standardized classification system developed by the North American Ornithological Atlas Committee (NAOAC 1990).

Mammals

Previous inventories

Saguaro National Park has never had a comprehensive survey of its mammals, and surprisingly little research has been conducted on mammals in the Rincon Mountain District considering the park's long history as a unit of the National Park System. However, a few studies provide valuable information on mammals, particularly Lowell Sumner's work in the mid-20th Century (Sumner 1951) and Russell Davis and Ronnie Sidner's survey of mammals in the high country of the Rincons in the early 1990s (Davis and Sidner 1992). H. Brown and L. Huey (unpubl. data) made collecting trips to the Rincons in 1911 and 1932, respectively (Davis and Sidner 1992). In addition, the park's administrative records at the Western Archeological and Conservation Center contain invaluable files (dating from the 1940s and 1950s) on mammal sightings and species of concern including the Mexican gray wolf and tree squirrels. More recent surveys were conducted by McCloskey (1980), Duncan (1990), Sidner (1991), Sidner and Davis (1994), Fitzgerald (1996), Lynn (1996), Bucci (2001), Swann (2003), and Sidner (2003).

This inventory

We surveyed for mammals using five field methods: trapping for small mammals, infrared-triggered photography for medium and large mammals, netting for bats, pitfall traps for shrews and pocket gophers, and incidental observations for all mammals.

Small Mammals

We trapped small mammals using Sherman live traps set in grids (White et al. 1983) along focal-point transects. The majority of our trapping effort in 2001 was at focal-point transects. We trapped for 4,589 trap-nights. We had the most trapping effort in the middle elevation stratum, less in the high elevation stratum, and the least in the low elevation stratum. In non-random areas, the percentage of the total number of trap nights was 36%, 50%, and 37% for the low, middle, and high elevation strata, respectively.

Bats

We surveyed for bats using two field methods: roost-site visits and netting. For netting, we concentrated our survey effort in areas that were most likely to have bats, mostly riparian areas with surface water present. We did not survey for bats near focal points because of the low probability of success in these areas. We visited roosts that were known to have bats based on historic records or were likely to have bats based on habitat characteristics. We netted bats at six sites for a total of 13 nights of netting in 2001 and four nights of netting in 2002. Most of our netting effort was at lower Rincon Creek and at Manning Camp Pond; we netted at each site for five nights. Deer Creek was the only site at which we netted on the east slope of the Rincon Mountains.

Large and Medium Mammals

Saguaro National Park initiated a medium and large mammal inventory in 1999 (Aslan 2000; Wolf and Swann 2002; Swann et al. 2003a; Swann 2003). We used infrared-triggered cameras to detect medium and large mammals at a combination of random and non-random sites from January 1999 to June 2005. We located non-random sites primarily at known water sources and animal trails. We chose the location of these sites to be in areas that we believed would have the highest species richness. We placed cameras at 74 non-random and 40 random sites throughout the district. We placed 54% of the camera time in the low elevation stratum, 28% in the middle, and 18% in the high elevation stratum. The total number of camera nights at all sites was 3,895.

Pitfall trapping

To survey for shrews and pocket gophers we placed pitfall traps in moist, north-facing slopes of the Rincon Mountains in 2001. We placed traps adjacent to a natural feature such as a fallen log or rock. We placed 10 traps (22 May to 24 September) at the North Slope Trail site, and four traps each at Italian Spring and Spud Rock Spring.

RESULTS AND DISCUSSION

Plants

We collected 741 specimens representing 523 species from the Rincon Mountain District of Saguaro National Park (Table 1). We found 39 species that had not previously been documented in the district, almost one-half of them (n = 19) during the course of surveying at point-intercept and/or modified-Whittaker plots. The list of new species that we found included five non-native species, most notably African sumac. Native species of note that we added to the flora included cleftleaf wildheliotrope, Arizona dewberry, and American black nightshade.

Based on a thorough review of past studies, floras, and collections located at the University of Arizona, there have been a total of 1,170 specific and intraspecific taxa documented at the district, of which 78 are non native (6.7%). Excluding eight species in the UA collection that Bowers and McLaughlin (1987) cite as likely extirpated from the district, there have been 1,120 species (1,162 including intraspecific taxa) documented since the early 1980s. Of these species, six were thought to be extirpated by Bowers and McLaughlin (1987) but were found by other studies: purple scalystem, Lemmon's hawkweed, alderleaf mountain mahogany, Baltic rush, poverty rush, and common barley.

We found 367 species associated with the 17 focal points. Approximately 47% of these species we found associated with only a single focal point, whereas six species (spidergrass, side-oats grama, plains lovegrass, bullgrass, sacahuista, and skunkbush sumac) were associated with 10 or more focal points. The skunkbush sumac was the most widespread species; we found it at 71% of focal points. We recorded 307 species on 13 modified-Whittaker plots. The mean number of species per

Table 1. Summary of vascular plant and vertebrate inventories at Saguaro National Park, Rincon Mountain District, 1999–2005.

	UA inventory			
Taxonomic group	Number of species recorded	Number of new species added to district list	Number of non-native species	Total number of species on district list
Plants	523	39	78	1,162
Amphibians and Reptiles	46	0	2	56
Birds	173	10	3	198
Mammals	59	1	3	63
Totals	801	50	86	1,479

plot was 60 with the range from 97 species in one of the Sonoran Desertscrub plots to 20 species in one of the Conifer Forest plots.

We found 189 species on 17 point-intercept transects. The mean number of species per transect was 28.3, with a range from 8 to 43.

The district's flora is perhaps the most complete of any large natural area in the sky island region of southeastern Arizona. In our many days of collecting, we found 39 previously undocumented species, which represents a 3.3% increase in the flora for the district. Almost one-half of these species were found during the course of conducting surveys at focal points. We also found a number of species on the east slope of the Rincon Mountains, and collectively these areas, particularly those away from hiking trails, are the least-surveyed areas of the district and finding new species there is not surprising.

Assessing overall inventory completeness is problematic given the size of the district and difficulty accessing many areas because of rough terrain. Due to the fact that much of the district remains unsurveyed, it is possible that we and others have not reached the goal of documenting 90% of the plant species for the entire district. However, if we look at inventory effort in different areas, the completion estimates are mixed. For example, low elevation, more easily accessed areas almost certainly have a species list that is close to completion. We found only three new species at or near focal points in the low-elevation stratum, and only one new species in an area near the loop drive, a highly visited area. The park's monitoring efforts have had similar results in low-elevation areas; in their 25 long-term monitoring plots (surveyed for seven years), park staff have found only 15 new species for the district . The flora for the high-elevation areas of the district is similarly complete. We found only one species in the area around Manning Camp, an area that has had extensive plot-level research related to the fire effects program. That program has produced only 30 new species in 15 years of surveys of 71 plots (Saguaro National Park, unpubl. data). By contrast, the mid elevation areas are the least surveyed and our results reflect this; we found most of our new species at focal points in the middle elevation stratum where plots were in the most difficult areas of the district to reach. Based on this evidence, we suggest that the floras for low and high elevation areas are nearly complete and that future surveys should focus on middle elevation areas, especially the east slope of the Rincon Mountains and the north-eastern boundary of the district.

Amphibians and Reptiles

We recorded seven amphibian and 39 reptile species (Table 1). Reptile species included two turtles, 19 lizards, and 18 snakes. Species richness was highest for incidental (*n* = 43) and extensive surveys (*n* = 39) and lowest for intensive (*n* = 25) and road surveys (*n* = 22). We found seven species with only a single survey method, but all other species were found with two or more methods. Road and extensive surveys each yielded detection of one species that was not detected by using other methods (Great Plains toad, and Great Plains skink, respectively) and incidental surveys yielded detection of five species not detected by using other methods (Mexican spadefoot, canyon spotted whiptail, ring-necked snake, western ground snake, and Mojave rattlesnake). All 25 species that we detected during intensive surveys were detected using other methods, although Madrean alligator lizard was detected only during intensive and extensive surveys.

We detected 4,292 individuals during this study, 3,066 during intensive, extensive, and road surveys combined and 1,225 incidental observations. Most individuals (*n* = 1,909) were detected during extensive surveys and fewest (*n* = 469) were detected during road surveys. The number of individuals detected per unit time was greatest for road surveys (mean = 14.9 individuals/hr) markedly higher than for extensive (4.1 individuals/hr) or intensive (3.6 individuals/hr) surveys. The species with the most detections (all methods combined) was the ornate tree lizard (*n* = 750).

A review of our inventory effort and other efforts in the district indicates that the district supports a total of nine amphibians and 48 reptiles. All but five species have been confirmed with a specimen and/or photographic voucher. Our inventory did not result in detection of any species not already recorded in the district, although we produced the first documentation (in the form of specimen and photographic voucher) for a number of species, including the Mojave rattlesnake.

We recorded only two species of amphibians (Sonoran desert toad and canyon treefrog) during intensive surveys. During extensive surveys we recorded five amphibians: Couch's spadefoot toad, Sonoran Desert Toad, red spotted toad, canyon tree frog, and lowland leopard frog. Road surveys resulted in the collection of four species: Couch's spadefoot toad, Sonoran Desert Toad, red spotted toad, and Great Plains toad. Only one other species was documented during the incidental collection periods, the Mexican spadefoot toad.

Environmental factors that explained patterns of species richness and relative abundance varied. Snake richness increased with cover of grasses whereas lizard richness increased with decreasing bare ground. Species richness of snakes and lizards increased with shrub cover above 2 m, though influence of shrub cover was much greater for snakes, and richness of lizards decreased with tree cover between 0.5 and 2.0 m. Relative abundance of all lizard species combined declined with increasing cover of bare ground. The black-necked garter snake and western diamond-backed rattlesnake were the most common snakes and western and mountain patch-nosed snakes, Sonoran coral snake, and common kingsnake were the rarest.

Species accumulation curves nearly reached an asymptote for extensive and intensive surveys, suggesting that additional surveys would have produced few new species. In fact, many species that we found only incidentally or have been documented few times are so rare that encountering them is largely a function of chance. We believe that the goal of a 90% species list has definitely been achieved in the case of amphibians and reptiles.

Birds

We made over 15,000 observations of birds and found 173 species from 2001 to 2003. We found 10 species that had not previously been found in the district including the sulphur-bellied flycatcher, elegant trogon, and pinyon jay. Some had conservation designations, including the northern goshawk, yellow-billed cuckoo, Mexican spotted owl, and buff-breasted flycatcher. Unusual sightings included a nest of the sulphur-bellied flycatcher, a singing male buff-breasted flycatcher, and sightings of the wild turkey, common black hawk, and yellow-breasted chat. We recorded three non-native species, including the rock pigeon, a new species for the district. We recorded the most species during incidental observations ($n = 154$) and VCP surveys ($n = 149$), and fewest during nocturnal surveys ($n = 9$).

We recorded 143 species at all repeat-visit VCP stations. We found the most species in the Riparian community ($n = 102$) and fewest species in the Conifer Forest community ($n = 51$). The number of species found in the other three communities (Sonoran Desertscrub, Oak Savannah, and Pine-oak Woodland) was intermediate. We recorded twelve species in all five communities and 39 species in only a single community. The ash-throated flycatcher was the most widespread species; we recorded it on 21 of 23 repeat-visit transects. We recorded four other species at > 75% of transects: rufous-crowned sparrow, common raven, brown-headed cowbird, and white-winged dove. We recorded an additional 22 species on > 50% of transects and an equal number of species on only a single transect. The white-winged dove had the highest mean frequency of detection across strata and it was the only species for which we recorded an average of over one individual per station. The mourning dove and ash-throated flycatcher were the only other species with relative frequency of detection estimates > 0.75.

We calculated relative abundance for 120 species. The most abundant species for each community type were:

- Riparian: verdin, Lucy's warbler, and mourning dove;
- Sonoran Desertscrub: black-throated sparrow, cactus wren, and verdin;
- Oak Savannah: Bewick's wren, rufous-crowned sparrow, and ash-throated flycatcher;
- Pine-oak Woodland: Bewick's wren, spotted towhee, and black-throated gray warbler;
- Conifer Forest: yellow-eyed junco, mountain chickadee, and spotted towhee and cordilleran flycatcher.

We found 63 species during line-transect surveys in the winter of 2002 and 2003 including six species that we did not record during VCP surveys. We found the most species in the Lower Rincon Creek area ($n = 45$) on the south side of the district and fewest in the Douglas Springs area ($n = 31$) near the northern boundary.

We observed 154 species during incidental observations, including 13 species that we did not record during other surveys. We made 288 observations of 78 species that confirmed breeding in or near the district; we found 104 nests of 48 species. We found two instances of brown-headed cowbird parasitism: one blue-gray gnatcatcher feeding a fledgling cowbird and one Bell's vireo nest with a cowbird egg. Considering all of the other research and site-specific inventory efforts in the district, we are confident in concluding that at least 90% of the species that regularly occur in the district have been recorded.

Mammals

We confirmed a total of 59 species of mammals in the Rincon Mountain District. This included 12 species confirmed through specimens, 32 species confirmed through photographs, nine species captured for which a voucher specimen previously existed, five species confirmed through a combination of voucher specimens and photos, and one species confirmed through reliable observation. One species included in this total (eastern cottontail) was confirmed by photographs in appropriate high-elevation habitat, but requires further documentation. We confirmed three species of mammals not previously confirmed for the district: western red bat, fulvous harvest mouse, and Virginia opossum. The latter two species represent significant range extensions. We observed only one species listed by the U.S. Fish and Wildlife Service as endangered, the southern long-nosed bat. Three species of non-native animals were documented for the district (feral cat, domestic dog, and domestic cattle) but we do not believe that any of these species have established feral populations in the district.

There have been a total of 66 species observed or documented in the district in the last few decades based on this and previous studies. We did not document the presence of eleven species that were previously documented for the Rincon Mountain District. We did not confirm the deer mouse, captured in the early 1950s near Manning Camp. We did not confirm the banner-tailed kangaroo rat, previously confirmed by specimen voucher (Hoffmeister 1986), and did not observe any of the distinctive sign of this very large kangaroo rat. Three species of bats that we did not observe, the western small-footed myotis, Yuma myotis, and western pipistrelle, have been confirmed recently (Davis and Sidner 1992; Sidner 2003). One species of rodent (southern grasshopper mouse) is also present; a roadkilled individual found by Don Swann in 1997 was confirmed by Yar Petryzyn at the University of Arizona mammal collection. Four species are extirpated from the district (grizzly bear, jaguar, Mexican gray wolf, and bighorn sheep), and a fifth species (North American porcupine) may be extirpated, though it remains on the species list.

Small Mammals

We trapped 544 individual rodents (including recaptures) in 2001 and 2002, and documented 13 rodent species and three species of diurnal squirrels. One species, the fulvous harvest mouse (4 captures) was a new species for the district. We did not capture two species that have been previously documented for the district (the southern grasshopper mouse and banner-tailed kangaroo rat). In general, relative abundance was higher at both low and high elevations than at middle elevations. We trapped only one species (rock squirrel) in a single elevation stratum, and only one species (brush mouse) in all three strata. The remainder of the species we found in two strata, either in the low and middle or the middle and high elevation strata. We trapped no species solely in the middle elevation stratum.

Bats

We confirmed 15 species, including one species that was not previously found at the district (western red bat). We observed bats in only one roost site, where 500-1000 cave myotis and six southern long-nosed bats were found. This was the only site at which we confirmed the southern long-nosed bat. Lower Rincon Creek had the highest species richness of any site, and Manning Camp had the highest percent netting success and the most individuals captured. We captured five species at Lower Rincon Creek that we did not capture in any other site and one species at Manning Camp Pond that we did not capture at any other site. At no other site did we capture species that were not found elsewhere. The big brown bat was the most widespread and abundant species; it was found at five of the six sites and in all elevation strata. Big brown bats were captured in 80% of the visits to Lower Rincon Creek and Manning Camp Pond. The Brazilian free-tailed bat was the next most captured bat; we captured 16 individuals at three sites. Of the 14 species that we captured at the Rincon Mountain District, 10 were represented by four or fewer individuals. Even the cave myotis, for which we found a roost of > 500 individuals, was only represented by a few individuals captured by netting.

Medium and Large Mammals

In 3,895 estimated camera nights, 2,939 photographs captured at least one mammal, and a total of 3,407 individual mammals that could be identified to genus. We photographed 27 species, including two non-native species, domestic dog and cattle. We documented one species (Virginia opossum) not previously reported for the district and a large number of species for which there had previously been only observational records. The largest number of photographs was of the gray fox (1,018 photos), followed by collared peccary (588 photos), and ringtail (229 photos).

Pitfall Trapping

We trapped eight animals in pitfall traps: six desert shrews at the North Slope site, one western harvest mouse, and one Botta's pocket gopher.

SUMMARY

We confirmed a total of 59 species of mammals in the Rincon Mountain District and failed to confirm ten species that have been previously documented for the Rincon Mountains. Of these ten, four species (grizzly bear, jaguar, Mexican gray wolf, and bighorn sheep) are certainly extirpated from the district and two others (deer mice, North American porcupine, and banner-tailed kangaroo rat) may be extirpated. We believe that three species of bats and one rodent that were documented in the past are still present and would be confirmed with additional effort. Our inventory confirmed 93% of mammals known for the district. The species accumulation curves for small mammal trapping, bats, and infrared-triggered cameras also suggest that the mammal inventory for the district is at or above 90% completion.

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VEGETATIVE CHARACTERISTICS OF OAK SAVANNAS IN THE SOUTHWESTERN BORDERLANDS REGION

Peter F. Ffolliott and Gerald J. Gottfried

Much has been learned about the oak (encinal) woodlands of the Southwestern Borderlands region in recent years. Ecological, hydrologic, and environmental characterizations have been obtained through collaborative efforts involving a large number of people (McPherson 1992, 1997; DeBano et al. 1995; Ffolliott 1999, 2002; McClaran and McPherson 1999; Gottfried et al. 2005; and others). However, comparable characterizations of the lower-elevation oak savannas are also necessary to enhance the knowledge of all of the oak ecosystems in the Southwestern Borderlands region. Oak savannas differ from the more extensive oak woodlands in that they are more open in stand structure, and, therefore, a higher level of herbaceous production might be expected.

Species compositions, density patterns, and annual growth rates of the tree overstories and species compositions and seasonal and annual production (standing biomass) of the herbaceous plants in the understories of "representative" oak savannas of the Southwestern Borderlands regions are presented in this paper. Comparisons of these vegetative characteristics with tree overstories and herbaceous understories in the more densely stocked oak woodlands are also made. This collective information should contribute to the "knowledge-base" on the ecological relationships in the oak savannas of the region.

STUDY PROTOCOL

Study Areas

The study areas consist of twelve watersheds, ranging from 8 to 35.5 ha in size, on the eastern side of the Peloncillo Mountains in southwestern New Mexico. These watersheds were established by the U.S. Forest Service to evaluate the impacts of cool- and warm-season burning treatments on the ecological and hydrologic characteristics of the oak savannas (Gottfried et al. 2000, 2005; Neary and Gottfried 2004). The areal aggregation of these watersheds, called the Cascabel Watersheds, is 182.7 ha. The Cascabel Watersheds are situated within the Malpai Borderlands in the eastern part of the Coronado National Forest, on the western edge of the Animas Valley (Figure 1). The watersheds are 1,640 to 1,705 m in elevation. The nearest long-term precipitation station indicates that annual precipitation averages 597 mm, with nearly one-half occurring in the summer monsoonal season. Hendricks (1985), Vincent (1998), Osterkamp (1999), and Gottfried et al. (2000, 2005) have described the geologic, physiographic, and hydrologic characteristics of the general area of the Cascabel Watersheds. Bedrock geology is Tertiary rhyolite overlain by Oligocene-Miocene conglomerates and sandstone. Soils are classified as Lithic Argustolls, Lithic Haplustrolls, or Lithic Ustorthents. These soils are generally less than 50 cm to bedrock. Streamflow originating in the oak savannas is mostly intermittent in nature, and large flows follow high-intensity rainfall events.

The study areas that formed the basis to compare tree overstories in the oak savannas with those in the oak woodlands are located along the southern slopes of the Huachuca Mountains within the Coronado National Forest. Touchan (1988), Gottfried and Ffolliott (2002), and Ffolliott and Gottfried (2005) had selected these areas for earlier studies of tree overstories in the oak woodlands. Average elevation of these areas is 1,750 m. Annual precipitation averages about 655 mm, nearly equally split between the summer and winter seasons. The topography is gently sloping to a mostly level terrain. Hendricks (1985) classified the soils in the Casto-Martinez-Canelo Association. These soils are moderately fine to fine-textured and relatively deep.

The area in the oak woodlands that was used to estimate herbage production for comparison with the herbage production in the oak savannas was located in the Coronado National Memorial also on the southern slopes of the Huachuca Mountains. The area is situated at 1,756 to 1,785 m in elevation. Annual precipitation amount and its seasonal distribution are similar to that of the study areas selected to compare the tree overstories. Steep slopes up to 35 percent characterize the topography. Hendricks (1985) classified the soils in the Casto-Martinez-Canelo Association.

Study Methods

On each of the Cascabel Watersheds, between 35 and 45 sample points were established along transects that were perpendicular to the stream system and situated from ridge to ridge. The intervals between the sample points varied among the watersheds depending on the size and configuration (shape) of the watershed sampled. A total of 421 sample points were located on the watersheds. Measurements of tree overstory and herbaceous understory characteristics were obtained on varying-sized plots centered over these sample points. Sampling designs and intensities on the other study areas are discussed below.

Tree Overstory Measurements

Species compositions and the densities of the tree overstories in the oak savannas on the Cascabel Watersheds were measured on 0.1-ha circular plots. Single-stemmed trees were measured in terms of their diameter root collar (drc) and multiple-stemmed trees in equivalent diameter root collar (edrc) following the procedures outlined by Chojnacky (1988). A different study protocol was followed to measure the tree overstories in the oak woodlands on the southern slopes of the Huachuca Mountains. Species compositions and the densities of tree overstories were tallied on a total of 80 0.04-ha and 25 0.1-ha randomly located circular plots established as a sampling basis for published (Touchan 1988; Gottfried and Ffolliott 2002; Ffolliott and Gottfried 2005) and unpublished tree overstory inventories. The procedures outlined by Chojnacky were again the basis for the individual tree measurements in these inventories. Estimates of the tree densities on both study areas are expressed in numbers of trees per hectare and corresponding cubic-meter volumes per hectare.

Annual growth rates of the tree overstories in both of the oak ecosystems were estimated with applications of a growth and yield model (Fowler and Ffolliott 1995) that is based on the variable-density yield-table method of calculating growth rates (Avery and Burkhart 2002; Husch et al. 2003). Conversions of the solutions of the basic growth equation in this method from English to metric units provided estimates of the growth rates in terms of cubic-meter volume, with tree age classes, site quality values (Callison 1988), and current tree overstory densities of the oak stands sampled forming the input variables. Current and future volumes of the stands were estimated from these input variables. Differences between these two volume estimates represented a prediction of (net) growth rates for the period of consideration, which is one year (annual) in this study.

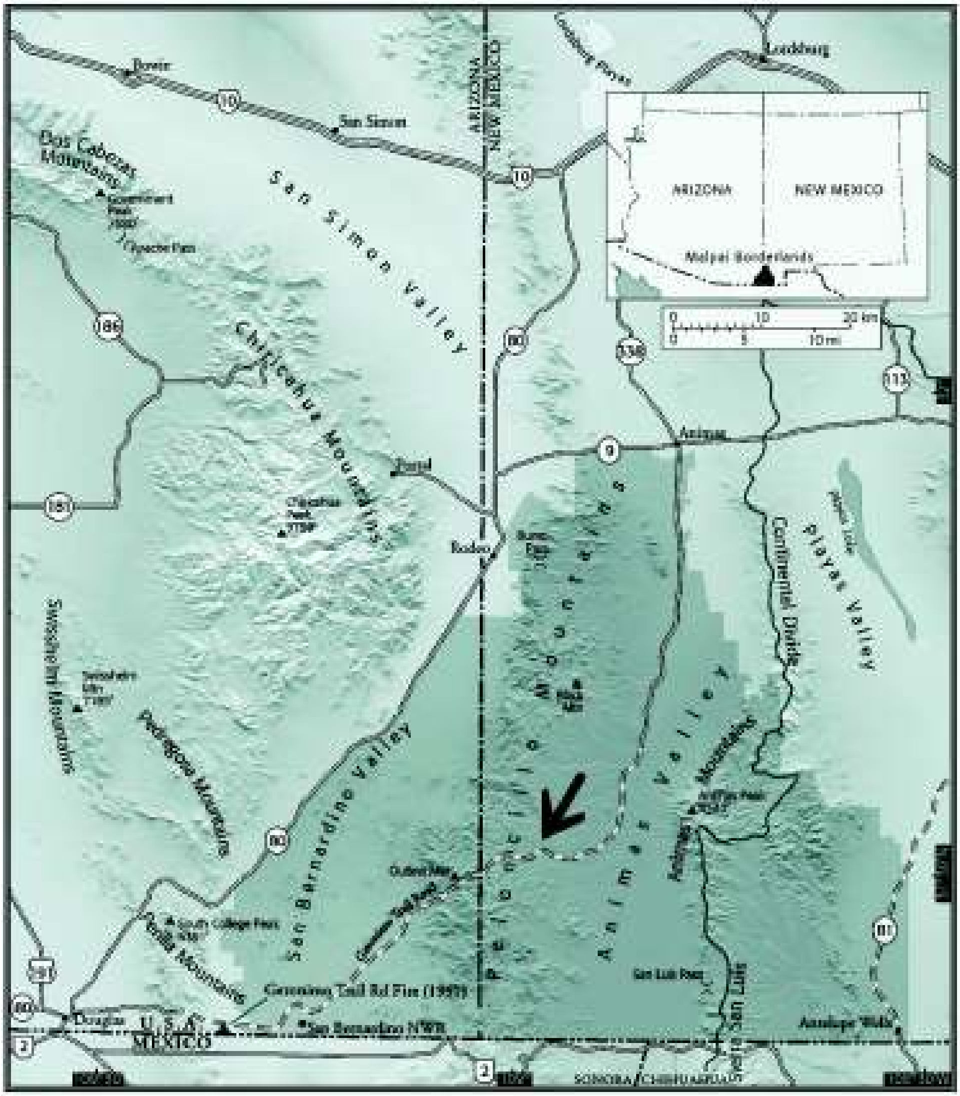

Figure 1. The Cascabel Watersheds (arrow) are located within the Malpai Borderlands, a 325,000-ha area managed by a landowner organization implementing ecosystem management on a virtually unfragmented open-space landscape.

Herbaceous Understory Measurements

Species compositions and seasonal (spring and autumn) estimates of the production of the grass, forb, and shrub plants comprising the herbaceous understories of the oak savannas on the Cascabel Watersheds were obtained in 2003, 2004, and 2005. The spring estimate was taken to represent the production of early-growing plants, with the autumn estimate reflecting the production of the late-growing plants. Temperatures and antecedent soil water derived from winter precipitation are the factors favorable to the early growers, while plant species that are late growers respond to the summer monsoonal rains. Summations of the production of grass, forb, and shrub components represented estimates of total herbage production for the estimation periods. Total herbage production of late-growing plants in the oak woodlands was estimated in the Coronado National Memorial at the same time as that in the oak savannas on the Cascabel Watersheds in the fall of 2005 to provide a basis for comparison. This estimate was obtained on six randomly located transects of 10 plots each.

All of the estimates of herbage production obtained in this study were expressed in kilograms per hectare. The weight-estimate procedures originally outlined by Pechanec and Pickford (1937) were followed. Estimates of on-site green weight of the herbaceous plants sampled were obtained on (approximately) 0.90 m^2 circular plots. Appropriate corrections were applied in converting these estimates of on-site green weight to actual oven-dry weights. Utilization of herbage by herbivores was minimal on the study areas. Less than 5 percent of the forage plants was utilized annually.

RESULTS AND DISCUSSION

Tree Overstories

Species Compositions

Tree species comprising the oak savannas on the Cascabel Watersheds and the oak woodlands on the southern slopes of the Huachuca Mountains were largely the same. The dominant species tallied on the Cascabel watersheds included Emory (*Quercus emoryi*) (60.1% of all trees tallied), Arizona white (*Q. arizonica*) (11.9%), and Toumey oak (*Q. toumeyi*) (4.4%), and alligator juniper (*Juniperus deppeana*) (15.3%). Minor components were redberry juniper (*J. coahuilensis*) (2.0%), Mexican pinyon (*Pinus cembroides*) (5.6%), and mesquite (*Prosopis velutina*) (0.7%). Species of trees observed in the forest inventories of the oak woodlands on the southern slopes of the Huachuca Mountains were dominantly Emory oak (89.3%), with inter- mingling Arizona white oak (8.7%), and a few scattered alligator juniper (1.3%) and Mexican pinyon (0.7%).

Tree Densities

Average numbers of trees per acre and 90% confidence intervals of the tree overstories in the oak ecosystems on the two study areas are presented by size-class categories in Figure 2. These size-classes coincide with those listed by O'Brien (2002) in describing the resource characteristics of the woodland types in the region; that is, saplings (2.5 to 12.5 cm drc), medium trees (12.6 to 22.5 cm drc), and large trees (22.6 cm drc and larger). The overall test of significance in analyzing the differences in numbers of trees per hectare for all of the size-classes (all trees) combined was evaluated at a 0.10 level. However, because the three size-classes shown were nested within the overall test, a Bonferroni adjustment was applied to maintain the Type I error in a test of significance for the size-classes at a 0.30 level.

Average numbers of medium and large trees and all trees combined per hectare in the oak savannas on the Cascabel Watersheds were significantly less than the corresponding numbers of trees in the oak woodlands on the southern slopes of the Huachuca Mountains. However, the numbers of saplings were similar. The reason for the similar densities of saplings might be a result of the episodic cycles of obtaining (sexual) reproduction of trees in the oak ecosystems of the Southwestern Borderlands region (Borelli et al.

1994). Numerous plantlets blanket the landscape when the reproduction events occur, largely obscuring the effects of site on surviving tree numbers. Such a regeneration event could have coincided with the approximate age of the saplings on the two study areas.

A local volume table based on the tree volumes calculated by Chojnacky (1988) was the basis for converting the average numbers of trees per hectare to corresponding estimates of average cubic- meter volume per hectare. It was estimated by these conversions that the volume of the trees in the oak savannas on the Cascabel Watersheds was 11.2 ± 3.46 (mean ± [$t_{0.10}$ x standard error]) m^3/ha, while the estimated volume of the trees in the more dense oak woodlands on the southern slope of the Huachuca Mountains was 18.5 ± 2.43 m^3/ha. Statistically significant differences in the cubic-meter volumes of the trees grouped by size-class categories (O'Brien 2002) and all trees combined were similar to the pattern observed in the estimated numbers of trees per hectare. Over 90 percent of the volume of the trees in the two oak ecosystems was contained in large trees.

Annual Growth Rates

Trees in the oak ecosystems in the Southwestern Borderlands region grow slowly, rarely exceeding a fraction of a cubic meter per hectare each year (McPherson 1992, 1997; Ffolliott 1999, 2002; McClaran and McPherson 1999), a value equivalent to a growth rate that is less than one percent of the volume of the trees. More specifically in this study, the estimated annual growth rate of the tree overstory in the oak savannas on the Cascabel Watersheds was nearly 0.049 ± 0.016 m^3/ha, while that in the oak woodlands on the southern slope of the Huachuca Mountains was 0.078 ± 0.011 m^3/ha. While a difference in annual growth rates is suggested, confidence

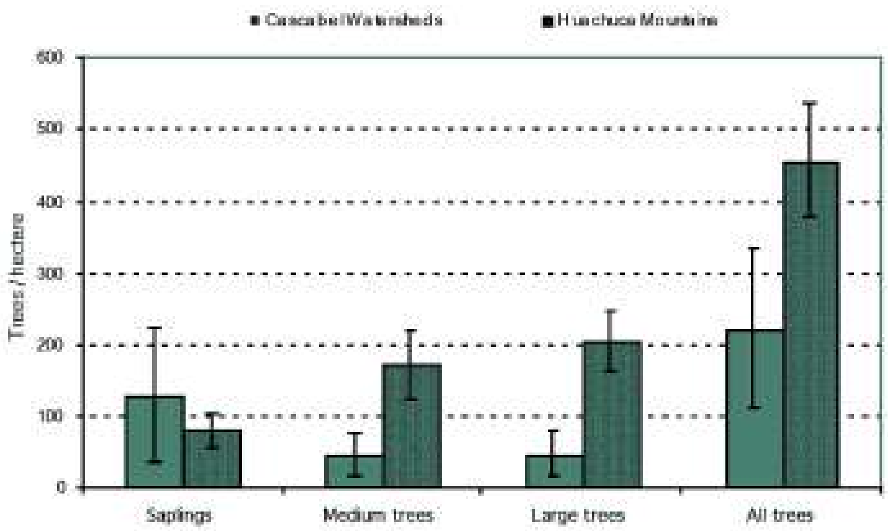

Figure 2. Average numbers of trees per hectare, and the 90% confidence intervals of the tree overstories, in the oak savannas on the Cascabel Watersheds and the oak woodlands on the southern slopes of the Huachuca Mountains.

intervals for the respective estimates are only approximate because the errors in the growth and yield model forming the basis for these estimates are unknown.

Increment-core analyses indicated that the annual growth rates of trees in the oak stands on both study areas were "comparatively fast" in their early and middle stages of their development; that is, for the saplings and medium trees. However, growth rates slowed as the trees got older to the point where the annual growth rates become negligible.

Spatial Distributions of Trees

The relative variability in the spatial distributions of tree overstories in the oak savannas on the Cascabel Watersheds was greater (coefficient of variation = 7.98) than that observed for tree overstories in the oak woodlands on the southern slopes of the Huachuca Mountains (coefficient of variation = 1.08). This difference in spatial distributions suggests a more heterogeneous stocking condition in oak savannas than in oak woodlands (Ffolliott and Gottfried 2005). However, this possibility must be "conditioned" by the fact that different sampling designs and intensities were employed on the two study areas. Nevertheless, the openings of varying sizes and shapes that are interspersed among the tree overstories in the oak savannas were less commonly encountered in the oak woodlands.

Herbaceous Understories

Species Compositions

Plant species observed in the herbaceous understories of the oak savannas on the Cascabel Watersheds and the oak woodlands on the Coronado National Memorial were similar. Included among the perennial grasses were blue (*Bouteloua gracilis*), sideoats (*B. curtipendula*), slender (*B. repens*), and hairy (*B. hirsuta*) grama, bullgrass (*Muhlenbergia emersleyi*), common wolfstail (*Lycurus phleoides*), and Texas bluestem (*Schizachyrium cirratum*). Forbs were a minor herbaceous component on both sites. There were also only minimal occurrences of half-shrubs such as beargrass (*Nolina microcarpa*), fairyduster (*Calliandra eriophylla*), and common sotol (*Dasylirion wheeleri*). Scattered shrubs included Fendler's ceanothus (*Ceanothus fendleri*), Mexican cliffrose (*Purshia mexicana*), and pointleaf manzanita (*Arctostaphylos pungens*). Occurrences of annual plants in the herbaceous understories of the two oak ecosystems were minimal.

Annual Production

Averages and 90% confidence intervals for the estimated seasonal production of early- and late-growing grasses, forbs, and shrubs and the annual production of all early- and late-growing herbaceous plants in the oak savannas on the Cascabel Watersheds for the three years of the study are summarized in Table 1. Because the values for the production of grasses, forbs, and shrubs were nested within the overall estimate of total herbage production, a Bonferroni adjustment was also applied in determining the statistically significant differences in the components of herbage production that are shown in this table. The levels of significance in these analyses were similar to those specified in analyzing the differences in numbers of trees per acre.

There were no significant differences between early- and late-growing forbs or early- and late-growing shrubs in the three years of herbage estimation. However, this was not the case with grasses, with the production of early-growing grasses significantly less than the production of late-growing plants. The occurrence of higher than the normally expected late summer rains in 2005 was the likely cause of a significantly higher estimated production of late-growing grasses (mainly grama) than early-growing grasses in that year. This difference in the production of grasses was also reflected by the significant differences in the production of total herbage in the oak savannas. With the exception of the estimates of the production of late-growers in 2005, all of the herbage estimates on the Cascabel Watersheds were obtained at a time of prolonged drought.

Table 1. Averages and 90% confidence intervals of the seasonal production of herbaceous plants in the oak savannas on the Cascabel Watersheds for 2003, 2004, and 2005.

Plant group	Spring	Autumn
	-kg/ha-	
Grasses	105.6 ± 13.3	176.6 ± 23.5
Forbs	26.0 ± 12.7	36.2 ± 12.1
Shrubs	22.8 ± 11.9	21.5 ± 11.9
Total	154.4 ± 13.5	234.3 ± 17.6

Estimated total herbage production of late-growing plants in the understories of the oak woodlands on the Coronado National Memorial in the autumn of 2005 was 174.8 ± 26.5 kg/ha. This value was significantly less than the 297.1 ± 13.6 kg/ha of late-growing plants in the oak savannas on the Cascabel Watersheds at the same time. It appears from this initial analysis of the comparison, therefore, that a higher level of production of late-growing herbage plants might (in fact) be expected in the more open oak savannas than the oak woodlands as suggested above. However, the estimates of herbage production should continue for a sufficient number of years to adequately represent the variability that precipitation in the region might have on herbage production before drawing definitive conclusions on the reported comparison.

Overstory-Understory Relationships. Comparisons of the frequently observed relationship of increasing herbage production with decreasing tree-overstory densities (Ffolliott and Clary 1982) indicated that there were no statistically significant correlations between either the production of early- or late-growing herbaceous plants and tree overstory density in the oak savannas on the Cascabel Watersheds or the production of late-growing herbaceous plants and tree overstory density in the oak woodlands on the Coronado National Memorial. That is, though the average tree overstory density in the oak savannas was significantly less than that in the oak woodlands, the relationships between the corresponding estimates of herbage production and tree overstory density on the sample plots on the respective study areas were not statistically significant for the range of tree overstory densities sampled on the areas.

Similar results showing little statistical correlation between herbage production and tree overstory density have also been reported in earlier studies in the oak woodlands of the region (Gottfried and Ffolliott 2002; Ffolliott and Gottfried 2005). It is possible, therefore, that tree overstory density in itself might not be a significant factor in "controlling" the production of herbaceous plants in the oak ecosystems of the southwestern United States. This possibility is further strengthened by the finding that there was no statistical correlation between annual herbage production and tree densities in the Gambel oak (*Q. gambelii*) stands that intermingle with the ponderosa pine (*Pinus ponderosa*) forests on the Beaver Creek Watersheds in northern Arizona (Reynolds et al. 1970).

While the densities of the oak overstories on the savannas and the oak woodlands might not affect the level of herbage production in these two oak ecosystems, the reverse situation might not always be true. McClaran and McPherson (1999) reported that a dense cover of perennial grasses can limit successful Emory oak regeneration on ungrazed sites in the Southwestern Borderland region. However, further study is necessary to verify the extent of this situation.

SUMMARY

In addition to presenting baseline information on the vegetative characteristics of the oak savannas in the Southwestern Borderlands region, this chapter also reports on the differences in the respective tree overstories and herbaceous understories characterizing the oak savannas on the Cascabel Watersheds and the oak woodlands on the southern slopes of the Huachuca Mountains, respectively. Tree overstories in the oak savannas were less dense (more open) and stocking conditions appeared to be more hetero- geneous than in the oak woodlands. As expected, therefore, a higher estimate of the production of late-growing herbaceous plants was observed in the oak savannas than in oak woodlands in the one year of estimation.

Assuming that the findings reported in this chapter represent the more general case, it might be that the two oak ecosystems in the Southwestern Borderlands region — which are both in the Upper Encinal Type (Turner et al. 2003) and classified in the *Quercus emoryi*/*Bouteloua curtipendula* (Emory oak / sideoats grama) habitat type — should not be considered "homogeneous management units" in terms of their tree overstory and herbaceous understory characteristics or other natural resources values linked to these characteristics such as livestock production potentials or the quality of wildlife habitat. While such a differentiation is often made in the management of oak savannas and more extensive oak woodlands in California (Standiford 1991, 2002; Pillsbury et al. 1997), more extensive study is necessary to verify this possibility in the Southwestern Borderlands region.

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DISTRIBUTION AND CONSERVATION PROTECTION OF NATURAL LAND COVER IN THE SONORAN DESERT ECOREGION IN ARIZONA, AS DESCRIBED BY THE SOUTHWEST REGIONAL GAP ANALYSIS PROJECT

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The goal of the U.S. Geological Survey's (USGS) National Gap Analysis Program (GAP) is to keep common species common by identifying vertebrate species and vegetation (plant communities) not adequately represented on lands managed for conservation (Gap Analysis Program 2006). The conservation assessment provided by gap analysis is proactive in the sense that it provides information on the conservation management of vertebrates and vegetation not listed as threatened and endangered, as well as those that are. Gap analysis products can be used for better-informed policy and land management decisions, which can potentially avert the ecological, economic, and legal dilemmas posed when a species is classified as legally endangered.

Gap analysis is conducted using three primary types of digital map products: 1) a land cover map, 2) a conservation management map consisting of stewardship (i.e., ownership) land boundaries and the conservation status levels assigned to those lands, and 3) vertebrate predicted-distribution maps. While we refer to these digital products as "maps" in this text, each is a digital geodatabase developed within a geographic information system (GIS). The conservation management map indicates the legal mandates for conservation management for each ownership parcel, coded by four status levels (1–4). The fundamental assumption is that management status 1 and 2 provide adequate protection for the long-term viability of biota on those lands (Gap Analysis Program 2000). The gap analysis is conducted as an overlay of the conservation management map with the land cover map and with each of the vertebrate species maps to determine the representation of vegetation and vertebrate species in each of the status levels (Scott et al. 1993).

The Southwest Regional Gap Analysis Project (SWReGAP) has mapped land cover, stewardship, conservation management, and predicted vertebrate distribution in the five-state Southwest region. This multi-institutional effort included Arizona, Colorado, Nevada, New Mexico, and Utah and represents the first formal regional Gap Analysis Project (Prior-Magee et al. 2007). Utah State University coordinated land-cover mapping efforts, and New Mexico State University coordinated vertebrate, stewardship, and conservation management mapping. Other collaborating institutions included the U.S. Geological Survey Southwest Biological Science Center in Arizona, the U.S. Environmental Protection Agency in Nevada, the Colorado Division of Wildlife, and Colorado State University. The project was assisted by NatureServe ecologists who coordinated development and application of the ecological system legend for land cover. Final products for the entire region can be obtained from the National Gap Analysis Program website (Gap Analysis Program 2006).

The land cover map describes natural and semi-natural vegetation as identified by ecological systems developed from the International Terrestrial Ecological Systems Classification (Comer et al. 2003). Ecological systems "represent recurring groups of biological communities that are found in similar physical environments and are influenced by similar dynamic ecological processes, such as fire or flooding" (NatureServe Explorer 2006). They relate to the National Vegetation Classification System (Federal Geographic Data Committee 1997) in that both describe characteristic vegetation associations and alliances. The online NatureServe Explorer (NatureServe Explorer 2006) provides a description of the 636 ecological systems currently identified. The 109 ecological systems identified for the 5-state SWReGAP region are also described online (SWReGAP Landcover Legend Descriptions 2006).

While the final products for SWReGAP are now available for the five-state region and for each of the five participating states, additional gap analyses can be applied to other boundaries within the region, such as ecoregions. Fifteen ecoregions are contained in part or entirely within the SWReGAP study area. We are here reporting gap analysis findings within the Arizona portion of the Sonoran ecoregion (hereafter referred to as the Arizona Sonoran), which includes much of the Arizona Upland and Lower Colorado Valley portions of the Sonoran Desert as described by Shreve (1951, 1964). The entire Sonoran ecoregion (Figure 1) is 223,425 km^2 and is comprised of parts of Arizona and California in the United States, and Baja del Norte and Sonora in Mexico. We conducted the ecoregional gap assessment for the Arizona Sonoran only, since comparable distribution data for land cover, vertebrate species, and conservation management do not exist for the California or Mexican portion of the Sonoran ecoregion. To define the Arizona Sonoran we used ecoregion boundaries defined by The Nature Conservancy's Ecoregions and Divisions Map and modified from the U.S. Forest Service Bailey's (1995) ecoregion boundaries (The Nature Conservancy Ecoregions and Divisions Map 2000). The Arizona Sonoran (Figure 1) is 90,190 km^2 or approximately 40 percent of the entire Sonoran ecoregion.

METHODS

We used the regional products of SWReGAP to conduct this gap analysis of the Arizona Sonoran ecological systems. We also report distribution statistics for mapped ecological systems, stewardship, and conservation management within the Arizona Sonoran.

The land cover and conservation management maps were constrained by the Arizona Sonoran boundary and summary statistics were derived for the distribution of the map categories. Gap analysis was conducted by creating geographic intersection of the land cover with the conservation management map, and calculating summary statistics of the intersected maps. A geographic information system (GIS)—with ESRI ® ArcGIS Desktop 9 software and Spatial Analyst extension—was used for map intersection and derivation of summary statistics. Microsoft Excel was used to further group and analyze summary statistics.

Datasets

The SWReGAP land cover map was published as provisional in 2004 and contains 125 legend classes, of which 109 are ecological systems and 16 land-use (Prior-Mcgee et al. 2007). The minimum mapping unit is one acre (.4 ha). The map was developed using decision-tree (also known as classification and regression tree, or CART) modeling (Breiman et al. 1984, Lawrence and Wright 2001) applied to Landsat Enhanced Thematic Mapper Plus (ETM+) remotely sensed images and derivates, a digital elevation model (DEM) and derivatives, and extensive ground observations. Full methods for the land cover map are reported in Lowry et al. (2007)

The SWReGAP conservation management map was published as provisional in 2005 and consists of boundary information for public and private lands (where provided) at variable resolution and with conservation management status assigned to each delineated land area (Ernst et

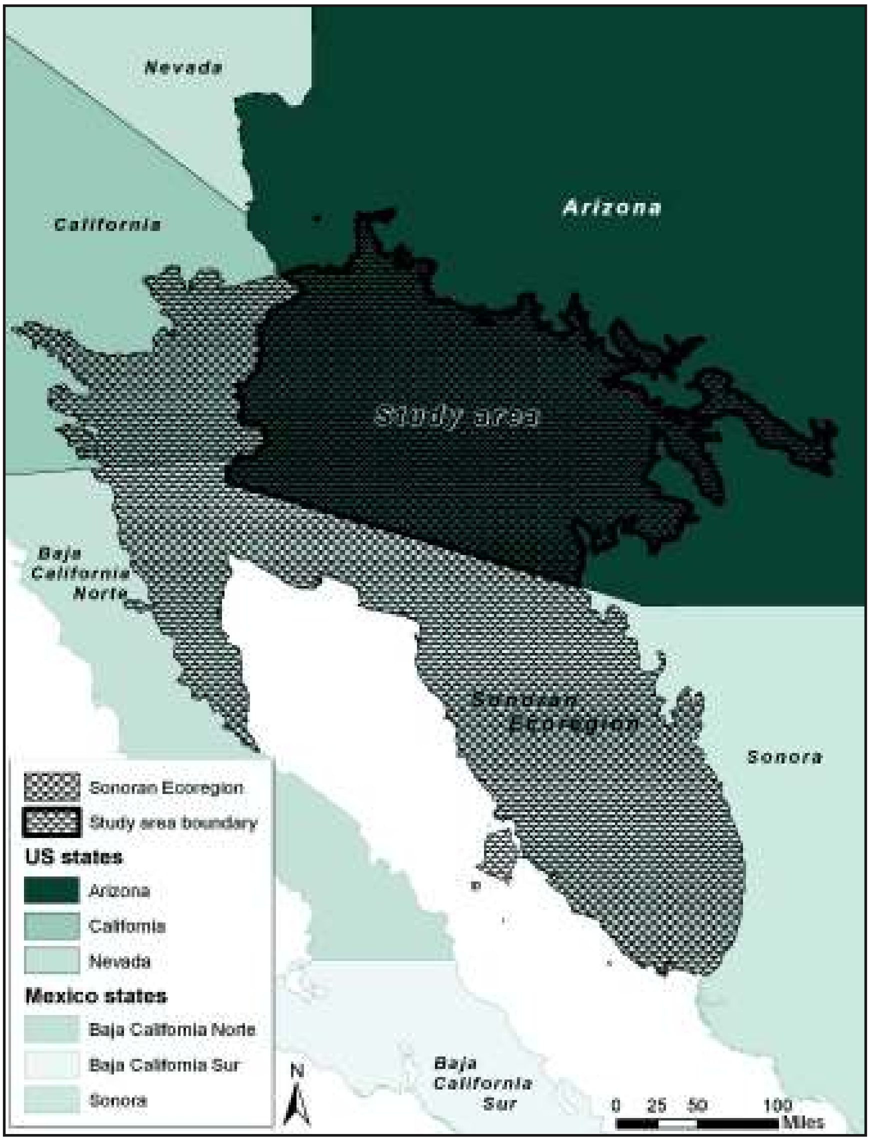

Figure 1. The extent of the Arizona portion of the Sonoran Ecoregion.

al. 2007). Four status levels are used to describe the legal mandate for conservation management (Crist 2000). A key to conservation management status was used to assign the appropriate level for the SWReGAP project (USGS Southwest Regional Gap Analysis Project 2006).

Status 1: An area having permanent protection from conversion of natural land cover and a mandated management plan in operation to maintain a natural state within which disturbance events (of natural type, frequency, intensity, and legacy) are allowed to proceed without interference or are mimicked through management.

Status 2: An area having permanent protection from conversion of natural land cover and a mandated management plan in operation to maintain a primarily natural state, but which may receive uses or management practices that degrade the quality of existing natural communities, including suppression of natural disturbance.

Status 3: An area having permanent protection from conversion of natural land cover for the majority of the area, but subject to extractive uses of either a broad, low-intensity type (e.g., logging) or localized intense type (e.g., mining). It also confers protection to federally listed endangered and threatened species throughout the area.

Status 4: There are no known public or private institutional mandates or legally recognized easements or deed restrictions held by the managing entity to prevent conversion of natural habitat types to anthropogenic habitat types. The area generally allows conversion to unnatural land cover throughout.

RESULTS

Land cover in the Arizona Sonoran

Thirty-eight land cover classes are mapped within the Arizona Sonoran; eight of these classes represent development, agriculture, water, and/or altered vegetation. High- and low-intensity developed lands constitute 4.5 percent of the ecoregion, and agriculture 5.5 percent of the area.

Approximately 88 percent of the ecoregion was mapped as natural land cover and consisted of 30 ecological systems (Table 1). Example descriptions of the meso-scale terrestrial ecological systems characteristic of the Arizona Sonoran are shown in Table 2.

Sonoran Paloverde-Mixed Cacti Desert Scrub (Figure 2) and Sonora-Mojave Creosotebush-White Bursage Desert Scrub dominate the landscape and together account for nearly 77 percent of all Arizona Sonoran landcover. The next most abundant ecological system, occurring as a distant third and covering 3.5 percent of the land area, is Apacherian Chihuahuan Mesquite Upland Scrub, considered a range extension of mesquite. Twenty-three ecological systems occur with less than 1 percent cover. Of these, nine are peripheral to the Arizona Sonoran with less than 1 percent of their statewide occurrence in the Arizona Sonoran (Table 1).

Six ecological systems are represented largely in the Arizona Sonoran when considered on a statewide basis (Table 1); more than 70 percent of the statewide occurrence for each is within the Arizona Sonoran ecoregion. These systems are: Sonoran Paloverde-Mixed Cacti Desert Scrub, Sonora-Mojave Creosotebush-White Bursage, North American Warm Desert Active and Stabilized Dune, Sonora-Mojave Mixed Salt Desert Scrub, North American Warm Desert Riparian Mesquite Bosque, and North American Warm Desert Riparian Woodland and Shrubland. The Sonoran Paloverde-Mixed Cacti Desert Scrub is unique in that nearly its entire regional range is endemic to the Arizona Sonoran.

Some ecological systems known to occur in the Arizona Sonoran occur in relatively small patches naturally (< 1 ha) and were not mapped as separate units. These include: Chihuahuan-Sonoran Desert Bottomland and Swale Grassland, North American Warm Desert Badland, North American Warm Desert Cienega, North American Warm Desert Pavement, North American Warm Desert Playa, Sonora-Mojave Semi-Desert Chaparral, Sonoran Fan Palm Oasis, and Sonoran Granite Outcrop Desert Scrub.

Conservation management in the Arizona Sonoran

The major land stewards (Table 3) within the Arizona Sonoran are federal agencies (51% of the land area), tribes (18%), private lands (17%), and state lands (13%). The Bureau of Land Management (BLM) manages nearly 26.5 percent of the land with the next largest federal land manager being the Department of Defense (12%). Nearly eighteen percent (17.7%) of the land area has status 1 or 2 conservation management (Table 3), the greatest legally mandated protection. Forty-

Table 1. Ecological systems within the Arizona Sonoran ecoregion and the proportion of their state and regional range that occurs within the ecoregion.

Ecological System	Arizona Sonoran (km²)	Arizona Sonoran cover (%)[1]	Proportion state cover in Arizona Sonoran (%)	Proportion regional cover in Arizona Sonoran (%)
Sonoran Paloverde-Mixed Cacti Desert Scrub	36,988.5	41.0%	93.0%	92.3%
Sonora-Mojave Creosotebush-White Bursage Desert Scrub	32,075.7	35.6%	93.0%	92.3%
Apacherian-Chihuahuan Mesquite Upland Scrub	3,185.5	3.5%	19.3%	9.9%
Sonoran Mid-Elevation Desert Scrub	1,607.4	1.8%	29.8%	29.8%
Chihuahuan Creosotebush, Mixed Desert and Thorn Scrub	1,109.4	1.2%	17.6%	4.0%
North American Warm Desert Active and Stabilized Dune	1,016.1	1.1%	100.0%	35.7%
Chihuahuan Mixed Salt Desert Scrub	865.1	1.0%	30.7%	19.5%
Sonora-Mojave Mixed Salt Desert Scrub	817.3	0.9%	80.9%	31.8%
North American Warm Desert Riparian Mesquite Bosque	588.7	0.7%	74.1%	69.5%
Apacherian-Chihuahuan Piedmont Semi-Desert Grassland and Steppe	395.9	0.4%	3.5%	0.9%
Madrean Pinyon-Juniper Woodland	265.0	0.3%	2.0%	1.2%
Mogollon Chaparral	216.8	0.2%	2.3%	1.9%
North American Warm Desert Riparian Woodland and Shrubland	216.8	0.2%	80.5%	47.0%
North American Warm Desert Bedrock Cliff and Outcrop	138.9	0.2%	18.3%	3.8%
Colorado Plateau Pinyon-Juniper Woodland	67.9	0.1%	0.2%	0.1%
North American Warm Desert Wash	45.6	0.1%	30.0%	6.9%
Chihuahuan Succulent Desert Scrub	42.8	0.1%	39.3%	22.7%
Chihuahuan Stabilized Coppice Dune and Sand Flat Scrub	41.1	0.1%	21.9%	0.7%
North American Warm Desert Volcanic Rockland	22.2	< 0.1%	10.8%	2.2%
Madrean Encinal	14.3	< 0.1%	0.5%	0.3%
North American Warm Desert Lower Montane Riparian Woodland and Shrubland	11.9	< 0.1%	6.6%	2.8%
Madrean Pine-Oak Forest and Woodland	11.5	< 0.1%	0.3%	0.2%
Madrean Juniper Savanna	11.5	< 0.1%	3.4%	1.2%
Inter-Mountain Basins Juniper Savanna	2.8	< 0.1%	0.1%	0.1%
Great Basin Pinyon-Juniper Woodland	1.5	< 0.1%	< 0.1%	< 0.1%
Colorado Plateau Mixed Bedrock Canyon and Tableland	1.2	< 0.1%	< 0.1%	< 0.1%
Rocky Mountain Ponderosa Pine Woodland	1.0	< 0.1%	< 0.1%	< 0.1%
Mojave Mid-Elevation Mixed Desert Scrub	0.6	< 0.1%	< 0.1%	< 0.1%
Chihuahuan Sandy Plains Semi-Desert Grassland	0.3	< 0.1%	1.9%	< 0.1%
North American Arid West Emergent Marsh	0.1	< 0.1%	0.2%	< 0.1%

[1] Arranged in descending order

eight percent has status 3 management and 34 percent status 4. The U.S. Fish and Wildlife Service (FWS) manages the largest area of status 1 and 2 lands (6,282 km^2) with the BLM second (5,901 km^2). While all of the FWS lands are status 1 and 2, 24 percent of the BLM lands are status 1 and 2, and the remainder status 3. The lands with the least legally mandated conservation protection are the state trust lands (11,191 km^2) and private lands, both with no known conservation restrictions (15,515 km^2). State trust and private land represent nearly 87 percent of all status 4 land in the Arizona Sonoran, those with no legal mandate for conservation management.

Conservation status of ecological systems

Although we conducted the gap analysis for all 30 ecological systems of the Arizona Sonoran, we report here the results for eleven ecological systems that are characteristic of the ecoregion (Table 4). These eleven ecological systems represent the three most abundant ecological systems and additional ecological systems with 30 percent or more of their state or regional range within the Arizona Sonoran, as shown in Table 1. Collectively these 11 ecological systems comprise 86 percent of the land cover of the Arizona Sonoran.

Status 1 and 2 lands provide the most

Table 2. Descriptions of two extensive ecological systems in the Arizona Sonoran.

Sonoran Paloverde-Mixed Cacti Desert Scrub
Primary division: North American Warm Desert (302)
Land cover class: Shrubland
Spatial scale and pattern: Matrix

Concept Summary: This ecological system occurs on hillsides, mesas, and upper bajadas in southern Arizona and extreme southeastern California. The vegetation is characterized by a diagnostic sparse, emergent tree layer of *Carnegia gigantea* (3–16 m tall) and/or a sparse to moderately dense canopy codominated by xeromorphic deciduous and evergreen tall shrubs *Parkinsonia microphylla* and *Larrea tridentata*, with *Prosopis* sp., *Olneya tesota*, and *Fouquieria splendens* less prominent. Other common shrubs and dwarf-shrubs include *Acacia greggii, Ambrosia deltoidea, Ambrosia dumosa* (in drier sites), *Calliandra eriophylla, Jatropha cardiophylla, Krameria erecta, Lycium* spp., *Menodora scabra, Simmondsia chinensis*, and many cacti including *Ferocactus* spp., *Echinocereus* spp., and *Opuntia* spp. (both cholla and prickly pear). The sparse herbaceous layer is composed of perennial grasses and forbs with annuals seasonally present and occasionally abundant. On slopes, plants are often distributed in patches around rock outcrops where suitable habitat is present.

Sonora-Mojave Creosotebush-White Bursage Desert Scrub
Primary division: North American Warm Desert (302)
Land cover class: Shrubland
Spatial scale and pattern: Matrix

Concept Summary: This ecological system forms the vegetation matrix in broad valleys, lower bajadas, plains, and low hills in the Mojave and lower Sonoran Deserts. This desert scrub is characterized by a sparse to moderately dense layer (2–50% cover) of xeromorphic microphyllous and broad-leaved shrubs. *Larrea tridentata* and *Ambrosia dumosa* are typically dominants, but many different shrubs, dwarf-shrubs, and cacti may codominate
or form typically sparse understories. Associated species may include *Atriplex canescens, Atriplex hymenelytra, Encelia farinosa, Ephedra nevadensis, Fouquieria splendens, Lycium andersonii*, and *Opuntia basilaris*. The herbaceous layer is typically sparse, but may be seasonally abundant with ephemerals. Herbaceous species such as *Chamaesyce* spp., *Eriogonum inflatum, Dasyochloa pulchella, Aristida* spp., *Cryptantha* spp., *Nama* spp., and *Phacelia* spp. are common.

Figure 2. A typical aspect of Sonoran Paloverde-mixed Cacti Desert Scrub

legally mandated protection to biota; so, often, the combined area of status 1 and 2 is considered in assessing the level of conservation protection. There is no set threshold of lands with protection to evaluate the adequacy of conservation protection for a plant community or vertebrate species. Various authors (Soulé and Sanjayan 1998; Odum and Odum 1972; Specht et al. 1974; Miller 1984; Noss and Cooperrider 1994) have recommended thresholds of 10, 20, or 50 percent of the distribution of a vegetation type or vertebrate species to have protected management.

The percentages of status 1 and 2 protection in the Arizona Sonoran for the 11 ecological systems ranged from 0.7 percent to 40.1 percent, all under the broadest threshold of 50 percent (Table 4). Nine of the ecological systems have 20 percent or less conservation protection and five with less than 10 percent conservation protection. Those five systems are: Apacherian-Chihuahuan Mesquite Upland Scrub (7.9%), Chihuahuan Mixed Salt Desert Scrub (1.1%), Chihuahuan Succulent Desert Scrub (0.7%), North American Warm Desert Riparian Mesquite Bosque (5.1%), and Sonora-Mojave Mixed Salt Desert Scrub (3.0%).

Conversely lands with status protection represent areas with the highest risk of loss of biotic populations due to habitat conversion. Sonora-Mojave Mixed Salt Desert Scrub has the highest proportion of area in status 4, 78 percent. All other ecological systems, except for North American Warm Desert Active and Stabilized Dune, have between 30 and 50 percent in status 4 (Table 4).

An additional consideration is the proportion of the state and regional status 1 and 2 protection for an ecological system that occurs within the Arizona Sonoran (Table 4). For five ecological systems, the status 1 and 2 conservation management provided in the Arizona Sonoran desert provides all or a high proportion of the systems status 1 and 2 protection within Arizona: Sonoran Paloverde-Mixed Cacti Desert Scrub (96%), Sonora-Mojave Creosotebush-White Bursage Desert Scrub (76%), North American Warm Desert Active and Stabilized Dune (100%), Sonora-Mojave Mixed Salt Desert Scrub (79%), and North American Warm Desert Riparian Woodland and Shrubland (71%). For the region, the proportion of status 1 and 2 protection within the Arizona Sonoran is considerably less for all except for the nearly endemic Sonoran Paloverde-Mixed Cacti Desert Scrub (96%, Table 4) and North American Warm Desert Active and Stabilized Dune (77%).

DISCUSSION

Gap analysis provides a "coarse filter" assessment of the conservation protection of biota (The Nature Conservancy 1982). There is no single statistic that fully describes the adequacy of the representation on lands with high conservation protection of an ecological system. Ecological condition of the land is not part of the gap analysis; and past management and other stresses (such as invasion of intro-

Table 3. Land stewardship and conservation management in the Arizona Sonoran ecoregion.

	Land area		Status 1		Status 2		Status 3		Status 4	
	km²	%	km	%	km²	%	km²	%	km²	%
Federal Lands										
Bureau of Land Management	23,912	26.5%	63	0.3%	5,838	24.4%	18,011	75.3%	0	0.0%
Bureau of Reclamation	382	0.4%	0	0.0%	0	0.0%	0	0.0%	382	100.0%
Fish and Wildlife Service	6,282	7.0%	5,984	95.2%	298	4.8%	0	0.0%	0	0.0%
Forest Service	3,429	3.8%	10	0.3%	736	21.5%	2,683	78.3%	0	0.0%
Defense or Energy	10,611	11.8%	0	0.0%	1,243	11.7%	9,368	88.3%	0	0.0%
National Park Service	1,455	1.6%	1,453	99.9%	2	0.1%	0	0.0%	0	0.0%
Tribal	15,838	17.6%	0	0.0%	0	0.0%	12,952	81.8%	2,886	18.2%
State										
State Parks and Recreation	181	0.2%	0	0.0%	0	0.1%	1,819	99.9%	0	0.0%
State Land Board	11,465	12.7%	0	0.0%	237	2.1%	37	0.3%	11,191	97.6%
State Wildlife Reserves	111	0.1%	0	0.0%	99	89.0%	121	0.7%	0	0.3%
Local Governments										
Regional Government	486	0.5%	0	0.0%	0	0.0%	0	0.0%	486	100.0%
City Land	165	0.2%	0	0.0%	0	0.0%	0	0.0%	165	100.0%
County Land	156	0.2%	0	0.0%	0	0.0%	0	0.1%	156	99.9%
Local Land Trust	2	0.0%	0	0.0%	1	65.7%	1	34.3%	0	0.0%
Private										
TNC	29	0.0%	3	10.9%	15	53.4%	10	35.7%	0	0.0%
Private/Unrestricted	15,515	17.2%	0	0.0%	0	0.0%	0	0.0%	15,515	100.0%
Water[1]	169	0.2%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
Total[2]	90,190	100.0%	7,514	8.3%	8,469	9.4%	43,255	48.0%	30,782	34.1%

[1] Water was not assigned a status category
[2] Column totals indicate the total land and porportion of land in each status category; rows indicate the proportion for each category of land owner

duced species, altered ecological processes, and habitat fragmentation) may greatly influence the adequacy of land to support targeted biodiversity.

This gap analysis provides information that can be used in several ways:

1) The analysis identifies ecological systems or vertebrate animal habitats that lack legal protection or have minimal legal protection. Additional legal protection may be required for adequate conservation management;

2) The analysis indicates ecological systems whose representation within status 1 and 2 lands may be adequate, but the adequacy of management at status 1 or 2 level is not known. Inadequate status 1 and 2 management may be due to lack of appropriate management or may occur because impacts to the land preclude the ability to manage at the status 1 or 2 level. The gap analysis statistics can provide an indication of the importance of providing management or mitigating impacts so that the status 1 or 2 level conservation management is achieved where mandated.

3) The analysis identifies the proportion of an ecological system within status 4 lands. This provides an indication of the impact on

Table 4. Representation of ecological systems in status 1 and 2 for the Arizona Sonoran ecoregion, Arizona state and the region and in status 4 for the ecoregion.

Ecological System	Status 1 & 2 in Arizona Sonoran (%)	Status 4 in Arizona Sonoran (%)	Proportion state status 1 & 2 in Arizona Sonoran (%)	Proportion regional status 1 & 2 in Arizona Sonoran (%)
Sonoran Paloverde-Mixed Cacti Desert Scrub	22.9%	24.3%	96%	96%
Sonora-Mojave Creosotebush-White Bursage Desert Scrub	18.9%	27.5%	76%	37%
Apacherian-Chihuahuan Mesquite Upland Scrub	7.9%	33.4%	42%	15%
Sonoran Mid-Elevation Desert Scrub	17.6%	32.7%	23%	23%
North American Warm Desert Active and Stabilized Dune	40.1%	2.9%	100%	77%
Chihuahuan Mixed Salt Desert Scrub	1.1%	23.9%	6%	6%
Sonora-Mojave Mixed Salt Desert Scrub	3.0%	78.3%	79%	5%
North American Warm Desert Riparian Mesquite Bosque	5.1%	29.2%	44%	38%
North American Warm Desert Riparian Woodland and Shrubland	20.3%	48.4%	71%	52%
North American Warm Desert Lower Montane Riparian Woodland and Shrubland	30.4%	40.6%	11%	5%
North American Warm Desert Wash	15.0%	47.1%	22%	7%
Chihuahuan Succulent Desert Scrub	0.7%	34.9%	5%	2%

the ecological system if its occurrence on status 4 lands were lost.

While status 1 and 2 lands indicate that land has a legal mandate to be managed so as to conserve biota, legal mandate does not insure that such management is actually implemented. For example, illegal immigration and various smuggling activities across the Arizona-Mexico border have resulted in a proliferation of informal foot trails, informal roads, and deposition of large amounts of trash and human waste on status 1 and 2 lands in the border states (Segee and Neeley 2006). An extensive barrier is being constructed at the international border that has the potential to fragment movement of vertebrates across the border (Vacariu 2004-2005). Uncontrolled infestations of invasive biota have degraded habitat in the Arizona Sonoran and are linked with changes in fire magnitude and frequency (Brooks and Pyke 2001) that can convert a vegetation type.

Conversely, the assignment of land to status 4 does not necessarily mean that land is not being managed for conservation of natural biota. Private land owners may enter into conservation easements that have not been included in the stewardship mapping (since these data are included only if voluntarily provided to SWReGAP). Private land owners may choose to manage for biodiversity without any such legal mandates on the land.

Our assessment of ecological systems in the Arizona Sonoran identified 11 systems that are either spatially dominant or have over a third or more of their range within the Arizona Sonoran. Five ecological systems have very low status 1 and 2 protection (< 10%). However, four of those ecological systems appear to have half or more of their state and regional status 1 and 2 protection in other ecoregions. The fifth, Sonora-Mojave Mixed Salt Desert Scrub is an exception in that it has low status 1 and 2 protection within the Arizona Sonoran and this protection is nearly 80 percent of all status 1 and 2 protection for the ecological system within the state. In addition, within the Arizona Sonoran 78 percent of Sonora-Mojave Mixed Salt Desert Scrub is in status 4 lands, which have no conservation mandate. Sonoran Paloverde-Mixed Cacti Desert Scrub, Sonora-Mojave Creosotebush-White Bursage Desert Scrub, and North American Warm Desert Riparian Woodland and Shrubland are also notable in that they have between 18 and 23 percent status 1 and 2 protection within the Arizona Sonoran, which represents over 70 percent of the state status 1 and 2 protection for these ecological systems. North American Warm Desert Active and Stabilized Dune is the best protected within the Arizona Sonoran (40.1% status 1 and 2) yet this protection represents all of the state protection and over three-fourths of the regional protection.

These results of the ecoregional gap analysis suggest that conservation management should be maintained or increased for: Sonoran Paloverde-Mixed Cacti Desert Scrub, Sonora-Mojave Creosotebush-White Bursage Desert Scrub, North American Warm Desert Active and Stabilized Dune, Sonora-Mojave Mixed Salt Desert Scrub, and North American Warm Desert Riparian Woodland and Shrubland using the criteria of the high proportion of statewide status 1 and 2 protection occurring in the Arizona Sonoran. The Sonoran Paloverde-Mixed Cacti Desert Scrub and Sonora-Mojave Mixed Salt Desert Scrub are additionally highlighted in that the former is nearly endemic to the ecoregion and the small area of the latter with status 1 and 2 protection in the Arizona Sonoran represents most of the status 1 and 2 protection in the state.

This gap assessment for the Arizona Sonoran provides a first-level, coarse-filter analysis of conservation protection. Our results should be considered with respect to conservation protection provided on adjacent lands and to “fine filter” information potentially available on the biota for the areas of interest. Other criteria, such as the actual total land cover of an ecological system, especially in combination with a view of the historical extent of the ecological system or the number of vertebrate species the ecological system supports, may highlight the need for maintenance and/or increase in the conservation protection of other Arizona Sonoran ecological systems. The results of our ecoregional gap analysis can be used to derive location data for examining potential additional legal protection or changes in conservation management planning.

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VERTEBRATE SPECIES IN DESERT CAVES AND MINES — A COMPARISON BETWEEN THE CHIHUAHUAN AND SONORAN DESERTS

Thomas R. Strong

Caves are widely known to provide habitat for a variety of vertebrate species that spend all or significant portions of their life cycles inside the totally dark areas. It is less well known that caves, and particularly cave entrance areas, can provide an important resource for a wide variety of other species. Especially in arid regions, caves may provide temporary relief from extreme temperature or low humidity (Kingsley et al. 2001), they may provide den sites, nest substrates, hunting locations for predators, or hiding places to escape predators.

While many individual observations of vertebrate species in caves have been reported, there have been few attempts to compile this information in any systematic way. Kingsley et al. (2001) compiled a list of species known to use caves or abandoned mines in the Sonoran Desert. This list was based primarily on personal observations or knowledge of the four authors and on records listed in Hoffmeister (1986), but it did not include a thorough literature review. Still, this preliminary list included 67 vertebrate species (4 amphibians, 14 reptiles, 11 birds, and 38 mammals). The primary conclusion of the paper was that caves and mines are significant wildlife habitat resources and worthy of protection through the Sonoran Desert Conservation Plan proposed by Pima County.

The Chihuahuan Desert covers a large area of southern New Mexico, western Texas, and the extreme southeastern corner of Arizona. This desert includes an even larger area of Mexico, extending far south in the central plateau. Average annual rainfall in the Carlsbad, New Mexico, vicinity is about 35.9 cm (14.1 in), with most precipitation coming during a summer rainy season. Summer daytime high temperatures are around 35° C (95° F), and winter lows are around –2° C (28° F).

Many caves are located in extensive deposits of limestone and gypsum in the Chihuahuan Desert. These caves provide more moderate conditions of temperature and humidity that may be a critical resource for many species. As in other desert regions of North America, there have been no systematic studies of vertebrate species using the cave habitats, although Bailey (1928) mentioned the use of caves by many species in his account of the vertebrate biology of the Carlsbad Caverns region.

The Sonoran Desert covers most of southern and western Arizona, southeastern California in the U.S.; and Sonora and the Baja Peninsula in Mexico. Within Arizona, typical annual precipitation values are 6.9 cm (2.7 in) at Yuma and 27.9 cm (11.0 in) at Tucson. Summer monthly average daytime high temperatures range from about 38° to 42° C (100° to 107° F), and monthly average winter lows range from about 4° to 8° C (39° to 46° F).

This part of Arizona is in the Basin and Range physiographic province, with broad, low valleys separated by mountain ranges. Some of these mountain ranges may be several thousand feet above the valleys, such that the mountain tops are above the Sonoran Desert biome. Geology of this region is complex, with bedrock exposures in the mountains separated by wide valleys of alluvial deposits. Sedimentary rocks, including limestone and gypsum, are present in isolated patches, and igneous and metamorphic rocks are common in the mountain ranges.

METHODS

Data in this analysis were compiled from a variety of sources. The primary sources of information for the Chihuahuan Desert were in the unpublished records in the files of Carlsbad Caverns National Park and the Carlsbad Field Office of the Bureau of Land Management. Several internet sites have extensive information on vertebrate species and their habitat usage and requirements. In particular, Biotic Information System of New Mexico (BISON-M; BISON 2004), supported by the New Mexico Department of Game and Fish, and NatureServe Explorer (NatureServe 2004), supported by natural heritage programs. Other standard literature sources were also searched for relevant information. Underground features in the Chihuahuan Desert are limited to caves in soluble rocks. Extensive limestone and gypsum karst areas with many caves are readily accessible in the vicinity of Carlsbad, New Mexico. Direct observations were made in many limestone and gypsum caves of this region.

For the Sonoran Desert, there are no dense concentrations of caves on public lands, and there are no file records comparable to those in New Mexico. Kingsley et al. (2001) provide a reliable list of species known to utilize caves and mines in southern Arizona, but they did not document species in relation to specific locations. Other sources, in particular Hoffmeister (1986) and Cockrum and Petryszyn (1991), provided valuable information, including site records. While caves are relatively rare in the Sonoran Desert, abandoned mines are relatively common and provide underground resources similar to natural caves. Direct observations were made in numerous caves and abandoned mines in southern Arizona.

Observational evidence of vertebrate species can take several forms. Visual observations of living animals are the most reliable evidence of species using underground resources. These animals got into the cave or mine under their own power, which suggests that they made a conscious choice to use the underground site for some purpose. The presence of nests or den sites is also positive evidence of the mammal or bird that constructed the nest, and it also provides evidence of the reason for the use of the underground feature. Similarly, the presence of feathers and egg shells indicates that birds were nesting in the cave or mine, and the condition of the egg shells can indicate successful hatching. The presence of scat in a cave or mine demonstrates that the animal was alive while in the site, and it also indicates that the animal was in the site for a significant period of time. Tracks indicate the presence of a live animal in the site, but they provide no evidence for the reason for or the duration of the visit. Skeletal material in a cave or mine is even more ambiguous. While it can generally be identified to species, it does not necessarily provide confirmation that the animal entered the site by its own choice, or even whether it was alive when it entered the site. Skeletal material at the bottom of a pit generally indicates that the animal died as a result of the fall. Although it may have entered the cave by choice, it probably did not intend to fall into a pit.

Data from all of these sources were entered into spreadsheets, including species, caves, dates of observation (if known), and original observers (if known). Each report of a species from a cave or mine was entered as a separate record. For common species, there were often multiple reports from a single site.

RESULTS

Chihuahuan Desert

The literature and file searches and personal observations provided over 730 reports of 81 species of vertebrates in the caves of the Chihuahuan Desert in the vicinity of Carlsbad, New Mexico. These records are a little vague, because a primary source of information (Bailey 1928) reports many species as being found in numerous other caves near Carlsbad Cavern, without any specific details. Another drawback in the data obtained from the file searches is that most reports are not from trained biologists, and many sightings are not identified to species. In addition, large, easily recognizable, or dangerous animals, such as mountain lions, porcupines, or rattlesnakes, are more likely to be reported than wood rats that are so common no one feels a need to report seeing them. However, reports for a single cave as "unidentified bat," "unidentified rodent," and "unidentified snake" would still count as at least three different vertebrate species for that cave. Vertebrate records are available for at least 160 caves in the Carlsbad vicinity, including 80 caves in Carlsbad Caverns National Park, 79 caves on BLM lands, and 1 cave on State of New Mexico land. Additional details of the Chihuahuan Desert species diversity and distribution will be provided in another publication (Strong, in preparation).

Sonoran Desert

Data for the Sonoran Desert are relatively sparse compared with the Chihuahuan Desert, for the reasons given above. However, because of the sources of data, there are very few observations that are not identified to species. I have compiled records with at least 210 reports of vertebrates, including 31 species documented with specific locations. Another 43 species are considered confirmed, but without specific locations, based on Kingsley et al. (2001). Confirmed records are known for 13 caves, including 11 limestone caves and two basalt caves, and for 52 abandoned mines.

Species Distribution

The data from these two desert regions may be analyzed is several ways. The simplest and most direct approach is to compile a list of species for each region, as shown on Table 1. This table is limited to those reports that identified an organism to species. In this table, the data are the number of different sites from which a species was reported at least once. For the species in the Sonoran Desert that were considered confirmed but not documented in specific sites, a minimum number of one was assigned. It is apparent from this list that a few species are reported from many sites and many species are reported from only one or two sites.

The data from Table 1 are summarized in Table 2 to show the numbers of vertebrate species of each class found in each desert region, and the numbers shared by the two deserts. Mammals dominate the vertebrate species sets in each desert region, and not surprisingly, bats provide the most species in each area. Birds and reptiles are reasonably well-represented in the underground features of both desert regions. Amphibians and fish are poorly represented, but they are relatively scarce in most other habitats of these deserts.

These data on species distribution in the caves and mines are presented graphically in Figures 1 and 2 for the Chihuahuan and Sonoran Deserts, respectively. The horizontal axis of this figure represents the number of vertebrate species that are found in the number of underground features shown on the vertical axis. These graphs clearly illustrate that many species are found in very few sites, while only a few species are widely distributed in many locations. The graph for the Sonoran Desert is skewed because of the large number of species that are not documented for specific sites and are assigned the minimum value of one site. Additional information would likely change the shape of the graph and it would retain the same general pattern as in the Chihuahuan Desert.

Site Diversity

An alternative way to analyze these data is to examine the number of vertebrate species using each cave or mine. These results are illustrated in Figures 3 and 4 for the Chihuahuan and Sonoran Deserts, respectively. Even though data are available for many more sites in the Chihuahuan Desert, the diversity

Table 1. Vertebrate species in underground sites. Data indicate the number of sites in which each species has been documented. Nomenclature follows ITIS 2007.

Scientific Name	Common Name	Chihuahuan Desert	Sonoran Desert
Mammals			
Notiosorex crawfordi	Desert Shrew	2	1
Macrotis californicus	California Leaf-nosed Bat		21
Choeronycteris mexicana	Mexican Long-tongued Bat		6
Leptonycteris yerbabuena	Lesser Long-nosed Bat		15
Myotis velifer	Cave Myotis	14	16
Myotis thysanodes	Fringed Myotis	4	
Myotis volans interior	Long-legged Myotis	2	
Myotis californicus	California Myotis	1	2
Myotis leibii	Small-footed Myotis	2	1
Myotis yumanensis	Yuma Myotis	2	1
Lasiurus cinereus	Hoary Bat	2	
Lasiurus borealis	Eastern Red Bat	2	
Lasionycteris noctivagans	Silver-haired Bat	1	
Pipistrellus hesperus	Western Pipistrelle	3	1
Eptesicus fuscus	Big Brown Bat	2	2
Euderma maculatum	Spotted Bat		1
Idioinycteris phyllotis	Allen's Big-eared Bat		1
Plecotus townsendii	Townsend's Big-eared Bat	16	5
Antrozous pallidus	Pallid Bat	2	8
Tadarida brasiliensis	Brazilian Free-tailed Bat	5	4
Nyctinimops macrotus	Big Free-tailed Bat	1	1
Nyctinimops femorosacca	Pocketed Free-tailed Bat	1	1
Eumops perotis	Western Mastiff Bat		1
Eumops underwoodi	Underwood's Mastiff Bat		1
Lepus californicus	Black-tailed Jack Rabbit	4	2
Sylvilagus auduboni	Desert Cottontail	5	3
Ammospermophilus harrisii	Harris' Antelope Squirrel		2
Eutamias canipes	Gray-footed Chipmunk	1	
Spermophilus variegatus	Rock Squirrel	3	1
Thomomys bottae	Valley Pocket Gopher	2	1
Pappogeomys mexicana	Mexican Pocket Gopher	1	
Pappogeomys castanops	Yellow-faced Pocket Gopher	2	
Chaetodipus intermedius phasma	Rock Pocket Mouse		1
Chaetodipus baileyi baileyi	Bailey's Pocket Mouse		1
Peromyscus eremicus	Cactus Mouse		1
Peromyscus crinitus	Canyon Mouse		1
Peromyscus boylii	Brush Mouse	1	1
Peromyscus leucopus	White-footed Mouse	1	
Peromyscus pectoralis	White-ankled Mouse	1	

Table 1. *continued*

Scientific Name	Common Name	Chihuahuan Desert	Sonoran Desert
Dipodomys spectabilis	Banner-tailed Kangaroo Rat	1	
Dipodomys merriami	Merriam's Kangaroo Rat	3	3
Dipodomys deserti	Desert Kangaroo Rat		1
Neotoma albigula	White-throated Wood Rat	1	3
Neotoma lepida	Desert Wood Rat		1
Neotoma mexicana	Mexican Wood Rat	2	
Sigmodon hispudus	Hispid Cotton Rat	1	
Erethizon dorsatum	Porcupine	37	1
Canis latrans	Coyote	4	
Urocyon cinereoargenteus	Gray Fox	2	1
Vulpes velox	Swift Fox	1	
Vulpes microtus	Kit Fox		2
Ursus americanus	Black Bear	2	
Procyon lotor	Raccoon	6	1
Nasua nasua	Coati		1
Bassariscus astutus	Ringtail	39	4
Mustela frenata	Long-tailed Weasel	1	
Taxidea taxus	Badger	1	
Conepatus leuconotus	Common Hognosed Skunk	2	1
Spilogale gracilis	Western Spotted Skunk	1	1
Mephitis mephitis	Striped Skunk	3	1
Puma concolor	Mountain Lion	18	1
Lynx rufus	Bobcat	2	1
Peccari tajacu	Collared Peccary	1	3
Odocoileus hemionus	Mule Deer	15	1
Ovis canadensis	Desert Bighorn Sheep	2	1
Ammotragus lervia	Barbary Sheep	12	
Capra hircus	Domestic Goat	15	
Birds			
Coragyps atratus	Black Vulture		1
Cathartus aura	Turkey Vulture	5	3
Buteo regalis	Ferruginous Hawk	1	
Tyto alba	Barn Owl	5	2
Megascops kennicottii	Western Screech-Owl	1	
Bubo virginianus	Great Horned Owl	20	2
Phalaenoptilus nuttallii	Common Poorwill	1	
Zenaida macroura	Mourning Dove	1	
Aeronautes saxatalis	White-throated Swift	3	1
	Hummingbird sp.	1	
Colaptes auratus	Northern Flicker	5	
Sayornis saya	Say's Phoebe	5	2

Table 1. *continued*

Scientific Name	Common Name	Chihuahuan Desert	Sonoran Desert
Myiarchus cinerascens	Ash-throated Flycatcher	1	
Petrochelidon fulva	Cave Swallow	19	
Petrochelidon pyrrhonota	Cliff Swallow		1
Tachycineta thalassina	Violet-green Swallow		1
Salpinctes obsoletus	Rock Wren	10	1
Catherpes mexicanus	Canyon Wren	8	1
Junco hyemalis	Dark-eyed Junco	1	
Spizella atrogularis	Black-throated Sparrow		1
Reptiles			
Terrapene ornata	Ornate Box Turtle	1	
Chrysemys picta	Painted Turtle	1	
Gopherus agassizii	Desert Tortoise		1
Crotophytus collaris	Collared Lizard	2	
Sceloporus magister	Desert Spiny Lizard		1
Sceloporus clarkii	Clark's Spiny Lizard		1
Sceloporus undulatus	Eastern Fence Lizard	1	1
Uta stansburiana	Common Side-blotched Lizard		1
Urosaurus ornatus	Ornate Tree Lizard		1
Heloderma suspectum	Gila Monster		1
Pituophis catenifer	Gopher Snake	2	
Salvadora grahamiae	Mountain Patch-nosed Snake	1	
Thamnophis sp.	Garter Snake	1	
Tantilla sp.	Black-headed Snake	1	
Crotalus atrox	Western Diamondback Rattlesnake	8	1
Crotalus lepidus	Mottled Rock Rattlesnake	7	
Crotalus lepidus	Banded Rock Rattlesnake		1
Crotalus mitchelii	Speckled Rattlesnake		1
Crotalus molossus	Black-tailed Rattlesnake	3	2
Crotalus tigris	Tiger Rattlesnake		1
Crotalus scutulatus	Mojave Rattlesnake		1
Amphibians			
Ambystoma mavortium	Tiger Salamander	6	1
Anaxyrus punctatus	Red-spotted Toad	1	1
Lithobates yavapaiensis	Lowland Leopard Frog		1
Fish			
Fundulus zebrinus	Plains Killifish	1	

Table 2. Summary of species numbers in each desert by class.

Vertebrate Class	Chihuahuan Desert	Sonoran Desert	Species in Both Deserts
Mammals	51	47	32
Birds	16	11	7
Reptiles	11	13	4
Amphibians	2	3	2
Fish	1	0	0
Total	81	74	45

within sites has a similar pattern for both deserts, with many sites having only a few species and a few sites having many species. The site with the greatest number of species in the Chihuahuan Desert is Carlsbad Cavern, a large cave which has been studied intensively for several decades by many researchers. In contrast, the site with the greatest number of species in the Sonoran Desert is a small basalt cave with all species recorded in a single visit.

DISCUSSION

Confirmed Resource Uses

While the diversity and distribution of vertebrates using underground features is of interest, from an ecological point of view the reasons why vertebrates seek out these resources is even more interesting. Data on the uses of caves or mines are generally more available for the Chihuahuan Desert, but some data are available for the Sonoran Desert. The simplest use of a cave or mine would be as a temporary roost site. Several species of birds have been observed roosting in caves, particularly owls using caves as daytime roost sites (T. Strong, pers. obs.). Similarly, many species of bats use caves or mines as temporary nighttime roosts between foraging bouts.

Caves and abandoned mines provide good sites for nests or dens for many species of birds and mammals. Wood rat (*Neotoma* sp.) nests are found in many sites in both the Chihuahuan and Sonoran deserts, but the species building the nests cannot be identified without visual confirmation (Novack 2004; Allison 2004). Bailey (1928) reported that mountain lions were using caves as den sites in the Carlsbad Caverns vicinity, and lions have been encountered in other caves in this region (Parent 1998; Allison and Roemer 1998; J. Goodbar, pers. comm.). Piles of small mammal bones may indicate the presence of carnivore den sites (T. Strong, pers. obs.). Porcupine den sites have been noted in numerous caves in the Chihuahuan Desert (Fleming and Hummel 1977b; Hummel 1977; Belski 1979), and live porcupines have been encountered (Pate 1992; Fleming 1977; T. Strong, pers. obs.). Birds also use caves and mines as nest sites, with confirmed nesting for at least nine species in caves of the Chihuahuan Desert and at least four species in the Sonoran Desert (Bailey 1928; Belski 1989; Fleming and Hummel 1977a; Lindsley 1967; Pate et al. 1995; Spangle and Thompson 1958; Corman and Wise-Gervais 2005; T. Strong, pers. obs.). The cave swallow (*Petrochelidon fulva*) is the most common nesting bird in Chihuahuan Desert caves, with nesting confirmed in at least 15 caves.

Caves and mines are also important as maternity sites for many bat species. The Brazilian free-tailed bat (*Tadarida brasiliensis*) is well-known for its maternity colony in Carlsbad Caverns. Maternity colonies for cave myotis (*Myotis velifer*) and fringed myotis

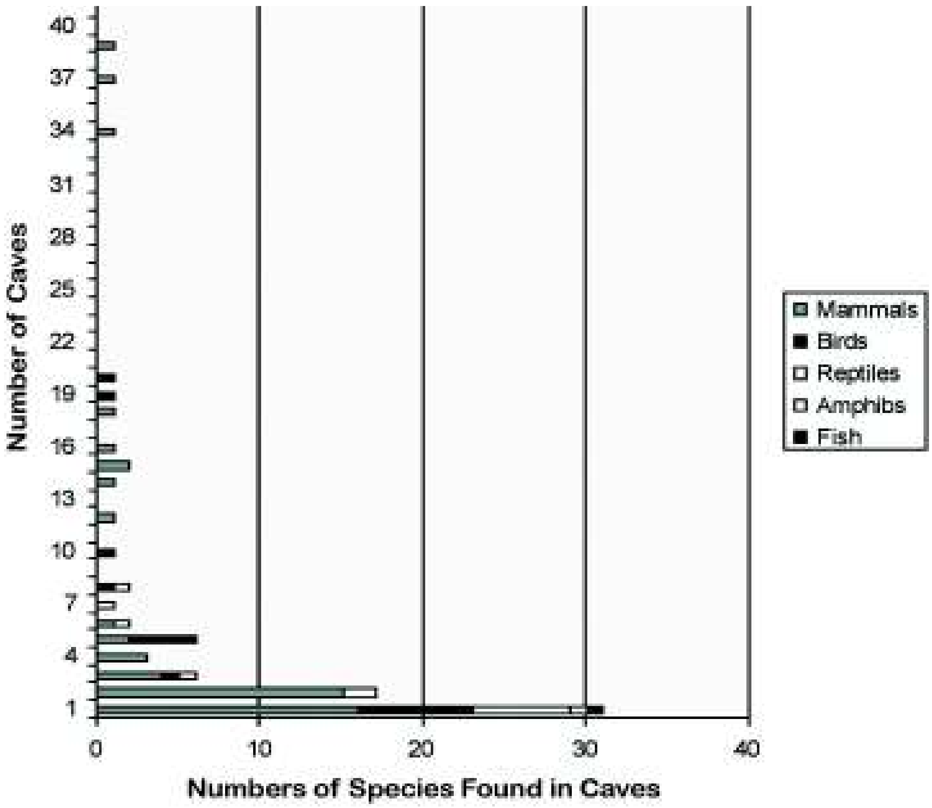

Figure 1. Distribution of vertebrate species found in caves of the Chihuahuan Desert near Carlsbad, New Mexico.

(*M. thysanodes*) (Ek 1990; Pate 1994) have also been reported for the Carlsbad Cavern vicinity. The only reported maternity sites for the endangered lesser long-nosed bat (*Leptonycteris yerbabuenae*) are in caves and mines of the Sonoran Desert (Cockrum and Petryszyn 1991).

Many vertebrate species are known to use caves or abandoned mines as hibernation sites. In particular, bats have been observed hibernating in several caves of the Chihuahuan Desert (Bailey 1928; Belski 1988; Baker et al., no date; Kerbo 1978; Ek 1991). It is likely that several bats hibernate in Sonoran Desert caves and mines, but this behavior has not been specifically reported. The poorwill is the only known bird confirmed to hibernate, and it could use caves or mines in these deserts as hibernation sites. It has been reported hibernating (not in a cave) at Carlsbad Caverns National Park (S. West, pers. comm.), and it has been observed in a crevice in a pit entrance to a cave in the Park (P. Seiser, pers. comm.). It is likely that several reptiles and amphibians use caves as hibernation sites, but there are no documented observations in the caves or mines of either desert.

Probable Resource Uses

Underground features in arid regions are likely to provide water sources for a variety of animals. Caves and mines may provide points

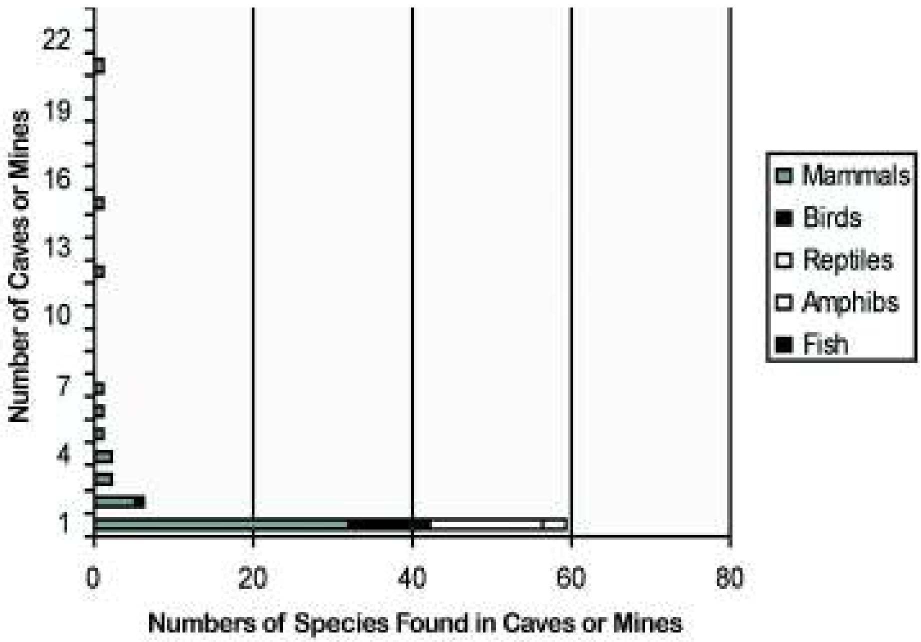

Figure 2. Distribution of vertebrate species found in caves and mines of the Sonoran Desert of Arizona.

of access to groundwater or small perched aquifers in areas where surface water is rare. Mule deer and bighorn sheep have been reported to obtain water from pools in caves with large entrances in Slaughter Canyon in 233 National Park (Bailey 1928; Welbourn 1978). It seems almost certain that other vertebrate species are using these water sources in both desert regions, but if it has been observed, it has not been reported.

Some species are apparently using caves as foraging sites. Bailey (1928) reported that white-footed mice were common throughout Carlsbad Cavern and were feeding on crickets and food dropped by tourists. Ringtails are likewise found in deep areas of Carlsbad Cavern (Bailey 1928; D. Pate, pers. comm.), and it seems likely that they are feeding on mice. Bailey (1928) also suggested that mountain lions were using a cave with a large entrance as a hunting site. Snakes are also likely to use caves as foraging sites. A paralyzed mouse seen in the entrance of a cave on 233 National Park had probably been bitten by a rattlesnake that was seen nearby (Reames and Barber 2003). A live mountain patch-nosed snake (*Salvadora grahamiae*) at the bottom of a 13 meter pit was probably foraging on mice that have been seen at the bottom of the pit (T. Strong, pers. obs.). In another cave, the presence of a pile of cave swallow feathers on a ledge with ringtail scat suggests the possibility of predation (T. Strong, pers. obs.).

Another probable use of caves or mines is to obtain relief from extreme environmental conditions. In desert regions with very high summer temperatures and very low humidity, caves and mines could provide sites with lower temperatures and much higher relative humidities. It seems likely that many vertebrate species would deliberately select these favor-

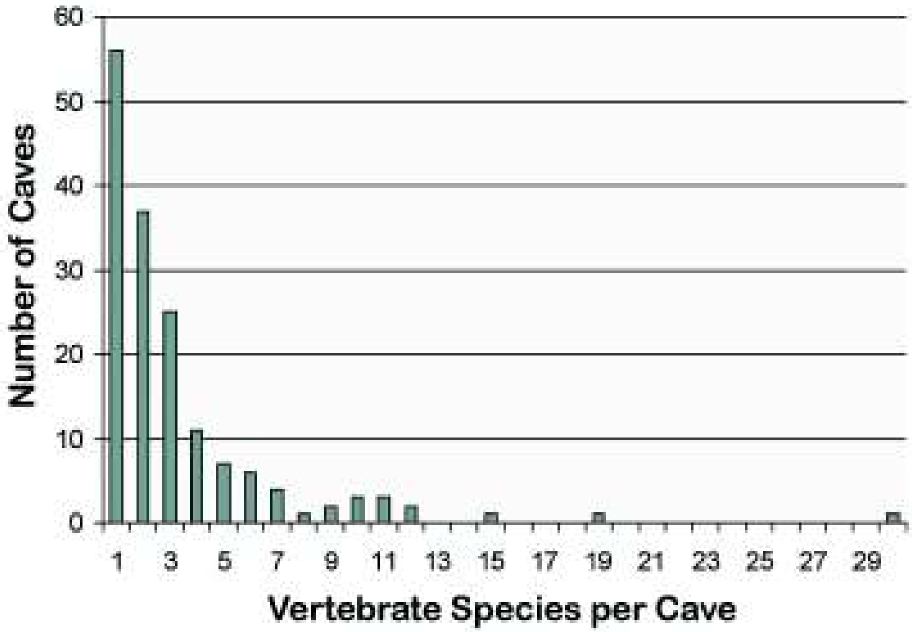

Figure 3. Diversity of vertebrate species in caves of the Chihuahuan Desert near Carlsbad, New Mexico.

able microclimates, although choice might be very difficult to demonstrate.

Incidental or Unintentional Uses

Numerous species of mammals have been identified through the presence of tracks or scat, indicating use of the cave. Birds and reptiles may also leave evidence of this type in caves. These observations could fall into the category of incidental use. While evidence of this sort confirms that an animal was alive while in the cave or mine, it cannot be interpreted to explain why the animal was using the site.

The presence of skeletal material in caves and mines may mean that the animals entered the cave deliberately, but they may have been unable to find their way back out. Animals whose remains are found at the bottom of a pit may have entered the site deliberately, but probably did not intend to fall into a pit. Some of these animals may have been killed by the fall, or they died because they were unable to climb out. Some vertebrates, particularly reptiles, appear to be able to survive relatively long drops. As noted above, a mountain patch-nosed snake apparently survived a 13 m fall into an overhanging pit in a Chihuahuan Desert cave (T. Strong, pers. obs.).

Skeletal material found in some caves may also suggest that these animals (or parts thereof) had been carried into the caves as prey items. For example, jackrabbit and cottontail bones were found in a cave with a short climb down into the entrance of this cave which would make it very difficult for these animals to get out of the cave. However, carnivores could easily climb in and out, and ringtail and bobcat tracks were common in the cave, suggesting that these carnivores could have carried the rabbits into the cave (T. Strong, pers. obs.). Deer legs found in a cave with a large entrance were probably brought into the cave by a large predator (Carrington 1999),

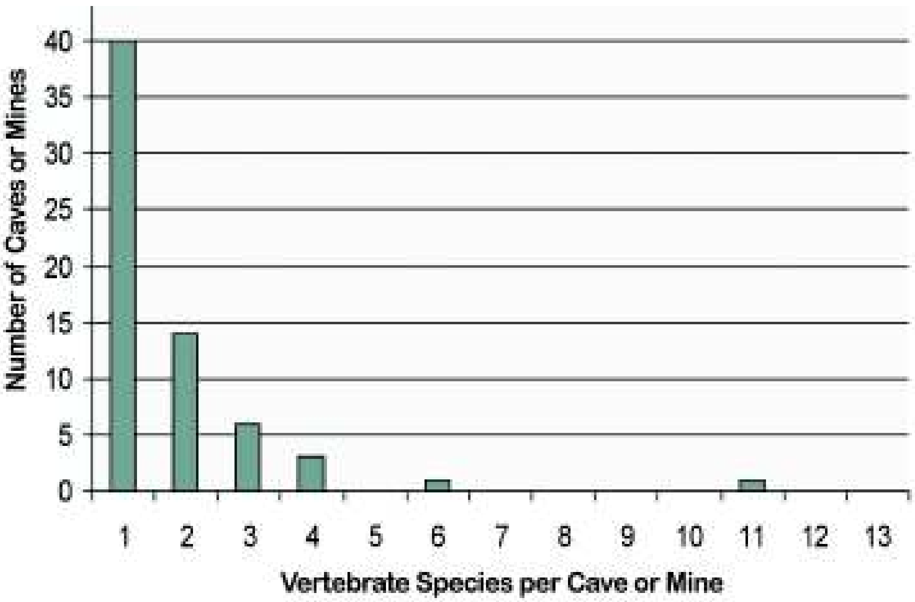

Figure 4. Diversity of vertebrate species in caves and mines of the Sonoran Desert of Arizona.

and mountain lions are known to use this cave (Roemer 2000). In some caves in both deserts, quantities of rodent bones are probably related to the use of these sites by great horned owls and barn owls, which eject pellets containing many small bones (T. Strong, pers. obs.).

Comparisons

Some of the observed differences in species distributions may be explained by a variety of differences between the underground features in the Sonoran and Chihuahuan Deserts. The following comments are generalizations, and some exceptions are likely for each of these comparisons. Geologically, the Carlsbad region of the Chihuahuan Desert is underlain by soluble rocks, primarily limestone and gypsum. The Carlsbad Caverns National Park is dominated by limestone formations in the Guadalupe Mountains, including Permian reef, fore-reef, and back-reef units. BLM lands north, east, and south of Carlsbad include extensive areas of gypsum karst. These soluble rocks allow the formation of large and small caves. Other rock types are rare in this vicinity, and none of the vertebrate records in this part of the Chihuahuan Desert are from mines. Topographically, the gypsum areas are on relatively flat-lying plains east and southeast of the Guadalupe Mountains. The mountain range rises gradually from the eastern plains and then drops abruptly to the south and west, and it is cut by numerous deep canyons.

In the Sonoran Desert of Arizona, limestone and gypsum are relatively rare, and only a few of the recorded underground sites are limestone or gypsum caves. This region is in the Basin and Range topographic province, with numerous mountain ranges separated by broad alluvial valleys. Some extrusive volcanics are present with vertebrates in two small caves of a basalt flow. Metamorphic rocks are common in the mountain ranges, and hydrothermal intrusions have created many deposits of copper and other metals. Early mining activity in these mineral deposits created large numbers of now-abandoned mine adits and shafts, many of which are now used by vertebrates. Most of the underground records of vertebrates in the Sonoran Desert are from abandoned mines. Topographically, most sites in the Sonoran Desert are located in the lower parts of mountain ranges where bedrock is exposed. These sites also tend to be at slightly lower elevations than the sites in the Chihuahuan Desert, leading to slightly higher average underground temperatures.

The general morphology of the underground features also varies between desert regions. Many of the limestone caves in the Guadalupe Mountains have large entrances that are visible from long distances. These large entrances provide easy access for small and large vertebrates. Large entrances also allow light to penetrate far into a cave, making a larger area suitable for animals that are limited to twilight zones of caves. Most of the gypsum caves in the Carlsbad vicinity have smaller entrances in sinkholes in the plains. These smaller entrances would limit the extent of light penetration and could preclude their use by larger animals.

The limestone and basalt caves in the Sonoran Desert have relatively small entrances, with limited light penetration and limited accessibility for larger animals. The abandoned mine entrances tend to be roughly the same size, being high enough and wide enough to allow relatively easy human entry, which also allows easy access for most animals. Light penetration in these features will be controlled to some extent by orientation.

The availability of water within the underground features also differs between deserts, and even among caves or mines within either the Sonoran or Chihuahuan Desert. In the Chihuahuan Desert, the gypsum caves on the plains east of the mountains are generally conduits for ephemeral floodwaters. Any surface water from rainfall runoff is captured in sinkholes and transported through the caves toward the Pecos River. In contrast, the limestone caves often have dripping water or pools of water, but flowing streams are rare. In the Sonoran Desert, the basalt caves are very dry, and the limestone caves are generally dry, although some may have some dripping water or small pools. The abandoned mines range from very dry to moderately wet, but there are no underground flow channels in the caves and mines of the Sonoran Desert. However, even features that have no free water are likely to have relative humidity conditions that are higher than the surrounding ambient conditions. The differing availability of water will influence the variety of vertebrate species that are able to utilize specific sites.

Another obvious difference between the Sonoran and Chihuahuan Deserts is the pool of species present in these two regions. The species found in underground features will be restricted to the available set of species in the vicinity of the underground sites. As can be seen in Table 1, some species are common to caves or mines in both deserts, but many other species are found in only one region or the other.

In summary, there are wide contrasts between the physical conditions of the underground features in the Sonoran and Chihuahuan Deserts. In addition, the data sets for each region are based on diverse sources, with non-uniform collection or observation procedures. In spite of these drawbacks, the patterns of species distribution among caves and mines and the patterns of species diversity within these features are similar in the two deserts. It is anticipated that further, systematic collection of data on vertebrates in these features will increase our list of species using these features as well as the numbers of sites for each species and will increase the record of the number of species within each site.

CONCLUSIONS

The results of this study demonstrate that underground features of both the Chihuahuan Desert and the Sonoran Desert are being used regularly by a wide variety of vertebrates. This level of usage and the documented types of usage by species demonstrates that these underground sites provide a habitat feature that is an important resource. In an arid environment with extremes of high temperatures and low relative humidity, caves could be critical to the survival of many vertebrates. Although few of the species observed in these sites are listed as threatened or endangered, their continued presence in the Chihuahuan or Sonoran Desert may depend on these underground resources.

With so many species depending on the underground features of these deserts, it is imperative that federal and local land management agencies maintain policies that provide protection for cave and mine resources. Most caves on Carlsbad Caverns National Park are administratively closed, although three caves are open for commercial tours (including tours in undeveloped areas) and eight others are open for recreational caving. As noted above, Carlsbad Cavern has a high diversity of species in spite of the heavy annual visitation. The Bureau of Land Management maintains a permit system for several of its caves, and there are some seasonal restrictions on visitation because of bats. However, many BLM caves are open for recreational caving with no restrictions. Many of the abandoned mines in the Sonoran Desert are controlled by large mining corporations, although they may be located on federal land. However, because of relatively easy public access, many of these sites are in danger of being closed for public safety and liability reasons.

Under the National Environmental Policy Act (NEPA), federal agencies are required to analyze potential environmental impacts prior to taking any action. Based on the evidence of vertebrate use of these caves and mines, potential impacts on these wildlife species and their habitat requirements must be considered. In addition, whether these agencies are giving permits for recreational caving or for scientific research, they should be encouraged to provide the permitees with information about wildlife species using the caves and any precautions they should take when visiting the caves. When mines are to be closed for public safety, surveys should determine the use or potential for use by vertebrates, primarily bats, and specially-designed gates could provide access for bats and other vertebrates while preventing human access.

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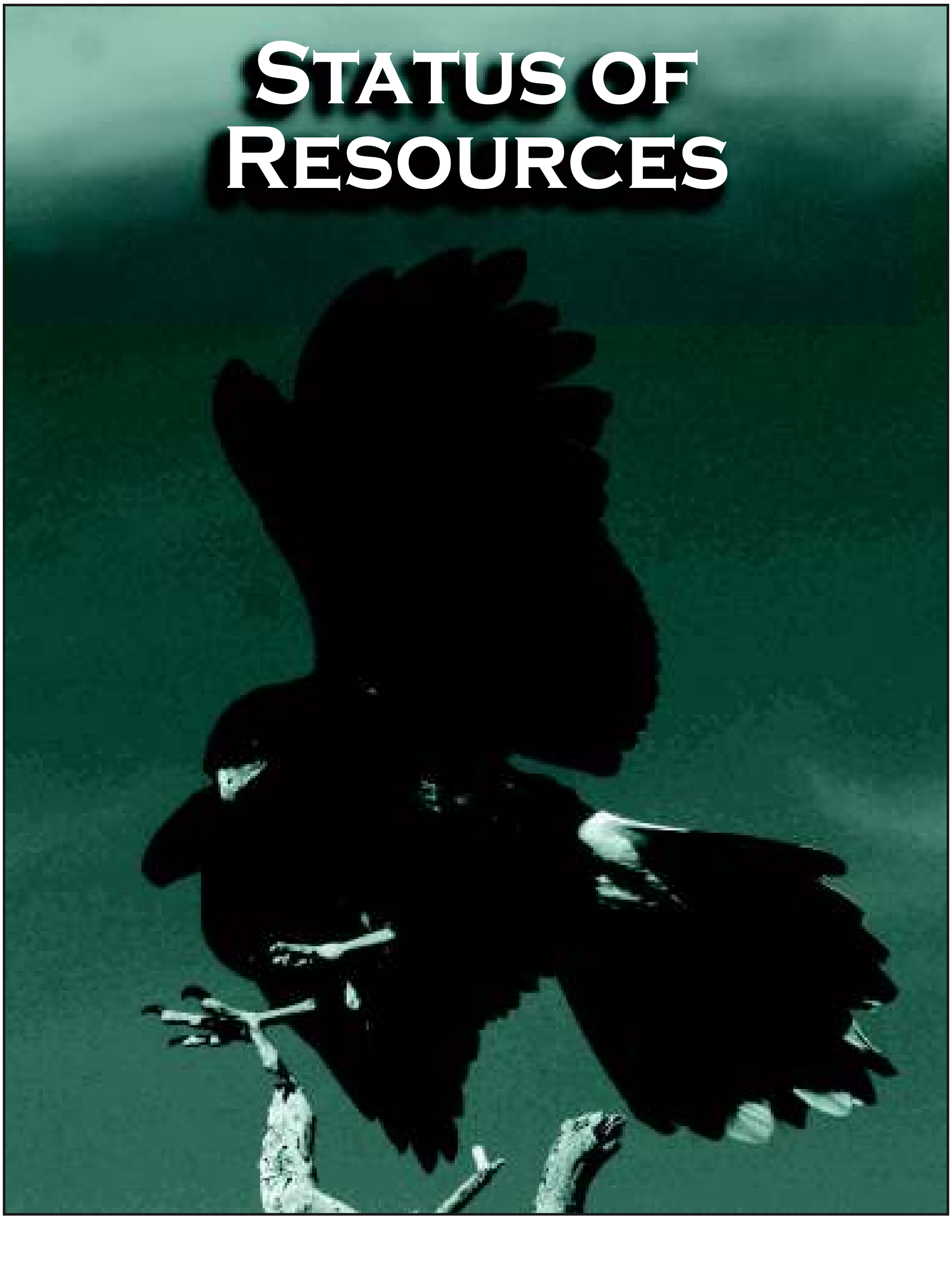
Status of Resources



IMPLICATIONS OF ILLEGAL BORDER CROSSING AND DRUG TRAFFICKING ON THE MANAGEMENT OF PUBLIC LANDS

Craig C. Billington, Randy Gimblett, and Paul R. Krausman

Increasing numbers of illegal immigrants are crossing rugged parts of the 3,122 km U.S.-Mexico border that traverses the Sonoran Desert. With increases in border-crossing come larger numbers and groups captured by Border Patrol and other agencies on state, federal and tribal lands. Increases in border security in urban portions of the border over the past several years have caused entrants and smugglers to attempt more difficult crossings, traversing public and tribal lands in Southern Arizona.

Between 1977 and 1987 the number of undocumented aliens (UDA) apprehended by the U.S. Border Patrol in the U.S. doubled from 1 to 2 million (Weber 1988). The reported increases in apprehensions have continued and represent increased enforcement, and increased UDA activity (Andreas 2000; Nevins 2002). The U.S. Immigration and Naturalization Service (INS) estimated that for every UDA apprehended two to three more cross the border undetected (Weber 1988). This does not include human traffic related to narcotics smuggling. Since immigration reform in 1996 and the increasing enforcement under Operation Gatekeeper (i.e., an increased effort and concentration of federal agents to tighten border security along U.S.-Mexico border cities, e.g., El Paso, Texas; San Diego, California), UDA and narcotics traffic shifted to remote areas (Cohen 1997; Andreas 2000; Nevins 2002; McIntyre and Weeks 2002; Jacoby 2004). Border Patrol activity has also increased in wildlands, which has caused more vehicle traffic, new roads, off-road vehicle (ORV) traffic, and aerial surveys associated with patrolling. The cumulative effect of this increased activity and the natural resource degradation is unknown.

Illegal activities in Arizona are indicative of the severity of the problem throughout the southwestern U.S. In 1999, the INS apprehended 470,499 UDA in Arizona, double the number apprehended in 1995 (McIntyre and Weeks 2002). In the Tucson sector, apprehensions by the U.S. Border Patrol related to illegal immigration increased from 333,648 in 2002 to 491,771 in 2004. Marijuana seized by the U.S. Border Patrol in the Tucson sector increased 31.6% between 2002 and 2004. This illegal activity contributes to the overall increase in human activity leading to natural resource degradation in remote areas of the desert near the Mexican border (McIntyre and Weeks 2002; Jacoby 2004; Tobin 2004). Areas that have been set aside as reserves — i.e., Organ Pipe Cactus National Monument (OPCNM), Cabeza Prieta National Wildlife Refuge (CPNWR), Buenos Aires National Wildlife Refuge (BANWR), and Ironwood Forest National Monument (IFNM) — have experienced increases in human activity (T. Tibbitts, biologist, OPCNM; C. McCasland, biologist, CPNWR, pers. comm.). Natural resource degradation due to humans occurs in all these areas, but remains largely undocumented (T. Tibbitts; C. McCasland, pers. comm.). Furthermore, the numbers of migrant deaths has climbed steadily since 1994 when

Operation Gatekeeper imposed strict enforcement on crossings in the urban areas surrounding Tijuana, San Diego, Ciudad Juarez and El Paso. In 1998, 28 people died during border crossings. In 2005, 7,200 were documented as deceased. This dramatic increase reflects the growing problem along the U.S.-Mexico border.

There have been corresponding increases in Border Patrol and other law enforcement activities in the Tucson sector. In fact, an initiative called the Arizona Border Control (ABC) has increased the number of Border Patrol agents in the Tucson sector (from 200 to greater than 2,000 agents), the number of aircraft, and unmanned aerial vehicles, and the detention center mentioned above (Department of Homeland Security 2004). Law enforcement agencies have been trying to decrease the number of migrant deaths by imposing strict enforcement on smugglers putting their human cargo in danger, using a search and rescue group, and avoiding apprehending immigrants near water stations. Humane Borders, a Tucson-based non-profit, has established water stations along the U.S.-Mexico border to improve migrant safety. Some view these water stations as encouraging illegal immigration, which may lead to vandalism. Stations in IFNM have been destroyed (Vanderpool 2003; Marizco 2004).

The vast stretches of unpopulated borderlands in Southern Arizona are a major corridor of human and drug smuggling. The Tohono O'odham Nation law enforcement officers routinely apprehend drug smugglers, netting between 2,000 and 6,000 pounds of cocaine and marijuana each month that have crossed their 75-mile stretch of border with Mexico (Hinkle 2001). These figures do not account for drugs confiscated by the Border Patrol or other law enforcement agencies operating in the area. More recently, the Border Patrol has been confiscating at least 5,000 pounds of drugs per month in the Tucson sector.

IMPACTS IN THE IFNM

Public lands in Southern Arizona, including the IFNM, have become a crossroads of illegal immigrant and drug smuggling, law enforcement activities, ranchers and recreational users. The IFNM, which was established by a Presidential Proclamation in 2000 (Clinton 2000), lies between the Tohono O'odham Nation to the south and west, and Interstate 10 to the northeast (Figure 1). The area contains many routes between the international border shared by the Tohono O'odham Nation, Mexico and Interstate Highway 10. Illegal immigrants and drug smugglers impact the natural environment of IFNM, leaving trash and creating new double-track, or "wildcat," roads. These illegal activities also impact the broader landscape of IFNM and its surroundings. The smuggling traffic in IFNM is a threat to many of the natural features unique to the area. Biologists from the Arizona Sonoran Desert Museum (ASDM) documented the impacts of smuggling traffic in the area. They noted impacts consisting of trash at camps, pickup sites, and travel routes within the monument (ASDM website). The ranchers living on the private property in and around IFNM are concerned about the dangers posed by drug smugglers and UDAs (Turf 2002).

Trash and illegal activity affects the whole community of IFNM users. Law enforcement and undocumented immigrants have been cited as major issues that have received considerable public comment during the scoping process (Bureau of Land Management 2004). In fact, 38.3% of the letters received in this process specifically cited these concerns. These concerns have also been voiced in the trip reports filled out by recreation users and recipients of hunting permits as part of the recreation study conducted by the University of Arizona (Gimblett 2004). In this study, over 50% of respondents ranked garbage dumping and illegal immigrant activity as the most serious problems facing the management of the monument.

The conflicts between drug smuggling, illegal immigration, illegal dumping, recreation use and ranching all pose challenges to IFNM's long-term planning and management strategies. The purpose of this paper is to describe a study that was intent on under-

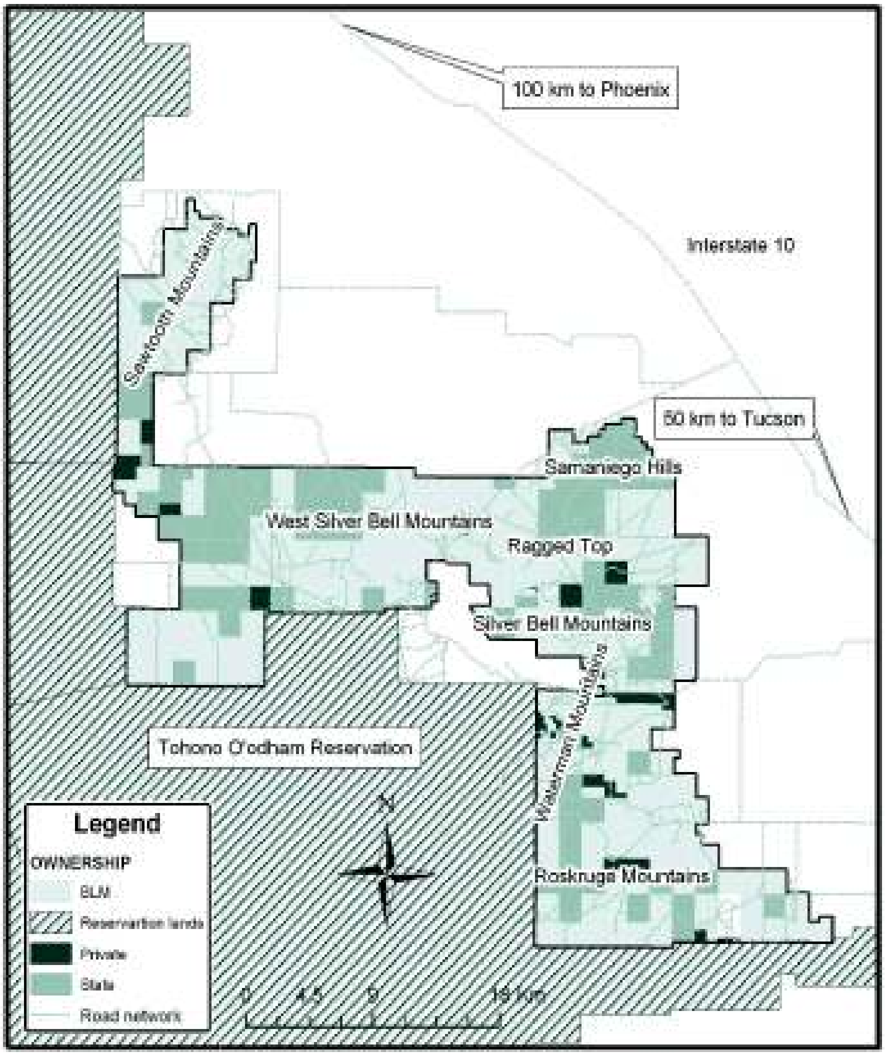


Figure 1. Location and land ownership for Ironwood Forest National Monument, Arizona, 2004.

standing the spatial distribution of human use across the monument and documenting the amount of nighttime use that was occurring.

STUDY AREA

The IFNM was established on 9 June 2000 by presidential order and is managed by the Bureau of Land Management (BLM). The IFNM encompasses 76,781 ha in the Sonoran Desert and includes 52,232 ha (68%) of federal, 22,135 ha (29%) State of Arizona, and 2,433 ha (3%) of private land (Figure 1). It is located within Pima and Pinal counties, and is easily accessible from the Tucson (50 km) and Phoenix (100 km) metropolitan areas from paved and dirt roads connecting with Interstate

Highway 10 (Figure 1). The monument was established to protect natural and cultural resources and is one of the most biologically diverse areas within the Sonoran Desert with > 670 species of flora and fauna (Tersey et al. 2001). The area contains federally listed threatened and endangered species — the lesser long-nosed bat (*Leptonycteris curasoae yerbabuenae*) and cactus ferruginous pygmy-owl (*Glaucidium brasilianum*). Other wildlife in the area include: cougars (*Puma concolor)*, mule deer (*Odocoileus hemionus*), mountain sheep (*Ovis canadensis*), collared peccary (*Pecari tajacu*), coyotes (*Canis latrans*), bobcats (*Lynx rufus*), desert tortoise (*Gopherus agassizii*), and a variety of small mammals, migratory and non-migratory birds, reptiles, and amphibians.

The IFNM is made up of a series of interconnected mountain ranges separated and surrounded by valleys of creosote bush (*Larrea tridentata*). These mountain ranges extending south to north include the Roskruge, Waterman, Silver Bell, West Silver Bell, Samaniego Hills, and Sawtooth Mountains (Figure 1). The IFNM is bordered by the Tohono O'odham Nation to the south and west, cotton fields on the Santa Cruz flood plain on the north, and private lands to the east. It extends 48 km from south to north and 50 km from west to east.

Four main vegetation associations occur within IFNM. Lowland plains are dominated by creosote bush and bursage (*Ambrosia deltoidea*). Hillsides are made up of palo verde (*Parkinsonia microphylum*), ocotillo (*Fouquieria splendens*), and mixed cacti — e.g., cholla (*Opuntia* spp.), saguaro (*Carnegiea gigantea*), and prickly pear (*Opuntia*). Desert riparian communities exist along washes that include palo verde, mesquite (*Prosopis velutina*), ironwood (*Olneya tesota*), and acacia (*Acacia* spp.). A chaparral community of jojoba (*Simmondsia chinensis*) and mixed scrub occurs at higher elevations (Bristow et al. 1996).

Elevation ranges from 580 m on the valley floor to 1,290 m at Silver Bell Peak. Rainfall is bimodal with rainfall primarily in winter (December–February) and late summer (July–September). Since 1956 the average annual precipitation has been 31.8 cm. The daytime high temperatures range from 15 to 20° C in the winter to > 40° C during summer (National Oceanic and Atmospheric Administration official website; http://www.noaa. com/). The year was divided into 5 seasons: winter (December–January), spring (February–April), dry summer (May–June), wet summer (July–September), and autumn (October–November) based on temperature and precipitation (Sellers and Hill 1974). Human activities that take place in and around IFNM include mining, ranching, livestock grazing, hunting, camping, hiking, off-highway vehicle use, target shooting, research and conservation, and illegal immigrant and drug traffic (Bristow et al. 1996; Tersey et al. 2001).

METHODS

We evaluated human activities in IFNM from 1 January 2002 to 13 July 2004 generally following the methods of Gimblett (2004) and Titre et al. (2004). We used sensors and survey data to determine human activity patterns and provide estimates of visitor use. Sensors provide data on level of use in specific areas, entry and exit points, time of use, and routes traveled. Surveys provided data on group size, entry and exit points, destination, time of use, and activity type. We downloaded data from data loggers connected to the sensors. We designed specific Microsoft Access queries to assist in data analysis. We constructed queries for each individual sensor and all sensors combined to evaluate human traffic on an hourly, weekly, monthly and annual basis.

We used a global positioning system (GPS) receiver (Trimble Navigation, Lafayette, LA) to map all of the roads in IFNM. Twenty-six traffic/trail sensor pads (Scott Technical Instruments Ltd., Hamilton, New Zealand) were placed on routes to monitor vehicle traffic for 8–30 months (Figure 2). Sensors were placed at a sampling of access points throughout IFNM. Sensor pads were concealed 0.3 m under the ground. A HOBO® data logger (Onset Computer Corporation, Pocasset, MD)

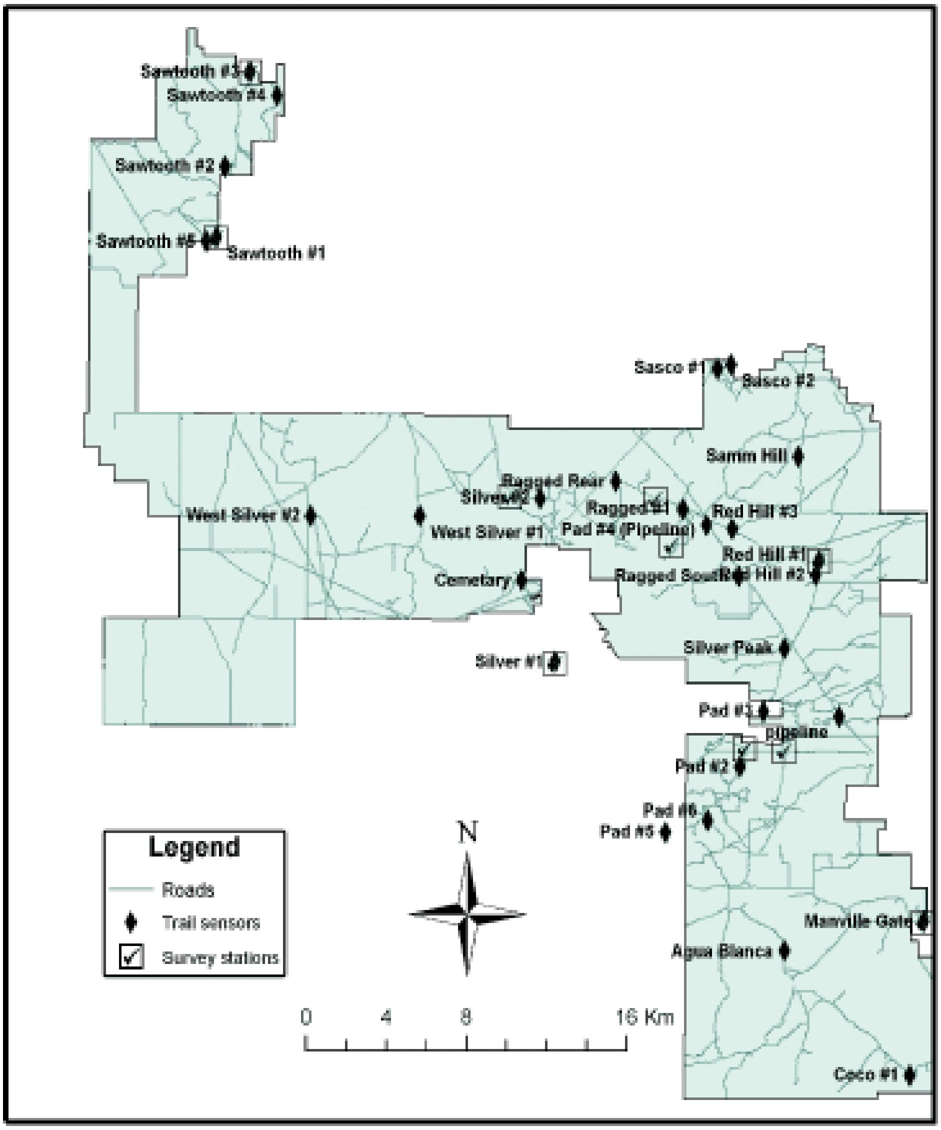


Figure 2. Trail sensor and survey station locations in Ironwood Forest National Monument, Arizona, 1 January 2002–13 July 2004.

was attached by a cable buried 2–3 m from the route that recorded date and time of event that each vehicle or human that moved over them. Four vibration sensors (Scott Technical Instruments Ltd.; Hamilton, New Zealand) were concealed inside cattle guards or gates on roads.

In addition to the counter pads, we placed nine survey stations throughout IFNM between September 2002 and March 2004, in areas where people were observed to stop (e.g., recreation sites, gates, intersections) (Figure 2). Survey stations provided a questionnaire with a map and instructions for visitors to fill out describing their use of IFNM (Billington 2005). Respondents recorded their trips on the maps and answered questions that related to issues of concern and encountered in IFNM and assigned ratings 1 (not serious) to 4 (most serious) to indicate the degree of the problem encountered. Other questions included date and time of visit. The survey was self-administered with forced choice questions/answers related to management issues and a map itinerary. The survey was intended to inform the visitor about the IFNM and capture more detailed information on the distribution of visitation in the monument.

Trail sensors and survey stations were checked twice a month and data were downloaded into a laptop computer. Survey stations were stocked each time completed surveys were collected. We spent 2 nights (1800–0600 hr) during 4 seasons (i.e., spring, dry summer, wet summer, and autumn) to observe who was driving at night by sitting near the side of a dirt road that had high night use (based on previous traffic pad data and personal communication with Border Patrol and BLM). All human activity was recorded that passed by the observation point. The research team was positioned within a safe distance of the observation point, but had a clear vision of visitors. It was assumed that a vehicle was involved in UDA transportation or illegal activity if it was driving with its lights off, had > 5 occupants, was an older vehicle in relatively poor condition, and did not have any government or law enforcement markings and license plates. Based on these criteria vehicles were classified either as illegal, government, or other.

We compared night (1800–0600) and day (0600–1800) data using a simple 2-tailed t-test. We modeled seasonal data using analysis of variance (ANOVA) to compare levels of human activity among seasons. We modeled annual, seasonal, and night and day events together using MANOVA with all possible interactions considered. We used linear regression to model and compare the overall trends in nighttime use and daytime use over time. Statistical analysis was all performed using JMP IN version 5 (Sall et al. 2005). Confidence intervals and correction factors for sensor counts were calculated and performed using the procedures established by Titre et al. (2004).

RESULTS

Our data were normally distributed. Twelve to fifteen thousand visitors (i.e., recreation visitors, local residents, law enforcement, UDA) travel through IFNM annually based on sensor and survey data (Gimblett 2004). Because we did not monitor every entrance our estimates represent a minimum. The estimated number of annual visitors includes residents who live and work within the IFNM boundary.

The number of recorded events (i.e., vehicles recorded by a sensor, 1 event = 1 vehicle driving over a sensor) varied among sensors (Figure 3). Manville Gate had the greatest number of recorded events (n = 3,075). Sasco 2 had the fewest recorded events (n = 128). When factoring in the number of days in operation, Pipeline was the most active (n = 15.53 events/day, 95% CI = 11.54–19.53) and Red Hill 3 was the least active (n = 0.45 events/day, 95% CI = 0.33–0.57). The number of recorded events on the 23 sensors from 1 January 2002 to 13 July 2004 was 19,369 during 9,893 sensor days. Events/day on all 23 sensors combined was 76.92 (95% CI = 57.27– 96.87). Visitor use followed a general loop following main roads through the central section of IFNM. Primary destinations for recreation users included trails and campsites surrounding Ragged Top Mountain. Peak hours of use compared between sensor data and survey data (Billington 2005) differed. Peak hours of recreation use were between 0700 and 1500 with little nighttime use. Sensor data showed more nighttime use (31.2%) than the survey respondents (10.9%).

Survey respondents rated trash dumping and illegal immigration as the two greatest problems in IFNM (Table 1). About 36% of respondents who reported these as problem

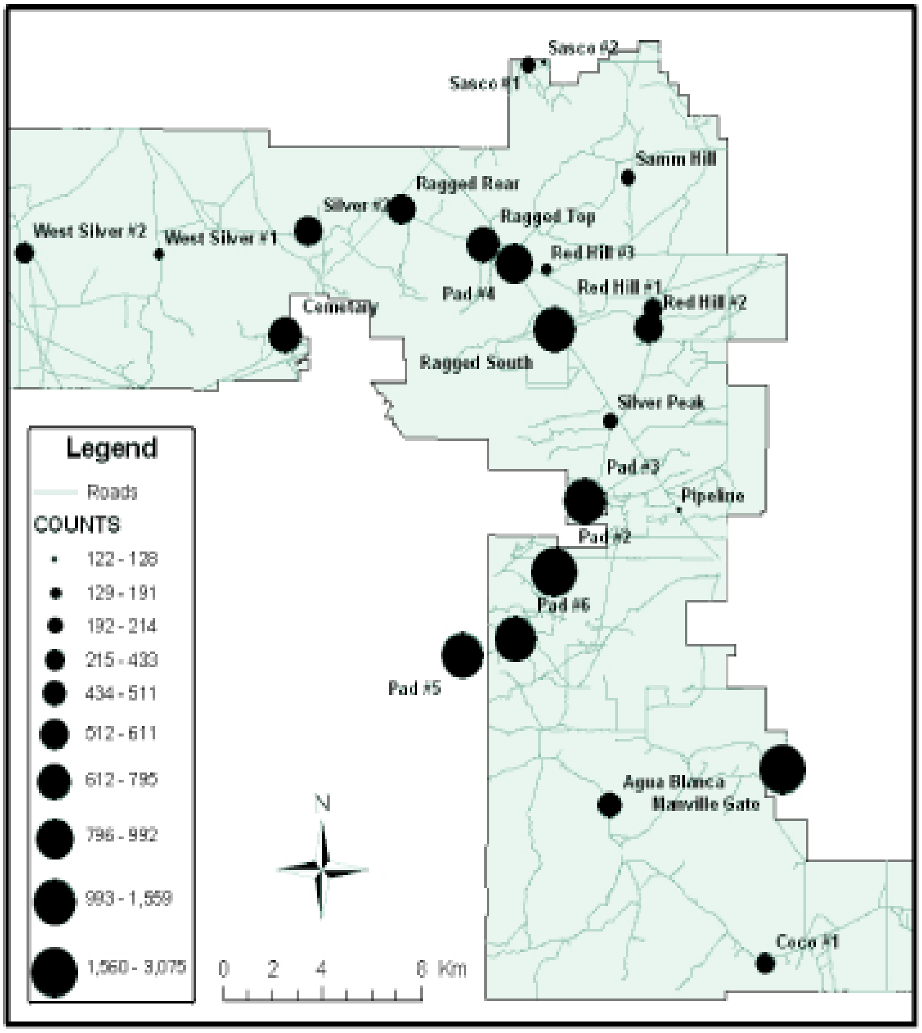


Figure 3. Events (i.e., vehicular traffic) recorded on sensors in Ironwood Forest National Monument, Arizona, 1 January 2002–13 July 2004.

situations consider them to be most serious (scored 4). Garbage dumping (x = 2.56, SD = 1.24, n = 88) and illegal immigrant activity (x = 2.34, SD = 1.38, n = 89) were considered problematic by 83 and 84% of the respondents, respectively.

Nighttime activity was common (31.2%) in IFNM (Figure 4). Sensors in the central section of IFNM near Ragged Top Mountain had the greatest proportion of daytime events. Sensors located in the southern section of IFNM near the border of the Tohono O'odham Nation and extending northeast towards Interstate 10 had the greatest proportion of nighttime events (Figure 4). Eight sensors that formed a loop around Silver Bell and Ragged Top Mountains (i.e., Silver Peak, Ragged South, Pad 4, Red Hill 3, Ragged Top, Ragged Rear, Silver 2, and

Table 1. Problems reported by visitors (n = 103) to Ironwood Forest National Monument, Arizona, 1 January 2002 through 13 July 2004.

Situation	n	x	SD
Garbage dumping	88	2.56	1.24
Illegal immigrant activity	89	2.34	1.38
Lack of visitor information	76	1.96	1.14
Lack of law enforcement	79	1.75	1.11
Unsafe target shooting	73	1.66	1.03
Impacted visual resources	73	1.60	1.01
Damage/collection of vegetation	72	1.56	1.01
Damage/collection of petroglyphs	72	1.56	1.07
Lack of trails for non-motorized activities	86	1.55	1.00
Reckless drivers on or off trails	76	1.51	0.95
Feeling safe	81	1.51	0.90
Lack of camping facilities	74	1.32	0.74
Damage to livestock	72	1.25	0.78
Conflicts with other users	71	1.21	0.56
Noise	72	1.18	0.61

Cemetery) were compared to the 8 sensors that extended from the Reservation border towards main roads (i.e., Agua Blanca, Pad 5, Pad 6, Pad 2, Pad 3, Red Hill 2, Red Hill 1, and Samm Hill) (Figure 4). The Ragged Top loop sensors averaged 0.39 (95% CI = 0.30–0.50) events/night and overall 31.8% of the events recorded by these sensors were at night. The sensors extending from the reservation averaged 1.56 (95% CI = 1.10–1.85) events/night and overall 67.8% of the events recorded by these sensors were at night.

Events per 24 hour period by year, time period (night or day), season, and all possible interactions using MANOVA ($F_{19,6}$ = 4.074, P = 0.045). Time period influenced the model ($F_{1,6}$ = 11.747, P = 0.014). Means were tested for all sensor events per 24 hour period combined between night and day. We concluded that there was a strong indication of a difference between means (t_{12} = 2.01, P = 0.057) of night (x = 0.86, 95% CI = 0.39–1.32) and day (x = 1.38, 95% CI = 1.04–1.72). The year did not influence the MANOVA model ($F_{1,6}$ = 0.980, P = 0.359). Season warranted further investigation ($F_{4,6}$ = 3.809, P = 0.071) using ANOVA.

The number of events recorded during winter was 4,070 (2.31 events/day), spring n = 4,555 (2.22 events/day); dry summer, n = 4,757 (1.78 events/day); wet summer, n = 1,983 (1.76 events/day); and autumn, n = 4,004 (1.85 events/day). The means of events per 24 hour period for the 5 seasons were compared using ANOVA. None of the means were significantly different ($F_{4,12}$ = 0.646, P = 0.645); events per 24 hour period ranged from a mean of 1.68 (95% CI = 0–3.65) in wet summer to a mean of 2.86 (95% CI = 1.33–4.40) in spring. Means of events/day compared by season were not significantly different ($F_{4,8}$ = 0.545, P = 0.708); events per 24 hour period ranged from a mean of 1.03 (95% CI = 0.13–1.95) in dry summer to a mean of 1.83 (95% CI = 0.70–2.96) in autumn. Means of events/night by season were not significantly different ($F_{4,8}$ = 0.619, P = 0.662); events per 24 hour period ranged from a mean of 0.40 (95% CI = 0–1.73) in autumn to a mean of 1.25 (95% CI = 0.16–2.34) in spring.

Linear regressions indicated no change in nighttime and daytime events over the study period, when analyzed separately. The slope of the line was not significantly different from 0

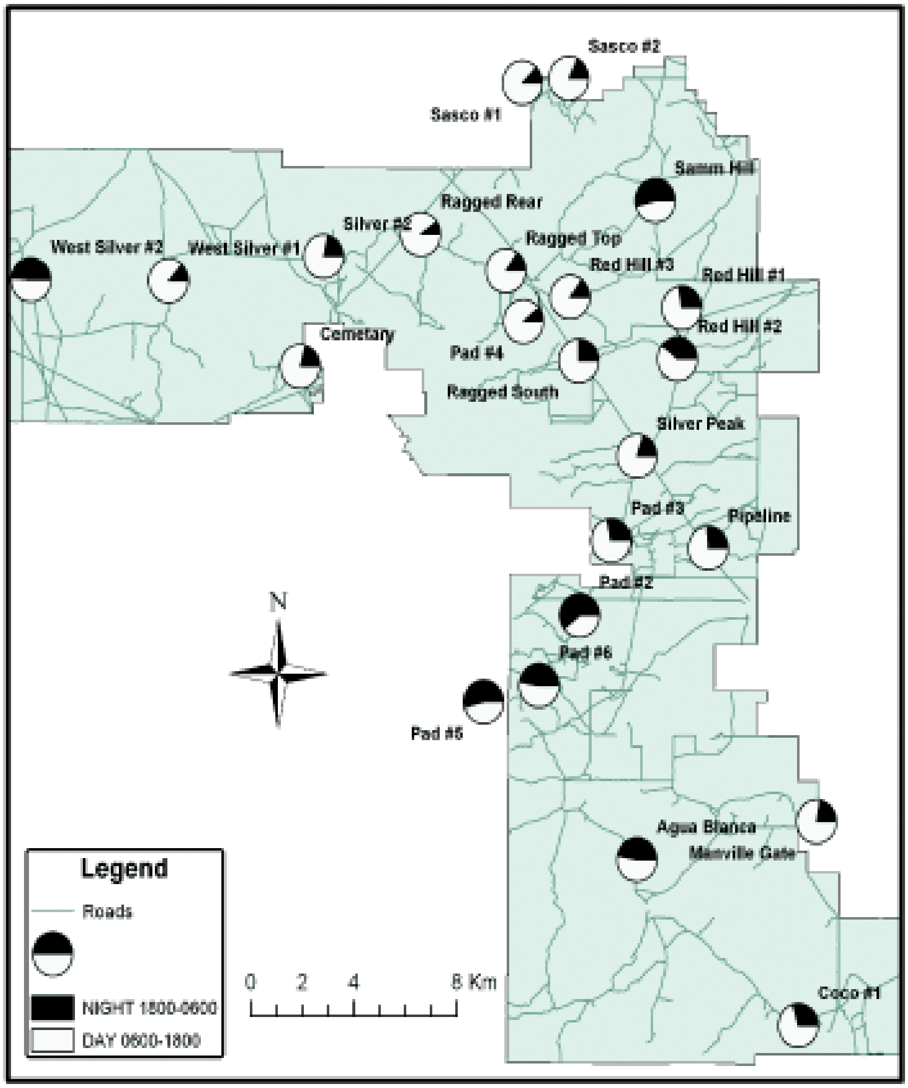


Figure 4. Ratios of nighttime and daytime vehicular traffic, determined from sensors in Ironwood Forest National Monument, Arizona, 1 January 2002–13 July 2004.

($F_{1,53}$ = 0.048, P = 0.827) for events/night or events/day ($F_{1,53}$ = 0.127, P = 0.723). There was no overall increase in nighttime or daytime events during the study. However, when night and day data were combined and modeled by year and season there was a general overall decline in activity ($F_{1,24}$ = 4.407, P = 0.047) (Figure 5).

When examined within season, nighttime events (Figure 6) and daytime events (Figure 7) revealed no consistent pattern of increase or decrease. For example, in 2002 there were 0.87

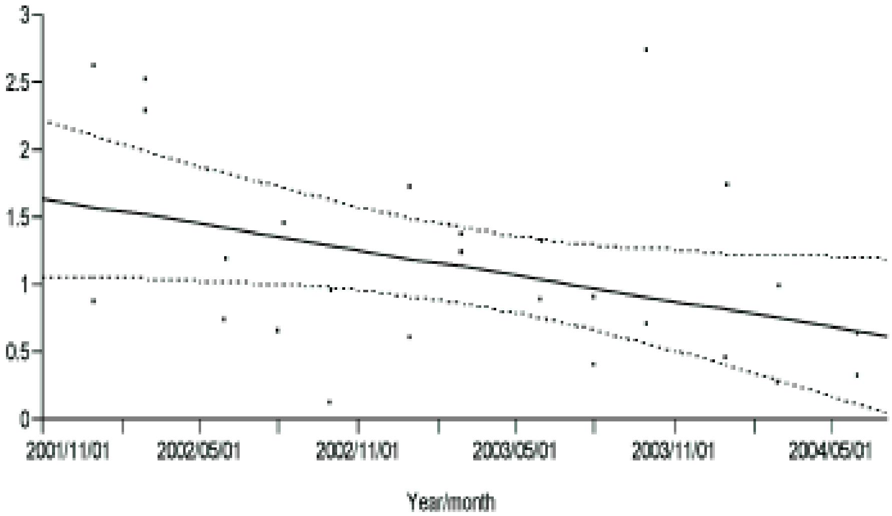


Figure 5. Linear regression model of events/day by year/month, Ironwood Forest National Monument, Arizona, 1 January 2002–13 July 2004.

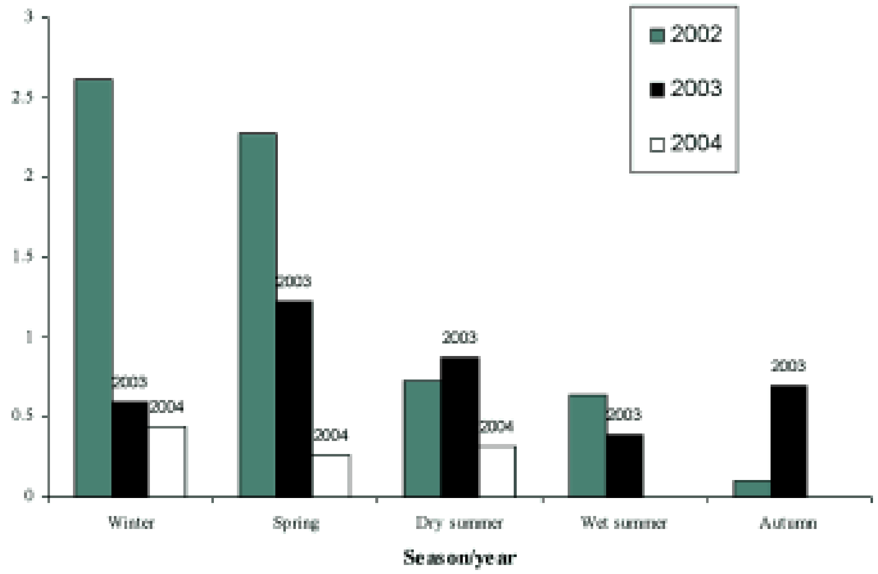


Figure 6. Events/night recorded by season and year in Ironwood Forest National Monument, Arizona, 1 January 2002 – 13 July 2004.

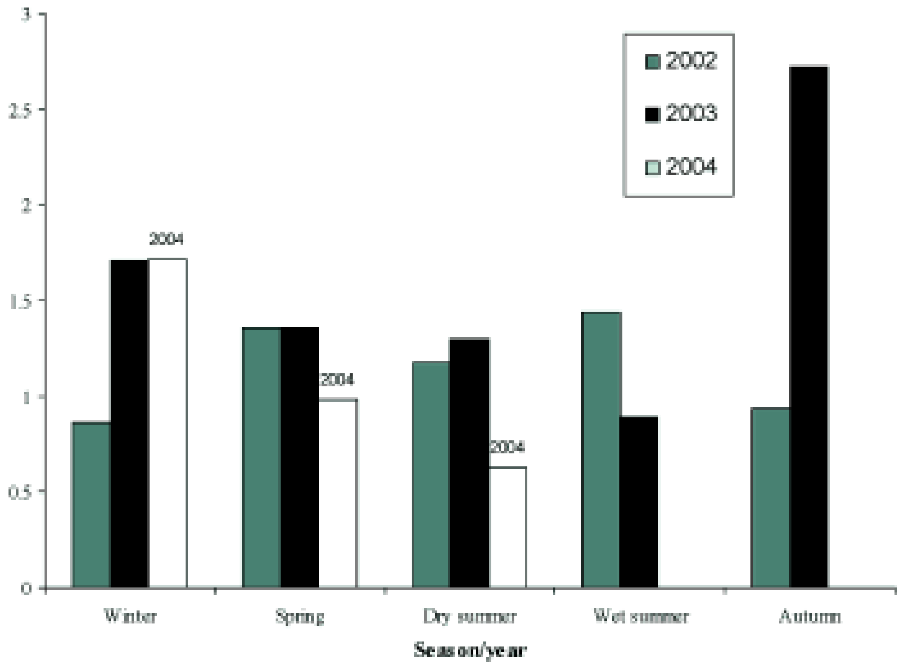


Figure 7. Events/day recorded by season and year in Ironwood Forest National Monument, Arizona, 1 January 2002 – 13 July 2004.

events/night (95% CI = 0.64–1.09), in 2003 n = 1.16 (95% CI = 0.86–1.45), and in 2004 n = 0.57 (95% CI = 0.42–0.72). In 2002 there were 1.65 events/day (95% CI = 1.23–2.08), in 2003 n = 2.15 (95% CI = 1.59–2.70), and in 2004 n = 1.57 (95% CI = 1.16–1.97).

During the 8 nights (1800–0600 hr) that traffic was observed (Table 2), 6 vehicles were counted and 5 met the criteria for being considered illegal. The level of nighttime traffic along this road averaged 3.58 (95% CI = 2.66–4.50) vehicles/night according sensor data.

DISCUSSION AND CONCLUSIONS

This study started out with the assumption that human use in IFNM was increasing, particularly nighttime use. Results of this study indicate that both day and nighttime use actually have slightly declined over the years for which we collected data, but remain significant. Perhaps shifting drug operations, increased media attention and law enforcement activities along the border have lead to this reduction in activity. It is possible that this slight decline might be a result of Operation Gatekeeper launched in 1994 or at least since IFNM was established in 2000. It is also possible that illegal activity has decreased or shifted to other areas (e.g., near Yuma, Arizona) as the result of the Arizona Border Control Initiative, which increased enforcement efforts in the Tucson sector especially in and around the Tohono O'odham Nation starting in Fiscal Year 2004 (C. Griffin, pers. comm.; LoMonaco 2005).

What we did find in this study is that human use by season in IFNM is fairly consistent throughout day, night, season, and year. Other studies in arid regions that examined human recreation patterns found heavier use in cooler seasons than warmer seasons (Purdy and Shaw 1981; Gimblett 2002; Gimblett and Sharp

Table 2 - Night (1800-0600 hr) observations of vehicles in Ironwood Forest National Monument, Arizona, 2004 for 8 nights (96 hr total).

Date Time	Direction of travel	Vehicle type Age	Number of occupants	Lights on/off	Activity category
5/12/04 1920	North	Mid size pickup truck Early 1980s	18	Off	Illegal immigration
5/13/04 0440	North	Pickup truck w/camper 1990s	> 5	Off	Illegal immigration
8/22/04 0515	North	Full size pickup truck Early 1990s	> 5	Off	Illegal immigration
11/05/04 1159	South	Small pickup truck Late 1990s	2	Off	Illegal immigration
11/06/04 0320	North	Mid size pickup truck Late 1990s	> 5	Off	Illegal immigration
11/07/04 0545	South	Sport utility Early 1990s	2	On	Recreation

2005). This pattern was not observed for nighttime activity during this study and overall seasonal differences were not significant. Illegal traffickers traveling through the desert at night are likely responding to factors other than temperature (e.g., law enforcement activity, economic influences).

Based on the survey responses related to the times of visitor use and sensor data on times of recorded events it is reasonable to assume that the majority of nighttime use is illegal. This was also supported by our night observations of traffic where 5 of 6 vehicles fit our criteria for illegal activity. Illegal activity occurring in IFNM is also evidenced by the amount of refuse (e.g., water bottles, food containers, and clothing) left behind and collected by BLM (F. Mendoza, pers. comm.).

The value of incorporating visitors into the decision making and the management of IFNM was revealed in their responses to our surveys. This important information from perceptions of visitors did indicate that trash dumping and illegal immigration were their greatest concerns. While a detailed study of the spatial pattern of trash dumping has not specifically been undertaken, it is impossible to directly link such activity to illegal immigration. Circumstantial evidence does indicate however, that in specific areas on the monument (pick up or stop over areas) there is an accumulation of specific types of trash that are associated with illegal immigrants (white plastic water containers, clothing and other identifiable supplies). Certainly, more work needs to be done in this area.

One of the interesting findings of this study is that the pattern of illegal activity is not evenly distributed throughout IFNM but intentionally spatially focused and concentrated. The main corridor for illegal activity extends from the southwestern section along the IFNM border with the Tohono O'odham Nation northeast towards the main roads (e.g., Avra Valley Road and Interstate 10) (Figure 4). This is one of the critical areas where IFNM intersects with a main corridor for illegal trafficking coming across the United States-Mexico border and traveling north through the Tohono O'odham Nation (F. Mendoza, pers. comm.).

Trafficking activity probably leaves the Nation and spreads through IFNM as it connects with main roads. Coincidentally, the patterns of illegal or nighttime use in the southwestern section of the IFNM coincided with the location of the highest concentration of recreation sites (campsites). These recreation sites represent a majority of the class 4 (high impact) recreation sites in the monument. A majority of these recreation sites are commonly used temporarily by illegal visitors as rest spots and by legal visitors undertaking recreational camping in the area. Evidence of trash associated with illegal entrants is commonly found in some of these and other sites in the area. While there is no observed use data on these sites by illegal activities, just knowing that nighttime use frequents these sites and is relatively high at times when legal visitors are potentially camped at these locations represents a serious conflict and ultimately a safety concern for the management staff of IFNM. In addition, anecdotal evidence suggests this traffic pattern of illegal entrants and trafficking is not only going northbound but humans also travel south to bring money across the border and pick up people and goods to smuggle. Other areas in IFNM have a much smaller proportion of nighttime activity (e.g., the central section of IFNM around the Silver Bell and Ragged Top Mountains). This area is a popular destination for recreation activity and other daytime use (Figure 4).

Illegal activity is a significant portion of the activity occurring in IFNM, however, it is has remained consistent from 2002–2004. The traffic, illegal roads and trails, trash, and natural resource degradation associated with UDA trafficking are a significant concern in IFNM and a major reason that neighboring OPCNM has been placed on the list of the United States' 10 most endangered national parks (National Parks Conservation Association Official website; http://www.npac.org).

In conclusion, studying spatial/temporal movement patterns of humans for public lands management is imperative. Resource managers need to understand how the landscape they manage is being used by legal and/or illegal activities. Studying the spatial/temporal patterns of human use reveals that areas within public lands are not being equally visited rather that some areas are more heavily visited and impacted than others and by certain types of groups. Resource managers need to understand such patterns of use and the seasonal distributions in order to develop effective management plans and recommendations that respond to and address such disparities. Too often visitor survey tools employed to gather information about visitors for human management have done little to provide useful information to managers who need to manage for dispersed and concentrated use in large scale settings. Too often this information is used to characterize the visitor but says nothing about how they interact with other visitors and impact the setting they frequent. This non-traditional method for monitoring, evaluating and managing human use described in this chapter provided information on the nature of the visit, and captured the spatial/temporal patterns of daily and seasonal use. This information is valuable for resource managers attempting to balance recreation use with resource protection.

While this study was undertaken to evaluate the spatial/temporal distribution of visitors who frequent IFNM, through a sampling and monitoring plan, it was never intended to capture illegal or nighttime activity. Few studies, if any have been specifically designed to evaluate the impacts of illegal entrants and trafficking on public lands. By using non-invasive pressure sensitive pads and other technologies such as Global Positioning Systems (GPS), radio frequency technology and others in combination with surveys and observation, visitor use patterns can be discovered and documented. Future work needs to address the short and long-term impacts of illegal activities before our public land is so severely impacted for future generations.

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THE U.S.-MEXICO BORDER AND ENDANGERED SPECIES

Douglas K. Duncan, Erin Fernandez, and Curtis McCasland

THE SPECIES

The Arizona-Sonora Border area has a great diversity of ecosystems and species. The Endangered Species Act (ESA) protects 26 listed species of plants and animals in the area, 18 of which are endangered (10 of those have designated critical habitat) and 8 of which are listed as threatened. Species that occupy riparian and aquatic communities make up half the group. At least 25 of these are certain to occur in the border region (Table 1). Additionally, species that are candidates for listing, managed under conservation agreements or considered sensitive, also occur in this area.

Listed species occur along much of the international border in Arizona. From the Colorado River in the west to the Peloncillo Mountains in the east, species occurring along the borderlands of Arizona include the Yuma clapper rail (*Rallus longirostris yumanensis)*, Sonoran pronghorn (*Antilocapra americana sonoriensis*), Pima pineapple cactus (*Coryphantha scheeri* var. *robustispina*), Chiricahua leopard frog (*Rana chiricahuensis*), and the New Mexico ridge-nosed rattlesnake (*Crotalus willardi obscurus*). Many of the species, such as the Chiricahua leopard frog and Huachuca water umbel (*Lilaeopsis schaffneriana* ssp. *recurva*) occupy riparian and aquatic communities, so their distribution is discrete. Other species that are more mobile, such as the lesser long-nosed bat (*Leptonycteris curasoae yerbabuenae*), could occur almost anywhere in suitable habitat. The species most affected by illegal border crossing and law enforcement is the endangered Sonoran pronghorn.

Sonoran Pronghorn

Sonoran pronghorn inhabit the hottest and driest portions of the Sonoran Desert. Historically this subspecies ranged in the U.S. from the Imperial Valley, California to near the Santa Cruz River in the east, from Gila Bend and the Kofa Mountains south to the international border. Currently the subspecies ranges from the Copper and Cabeza Prieta Mountains east to State Route 85, and from Interstate 8 south to the international border. The subspecies' range and population size declined dramatically in the early 20th century, however there were no definitive studies or information available to document population size before 1925. Within the last 12 years, the U.S. population of pronghorn has ranged from 142 individuals in 1998 to 21 animals in 2002. We currently (2009) estimate the wild population at about 85 individuals, which includes animals released from the semi-captive breeding pen.

Fawn survival is considered to be one of the most important factors affecting population size, and this is our most significant management issue. Pronghorn fawn survival is strongly correlated with the length of time between winter and summer rain events. The number of fawns surviving until the first summer rains is also correlated with the amount of winter rainfall (Hervert et al. 2000). Obviously, severe drought affects not only fawns but the whole population; the severe drought of 2001 and 2002 nearly extirpated the entire U.S. population. We are currently implementing numerous recovery actions to increase

Table 1. Listed species status and presence[1] along the Arizona-Mexico border.

Species group	Listed	Endangered	Critical habitat	Present
Plants	5	4	1	5
Amphibians	2	1	0	2
Reptiles	2	0	0	2
Fish	8	5	6	8
Birds	7	5	3	5
Mammals	6	6	0	3
Total	30	21	11	25

[1] Certain to be found within 100 kilometers of the border at least part of the year.

fawn survival both through direct intervention (semi-captive rearing), irrigation of native forage plots, and providing numerous waters sources around heavily used portions of their range.

EFFECTS

Effects to listed species and the ecosystems on which they depend occur both from illegal cross border traffic and law enforcement activities aimed at interdicting it. Illegal traffic can be categorized in several ways. The illegal border crossers themselves are generally either immigrants seeking work or smugglers of contraband, largely drugs. The effects of coyotes, or people smugglers, will be considered the same as illegal immigrants. Typically, illegal immigrants cross the border via foot, rarely using a vehicle, while smugglers most often use vehicles to cross even in roadless areas. Bicycles, especially in flat terrain, and stock animals are also used.

Law enforcement interdiction activities, chiefly by U.S. Border Patrol (USBP), are largely conducted by vehicle. Most vehicles being used have four-wheel drive, and range in size from quads to heavy specialty vehicles. A greater proportion of law enforcement vehicle use is on designated roads and trails, when compared to vehicle use by illegal entrants. Law enforcement personnel also use motorcycles and horses, and they sometimes patrol on foot. Unmanned aerial vehicles are also deployed along the Arizona border.

Direct, indirect, and cumulative effects from the above border activities are analyzed under section 7 consultations on border activities. All the classes of effects occur from both law enforcement and illegal entrants. Many of the specific effects are common to both groups. For example both illegal and law enforcement activities can create new roads and trails; disturb vegetation and soils; disturb wildlife; impact wildlife movement corridors; and move nonindigenous species. Some specific effects, however, such as entrant trash, are only associated with illegal entrants.

Actions by illegal entrants are basically all associated with the act of crossing the international border and journeying towards a destination. Smugglers usually travel both directions. Some smugglers turn themselves in to the USBP, posing as illegal immigrants, and get a free trip back to the border. Illegal entrants travel on all roads and trails, from Interstate Highways to designated trails in federally designated wilderness areas. Vehicular travel, both illegal and law enforcement, on designated roads has little to minimal effects, except for back country roads that receive a lot more use now than they did historically. Significant effects to resources occur when the illegal entrants and pursuant law enforcement travel off of roads. Off-road travel may adversely affect listed species from the creation of roads and trails; increased human disturbance, especially in wilderness areas or caves and mines; use of water sources; soil compaction and resultant changes in hydrology; introduction of nonindigenous species; spread of disease; destruction or vandalism of wildlife waters or other wildlife projects such as fences (e.g., Sonoran pronghorn pen fence); trash; pollution; destruction of vegetation; and fires.

Direct effects occur when an individual listed species or occupied habitat are impacted by an activity. Both illegal and law enforcement activities have direct effects on listed species. Direct effects could occur to listed species when vehicles cross a stream and run over an individual listed plant or animal, by aircraft disturbing nesting listed birds, or even humans capturing listed animals for food. Direct effects are usually more obvious than the impacts discussed below, however, effects that are not direct often cause the greatest harm or concern because they can be more subtle and difficult to analyze, can occur outside of the foot print of an action, can occur later, or can be difficult to measure.

Recovery actions designed to help recover the U.S. population are significantly impacted by illegal cross-border traffic. Illegal border crossers have exploited water sources we know are important for pronghorn, smashed irrigation lines used to promote quality native forage for pronghorn, and cut and dug under fences around the pronghorn captive rearing pen. Vehicles smuggling drugs and people routinely drive off-road through areas used by pronghorn during the hot dry summer months. These actions likely result in the most significant effects to pronghorn from illegal traffic. Any activity forcing pronghorn to flee from habitat used to stay cool when free water and water found in forage is scarce to absent has the potential to devastate the pronghorn population. These activities may force females to stop nursing fawns, leading to greater fawn mortality. Recently weaned fawns may also be affected from these disturbances, and adult mortality may even occur. Furthermore, law enforcement personnel responding to sensors, vehicle tracks, or foot sign also travel through these areas. Unfortunately, it is not possible to specifically quantify the impacts associated with these activities; however, we believe the impacts are significant. The drought of 2001-2002 and the dramatic pronghorn population decline occurred at a time of rapid increase in illegal smuggling of people and contraband into the U.S. and a subsequent increase in interdiction efforts by Federal law enforcement agencies.

Indirect effects of an action are those that occur later in time but are reasonably certain to occur. An example would be a road constructed through a Sonoran pronghorn fawning area, and the later use of that road causing fawning to cease or occur in less suitable habitat, resulting in decreased fawn recruitment.

An interdependent action is one that has no independent utility apart from the action being considered. An example would be if the USBP proposes building a barrier fence at the border. To construct the barrier, vehicles must use existing or new roads to access the project site. The use of these roads is interdependent to construction of the barrier, and would not occur "but for" the barrier. The road itself is not interdependent.

Interrelated actions rely on the larger action for their justification. Using the previous example, the construction of the barrier requires water, but there is no well nearby. To facilitate construction of the barrier, USBP proposes to drill a well that will be used for nothing but construction. Because the well must be constructed to construct the barrier, drilling the well is an action that is interrelated to the proposed action of barrier construction.

Under section 7 regulations [50 CFR §402.02], cumulative effects are those effects of future State or private activities, not involving Federal activities, that are reasonably certain to occur within the action area of the Federal action subject to consultation. This definition applies only to section 7 and should not be confused with the broader use of this term in the National Environmental Policy Act or other environmental laws. Let's suppose the barrier example above is proposed to be built near Lukeville. About that time, the town of Lukeville announces plans to expand (and was able to do so), and had the appropriate approval to do so. As long as there is no Federal connection or tie to the Lukeville expansion (permit, funding, or approval), then the effects of that expansion to the Sonoran pronghorn would be cumulative to the construction of the barrier. Cumulative effects only come into play in section 7 consultation during formal consultation, to determine if the proposed action may jeopardize the continued existence of the species. No incidental take is anticipated for cumulative effects.

Incidental take is take of listed fish or wildlife species that results from, but is not the purpose of, carrying out an otherwise lawful activity conducted by a Federal agency or applicant (50 CFR §402.02). Take is further defined as to harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect or attempt to engage in any such conduct (ESA §3[19]). "Harm" is further defined by U.S. Fish and Wildlife Service (USFWS) to include significant habitat modification or degradation that results in death or injury to listed species by significantly impairing behavioral patterns such as breeding, feeding, or sheltering. "Harass" is defined by USFWS as actions that create the likelihood of injury to listed species to such an extent as to significantly disrupt normal behavior patterns which include, but are not limited to, breeding, feeding or sheltering (50 CFR §17.3).

ESA COMPLIANCE

Endangered Species Act compliance along the border is extremely complicated because of the number of land owners and managers in the region, the number of Federal agencies involved with border issues, the geographic and technical scope of border problems, and the ever-changing nature of illegal cross-border traffic and law enforcement. Additional complication stems from the creation of the Department of Homeland Security (DHS) and U.S. Customs and Border Protection (CBP) and its resultant complex internal structure.

Every Federal agency must determine if any of their actions may affect a listed species or critical habitat, and if so, consult with the USFWS. All Federal agencies are required by section 7 (Interagency Cooperation) of the ESA to ensure that their actions do not jeopardize a listed species or result in the destruction or adverse modification of critical habitat. A Federal action or Federal nexus is defined as an action that is authorized, funded, or carried out by the agency. Consultation can be either informal or formal. If an action agency determines that there is no effect to listed species from the Federal action, then nothing further is required by the Act. If the agency determines the action may affect, but is not likely to adversely affect listed species, they then seek the written concurrence of the USFWS (informal consultation). When the action agency determines that their action may affect and is likely to adversely affect listed species, then formal consultation with the USFWS begins and a biological opinion is written by the USFWS. The biological opinion examines the effects of the proposed action, analyzes the proposed effects against the species' status and environmental baseline, and determines whether the proposed effects will jeopardize the continued existence of the federally listed species.

The ESA allows for actions to occur before section 7 consultation if the action agency determines there is an emergency. An emergency is a situation involving natural disasters, casualties, national defense or security emergencies, and includes response activities that must be taken to prevent imminent loss of human life or property. Broad discretion is given to the action agency to determine when an emergency has occurred. Many Border Patrol actions have been deemed emergencies;

creation and operation of camp details, various border initiatives, and helicopter landings in wilderness were all considered emergency actions by the Border Patrol.

In an emergency, an action agency must first determine if their response to the emergency may affect listed species and, if so, notify the USFWS. Upon notification, the USFWS identifies conservation measures that may reduce the adverse effects of the emergency response to listed species. Conservation measures are discretionary and may not interfere with the emergency response. The USFWS follows up the notification from the agency noting any conservation measures and emergency consultation procedures. The agency can respond to the emergency before notifying the USFWS. When an action agency determines an emergency has occurred *and* their response to it may affect listed species or critical habitat, they must consult under section 7.

Section 7 consultation on an emergency action analyzes only the response to the emergency, and not the emergency itself. For example, when the USBP established camp details (a remote base) in southwestern Arizona in response to illegal entrant health and safety issues, the section 7 consultation only analyzed the effects to federally listed species from establishment and operation of the camps. The action causing the emergency declaration, illegal border traffic, is analyzed as part of the environmental baseline. The environmental baseline section in the biological opinion includes past and present effects of all Federal, State, or private actions in the action area, the anticipated effects of all proposed Federal actions in the action area that have undergone formal or early section 7 consultation, and the impact of State and private actions which are contemporaneous with the consultation process. The environmental baseline defines the current status of the species and its habitat in the action area to provide a platform to assess the effects of the action now under consultation (USFWS 1998).

The above described section 7 consultation process for some CBP projects was significantly affected by the enactment of the Real ID Act of 2005, which allows the Secretary of the DHS to waive many laws, including the ESA, to expeditiously construct border fences and roads. The April 1, 2008, waiver covers environmental laws, including the ESA. This waiver covers the construction, operation, and maintenance of tactical infrastructure to include fixed and mobile barriers (such as fencing, vehicle barriers, towers, sensors, cameras, and other surveillance, communication, and detection equipment) and roads near the international border (Department of Homeland Security 2008; website accessed on 12 January 2010; http://cbp.gov/xp/cgov/border_security/ti/ti_docs/esp_information.xml). About 470 miles of the U.S./Mexico international border are covered by the waiver.

As of December 25, 2009, CBP completed roughly 643 miles of fencing (344 miles of primary pedestrian fence and 299 miles of vehicle fence) and accompanying roads along the U.S./Mexico border (about half were in Arizona) without undergoing section 7 consultation (Department of Homeland Security 2009; website accessed on 12 January 2010; http://cbp.gov/xp/cgov/border_security/ti/ti_news). In lieu of consultation, CBP addressed its environmental impacts through a voluntary process that included the preparation of Environmental Stewardship Plans and Biological Resource Plans to substitute for Environmental Assessments and Biological Assessments respectively. However, many of these plans were completed without USFWS input and did not thoroughly address effects on listed species.

The U.S. Army Corps of Engineers (COE) manages environmental compliance for border fences and related roads for the USBP in Arizona. The COE often contracts with outside parties to assist with environmental compliance. Private consultants awarded these contracts often utilize subject matter experts as subcontractors. In addition, about 65 percent of the Arizona-Mexico border is managed by Federal agencies; USBP must work with land management agencies to ensure the USBP can effectively complete their mission while not compromising the missions of the various land management agencies. Thus, in addition to USBP, CBP, and COE, various consultants, and the land manager(s) are involved in section 7 consultations.

The USBP conducts a variety of actions that affect listed species in the border region. USBP activities fall into two broad categories: patrol and infrastructure. Patrol activities include all normal patrol mechanisms, including all types of vehicles on and off road, horse patrol, foot patrol, and the use of drag roads. Discussion on patrol activities has been batched into one consultation for each sector. Consultation on infrastructure tends to be project specific. However, we have consulted on projects that include both patrol and infrastructure, such as detection towers. Infrastructure can include new roads, camps, fences, detection equipment, and offices.

One of the major problems regarding consultation on border law enforcement efforts is that law enforcement responses must change in response to constantly changing border crossing patterns. Consultations examining the effects of patrol activities on federally listed species are extremely difficult; project descriptions and impacts to listed species can dramatically change within extremely short time frames, rendering finalized biological opinions outdated.

Infrastructure projects that are small or next to urbanized areas tend not to need consultation because they normally do not affect listed species. Listed species rarely occur in or next to developed areas, and small projects are much less likely to intersect with listed species or their habitat. Many of the infrastructure projects completed by the USBP or in various planning stages are small, or in developed or otherwise already disturbed areas.

However, the USBP has also completed and proposed the development of larger infrastructure projects that are within listed species habitat. A few completed projects have been through section 7 consultation, but there are many more potential infrastructure projects likely to need section 7 consultation. There are two basic kinds of infrastructure projects: linear and areal. Linear projects can include development of roads, fences, drag roads, and lights. Areal projects which cover a discrete area can include the development of offices, camps, helipads, or surveillance systems. Though linear projects usually do not have a wide footprint, their extensive length is likely to affect listed species. Furthermore, there is concern that linear infrastructure projects may act as barriers, further fragment habitat, or act as pathways for increased predation or disease, affecting the potential survival and recovery of federally listed species in the area. Much of the Arizona-Sonora border has some sort of linear project associated with border enforcement. Also, since many of the projects need to be as near the border as possible, there are fewer options in situating those projects to reduce potential effects to listed species. Complicating this matter is the issue of timing; the USFWS often negotiates for timing restrictions to minimize or avoid impacts to federally listed species. Unfortunately, timing restrictions make scheduling work even more problematic.

The complex operational structure of the DHS/CBP/USBP makes environmental compliance difficult. Since DHS is a relatively new Department, program responsibility and project roles are sometimes unclear between constituent bureaus. USBP or CBP actions often require review and approval of multiple agencies in DHS. As an example of the complexity, a meeting regarding endangered species issues on a larger project may include CBP, USBP, COE, USFWS, and consulting firms, as well as multiple levels (e.g., local and national) and offices within one agency or consulting firm. Federal land manager(s) and the Arizona Game and Fish Department (AGFD) may also be involved. Coordinating meetings, following approval processes, and completing project and document review is complicated with so many entities involved.

An additional complicating factor in compliance is the direct and indirect involvement of other Federal agencies, mainly land management agencies. Though not as often as USBP, most Federal land managers are directly involved with border enforcement issues, mainly through their law enforcement officers and coordinating with USBP on law enforcement activities within each land management unit. Initially USBP assumed they had completed all environmental regulatory requirements upon discussing needs with the managers of the various land management units. Federal land managers are indirectly involved with USBP ESA compliance through operational coordination between their law enforcement staff and USBP, and with pre-planning infrastructure projects. An interesting example of another complicated and complex issue is that other agencies sometimes request consultation basically on behalf of USBP.

A relatively recent improvement for environmental compliance was the creation of Public Lands Liaison Agents in the Tucson and Yuma Sector USBP offices. Though the main duties of the agents are to coordinate access and other issues with public land managers, they have also been involved with project planning and environmental compliance. The liaisons have helped with several endangered species issues, including the reduction of USBP helicopter over flights of the Sonoran pronghorn semi-captive breeding pen.

Avenues other than the more formalized structure provided by section 7 consultation have been developed which allow for input on USBP actions. The Borderlands Management Task Force (BMTF) includes mostly Federal agencies, but also includes Tribal governments, state agencies, and Congressional staff. Membership is limited because sensitive law enforcement information is discussed. The mission of the BMTF is:

> "to facilitate an intergovernmental forum for cooperative problem-solving on common issues related to the Arizona-Mexico border. The primary mission is to address border security, human safety, and natural and cultural resource protection through shared resources, information, communication, problem-solving, standardization and training."

Border infrastructure project planning occurs through monthly Project Delivery Team (PDT) meetings. The main purpose of the PDT is to construct new and enhance existing border infrastructure to improve the effectiveness of USBP operations and activities (CBP 2005). Most staff involved with the PDT are project managers, engineers, and USBP agents, though certain state and Federal agencies may attend. The PDT develops and tracks projects from concept through construction.

The BMTF and PDT meetings facilitate communication between the USBP and others, though specific endangered species issues or compliance are rarely discussed.

The AGFD may also be involved with ESA compliance and border issues. There is an existing Memorandum of Agreement between the USFWS and AGFD that allows the AGFD to participate in Section 7 consultation, subject to action agency approval (CBP or USBP in this case). AGFD staff periodically attends BMTF and PDT meetings. AGFD's concerns include effects to all fish and wildlife and their habitats.

SOLUTIONS

There are procedures and measures that Federal agencies can take to make ESA compliance more efficient from a procedural perspective and more protective of listed species and their habitats. The PDT, BMTF, and Public Lands Liaison agents have all helped improve communication and processes regarding natural resource protection. Their continued use and staffing, especially by FWS and USBP will continue to improve ESA compliance and resource protection. Additional measures that can also improve process, compliance, and resource conservation include: batch or programmatic section 7 consultations, environmental staff at USBP Sectors, streamlined and simplified processes, and environmental training for CBP, USBP agents, consultants and other staff.

A batch consultation is one where similar actions are grouped together. Examples might be all USBP road projects in the Tucson Sector, or all infrastructure in the San Rafael Valley. A programmatic section 7 consultation is one that covers a program. An example is a USBP operations consultation on border activities that covers an entire sector of USBP. This consultation will cover all ongoing patrol actions, and will also address the potential for an increase in USBP staffing levels and patrol activities. Batch and programmatic consultations take more effort initially, but they can preclude work later, or at least make it simpler.

The addition of environmental staff at the USBP Sector level would address several issues. A main complicating factor with CBP and USBP ESA compliance is the difficulty in communicating with all the entities involved, and within the CBP/USBP hierarchy. Having a local CBP/USBP environmental staff to coordinate compliance and local CBP/USBP communications would greatly enhance ESA compliance and resource protection. A related action that would also streamline and enhance compliance would be to have CBP and USBP delegate ESA compliance to the lowest levels possible. To be effective that would require sufficient staffing, funding, training, and resources.

Finally, the real solutions to illegal cross-border traffic and its impacts to listed species will not be achieved by the CBP/USBP or USFWS, or even any of the Federal agencies or consultants involved. The root causes of contraband smuggling and illegal immigration need to be dealt with. The incentives for cross border traffic must be removed and will be addressed where policy, legislation, and economics intersect. The problems have been decades in the making, and will likely take decades to truly fix.

The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the U.S. Fish and Wildlife Service.

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ADAPTIVE MANAGEMENT OF THE GRASSLAND-WATERSHED AT LAS CIENEGAS NATIONAL CONSERVATION AREA: THE ROLE OF MONITORING, RANCHER ENGAGEMENT, AND MULTI-STAKEHOLDER ADVISORY TEAMS

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Land managers are frequently forced to make land management decisions with little or no information regarding the outcomes of those decisions. Science-based adaptive management is a process designed to change this through the collection of information that assists in evaluating the effects of management actions and in identifying knowledge gaps that can be addressed by research or additional monitoring. The result is a decision-making process based on learning and information.

The adaptive management process requires seven primary steps:

1) Identification of management goals or objectives and measurable thresholds in resource condition.
2) Development of a monitoring protocol with adequate sampling effort to detect biologically meaningful change in resource condition over a specified time period and an optimal frequency and timeframe during which monitoring should be conducted.
3) Consistent implementation of the monitoring protocol.
4) Analysis of data.
5) Review of data against established goals and thresholds to determine the need for changes in management.
6) Implementation of needed management changes (and continued monitoring).
7) Implementation of follow-up scientific studies to fill identified information gaps.

In this paper, we describe an ongoing adaptive management process at Las Cienegas National Conservation Area that assists the Bureau of Land Management (BLM) and the rancher who holds a grazing permit there (hereafter, referred to as the permittee) in making grazing management decisions. As part of this adaptive management process, we evaluated the upland monitoring protocol and proposed revisions that increased the protocol's statistical power to detect change in grassland-watershed condition. Data collected in 2004 and 2005 using the revised protocol were analyzed and used by the BLM, the permittee and multi-stakeholder teams to modify the permittee's proposed annual grazing plan, including stocking numbers and planned pasture rotation. Follow-up monitoring documented the effect of these grazing management decisions.

THE SITE

Las Cienegas National Conservation Area (NCA) and the surrounding Sonoita Valley Acquisition Planning District (SVAPD) are a mix of BLM, Arizona State Trust, and private lands, encompassing nearly 39,000 ha (96,371 ac). Both were designated by Congress and signed into law by the President in December, 2000, in order to conserve, protect, and enhance the unique and nationally important resources there. Among these resources, the NCA and SVAPD support five of the rarest habitat types in the Southwest—cienega wetland, cottonwood-willow riparian forest, sacaton riparian grassland, mesquite bosque, and desert grassland—as well as six federally-listed species. The NCA's enabling legislation also allows for the continuation of livestock grazing and recreation. Las Cienegas NCA forms the northern anchor of a 323,887 ha (800,342 ac) conservation area identified in The Nature Conservancy's (TNC) Apache Highlands ecoregional assessment of conservation priorities (Marshall et al. 2004). In an analysis of 600 TNC conservation areas identified in the five ecoregions overlapping Arizona, the conservation area that includes Las Cienegas NCA ranked highest in terms of biological uniqueness and irreplaceability.

The NCA contains a portion of one of the best remaining open native grasslands in the borderland region; however, shrub encroachment is becoming an increasing problem in the middle and northern parts of the NCA and SVAPD (Enquist and Gori 2005; Gori and Schussman 2005). This grassland forms the watershed for upper Cienega Creek and the riparian and aquatic habitats there, making it an important focus for BLM management.

The Las Cienegas Resource Management Plan (RMP) was approved in July 2003, completing a collaborative planning process that occurred over an 8-year period with the Sonoita Valley Planning Partnership (SVPP). The SVPP is a voluntary association of federal, state, and local agencies, organizations, and private citizens who share a common interest in the resources and management of the public lands within the Sonoita Valley, an area that includes the NCA and the entire upper watershed of Cienega Creek. The BLM incorporated the vision, goals, and objectives of the SVPP as the foundation for the Las Cienegas RMP (BLM 2003).

BIOLOGICAL PLANNING

The Las Cienegas RMP states that the BLM will adopt an adaptive management strategy (BLM 2003). As part of this strategy, the RMP prescribes a flexible grazing program whereby authorized use (stocking numbers and pasture rotation) is varied annually based on an assessment of range conditions including monitoring data. The RMP formalized an ongoing Biological Planning process that assists the BLM by providing input and information that the agency can use in making livestock grazing and other management decisions. Through the process, the Biological Planning Team assists BLM with review of monitoring data and provides input into proposed actions. Composition of the team is a balance between resource managers and users. The Biological Planning Team includes the Rangeland Resource Team (RRT), the Technical Review Team (TRT) and other interested agencies and public. The RRT is a committee of nine members representing commercial and recreational users, environmental organizations, academia, and elected officials, and the TRT is composed of state and federal agency resource specialists with expertise in range, riparian, watershed, and wildlife management. In addition, public participants, including other interested agencies, provide input on TRT and RRT recommendations during Biological Planning meetings (see below).

The Biological Planning process generally consists of the following steps that incorporate components of the adaptive management process described above:

1) Proposed annual grazing plan is developed by the permittee.
2) Monitoring data are collected and analyzed by members of the BLM, TRT, and other collaborators; based on this analysis, modifications to the initial grazing plan are proposed.
3) Monitoring data are reviewed by the RRT in context of other issues that may have arisen for the NCA. The RRT reviews the TRT's recommended modifications to the grazing plan or other proposed actions based on the monitoring data, and makes additional recommendations, as needed.

4) All recommendations are discussed by the Biological Planning Team as a whole during twice-yearly Biological Planning meetings and receive additional public input at each meeting.

5) After review of existing data and recommendations from the Biological Planning Team, the BLM Field Manager will then approve or make any necessary changes to the annual grazing plan.

RESOURCE OBJECTIVES AND AN EVALUATION OF EXISTING MONITORING: AN ILLUSTRATION

The Las Cienegas RMP identifies two general upland objectives for the grassland-watershed (BLM 2003):

1) Maintain or achieve properly functioning upland condition and a high similarity index (> 50% by weight) to the historical climax plant community; and

2) Maintain or achieve ground cover in grassland communities in excess of 70% (< 30% exposed bare soil) on 80% or more of the ecological sites on the NCA and SVAPD by 2015.

Ecological sites are land units classified by the USDA Natural Resources Conservation Service (NRCS) to assist management; they are defined by soils, terrain, climate, and potential and current vegetation (USDA 2009).

Because this paper describes a *process* for evaluating monitoring protocols used in adaptive management, and because the similarity index is a derivative parameter that does not lend itself to an analysis of statistical power, we focus on the second general objective for the grassland watershed and its associated monitoring protocol for illustrative purposes.

To determine if this objective was being met, BLM established 31 key areas between 1995 and 1998 on the Empire-Cienega Allotment (30,000 ha /74,132 ac), the largest of four grazing allotments in the NCA and SVAPD. The key areas, scattered in different pastures and ecological sites within the allotment, were periodically monitored between 1995 and 2003 using a pace-frequency method for estimating plant species frequency and a point-intercept method for estimating substrate cover (Herrick et al. 2005; Ruyle, no date). One hundred quadrats, each 40 cm x 40 cm (pace frequency) and 100 points (point intercept) were sampled at one-pace intervals (~ 1.5 m) along two parallel, 76 m (833 yd) transects.

For frequency sampling, the occurrence of all plant species, herbaceous and woody, within quadrats was recorded. From this, the frequency of occurrence for each species was calculated by dividing the number of quadrats the species occurred in by the total number of quadrats sampled. For dry weight rank sampling, the three most abundant species on a dry weight basis were identified in the quadrat and ranked. A pointer attached to the quadrat frame was used to collect point-intercept data. The following categories of substrate cover were distinguished: bare ground, gravel, rock, litter and live basal vegetation. Descriptions of these categories can be found in BLM (2003). Percent cover by substrate category was calculated by dividing the number of "hits" in each category by the total number of points sampled (n = 100). All measurements were conducted in the fall (September-October) after the summer rains when flowering and annual production of warm-season grasses and herbs, which dominate these grasslands, had been completed.

We evaluated the upland monitoring protocols described above based on three criteria:

- How well do the parameters derived from the existing monitoring protocols address management objectives;
- What is the statistical power of these protocols to detect change; and
- How much time do they take to implement?

In addition, we identified several corollary considerations to facilitate our evaluation, including:

- Estimated parameters should explicitly address upland objectives or critical stresses that, if unchecked, would prevent key areas from meeting these objectives (our logic here is that since resources for monitoring are limited, parameters that directly measure progress toward objectives or changes in critical stresses are more important than those that do not);

- Sampling effort should be adequate to detect biologically-meaningful change in parameter values over appropriate time frames;
- Existing agency protocols should be used or expanded upon when possible; and
- Modifications to protocols should not significantly increase the total time already spent monitoring; placing greater emphasis on one set of measurements may be offset by de-emphasizing others.

A comparison of the upland resource objective with information obtained from pace-frequency and point-intercept methods indicated that only the point intercept method yielded data pertinent to the bare-ground objective (Table 1). In addition, neither method directly estimated the extent of shrub encroachment, a critical threat in grasslands. Shrubs may compete with perennial grasses for soil moisture, reducing perennial grass cover and increasing the amount of exposed soil and erosion rates (Hennessey et al. 1983; McPherson 1995, 1997; McPherson and Weltzin 2000; Schlesinger et al. 1990). These factors may prevent sites from achieving upland objectives.

We also evaluated the stratification of key areas to determine if their distribution was adequate to meet the RMP's upland objective of "80% or more of the ecological sites on the NCA." Twelve of 13 (92%) of the possible ecological sites had key areas located in them, while nine of the 13 (69%) of the ecological sites had key areas that were appropriate for evaluating livestock grazing effects, i.e., key area located 0.8–1.6 km (0.5–1 mi) from water. Additional key areas that can be used to evaluate grazing effects are needed to obtain adequate representation across ecological sites on the allotment.

We performed a power analysis for the pace frequency and point intercept methods to determine the sampling effort needed to detect a biologically-meaningful change in frequency or cover between two points in time with a specified level of false-change (α) and missed-change (β) errors. Since both parameters are expressed as a proportion or percent, the analysis is similar for both. For

Table 1. A comparison of the parameters obtained from specific monitoring methods with information needed to address management objectives. Prior to 2004 there was no monitoring protocol in place to measure shrub cover, a critical threat in grasslands, in key areas.

Monitoring Protocol	Grassland Variable Estimate	Addresses Management Objective?
Point Cover	Substrate cover including bare ground and litter cover Change in perennial grass cover/ composition Increase in exotic grass cover	Yes
Frequency	Combination of density and dispersion of plant species	No
Line-intercept Cover	Shrub cover by species	Critical threat, may prevent key area/pasture from meeting substrate cover objectives

simplicity, we begin our discussion with the substrate cover/point-intercept method. The key step in the analysis is to identify what a meaningful level of change is from a biological or management standpoint. The objective for bare ground cover requires that the protocol is sensitive to changes that approach and pass the 30% value so that pro-active changes in grazing management can be made before the system is severely damaged. Furthermore, in desert grasslands, perennial grass basal cover normally ranges between 10% and 30% and reaches a critical threshold near 5% cover; when grass cover is less than or equal to 5%, erosion potential on many ecological sites increases dramatically and grazing rest may not result in vegetation recovery if soil movement and loss are severe (Hennessey et. al. 1983; P. Warren, unpubl. data). Therefore, we determined that a biologically meaningful level of change was 2-5% when perennial grass basal cover was low (less than 10%), and a 7-10% change was meaningful when bare ground cover was 20-40% (near the BLM threshold value of 30% for bare groundcover).

Once identified, the biologically meaningful level of change can be substituted into the following equation, as p_1 and p_2, and the necessary sample size for detecting differences between two proportions calculated (Elzinga et al. 2001):

$$n = (Z_A + Z_B)^2\ (p_1q_1 + p_2q_2) / (p_2-p_1)^2$$

where n is the estimated necessary sample size; Z_A is the Z coefficient for the false-change error rate; Z_B is the Z coefficient for the missed-change error rate; p_1 is the proportion value for the first sample, expressed as a decimal; q_1 is $(1 - p_1)$; p_2 is the proportion value for the second sample, expressed as a decimal; and q_2 is $(1 - p_2)$.

We set the acceptable level for false-change (Type I) and missed-change (Type II) errors at 10%. A 20% probability for Type I and II errors is usually recommended for monitoring programs; however, we decreased the probability because of the regional and national importance of the NCA and BLM's management prescription of a flexible livestock grazing strategy.

Sample numbers necessary to detect 5%, 10% and 20% changes in cover with a 10% probability of false- and missed-change errors vary with the percent change in basal cover as well as the original percent cover (Figure 1). Our results showed that a 20% change can be detected with 102 points for all cover values (0% to 100%), a 10% change can be detected with 422 points for all cover values, and a 5% change can be detected with 981 points for values from 0% to 20% and 85% to 100%. Comparison of the level of change detectable with 102, 422, and 981 sample points with the desired level of detectable change (e.g., 2-5% for perennial grass basal cover and 10% for bare ground cover) indicates that a minimum of 981 sampling points are needed. With this sampling effort, at least a 6-7% change in cover (bare ground, perennial grass or other) can be detected across the full range of initial parameters values (0%-100%). With only 100 points sampled in the original protocol, sampling effort was insufficient to detect the desired level of change; however, that effort could detect a 20% change in cover for cover values from 0% to 30% and 50% to 100% and a 10% change in cover for cover values between 0% and 10%.

The preceding analysis assumes that points along transects are independent and that replication (i.e., sample size) is at the level of the point. If the transect is the unit of replication, then the analysis differs (Sundt 2002) and an estimate of the pooled sample variance between transects (s^2) is required to solve the following equation:

$$MDC = [\sqrt{(s^2/n)}]\ (Z_A + Z_B)$$

where MDC is the size of the minimum detectable change, expressed in absolute terms rather than as a percentage; and n, Z_A, and Z_B are as above (Elzinga et al. 2001). Our results indicated that 10 transects (with 100 points per transect) were sufficient to detect the targeted changes in parameter values identified above but 2 transects, as currently implemented, were not (Gori and Schussman 2005).

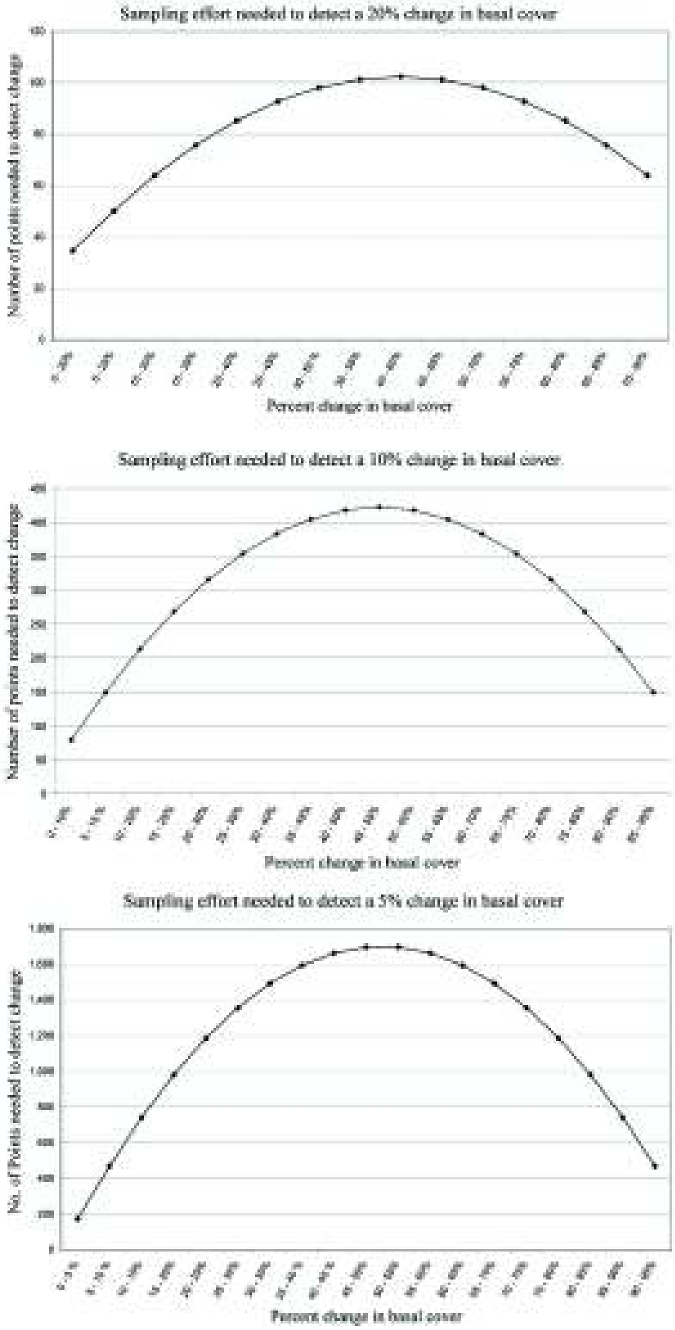

Figure 1. Comparison of the number of sampling points needed to detect a 5%, 10%, and 20% change in basal cover or canopy cover, assuming a 10% probability of false or missed change errors.

As indicated, the first analysis is also applicable to the frequency protocol. However, without specific management objectives for plant species' frequency, it is difficult to evaluate if a sample size of 100 quadrats will be able to detect changes that are meaningful from a management perspective because the context for what management is trying to achieve with respect to the density or dispersion of individual species or identification of a threshold value that could trigger a change in management is lacking. Although an advantage of frequency sampling is its low level of observer bias, there are several disadvantages. Since frequency is a function of both density and dispersion, frequency data can show significant changes in percent values where no real changes in abundance (or cover) exist. Therefore, frequency sampling is of limited use as an "early warning" system to detect changes in watershed condition or the abundance and cover of perennial grasses. In addition, frequency data are time consuming to collect because monitors must typically recognize 30 to 40 plant species per key area at Las Cienegas and, with a 40 cm x 40 cm quadrat frame, most species are too rare (< 5% frequency) to detect a statistically significant change in frequency over time (Ruyle, no date).

UPLAND MONITORING PROTOCOL REVISIONS

Based on the above analyses, the original protocol for estimating substrate cover was revised, building on an existing NRCS-BLM protocol (Herrick et al. 2005), and field tested in the fall of 2004. Key areas were enlarged to 50 m x 100 m to accommodate the greater number of transects (10) and sampling points (1,000). Point-intercept measurements were made at 0.5 m intervals along 10 transects, each 50 m in length, for a total of 1,000 sampling points. Plot size was increased to 100 m x 100 m and sequential point measurements were made at 2 m intervals in loamy bottom ecological sites dominated by giant sacaton (*Sporobolus wrightii*) to maintain independence of sequential sampling points (Gori and Schussman 2005). Substrate categories were expanded from the original protocol to include, as components of live basal vegetation, perennial grasses by species, annual grasses, and forbs. No species identifications were made for annual grasses and forbs. This modification allowed us to track changes in perennial grass cover and composition over time, information that is important in evaluating grassland condition and that can be inferred only with some uncertainty from pace-frequency measurements (Thurow et al. 1986, 1988a, b). Canopy (1st hit) and basal (2nd hit) cover hits were recorded separately. Canopy cover estimates provide information on watershed condition beyond what basal cover estimates of bare ground and live (basal) vegetation can provide because grass, forb, or litter canopies can protect bare ground (soil) beneath them from the erosive impacts of raindrops (Thurow et al. 1988a; Pellant et al. 2000).

The revised protocol for substrate cover is equivalent (i.e., 10 transects, 1,000 points) to substrate cover protocols being applied at the San Rafael Ranch and San Rafael Ranch Natural Area (Arizona State Parks) and on the Diamond A Ranch in the Peloncillo Mountains and in the San Bernardino Valley (Malpai Borderlands Group). A similar protocol (15 transects, 750 points) is also being applied at TNC's Aravaipa Canyon Preserve and at Muleshoe Ranch Cooperative Management Area to measure prescribed burn effects on shrub-invaded grassland watersheds.

Because it doesn't directly address any upland objective, TNC recommended that the pace-frequency sampling be discontinued. However, a couple of TRT members stressed the importance of maintaining this long-term data set. BLM decided that the pace-frequency measurements will be continued at a reduced frequency (every 3-5 years) assuming there are adequate resources to complete the other upland monitoring.

No estimates of shrub cover were made in the original protocol. Because this information relates to an important stress on grassland systems and will be useful in planning, prioritizing and evaluating the success of shrub control treatments, the revised protocol calls for measuring shrub cover by species using a line-intercept method. Measurements occurred along the same 10 transects (per key area) used for substrate cover monitoring but will be repeated at a frequency of every 5-6 years.

The upland monitoring plan for Las Cienegas consists of the revised protocol and a protocol for estimating the similarity index value of key areas (via the dry weight-rank method), which addresses the first general upland objective (see above). The monitoring plan increases the total monitoring effort for key areas *annually* only because BLM decided to continue implementation of the original pace frequency sampling (Gori and Schussman 2005). That is, the time it takes to implement the revised substrate cover protocols annually is essentially the same as the estimated time to implement the original BLM annual monitoring protocols for substrate cover, dry-weight rank, and pace frequency: approximately 2 hours per key area for a 4-person crew. Sampling for shrub cover and the similarity index both add an additional 1 hour per key area, but the recommended sampling frequency is every 5-6 years and 10 years, respectively. An increase in the total number of key area plots to better represent ecological sites and pastures in the allotment will also increase the total monitoring effort. However, we are now considering a monitoring schedule where individual key areas *that have met resource objectives* will be sampled every 3 years. This schedule should partially offset the increased time costs of continuing the pace-frequency sampling and sampling additional key areas. Thus, implementation of the revised protocol can be accomplished with existing resources.

Additional details on the revised substrate cover protocol, evaluation of the similarity index protocol, and their time costs can be found in Gori and Schussman (2005).

THE ADAPTIVE MANAGEMENT PROCESS

The revised upland monitoring plan was reviewed by the TRT and RRT as well as outside experts in 2004. In addition, a workshop for these teams was held in fall 2005 to compare the results of the original and revised protocols for two adjacent key-area sites. The participants confirmed that the protocols gave comparable results for substrate cover and plant species' composition.

Following completion of the protocol review in 2004, the monitoring plan was field-tested by TNC and BLM staff in September and October, 2004. Monitoring was repeated at the same time of year in 2005. In both 2004 and 2005, key areas were prioritized and selected for measurement based on the permittee's proposed annual grazing plan to ensure that information collected would be germane to decision-making. Twenty-four key areas were measured in 2004 and 22 in 2005. The monitoring data was analyzed and presented to the TRT, RRT, and interested public during Biological Planning in fall 2004 and 2005. Monitoring information included: (1) bare ground cover, basal and canopy cover of perennial grasses, shrub canopy cover, and dominant perennial grass and shrub species for all key areas; (2) a proposed livestock grazing plan for fall, winter, spring and summer, 2004-2005 and 2005-2006, including stocking rate and pasture rotation schedule; and (3) a comparison of bare ground and perennial grass cover with summer precipitation records by key area from 2001-2005.

In 2004, the TRT's review of the proposed grazing plan and monitoring data revealed concern over two northern pastures with proposed winter and spring use in 2004-2005. The concern was due to low basal cover of perennial grasses in 2004 (< 5% basal cover), a significant downward trend in live basal vegetation cover between 1995 and 2004 (R^2s > 0.48, p < 0.025), and relatively high shrub cover in two key areas in the two pastures (shrub cover > 27.4%, *n* = 2 key areas). Based on these concerns, the permittee revised his grazing plan and decreased by 2 months (50 %) the total amount of time that livestock would be grazing in these pastures. Specifically, the 300 head of livestock proposed to enter the two pastures on December 1, 2004, were held on sacaton pastures until February 1, 2005, in an effort to decrease the overall time livestock were grazing these areas. In addition, the permittee proposed using water sources strategically, keeping livestock on the sacaton portions of these northern pastures and away from more sensitive upland areas with lower perennial grass cover.

These two northern pastures received poor summer rainfall again in 2005, as did an adjacent pasture that also showed low perennial grass basal cover in 2005 (basal cover = 4%) and a declining trend in live basal vegetation cover since 1995 ($R^2 = 0.94$, 4df, $p < 0.01$). The latter pasture was proposed for winter-spring use in 2005-2006, but all three pastures were excluded from grazing in 2005-2006. Instead, the permittee kept livestock on nearby sacaton pastures with suitable forage during this period.

Another pasture, West Pasture, failed to meet bare ground objectives in fall 2004. The TRT and RRT recommended that livestock be removed immediately and the pasture rested. Summer rainfall for that pasture in 2005 was well above average and by fall 2005, perennial grass basal cover had increased from 12 to 19% (a 58% increase) and bare ground cover had decreased from 33 to 24% (27%); both changes were statistically significant (Fisher exact tests: perennial grass, $p < 0.001$; bare ground, $p < 0.001$). As a result of this recovery, the pasture was scheduled for 3 months of winter use in 2006. Although changes were made in pasture use, proposed stocking rates were not adjusted in 2004 or 2005.

The RRT concurred with the TRT's recommendation following careful review of the monitoring data analysis in both years. The BLM also concurred with these recommendations and the proposed grazing plans were modified accordingly.

Overall, there was no relationship between increases or decreases in basal grass cover or bare ground cover on key areas between fall 2004 and fall 2005 and whether a pasture was grazed in the intervening months, though this analysis did not account for the intensity of use (Fisher exact tests: perennial grass, $p = 0.61$; bare ground, $p = 0.56$). The change in perennial grass basal cover between 2004 and 2005 was positively related to the amount of summer rainfall key areas received in 2005, however, there was no relationship between bare ground cover and rainfall (bare ground: $R^2 = 0.01$, 16 df, $p > 0.65$; perennial grass: $R^2 = 0.22$, 16 df, $p = 0.05$). That is, key areas that showed greater increases in perennial grass cover between the 2 years received more summer rainfall in 2005 than did plots showing smaller increases or decreases in perennial grass basal cover between 2004 and 2005. Similarly, the change in perennial grass basal cover on key areas between 2004 and 2005 was positively related to the summer rainfall deviation in 2005 but the change in bare ground cover was not (perennial grass: $R^2 = 0.32$, 16 df, $p = 0.014$; bare ground: $R^2 = 0.03$, 16 df, $p > 0.5$); rainfall deviations were calculated as the difference between the amount of summer rainfall a key area received in 2005 and its mean summer rainfall calculated from gauge records starting in 2001 or earlier. Another precipitation variable, the difference in summer rainfall that key areas received in 2004 vs. 2005 was unrelated to changes in bare ground and perennial grass basal cover. Additional factors besides summer rainfall (e.g., differential effects of the ongoing drought on perennial grass species, degree of shrub encroachment, and intensity of livestock use) may also be contributing to changes in grassland condition on key areas in 2005.

CONCLUSIONS

The BLM, permittee, TRT, and RRT successfully completed steps 1 through 6 of the adaptive management process. In addition, the TRT and RRT, with BLM concurrence, identified the following information gaps or needs that would assist in future decision-making (i.e., Step 7):

- Identify biologically important thresholds for basal cover of perennial grasses by ecological site, including thresholds that may trigger a change in grazing management; and

- Establish additional key areas in northern pastures and on ecological sites that are under-sampled on the allotment to assist in the evaluation of livestock grazing and climatic factors in these pastures. This will be addressed through the addition of paired key-area plots and livestock exclosures on south-facing slopes.

The TRT and RRT also identified some refinements needed in the RMP's resource objectives, as well as additional planning to improve BLM's ability to manage the diverse expression of desert grassland on different soil types. These refinements include:

- Define *desired* objectives for basal cover of perennial grasses by ecological site; and
- Develop a shrub control plan for the Empire-Cienega Allotment, including future prescribed burns to reduce shrub cover in affected areas.

In February, 2004, the TRT selected five sites for additional key areas and paired adjacent livestock exclosures in northern pastures and fencing was completed in spring of 2006. Two of these pairs were on ecological sites that previously lacked key areas appropriate for evaluating livestock effects, increasing the total to 11 of 13 ecological sites (85%) on the Empire Cienega Allotment with key areas. In addition, the TRT will identify desired objectives and biologically important thresholds for basal cover of perennial grasses by ecological site by fall 2006.

The collaborative adaptive management process at Las Cienegas NCA has had a number of expected and unexpected benefits that ultimately contribute to BLM's and the permittee's success in managing the grassland-watershed. Specifically, Biological Planning with its reliance on interactions between BLM, the permittee, multi-stakeholder teams, and the interested public has:

- Built trust among participants and developed a solution-oriented approach to address potential conflicts over grazing and other resource concerns;
- Fostered an environment where decision-making is based on information instead of emotions;
- Increased knowledge of grazing effects to improve resource management;
- Provided access to different perspectives and expertise that has given participants the ability to go beyond measurements of vegetation change to consider wildlife use and needs; and
- Demonstrated that rigorous monitoring can be implemented without increasing the overall cost of monitoring.

Additional details on the science-based adaptive management process at Las Cienegas NCA can be found in Gori and Schussman (2005), BLM (2006), and Bodner et al. (2007).

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ECOLOGY AND CONSERVATION IN THE SONOYTA VALLEY, ARIZONA AND SONORA

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Lowland desert rivers, streams, and ciénegas are the most severely impacted environmental type in the southwestern United States (Bryan 1928; Hendrickson and Minckley 1985; Minckley and Deacon 1991; Logan 2002; Turner et al. 2003) and northwestern Mexico (Hendrickson et al. 1980; Hendrickson 1983; Miller et al. 2005). Huge areas of riparian forest have been lost in the low deserts (Ohmart 1982); most southwestern fishes in the U.S. have long been recognized to be endangered, threatened, or sharply declining (Miller 1961; Minckley 1973; Minckley and Deacon 1991); and many of the aquatic amphibians and reptiles are following suit (e.g., Rosen and Schwalbe 2002).

Río Sonoyta, Sonora, Mexico (Figure 1), which adjoins Organ Pipe Cactus National Monument and passes through the town of Sonoyta, Sonora, is a rare lowland desert stream that has not been completely degraded and desiccated, although the regionwide downcutting of ciénegas (Hendrickson and Minckley 1985) that began about 1891 has severely impacted the system at its upstream end. It retains perennial surface flow in a local area, which is protected within the Reserva de la Biosfera El Pinacate y Gran Desierto de Altar, and still supports its originally known native fish fauna (Snyder 1915; Miller et al. 2005). Native turtles and diverse, productive riparian forests and woodlands remain widespread despite serious environmental degradation during the past approximately 118 years.

Discussions regarding the status of the endemic Sonoyta mud turtle (*Kinosternon sonoriense longifemorale*) were convened by U.S. Fish and Wildlife Service (USFWS) in 1997. In 2001 a multi-agency conservation team consisting of representatives from USFWS, Instituto del Medio Ambiente y el Desarrollo Sustentable del Estado de Sonora (IMADES, now CEDES), Pinacate Biosphere Reserve, Organ Pipe Cactus National Monument (ORPI), Arizona Game and Fish Department (AGFD) and University of Arizona (UA) began conservation planning and initiated ecological monitoring at Quitobaquito, Quitovac, and the Río Sonoyta proper. As a result of small population sizes and other potential problems facing all populations of this turtle, which are detailed here, USFWS identified the Sonoyta mud turtle as a candidate for listing as threatened under the Endangered Species Act of the United States (Knowles et al. 2002a & b).

Sampling to determine the distribution, abundance, and status of the Sonoyta mud turtle, which has been conducted on an annual or bi-annual basis from 2001 through 2006, quickly led to the realization that a broader resource was at risk and to an expansion of taxonomic focus and conservation objectives. In this chapter we offer details on the status of and threats to the natural biodiversity resources of Río Sonoyta based primarily on published literature and our work there during 2001-2006. We also outline ideas on what might be done to reconcile the conservation of these resources with present and future human uses.

METHODS AND MATERIALS

Surveys were conducted once to twice per year during 2001 through 2006, generally during

March-November, and mostly in April or October. We selected sites to visit based on maps, aerial images, museum records, and interviews. We established two intensive study areas, one at and adjoining Presa Xochimilco on the east margin of Sonoyta and one at a lower section of perennial stream at the Rancho Agua Dulce pers. comm. or "Papalote") reach, in the Pinacate Reserve south of Quitobaquito. We recorded riparian and aquatic conditions photographically and according to annotated lists of dominant plants and notable bird species, and we sampled for fishes using minnow traps, dipnets, hoop nets, and seines. Trap locations and other places of interest were recorded with GPS units and with descriptive notes. Fishes and invertebrates captured in the traps were recorded. Detailed notes on ecological observations were maintained in an itinerary-based notebook, while turtle data were recorded on data sheets.

Potential habitat for the Sonoyta mud turtle in Sonora was surveyed using visual surveys and trapping. Visual surveys involved approaching water sources quietly and searching with binoculars for basking and surfacing turtles, looking for tracks in moist sand or mud, and muddling (probing by hand

Figure 1. Location map showing Río Sonoyta, Quitovac, and low-elevation cities in the Sonoran Desert. All of the cities except Sonoyta and Yuma have dried up their lowland streams or rivers, and native fishes are absent or nearly so, except in Río Sonoyta.

in burrows and undercut banks). Trapping employed 46 and 76 cm (18 and 30 in) diameter, 2.54 cm (1 in) mesh hoop nets baited with sardines and hot dogs for juvenile and adult turtles, and galvanized steel 6 mm (1/4 in) mesh minnow traps with openings enlarged to 5-8 cm (2-3 in) and baited with a piece of sardine for hatchling and juvenile turtles. Traps were set for 2-6 hours in the immediate area adjoining Sonoyta and for approximately 24 hours per checking cycle elsewhere.

Turtle study in the region by one of us (Rosen) began at Quitobaquito, in Organ Pipe Cactus National Monument in 1983 (Rosen and Lowe 1996), with occasional visits to Río Sonoyta starting the same year. Captured turtles were marked for individual recognition by notching marginal scutes on the carapace, using a nick on a bridge marginal to signify the general region — 5R for the study area at Presa Xochimilco and adjoining river reaches in Sonoyta, 5L for the Agua Dulce region, and no bridge mark for Quitobaquito. No movement among sites has ever been detected. Although we observed turtles at Quitovac on three trips, no turtles were marked there. Various shell measurements were taken on captured turtles, and growth rings were either measured to quantify yearly growth or counted backward to the year of hatching to determine age.

A principal threat identified during this study was groundwater depletion and loss of aquatic habitat. Sonoyta is presumed to have had a ciénega, and Río Sonoyta is thought to have originally had long-flowing reaches, and we therefore reviewed available historic descriptions of water in the Sonoyta Valley to more carefully evaluate former conditions. We contrasted our evaluation of former conditions with our field observations to assess hydrological changes and consequent threat levels of aquatic vertebrate species. We utilized these threat evaluations and discussions with people in the Sonoyta region as a basis for conservation recommendations.

STUDY REGION DESCRIPTION

Background details on current environmental conditions along Río Sonoyta, current place names, and conditions are provided in this section. Historical literature was reviewed for descriptions of original aquatic ecosystem conditions which allowed an assessment of changes in the Sonoyta Valley during the past century and a half. The reader should refer to Bennett and Kunzmann (1989), Fisher (1989), Felger et al. (1992), Nabhan et al. (1982, 2000), and Weir and Azary (2001) for descriptions of the oases at Quitobaquito and Quitovac, and for historical references for these largely intact spring systems.

Riparian and Aquatic Environments in 2001-2006

Hydrology and Extent of Water

Although the hydrology of Río Sonoyta basin is not fully understood, it appears that presently existing surface waters (Figure 2A) are closely associated with shallow rock which forces the aquifer to the surface, rather than impervious fine sediment layers — although MacDougal (1908) and others have suggested the latter. In 2001 and 2002 we found two areas, each with about 6-10 semi-perennial river pools with catfish and turtles, in reaches without streamflow adjoining hills just east of Sonoyta ("Vidrios" and "San Raphael" on topographic maps). Some of these pools were apparently perched on lenses of clay, as they were in areas without evidence of submerged bedrock and sat above 2 m (6.5 ft) drop-offs in the streambed. Below the drop-offs there was no surface water. We do not know if these pools continued to support aquatic vertebrates during and after the severe droughts of 2002-2004. Such perched aquifers were not evident in downstream reaches that currently support perennial water.

At Sonoyta, the only apparently natural perennial water in 2001-6 adjoined the south tip of the Sonoyta Hills, where bedrock is exposed in the river channel. At the head of this spring is Presa Xochimilco (Figure 3); which is apparently the same as "Presa Derivadora" of Broyles and Felger, in Felger (2000). The Presa occupies the site of the historic laguna (Hoy 1990), which was retained by a large stone dam, possibly the one

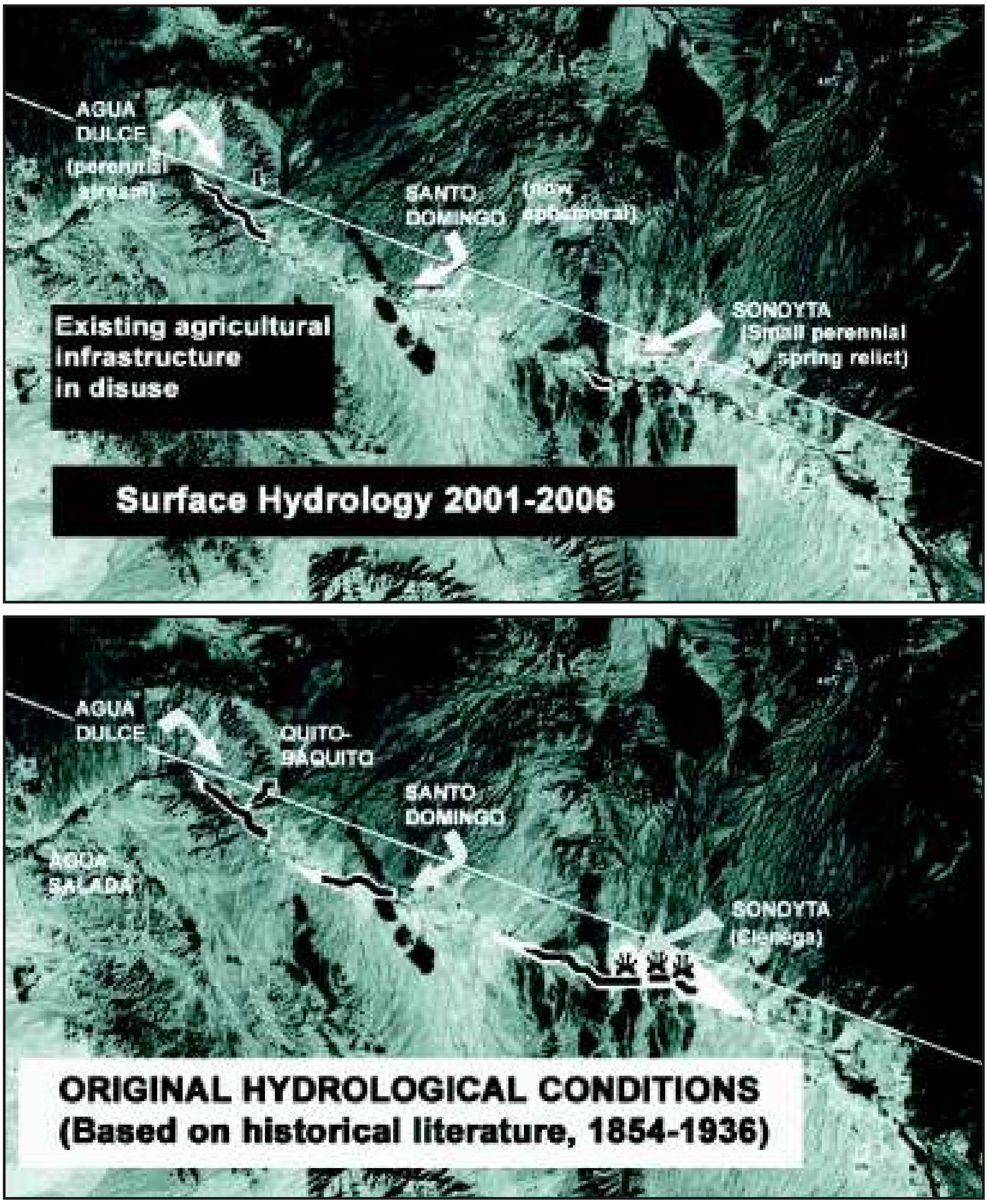

Figure 2. Hydrological conditions at Río Sonoyta. Perennial sections are indicated by black line outlined in white, with ciénega near Sonoyta indicated by marsh symbols. Figure 2A (top) shows conditions observed during current study, with lower end of flow shown as variable depending on year and season. Figure 2B (bottom) shows inferred original conditions (see text) with uncertainty suggested by narrowing white outlining.

Figure 3. Presa Xochimilco at the east edge of present-day Sonoyta. The photo was taken in 2001 from the dam, looking east. Photo by Rafaela Paredes.

still extant, placed on this bedrock. The dam served as a headgate for acequia water (Hornaday 1908) prior to the large-scale development of electric and gasoline-powered wells and the desiccation of the local aquifer. Early in our study, runoff maintained a pond well over 0.5 km long, which occupied the mapped laguna area. During most of our study perennial water occurred only as sewage effluent from an army base at the site of old Sonoyta released in the upper 0.3 km (0.2 mi) of the mapped laguna. Except in the kilometer (0.6 mi) above the dam, the river bottom near Sonoyta is entrenched within vertical walls up to 8 m (26.2 ft) deep.

The perennial spring below the dam was flowing for several hundred meters in 2001, but was reduced in 2005-6 to approximately 10 pools in the kilometer below the dam. The pools ranged from 0.3 to > 1.5 m (1-5 ft) deep, and some received small inputs of sewage effluent from individual homesteads atop the south arroyo wall. Lacking garbage collection service, many of these homesteads also disposed of copious domestic trash in the arroyo.

The wettest part of the riverbed we were able to locate between Sonoyta and Agua Dulce was at Ejido Josefa Ortiz, just upstream from the historic site of Santo Domingo. This non-perennial spring in the riverbed occurred at the river's narrow point between two rhyolitic hills. It was reported to flow for about 1 km (0.6 mi) during winter, when saltcedar (*Tamarix ramosissima*) was leafless and therefore not transpiring, but we found it no more

Figure 4. The Agua Dulce, or "Papalote" reach of Río Sonoyta in April 2003. Photo by P. C. Rosen.

than 300 m (328 yd) in length on 8-9 March 2002. A field of salt grass (*Distichlis spicata*) adjoins the spring source outside the riparian saltcedar thicket. This spring stands at the head of the irrigation developments of Santo Domingo, most of which was not in use during our surveys.

Downstream from Sonoyta, to Santo Domingo, we found decreasingly active use of the irrigation systems. From Santo Domingo to downstream reaches associated with Agua Dulce and Agua Salada, most irrigation systems were in disuse. Further, a number of those closest to the river lacked evidence of modern infrastructure and were overgrown with salt-tolerant desertscrub, especially desert saltbush (*Atriplex polycarpa*) and broom seep-weed (*Sueda moquinii*), and thus appeared to have been long-abandoned.

The Agua Dulce reach (Figure 4) as defined here is centered about 1.6 km (1 mi) south of Quitobaquito and Aguajita springs, near current Rancho Agua Dulce, rather than at a site 6.5 km (4 mi) southwest of Quitobaquito as stated in some earlier literature (e.g., Schott, in Emory 1857; Hoy 1990), which is close to the site we know as Agua Salada or La Salada. This perennial reach occurs at the next major rocky choke-point after Santo Domingo. There is identical-looking decomposing granite to the north (Quitobaquito Hills) and south (Cerro de Tres Verredos, an outlier of the Sierra los Tanques). It appears plausible that the river course is pushed to the south against the flank of Sierra los Tanques by the large bajada of the Puerto Blanco Mountains and water is forced to the surface by subterranean granitic rock.

Goodman (1992) reported deep alluvia between Sonoyta and Santo Domingo, at which point the valley is thought to be shallowly underlain by the Aguajita Springs Biotite Granite, of late Cretaceous age. Further details are poorly known or unknown, although Caruth (1996) reported that Quitobaquito Springs depend on water shed by the Puerto Blanco Mountains, which requires 500 to several thousand years to pass through bajada sediments until encountering subsurface rock which forces it up to emerge as springs. Goodman also found that the water of the springs along Quitobaquito Hills are all identical in chemical composition, but differ from that at Agua Dulce.

Until further information becomes available, the source and fate of the Agua Dulce reach are unknown and not precisely predictable. However, this last remaining free-flowing reach of the river is likely the product of the aquifer between Sonoyta and Santo Domingo and its attenuating continuation over the subsurface Aguajita Springs granite. Even though water may be in the ground for many centuries prior to emerging as spring flow, a depleted aquifer may reverse the upward movement of the groundwater, and weaken or kill the surface flow. Continued pumping for irrigation could desiccate Agua Dulce, and the closer to the perennial reach it occurs, the more likely that strong or immediate impacts will be seen.

The Agua Dulce reach fluctuates markedly in extent. During our current period of study, it usually varied from 1.6-2.7 linear km (1-1.7 mi) of surface water from a consistent source to a variable site of disappearance beneath the sandy riverbed. During the wet period of 1977-1984, and shortly thereafter, it was reported to be "at least 5-6 km (3-3.7 mi)" in extent by Miller and Fuiman (1987, p. 606), whose discussion implies that fish were found over a length of 10-13 km (6.2-8.1 mi) of river during 5-7 May 1986 (following a wet winter).

We found the Agua Dulce reach characterized by shallow runs of 3-10 cm (1.2-3.9 in) deep water over sand and fine gravel, with deeper — 10-30-cm (3.9-11.8 in) — sandy riffles and glides. There were local sandy to mud-bottomed pools that were mostly < 0.6 m (2 ft) deep prior to 2005. During 2005-6, several pools had maximum depths of 0.8-1.1 m (2.6 -3.6 ft). During the driest parts of our study, surface flow disappeared from most of the Agua Dulce reach, which was reduced to pools supported by subsurface flow, particularly in June and July from 2002-2005.

At Agua Salada in 2001, we successfully dug to water at a depth of about 0.6 m (2 ft).

Riparian Forest, Woodland, and Bank Vegetation

We observed riparian forest and woodland along Río Sonoyta over all of the region we investigated, from Colonia La Nariz downstream to the northeast side of the Pinacate lava region at Los Vidrios Viejos. Upper reaches were often characterized by a dominance of velvet mesquite (*Prosopis velutina*) bosque. We surveyed this region only briefly in 2001.

From Presa Xochimilco to at least 4.5 km (2.8 mi) upstream, we found a structurally diverse gallery forest composed primarily of velvet mesquite, Goodding willow (*Salix gooddingii*), and saltcedar mixed in relatively even abundances. This forest also contained a variety of other small desert trees and shrubs. Downstream of the presa there was a dense forest of saltcedar mixed with lesser representations of mesquite, willow, and local patches of giant reed (*Arundo donax*), bulrush (*Scirpes americanus*), and southern cattail (*Typha domingensis*). Throughout these reaches Bermuda grass (*Cynodon dactylon*) was the dominant groundcover.

Drier reaches below this area — i.e., below the Mexican Highway 2 bridge in Sonoyta — usually supported more open stands of velvet mesquite and saltcedar. Saltcedar formed dense thickets at Ejido Josefa Ortiz and a substantial part of Santo Domingo, at Agua Dulce, and at Agua Salada. Except for the Agua Dulce region, each of these areas was only examined briefly 1-3 times, and our survey of the river did not include 100% coverage of all reaches.

The Agua Dulce reach supported small, local stands of willow within the saltcedar thicket in at least two places. It had locally extensive stands of arrowweed (*Pluchea sericea*) and marginal bosque outside the saltcedar thickets, comprising primarily velvet mesquite and saltcedar. Despite heavy grazing by cattle, stream margins were stabilized by salt grass, Bermuda grass, spike rush (*Eleocharis* sp.), bulrush, and sedges (*Cyperus* sp.) in numerous areas free of saltcedar shade, and there were small patches of cattails. However, saltcedar provided the main stabilization of the flow channel and much of the most resilient stabilization of streambanks proper. Floristic information for parts of Río Sonoyta is available in Felger (2000).

Aquatic and Riparian Fauna

Dense accumulations of filamentous algae (e.g., *Cladophora* sp.) were found in the stream when flood scour was absent. A rich invertebrate fauna and numerous tiny juvenile fishes were found in these conditions despite extremely high densities of adult fishes, especially in extensive areas of shallow water, particularly in the stream margins.

One endemic invertebrate, the Quitobaquito spring snail, *Tryonia quitobaquitae,* has also been described from the Río Sonoyta basin. It belongs to the family Hydrobiidae, which has numerous endemic populations found in isolated springs, seeps, and drainages throughout the southwestern United States. The snail was first collected at Quitobaquito Spring in 1963 and was assigned to *T. imitator*, a more widespread species. Hershler and Landye (1988) described it as a separate species based on morphometric analysis of shell characteristics and soft body tissue. *Tryonia quitobaquitae* has been found at Quitobaquito Spring, Burro Spring, and Williams Spring approximately 2-3 km (1.2 – 1.9 mi) away, all along the south and west flanks of Quitobaquito Hills.

The aquatic vertebrates in the Sonoyta Valley are the Sonoyta mud turtle, the Arizona mud turtle (*K. arizonense*, which was collected once at Quitobaquito (Smith and Hensley 1957) and for which we have recently received a photographic record from Presa Xochimilco (A. Pate, pers. comm. 2007), anuran amphibians of at least six species (Rosen 2007), all toads, and five species of fishes, two of them native. The status of the amphibians is poorly known, but two species of interest deserve mention, the Great Plains narrow-mouthed toad (*Gastrophryne olivacea*) and the Sonoran green toad (*Bufo retiformis*), both of which, like the Arizona mud turtle, have regional distributions centered on the Tohono O'odham lands in south-central Arizona (Sullivan et al. 1996; Rosen and Funicelli 2008). We have not seen tadpoles or amphibians breeding in any of the perennial waters of the region.

At least 157 species of birds are known from the Sonoyta region, including 47 breeding species and 70 migratory species that winter in the region (Russell and Monson 1998). We found riparian birds to be abundant and diverse especially at and above Presa Xochimilco. Migratory and riparian birds were also prominent at the Agua Dulce reach, as were birds characteristic of aquatic habitats, including belted kingfisher, green heron, and black-crowned night heron.

Río Sonoyta appears to be preferentially utilized by some bats, such as Underwood's mastiff bat (*Eumops underwoodi*) (Barns and Pate 2004), that would likely be regionally absent without the river's resources. Similarly, a number of medium-sized mammal species have been recorded at ORPI that likely depend on the river for regional persistence, such as the raccoon, striped skunk, and hognose skunk (Cockrum and Petryszyn 1986). Pronghorn and mule deer are occasionally observed utilizing marginal mesquite and saltcedar woodland in the lowermost parts of the area we examined (Israel Barba, pers. comm., 2001-2).

Original Conditions

Historical Review

Hoy (1990) provides a summary statement about ciénega and stream conditions in Sonoyta Valley based on reports from American and some earlier Mexican sources. Here we examine this record in detail to determine what can definitely be said about original conditions — those that existed at and shortly after the arrival of Europeans in the region — and habitat losses in the river environment.

Padre Eusebio Kino, who first arrived at Sonoyta in 1698, is vague about ecological conditions at Sonoyta, but noted, upon his arrival, a Tohono O'odham community with extensive irrigation agriculture already fully developed. He described about 1,000 people at Sonoyta, and a considerable number more in surrounding communities (Bolton 1936). As the only perennial stream between Arivaca and the Colorado River, Río Sonoyta was a hub of the Tohono O'odham culture.

The boundary survey party headed by Emory (1857) and the railroad route survey of Andrew B. Gray (1856) and Peter R. Brady reported briefly on the environment at Sonoyta. Gray was there in May 1854, and reported (p. 87):

> *The valley is broad, with springs and a small stream (the Sonoita) which flows for a few miles in the dry months, when it sinks…*

This suggests that in times of average or low rainfall the river was not as large as might be surmised from other descriptions, such as in Bryan (1925, map based on a 1917 survey).

Arthur Schott, who was apparently in the Sonoyta region during 1853-5, reported hydrological details in Part II, Chapter IV of Emory (1857, pp. 73-75). He describes a considerably less extensive river scene, after first confirming that a ciénega-like environment was found at Sonoyta:

> *Besides numerous deep charcos and even small lagoons in its lower part, this cienega is blessed with a small stream fed at its outset by a number of small springs [which] afford a constant flow of water ... [which] is clear, of a bluish hue, but warm and slightly brackish. Notwithstanding this perennial supply, the little river of Sonoyta continues but about a mile as a running stream.*

This probably cannot be entirely attributed to intensive diversions for irrigation at the time, since Schott says the inhabitants of Sonoyta only "irrigate a small patch of ground." However, at this time Sonoyta may have referred to the Mexican town, rather than the Tohono O'odham community near the west end of present day Sonoyta. Downstream, Schott reported similar conditions:

> *Following the bed of the Sonoyta river, a narrow but smooth pass leads to another cienega ... but the water, except in two or three places does not come to the surface, and it is necessary to dig for it everywhere during the dry season. ... Upon some rising ground in the west end of the last-mentioned cienega there is a settlement, or, more properly, cattle rancho, the inhabitants of which are favored with spring water flowing out in abundance from a dozen little springs. ... This water resembles ... that of Sonoyta ...*

Since Schott then immediately goes on to mention "Quitobaquita" separately as he proceeds westward in his description, the "last-mentioned cienega" would almost certainly refer to Santo Domingo. He continues, clearly referring next to the Agua Dulce (Papalote) reach, and lastly Agua Salada, in order:

> *The water of the Rio Sonoyta appears above ground for the last time near Quitobaquita. On the southeast side of the Cerros de la Salada fresh palatable water can be got in its bed by digging to a depth of about three feet. Just below it, it becomes so salty that even famishing mules will not touch it.*

Edgar Mearns (1907) reported detailed biological observations at Sonoyta and Santo Domingo from 9-25 January 1894, and then at Quitobaquito from 25 January to 8 February before proceeding west by way of old Agua Dulce. He camped at Sonoyta, not long after a period of heavy rains which had recently washed out the marshy ciénega, and described a "pretty creek containing several species of fishes." (McMahon and Miller [1985] reported that pupfish and dace were in the Río Sonoyta at Sonoyta at least until 1950.) He reported that the river rose south of monument 164, which is near present-day Ejido Desierto de Sonora, 10 km (6.2 mi) ESE of present-day Sonoyta, and flowed about 40 km (24.8 mi). In 2001, we found a couple of small pools of water in the river bed near heavily agricultural Ejido Desierto de Sonora.

Mearns found that recent floods had largely wrecked irrigation agriculture at Sonoyta; fields that remained were a few that "received their water from springs at some distance [north] from the river" — evidence of multiple spring sources characteristic of ciénega conditions. Although old Sonoyta was small, the Tohono O'odham village at or just west of the site of present day Sonoyta was not:

> *Below the village of Sonoyta is a village of Papago Indians, who successfully irrigate large fields from the Sonoyta River. … A few miles further downstream is the Mexican town of Santo Domingo, distant about 14.5 km (9 miles) from Sonoyta.*

Ives (1936) describes a ciénega-like formation at the east edge of Sonoyta that lasted until flood scour caused an incision, reportedly (Lumholtz 1912 [1990]) on 6 August 1891:

> *Just east of the town is a meadow, which is being channeled at the present time. Until about 1890 this meadow was a swamp, but in that year, a barrier of calcareous mineral-spring deposit was washed out, draining the swamp and lowering the local watertable.*

Lumholtz was told that the ciénega had extended 4.8 km (3 mi) east from Sonoyta, and that "The swamps dried up in 3 years … . Where there had been before only a llano [a treeless plain, likely a wet meadow], a forest of mezquites sprang up." Lumholtz reported that abundant perennial surface water could always be found to Agua Dulce, which is at variance with Schott's and our information, and apparently reflects misinterpretations stemming from the large changes in flow of Río Sonoyta that track rainfall trends. Ives also notes (1936) that only on rare occasions is there any continuous surface flow between Sonoyta and Agua Dulce.

Interpretation

There is consistent evidence that the site of Sonoyta had multiple springs that would have produced an extensive marshy meadow with stream flow, and this would certainly have also included scour pools associated with the main paths of storm runoff (Figure 2B). Thus, references to a sizable ciénega are justified. Already by the time of the first written descriptions discussed here, the scene had long since been transformed by irrigation agriculture, and primeval habitat may have differed in extent from the original conditions inferred here. The evidence presented here indicates that Río Sonoyta existed in three distinct reaches that were perennial even during dry periods – Sonoyta, Santo Domingo, and Agua Dulce. These reaches occupied a minority portion (perhaps a fourth to a third) of a 25 – 35 km (15.5 – 21.7 mi) length of the Sonoyta Valley, rising first about 4 km (2.5 mi) above Sonoyta and ending due west or southwest of Quitobaquito. Original conditions probably involved alternative states of ciénega and scoured stream associated with each perennial reach, as suggested by Hendrickson and Minckley's (1985) model.

Prior to the flood damage and entrenchment of the river's arroyo beginning about 1890, the livestock and irrigation agriculture practiced in the valley probably altered the ecosystem in relatively benign ways. However, the extent of flowing stream and wet meadow must have been significantly reduced by diversion of springs and the river onto irrigated fields.

Now the large perennial springs and flowing streams at Sonoyta and Santo Domingo are essentially gone, but the location and probably the length of the Agua Dulce reach remains similar to conditions in 1855. We cannot infer whether the latter reach has already contracted due to upstream activities, but the location of its emergence is similar to Schott's description. Descriptions of the need to dig in the sand bed for water at the old site (La Salada) also suggests that conditions in this part of the river were much like those existing now, and the Agua Dulce perennial flow reach may not have been very much longer than it is now.

RESULTS

Status of the Sonoyta Mud Turtle

The Sonoyta mud turtle(for explanation of this use of the English name, see Rosen and Melendez [2010, this volume]), a locally endemic subspecies of the Sonoran mud turtle, remains common at Quitovac, Presa Xochimilco and the spring pools below it, the Sonoyta sewage lagoon, the Agua Dulce reach of Río Sonoyta, and Quitobaquito. It was rare and localized in the 4 km (2.5 mi) of river formerly supporting the main ciénega above the presa, but we trapped or hand-captured several individuals in each intermittent reach of pools there. In the Santo Domingo area, we found a single turtle at a soup-bowl-sized remnant of water at the semi-perennial spring at Ejido Josefa Ortiz, in October 2001. We did not find turtles upstream or downstream of these areas, but our surveys further upstream were not exhaustive, and turtles might exist there in river pools and artificial ponds.

Originally, the principal turtle population can be presumed to have been in the Ciénega de Sonoyta, and had already been greatly reduced during the period from the 1891 incision to 1970, when modern groundwater pumping began. Relatively wet conditions prevailed from about 1977 through 1995, and we found the remnant population at Xochimilco to consist mostly of turtles recruited in 1997 or earlier. In contrast, there was abundant evidence of consistent recruitment at Quitobaquito (Rosen and Lowe 1996) and at Agua Dulce. The turtle's persistence at the town of Sonoyta is largely dependant on sewage effluent from the army base, and at the Sonoyta sewage lagoon, which is about 150 m (164 yd) south of the river and 1.5 km (0.9 mi) downstream of the highway bridge. Thus, the entire Sonoyta population may become threatened by the imminent relocation and modernization of the town's wastewater system.

As described below, aquifer withdrawals west of Sonoyta may also threaten the turtle population at Agua Dulce. Mining interests in the springs at Quitovac (http://www.copper-ridge.com/s/Quitovac.asp) create a potentially immediate threat to that population, and the population at Quitobaquito (estimated at 90 – 150 by Rosen and Lowe 1996) is too small to provide a reliably viable long-term population to preserve the taxon. As a result of these threats, the USFWS recognizes the Sonoyta mud turtle as a candidate for threatened status, and AGFD is preparing a candidate conservation agreement.

Native and Non-native Fishes in Río Sonoyta

The Quitobaquito pupfish (*Cyprinodon eremus*) and longfin dace (*Agosia chrysogaster*) were confined to the Agua Dulce reach during our survey period. Non-native fishes were more widespread. Mosquitofish (*Gambusia affinis*) were found at all non-effluent perennial and semi-perennial waters we sampled, including at Quitovac, Colonia La Nariz, Santo Domingo, Ejido Josefa Ortiz, and southeast of Ejido Desierto de Sonora. An African cichlid population, probably *Tilapia zillii*, was found at Quitovac, and an individual was reported at Agua Dulce reach in 2003 but not seen subsequently. Black bullhead catfish (*Ameiurus melas*) were found at Agua Dulce, throughout the Xochimilco area, and in pools 4 km (2.5 mi) east of the presa; although we saw no evidence of them at Quitovac, the local people reported "bagre" (catfish) there. A single individual black bullhead was removed from Quitobaquito in 1995, and this species may occur elsewhere in the Sonoyta Valley. We did not observe fishes at the Sonoyta sewage lagoon during observations there in 2001-2.

Our results are similar to findings reported and summarized by Miller and Fuiman (1987) and Hendrickson and Varela (1989) with two important exceptions: (1) native fishes were found in Sonoyta in 1950 and in the reach between Sonoyta and Santo Domingo in 1987, and (2) our turtle sampling allowed us to detect non-native fishes, particularly catfish, at more localities.

The native fishes were numerically predominant at the Agua Dulce reach during 2001-6 (Figure 5), and both species were abundant until dry conditions produced die-offs of the longfin dace during foresummer droughts of 2002 (I. Barba, pers. comm.) and 2004 (our observations). During 2004 our trapping occurred in July at low water and over-represented dace, which were confined to pools where we could trap, and under-represented pupfish and mosquitofish, which were abundant in areas too shallow for our traps. In 2005 and 2006 we found the dace confined to the lower third of the reach and we estimated it at < 1% of the total fish population. Meanwhile, the pupfish population had continued to thrive and the mosquitofish population had increased markedly by 2006. A monitoring and exotic species removal program for fishes was instituted by the Pinacate Biosphere Reserve at

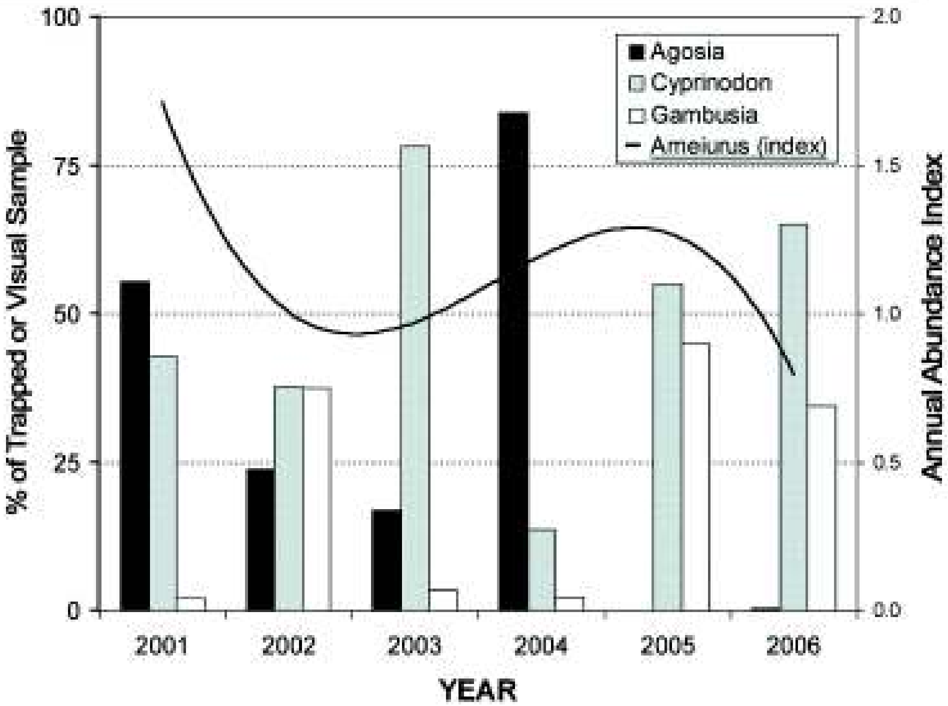

Figure 5. Relative abundance of fishes in the Agua Dulce reach of Río Sonoyta based on minnow trapping and direct counts during nighttime observations. Dace abundance is significantly over-represented in results for 2004 (see text). The catfish abundance index is an average of capture rates in hoop nets and minnow traps, standardize to unit mean.

Agua Dulce beginning in 2005 (E. Larios, pers. comm.).

Black bullheads are able to survive oxygen depletion by gulping air at the water surface, and thus they can remain in some of the most inhospitable waters, even in effluents at Presa Xochimilco. Mosquitofish may survive hypoxic water by respiring close to the water surface; in addition, they are widely distributed in the Sonoyta Valley upstream of Agua Dulce reach. We suspect they are planted for mosquito control and dispersed during floods, rapidly but temporarily occupying reaches at Ejido Josefa Ortiz and Santo Domingo during high flow in October 2003. Pupfish are highly tolerant of low oxygen, whereas longfin dace are hypoxia-sensitive like other Southwestern stream fishes (Lowe et al. 1967). Thus, the drought-associated decline of the longfin dace may be explained primarily by respiratory physiology, exacerbated by groundwater pumping; the longfin dace may also be threatened by the non-native fishes.

DISCUSSION

The Hydrologic Threat

Brown (1991) provides details showing that groundwater pumping for agriculture was virtually non-existent prior to the 1970s. It rapidly increased to a peak of 102.6 million m^3/yr (83,000 ac-ft/yr) in the 1980s, which he estimated to exceed natural recharge of the aquifer by 68 million m^3/yr (55,000 ac-ft/yr). At that time, approximately 8000 ha (20,000 ac) were being farmed, with 13,000 ha (32,000 ac) developed for irrigation. The total farmed in the most recent two decades is probably lower, judging from records through 1997 (C. Conner, pers. comm.) and the large number of unused wells, irrigation works, and fields seen during our surveys. Local farmers ascribed this to the high price of electricity for the pumps. Although a moratorium on new pumps and further irrigation developments went into effect in the 1980s, groundwater withdrawals vastly exceed recharge, and existing infrastructure has the capacity to more than double the maximal pumping of 1987 (Brown 1991).

Hendrickson and Varela (1989) reported native fishes and perennial water during 1-7 September 1987 near Sonoyta to a point 11 km (6.8 mi) below the highway bridge, where flow infiltrated into the streambed. Above the presa dam and town they found only non-native fishes. They reported only about 6 km (3.7 mi) of dry riverbed separating the Sonoyta reach from the Agua Dulce reach, which was apparently about 13 km (8.1 mi) long and supported native fishes. Although 1987 was a moderately dry year, local rains were good during August 1987 and the period 1977-1984 was the wettest in the instrumental record for the region reaching back to 1896.

In 1983-1987 we saw more water in Río Sonoyta than thereafter, with a large perennial pool at the highway bridge in Sonoyta becoming predominantly dry by 1989. During 2001-2006, we only found flow conditions equaling those reported for the early 1980s shortly after major cyclonic storm events in October 2003. During our study period, we never found evidence of perennial flow, or even clearly perennial pools, anyplace except below the bedrock outcrops near Presa Xochimilco and at the Agua Dulce reach. We suspect that normal drought conditions combined with aquifer depletion accounts for differences between our observations and the previous reports we have reviewed.

Our observations indicate that the springs (or ciénegas) at Sonoyta and Santo Domingo have almost completely disappeared and are not currently supporting native fish habitat. We found pools in the riverbed with catfish and turtles as far as 4.5 km (2.8 mi) east of Sonoyta, and with seepwillow (*Baccharis salicifolia*; indicating at least perched shallow groundwater) north of Ejido Desierto de Sonora in 2001. The river and its riparian forest are not fully degraded at Sonoyta despite the trend of rapid decline.

The Agua Dulce reach retains generally the character it had in our earliest available descriptions. However, we observed that almost all the formerly extensive irrigation agriculture developments below Santo Domingo were inactive during 2001-6. The Agua Dulce reach could face rapid, complete desiccation if large-scale agricultural pumping resumes in the lower Sonoyta Valley, especially from Santo Domingo to Agua Salada. Murguía (1998) provides an example of how sensitive this reach and its native fishes now are to human-caused desiccation. Whether the continuing aquifer overdraft closer to Sonoyta will impact streamflow in this reach cannot be determined at present.

Non-native Species Threats

The nature of exotic species threats to native fishes in Río Sonoyta is not entirely clear. Which species may have the greatest potential impacts, and which are likely to suffer from such impacts are not definitely known. At Agua Dulce, the four established species have persisted together since at least 1983 (Miller and Fuiman 1987; Rosen, pers. obs.), but they have not done so through protracted drought like the current one.

As detailed above, our observations indicate that the proportional decline of the longfin dace during 2001-6 was primarily caused by suffocation during foresummer droughts. However, in April 2006 mosquitofish reached their highest abundance during our observations, and were occupying the deeper currents (10-30 cm / 4-12 in) in the stream that previously comprised the spatial niche occupied by longfin dace. Abundant mosquitofish may depress dissolved oxygen levels sufficiently to increase hypoxia mortality in the dace. Further, mosquitofish, which are highly predatory and markedly piscivorous, might significantly impact recruitment in longfin dace and pupfish. Both introduced species — the mosquitofish and black bullhead — were most abundant in the deeper pools The catfish prey actively on mosquitofish (Rosen, pers. obs. 2001-2), and might possibly exercise control over mosquitofish density. The current program of attempting to eliminate catfish at Agua Dulce, which is designed to protect the pupfish from predation (K. Larios, pers. comm. 2006), could benefit the mosquitofish by removing its principal predator, and mosquitofish could then disproportionately impact the two native fishes. Thus, the fish community structure may be dynamic in unexpected ways, and we lack a firm scientific basis for deciding management strategies.

No nonnative species of fish are currently established in Quitobaquito. An individual black bullhead was removed from the pond (Rosen and Lowe 1996); golden shiner (*Notemigonus crysoleucas*) that were introduced in the 1960s were removed by draining the pond in 1969 (Minckley 1973; Bennett and Kunzmann 1989).

Individuals of several species of non-native turtles have been documented in Quitobaquito Springs. Smith and Hensley (1957) collected a mating pair of Arizona mud turtles in 1955, which may have been the last of a population or releases from east or north of Organ Pipe Cactus NM. A painted turtle, *Chrysemys picta dorsalis* was collected by Hulse (1974), a cooter (*Pseudemys* sp.) was reported by P. Bennett and M. Kunzmann (pers. comm. 1989), and a red-eared slider was removed by Rosen and Lowe (1996).

As with introduced fishes, the threat from non-native saltcedar is not entirely clear. Saltcedar uses water as liberally as other riparian forest and woodland trees, but grows more densely, and thus may have a negative impact on streamflow in the Agua Dulce reach. Obviously, it is also supplanting native riparian plant biodiversity, and thus likely reducing bird species diversity. Saltcedar thickets usually do not support large lizard populations (Jakle and Gatz 1985; Griffen et al. 1989), a finding consistent with what we have seen during our surveys. Nonetheless, attempts to eradicate it all at once could have dramatic impacts on threatened aquatic animals. Under present conditions, saltcedar is stabilizing the river channel at Agua Dulce. It provides bank structure utilized by the mud turtles for burrowing to retreat from predators and presumably to survive flood scour that would be severe without established woody, firmly rooted streamedge plants. Without saltcedar or some other plant with sufficient root structure, flood scour might also become severe enough to dramatically impact fish populations.

Grazing by introduced livestock may similarly have non-obvious effects. While grazing may be responsible for saltcedar recruitment dominance, this is presently moot because saltcedar is already thoroughly established. Removal of grazing from Agua Dulce would likely lead to further stabilization of the low-flow channel, producing more and deeper pools, and favoring the pool-dwelling non-native fishes (as well as the turtles) at the expense of the native fishes.

Conservation Measures

The most serious threats to the Río Sonoyta aquatic ecosystem come from water demands on the aquifer for agriculture and a growing town population. Virtually all other desert cities in the Sonoran and Mojave Desert region have desiccated the rivers upon whose banks they were situated. To prevent this pattern from repeating at Sonoyta, three general approaches may be considered. First, we suggest that future quality of life for human beings may be being sacrificed for present gains by poor planning or resource valuation, as may be suggested in the case of riparian and riverine damage that occurred at Tucson, Caborca, and other desert communities. Second, the direct economic value of the river resource may be increased by promoting ecotourism. Third, infrastructure improvements in the region might be promoted to enhance rather than degrade the river environment.

The riparian gallery forest adjoining Sonoyta on the east exists as a significant amenity and may be developed, along with other river reaches, for townspeople, travelers, and nature enthusiasts. Building on the rich bird diversity and pleasant shade, a park and birdwatching tour stop might be successfully established. The Agua Dulce reach in the Pinacate Reserve could also support nature tourism, although the sensitivity of the resource there currently suggests that less intensive use should be planned there. Three general steps can be recommended to facilitate this process:

1) Involve local community members and leaders in park development.

2) Conduct research with public participation in identifying bird and other nature resources for ecotourism development.

3) Establish an urban and agricultural wildlife program to preserve and enhance bird habitat quality within human-occupied landscapes.

Modernization of the sewage treatment and sanitation system of Sonoyta was under active consideration during our surveys. It is currently in progress, and some of the following recommendations may be implemented as a result of cooperation among several agencies and governmental entities from local to bi-national levels (Rosen 2009). Prospects for finding sufficient outside funds to support a high quality infrastructure upgrade may be significantly improved if the design will benefit habitat and rare and interesting animals as well as improve health and quality of life. Sewage effluents provide the only major aquatic and riparian environments near Nogales, Sonora, Tucson, Arizona, and parts of Phoenix, Arizona. These systems fail as biodiversity conservation for two principal reasons.

First, water quality is often very poor, with high nitrogen content which prevents fish from thriving. Lack of fish then contributes to human health concerns involving mosquito-borne pathogens. Improvements in technique and infrastructure design may readily resolve this problem in the future. For example, the relatively modern Pima County wastewater treatment facility in southern Avra Valley near Tucson, supports reproducing salamander and toad populations (Rosen, pers. obs. 2004).

Second, most wastewater treatment facilities and urban ecological “restoration” projects in the U.S. Southwest have emphasized the use of ponds and lakes. Deep, standing water ponds provide habitat suitable for establishment and population expansion of exotic aquatic species that can have negative impacts on native aquatic biodiversity. Such harmful species could include introduced crayfishes, American bullfrogs (*Rana catesbeiana*), and various fishes, including those already in Río Sonoyta and others, such as *Tilapia*, that are likely to be introduced (Rosen and Schwalbe 2002; Minckley and Deacon 1991). Native fishes are generally more flood resistant than non-natives (Meffe 1984; Minckley and Meffe 1987). These considerations suggest the following recommendations:

4) A modernized sewage treatment facility can be designed to produce high quality water suitable for native fishes, which can be introduced for mosquito control.

5) The infrastructure design can include creation of habitat preferentially suitable for native fishes by releasing suitably treated wastewater into the river channel, where it may also create riparian development with other benefits for people and wildlife.

6) This design may be presented to funding agencies likely to assist with capital and operations.

Control of non-native species is a less costly and socially complicated, yet still essential, issue for conservation in the Sonoyta Valley. A number of issues remain, requiring a combination of action and research:

7) Administrative and educational efforts should be directed toward preventing the spread of non-native cichlid fishes or other new aquatic species in the Sonoyta Valley.

8) Quitobaquito pupfish and longfin dace, rather than or in addition to mosquitofish,

could be used as vector control or established in other parts of the Sonoyta Valley where suitable waters exist or may be created. (Pupfish are likely to be superior, if not merely complementary additions to mosquitofish as agents of mosquito control [reviewed by Schoenherr 1988].) A refugium for the longfin dace seems most immediately pressing at the present time.

9) Research is needed to understand the interactions of the four existing fishes in Río Sonoyta prior to large-scale efforts to partially remove the non-native species.

10) Saltcedar control and eradication measures may be combined with novel, simultaneous revegetation programs to avoid inadvertently destroying some of the few remaining populations of threatened aquatic vertebrates.

Finally, the community's interest in protecting the aquifer and river are likely to be the crucial determinants of the success of biodiversity conservation in the Sonoyta Valley.

SUMMARY

Río Sonoyta, which adjoins Organ Pipe Cactus National Monument and the town of Sonoyta, Sonora, is a rare lowland desert stream that has not been completely degraded. Little perennial surface water remains at Sonoyta, although the river and aquifers near the town still support a woodland with many riparian birds, along with populations of the endemic Sonoyta mud turtle (a candidate for listing under the Endangered Species Act). Degradation has been less severe downstream, within the perennial Agua Dulce (or "Papalote") reach in the Pinacate Biosphere Reserve. This reach supports a bird-rich, saltcedar-dominated woodland, the mud turtle and two native fishes (longfin dace and the endangered Quitobaquito pupfish). Several species of bats are dependent on the river and oasis springs for their regional existence, and the endangered Sonoran pronghorn utilizes the downstream river corridor. Springs at Quitovac, Sonora, and Quitobaquito, Arizona, also support the mud turtle and, at Quitobaquito the pupfish, as well as riparian biotas. Much of the Sonoyta River valley faces threats, especially groundwater withdrawals that could lead to losses of species and riparian values. Additional threats are exotic saltcedar and introduced cichlid fish. There is interest from Mexican and U.S. agencies and NGOs in initiating conservation efforts in the region. Opportunities for conservation include ecotourism, urban park development, modernized sewage treatment with effluent available for use in river restoration, and landscape-level conservation planning.

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OVERVIEW OF THE LOWER COLORADO RIVER MULTI-SPECIES CONSERVATION PROGRAM

William E. Werner

Development of the lower Colorado River, including the construction of four large dams and five smaller weirs that provide water storage, pumping forebays, and diversion facilities (Table 1), has resulted in physical changes that, in combination with the introduction of non-native species, have affected the status of native fish and wildlife species. Species now listed under the Endangered Species Act (ESA) include the Yuma clapper rail (*Rallus longirostris yumanensis*), Southwest willow flycatcher (*Empidonax traillii extimus*), desert tortoise (*Gopherus agassizii*), bonytail (*Gila elegans*), Colorado pikeminnow (*Ptychocheilus lucius*), humpback chub (*Gila cypha*), and razorback sucker (*Xyrauchen texanus*). Agencies responsible for water and power-related operation, maintenance, and distribution, developed, in collaboration with other entities, the Lower Colorado River Multi-Species Conservation Program (LCR MSCP) to address and offset effects of ongoing and anticipated river operations on the listed species presently found in the area.

The origin of the LCR MSCP lies in the listing of the four "Big River" fish (Table 2) by the U.S. Fish and Wildlife Service (Service). In general terms, the listing rationale for the bonytail and razorback sucker were habitat fragmentation, alteration of the pre-development hydrograph, and introduction of and interaction with non-native aquatic species.

Following listing of the razorback sucker and designation of critical habitat for all four Big River fish in 1994, the Service advised the Bureau of Reclamation (Reclamation) that they should consult under Section 7(a)(2) of the ESA on their operation and maintenance of the Lower Colorado River (LCR) system.

The role of the Secretary of the Interior, acting through Reclamation, as watermaster on the LCR is defined in the decree of the U.S. Supreme Court in *Arizona v. California* (1964). Also, Reclamation has had much of the responsibility in the development of the river, and title to many of the river facilities remains with the federal government even though some of those facilities are operated and maintained by non-federal water users. An example is Imperial Dam, which is owned by the federal government but operated by the Imperial Irrigation District to divert water to that district in California as well as the Wellton-Mohawk Irrigation and Drainage District and Yuma area districts in Arizona. Because of these multiple roles, many actions have both federal and non-federal components. As Reclamation began to address the issue of consultation on operation and maintenance activities they chose to include their stakeholders in the process. Further, stakeholders were concerned that their interests would not be given sufficient consideration in a traditional ESA consultation process between Reclamation and the Service.

DEVELOPMENT OF THE LCR MSCP

The LCR MSCP planning area comprises areas up to and including full-pool elevations

Table 1. Lower Colorado River dams.

Name	Year Completed	Type
Laguna Dam	1924	Diversion
Hoover Dam	1936	Storage
Parker Dam	1938	Storage
Imperial Dam	1938	Diversion
Morelos Dam	1950	Diversion
Davis Dam	1950	Storage
Headgate Rock Dam	1950	Diversion
Palo Verde Weir	1957	Diversion
Glen Canyon Dam	1963	Storage

of Lakes Mead, Mohave, and Havasu and the historical floodplain of the Colorado River from Lake Mead to the international boundary with Mexico at San Luis, Arizona. Participants included agencies, water providers, power distributors, water and power contractors, and environmental organizations.

Federal participants were the Department of the Interior (including Bureau of Reclamation, Bureau of Land Management, Bureau of Indian Affairs, Fish and Wildlife Service, and National Park Service) and the Department of Energy's Western Area Power Administration.

Arizona participants included Arizona Electric Power Cooperative, Inc., Arizona Power Authority, City of Bullhead City, Central Arizona Water Conservation District, Cibola Valley Irrigation and Drainage District, Electrical District No. 3 – Pinal County, Town of Fredonia, Golden Shores Water Conservation District, City of Lake Havasu City, City of Mesa, Mohave County Water Authority, Mohave Valley Irrigation and Drainage District, Mohave Water Conservation District, North Gila Valley Irrigation and Drainage District, Salt River Project Agricultural Improvement and Power District, City of Somerton, Town of Thatcher, Unit "B" Irrigation and Drainage District, Wellton-Mohawk Irrigation and Drainage District, Town of Wickenburg, City of Yuma, Yuma County Water Users' Association, Yuma Irrigation District, Yuma Mesa Irrigation and Drainage District, Arizona Game and Fish Commission and Department, and Arizona Department of Water Resources.

California participants included Bard Water District, City of Needles, Coachella Valley Water District, Colorado River Board of California, Imperial Irrigation District, Los Angeles Department of Water and Power, Palo Verde Irrigation District, San Diego County Water Authority, Southern California Edison Company, Southern California Public Power Authority, and The Metropolitan Water District of Southern California.

Table 2. "Big river" fish of the Colorado River.

Species	Status under ESA, Year	Critical Habitat Designated
Colorado pikeminnow (*Ptychocheilus lucius*)	Endangered, 1967	1994
Humpback chub (*Gila cypha*)	Endangered, 1967	1994
Bonytail (*Gila elegans*)	Endangered, 1980	1994
Razorback sucker (*Xyrauchen texanus*)	Endangered, 1991	1994

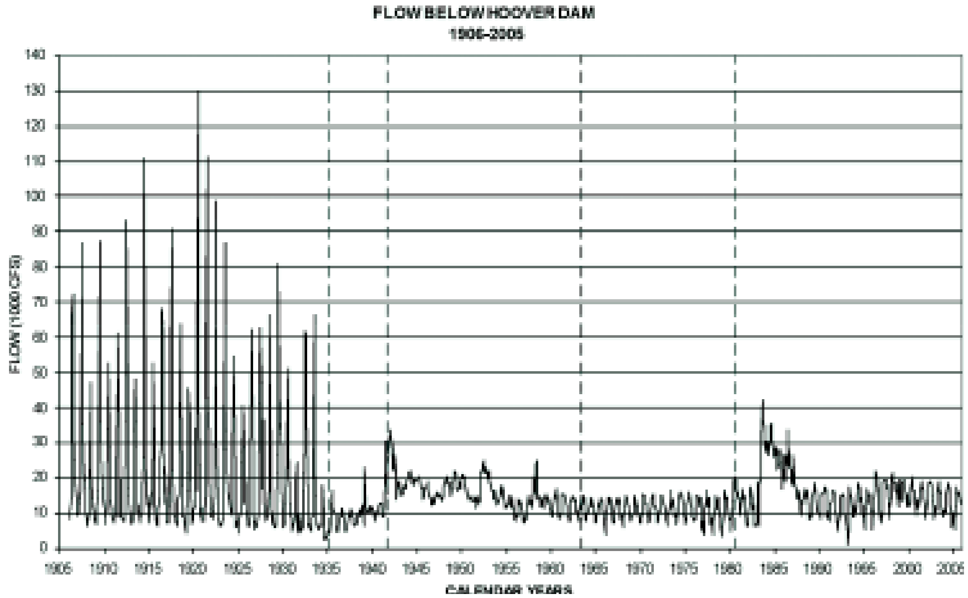

Figure 1. Colorado River flows below Hoover Dam (Courtesy U.S. Bureau of Reclamation)

Nevada participants included the Colorado River Commission of Nevada, Southern Nevada Water Authority, Nevada Department of Wildlife, and Basic Water Company.

Participation by environmental organizations varied through time with National Wildlife Federation participating at the time of completion.

Analysis of Effects

Construction of dams on the Colorado River has resulted in alteration of the hydrograph. Prior to the construction of Hoover Dam the river experienced large spring floods on a nearly annual basis. The baseline condition at the initiation of planning for the LCR MSCP was an altered riverine system and decoupled floodplain. The hydrograph of the river is altered by floodwaters being stored. Large intra-annual variability was dampened by the construction of Hoover Dam (Figure 1). The sediment regime has been altered in that sediment drops in calm waters of reservoirs and the water released from dams is clear. Clear water picks up new sediment and channel incision occurs. Consequently, a much greater discharge is needed to overtop the river channel and floodplain flooding no longer occurs. These changes are significant to the native biota in that the processes that naturally maintained riparian forest are altered, newly hatched and young fish don't have access to extra cover in flooded bottomlands, in clear water young fish are more susceptible to predation by sight-feeding predators, and system "reset" no longer occurs.

As Anglo settlement occurred in the Colorado River basin in the late 1800s and the early 1900s, fish and other aquatic organisms from the Mississippi Basin were introduced into the Colorado River system. The aquatic fauna of the Colorado River was distinct with relatively few species prior to settlement. Fish and other organisms were introduced from elsewhere as a food source and for sport fishing. Many of these introduced species quickly occupied newly changed habitats as river development occurred. Construction of dams limited movement of fish, such as Colorado pikeminnow, that once apparently moved great distances. The water of reservoirs became clear to the greater advantage to sight-feeding predators than species that evolved in the more turbid water of the Colorado.

The species addressed by the LCR MSCP are largely associated with riparian woodland habitat, marsh, and backwaters as those habitats have been most affected by river development. Species listed under the ESA include Yuma clapper rail (*Rallus longirostris yumanensis*), Southwest willow flycatcher (*Empidonax traillii extimus*), desert tortoise (*Gopherus agassizii*), bonytail (*Gila elegans*), humpback chub (*G. cypha*), and razorback sucker (*Xyrauchen texanus*). Other covered species include western red bat (*Lasiurus blossevillii*), western yellow bat (*L. xanthinus*), Colorado River cotton rat (*Sigmodon arizonae plenus*), Yuma hispid cotton rat (*S. hispidus eremicus*), western least bittern (*Ixobrychus exilis hesperis*), California black rail (*Laterallus jamaicensis coturniculus*), yellow-billed cuckoo (*Coccyzus americanus occidentalis*), elf owl (*Micrathene whitneyi*), gilded flicker (*Colaptes chrysoides*), Gila woodpecker (*Melanerpes uropygialis*), vermilion flycatcher (*Pyrocephalus rubinus*), Arizona Bell's virio (*Vireo bellii arizonae*), Sonoran yellow warbler (*Dendroica petechia sonorana*), summer tanager (*Piranga rubra*), flat-tailed horned lizard (*Phrynosoma mcalli*), relict leopard frog (*Rana onca*), flannelmouth sucker (*Catostomus latipinnis*), MacNeill's sootywing skipper (*Pholisora gracielae*), sticky buckwheat (*Eriogonum viscidulum*), and threecorner milkvetch (*Astragalus geyeri* var. *triquetrus*). Additional species are included for which sufficient information was not available for permit processing but will receive research effort and may be added as covered species if warranted, including California leaf nosed bat (*Macrotus californicus*), pale Townsend's big eared bat (*Corynorhinus townsendii pal-lescens*), lowland leopard frog (*Rana yavapaiensis*), and desert pocket mouse (*Chaetodipus penicillatus sobrinus*).

Four categories of covered activities are addressed by the LCR MSCP including ongoing flow-related activities, future flow-related activities, ongoing non-flow-related activities, and future non-flow-related activities. Included are operation and maintenance activities related to responsibilities of Reclamation for: flood control, improvement of navigation, and river regulation; storage and delivery of Colorado River water for agricultural, municipal, industrial, and other beneficial purposes; and for generation of electrical power, all as described in the LCR MSCP Biological Assessment (LCR MSCP 2004c). The LCR MSCP Habitat Conservation Plan describes non-federal activities (LCR MSCP 2004b). Ongoing non-federal flow-related activities include water diversions and returns of up to 9.251 billion cubic meters per year (gcmy) (7.5 million acre feet per year (mafy)) from existing facilities and diversions and returns of any surplus waters for water contractors in Arizona, California, and Nevada. Future flow-related activities include power production and changes in points of diversion up to 1.941 gcmy (1.574 mafy) by water contractors in Arizona, California, and Nevada of Colorado River water and consequent reduction in releases from Hoover, Davis, and Parker Dams. Changes in point of diversion are anticipated in response to changes in water demand within the states. Ongoing non-flow-related activities include operation, maintenance, and replacement of existing water diversion and distribution works and electrical generation and distribution facilities within the planning area and certain activities conducted by Arizona Game and Fish Department and Nevada Department of Wildlife along the river.

Hydrologic modeling and subsequent analysis were completed for flow-related covered activities to describe changes to hydrologic conditions and associated changes to river surface elevations, reservoir elevations, and groundwater levels (LCR MSCP 2004b,c). The analysis addressed impacts to groundwater, marsh, and backwater habitats from the lower river surface elevations caused by changes in point of diversion. Changes to groundwater may affect surface vegetation and surface elevations of backwaters not directly

Table 3. Habitat creation.

Land Cover Type	Area Affected by Covered Activities	Area to be Created as Offset to Effects
Cottonwood-Willow	866 ha	2404 ha
Mesquite	239 ha	534 ha
Marsh	104 ha	207 ha
Backwater	161 ha	146 ha*
TOTALS	1,370 ha	3,291 ha

* Habitat created to be higher quality than that impacted.

connected to the river. Changes in daily low river surface elevations may affect connected backwaters, marsh, and riverine habitats. Changes to Lake Mead elevations may affect aquatic habitats, such as spawning areas, and terrestrial vegetation within the pool. Reductions in flows past Morelos Dam, at the lower end of the system, may affect terrestrial habitat in the Limitrophe Division. Non-flow-related activities were typically analyzed as "footprint" impacts, i.e., quantification of the area under the action.

Conservation Plan

The basic conservation strategy for the LCR MSCP includes 3 core elements, a habitat-based approach for most species (Table 3), population augmentation for listed fish (Table 4), and a program to maintain habitat baseline values. During development of the proposed conservation strategy we used native habitat on the lower Bill Williams River as a conceptual model of pattern, juxtaposition, and interspersion for an integrated mosaic of habitat to be created through the LCR MSCP. On the Bill Williams River we see yellow-billed cuckoo in the cottonwood overstory, Southwest willow flycatcher in the mid-story and understory levels, Yuma clapper rail in the *Typha* marsh, and razorback sucker in interspersed open water. In the process of offsetting effects of covered activities it is not necessary to create separate acreage to mitigate effects to each species, provided that created acreage provides the habitat needs of target species. Also, by providing habitat for species that use early seral stages (e.g. sapling willow trees) such as the Southwest willow flycatcher, and late seral stages (e.g. mature cottonwood canopy forest) such as the yellow-billed cuckoo, we have addressed or have largely addressed the needs of many other species as well. Addition of missing components to basic early or late seral cottonwood/willow communities can ensure that the needs of additional species are met.

Table 4. "Big river" fish of the Colorado River.

Species	Activity
Razorback Sucker	Raise and release 660,000 fish over 50-year period
Bonytail	Raise and release 620,000 fish over 50-year period
Humpback Chub	$10,000/year to GCDAMP* for 50 years
Flannelmouth Sucker	$80,000/5 years + 85 acres (34 ha) of backwaters

* Glen Canyon Dam Adaptive Management Program.

Major conservation themes for listed fish include maintenance of existing genetic diversity, noting that Lakes Mohave and Havasu currently serve as genetic refuges. To maintain genetic diversity the Program will raise native fish to a size less vulnerable to predation prior to release. This will be accomplished through capture of wild larvae and through hatchery production of fish from broodstock (with careful genetic monitoring and management). Habitat creation and management for fish includes providing predator-free environments (refuges) for native fish. These areas will either serve as destinations for released fish or may be periodically connected back to the mainstream to allow adult fish to utilize natural habitat in the mainstream Colorado.

The LCR MSCP is continuing efforts of an *ad hoc* Lake Mohave Native Fish Workgroup to capture wild-hatched larvae of razorback sucker in Lake Mohave, and is now implementing similar efforts in Lake Mead. These larvae are raised in aquaria and then grow out ponds until large enough for release. This is possible because newly hatched larvae are attracted to light so biologists are able to capture the larvae with a dip net after hanging a light over the side of a boat at night.

Humpback chub are found in the Colorado River in Grand Canyon with potential overlap with the LCR MSCP planning area at the upper limits of Lake Mead. Conservation for this chub is to support efforts of the adjacent Glen Canyon Dam Adaptive Management Program. The flannelmouth sucker is found as an introduced population below Davis Dam that is naturally reproducing. The emphasis for this species is to better understand how it is successfully using habitat in that area, and to ensure that the amount of existing habitat remains, as that understanding may improve conservation measures for other species.

To maintain habitat baseline values, those existing at the time of plan development, a $25,000,000 Habitat Maintenance Fund was established. This fund, established up-front in the process in interest-bearing accounts, can be used to fund actions to maintain existing habitat values within the planning area. The rationale is that absent the processes that maintain habitat value through time, such as spring flood flows, existing habitat will degrade or change through natural aging and successional processes and will be of lesser value to covered species in the future, unless maintained. This fund is available to land managers with the consent of Reclamation, the Service, and State participants.

Because of uncertainty about the status and habitat requirements of some species, and regarding effective approaches for creation of functional habitat, research and adaptive management are important elements of the LCR MSCP. The program includes funding for research, with emphasis early in the program, to gain knowledge to design conservation measures to address species for which sufficient knowledge was lacking, to refine knowledge of specific habitat requirements or thresholds in variables, and to develop techniques for cost and water efficient creation and maintenance of habitat.

The LCR MSCP includes extensive monitoring of covered species, both at newly created habitat areas and throughout the lower Colorado River corridor, to document status, trends, and use of habitat.

During development of the conservation plan proposal a conservation opportunity area (COA) analysis was conducted. The purpose of this effort was to determine feasibility of implementation of conservation measures for covered species in the planning area. This analysis included a review of the geomorphic setting, a review of LCR hydrology, a survey of existing features such as relic sloughs and backwaters, an investigation of opportunities to establish an integrated mosaic of aquatic, marsh, and riparian habitats, and an assessment of availability of lands and water that could be used for conservation purposes. Generalized conclusions from the COA analysis are:

- The morphology of the lower basin is a constraint as it is a series of canyons and valleys with the canyons not providing sufficient space for large stands of trees,

- Because of physical changes to the river the acreage achieved through modification of flows is not great,
- Entrenchment and lack of sediment supply are system changing conditions,
- Soil salinity is increasing throughout the Lower Basin as "flushing" of salts has been reduced with changes to the hydrograph, and
- Large patch size is important for some species and to develop large acreages in blocks, conversion of some agricultural lands will be necessary.

The overall goal of the LCR MSCP is implementation of a program that will:

- Conserve habitat and work toward recovery of threatened and endangered species, as well as reduce the likelihood of additional species being listed;
- Accommodate present water diversions and power production and optimize opportunities for future water and power development, to the extent consistent with the law, and
- Provide the basis for incidental take authorizations.

IMPLEMENTATION

Implementation of the LCR MSCP is specified in a Funding and Management Agreement (FMA) among the parties (LCR MSCP, 2005a) and is carried out by Reclamation with oversight from a Steering Committee that includes permittees and other stakeholders, including a Federal Participant Group, an Arizona Participant Group, a California Participant Group, a Nevada Participant Group, a Native American Participant Group, a Conservation Participant Group, and an Other Interested Parties participant Group. The Steering Committee operates by consensus, with a dispute resolution process. Through the FMA funding is 50% from the federal government and 50% from the states of Arizona, California, and Nevada. The state share is split 50% California, 25% Arizona, and 25% Nevada.

As described in the FMA, the Program Manager (a Reclamation employee) shall annually develop and present to the Steering Committee an Implementation Report, Work Plan, and Budget. Those documents shall include: a current financial report; a description of all conservation measures initiated, continued or completed during the previous year; a description, purpose, and cost of all conservation measures to be initiated during the next three years; a running tabulation and description of all conservation measures completed to date; a description of any take of covered species during the previous budget period; a running tabulation of habitat created or restored by the MSCP; a description of all findings, conclusions, and results of monitoring, research, or conservation measures undertaken; any recommendations by the Service or state wildlife agency regarding the LCR MSCP; and approval or rejection of any minor modification. The annual workplan process is the means by which conservation measures are modified through adaptive management based on knowledge gained through research. A Science Strategy, which will be revised on a five-year cycle, complements the process to ensure that priority research needs are met to support adaptive management. Once reviewed by the Steering Committee, annual work plans are forwarded to the Service for their review prior to implementation. In addition to the Annual Implementation Report, Work Plan, Budget, and Contribution Payment Schedule, other matters that must be presented to the Steering Committee for its consideration include: additional or modified conservation measures proposed pursuant to adaptive management; land and water acquisitions; reports and responses to Congress and Federal and State regulatory agencies; and financial reports and accountings.

Two large blocks of agricultural land were available to the LCR MSCP at initiation of implementation, the Palo Verde Ecological Reserve (PVER) in the Palo Verde Valley in California and the Cibola Valley Conservation

Area (CVCA) in Arizona. Through agreement with Reclamation, the PVER was made available to the LCR MSCP without cost to offset costs to implement requirements of the California Endangered Species Act (CESA) Section 2081 permit. Non-California parties were concerned that CESA requirements would increase overall program costs and were not interested in sharing those additional costs. The CVCA is agricultural land in the Cibola Valley Irrigation and Drainage District purchased by Mohave County Water Authority for the associated water, part of which they intend to transfer upstream in the future. Access to these two large blocks of agricultural land has enabled Reclamation to move forward with pilot scale efforts to establish native vegetation as habitat. Initial efforts, planting gallon-size rooted cuttings by hand in augured holes, have evolved to mechanized mass planting of greenhouse-raised cuttings utilizing a planter designed for cauliflower. As adaptive management is a fundamental tenet of the LCR MSCP knowledge gained from research and pilot projects, such as the mass-planting project, will be fed back into the program with a goal of efficient and effective implementation. Examples of the more than twenty-five research projects in the first five years of the program include: a study to determine salinity, temperature and oxygen limits for bonytail and razorback sucker to facilitate design and management of off-channel habitats; a study of effectiveness of quagga mussel protocols for removing mussels from transport water during movement of native fish by truck; a study of nest predation on avian-covered species that may improve the design of habitat patches; a study of western red bat and western yellow bat roosting characteristics; and a study of hydrologic conditions such as soil moisture, depth to ground water, and amount of standing water underneath occupied habitat for the willow flycatcher and yellow-billed cuckoos in order to duplicate such conditions at habitat creation sites.

ENVIRONMENTAL COMPLIANCE

Environmental compliance documents for the LCR MSCP include the Final Programmatic Environmental Impact Statement/Environmental Impact Report (LCR MSCP, 2004a) that analyses, as required by the National Environmental Policy Act (NEPA) and California Environmental Quality Act (CEQA), effects of issuance of the ESA Section 10(a)(1)(B) permit by the Fish and Wildlife Service, implementation of conservation actions by the Bureau of Reclamation, implementation of the conservation plan and funding by California entities, and issuance of a CESA Section 2081 permit by California Department of Fish and Game. The Environmental Impact Statement does not provide NEPA compliance for ongoing operations and maintenance or future actions other than conservation measures. The Final Habitat Conservation Plan (LCR MSCP, 2004b) was submitted by the non-federal participants to the Fish and Wildlife Service with an application for the Section 10(a)(1)(B) permit. A Final Biological Assessment (LCR MSCP, 2004c) was submitted by Reclamation to the Fish and Wildlife Service during formal consultation under ESA on ongoing operation and maintenance activities and implementation of the conservation measures. Because of the size of the documents that shared much information, a volume of appendices (LCR MSCP, 2004d) and a separate volume that includes responses to comments on the entire package (LCR MSCP, 2004e) were produced. An Implementation Agreement (LCR MSCP 2005b) associated with the Section 10(a)(1)(B) permit defines terms between permittees and the Fish and Wildlife Service. The Funding and Management Agreement (LCR MSCP 2005a) defines funding, management, and terms between the permittees and Reclamation.

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TERMITE ACTIVITY ON GREEN TISSUES OF SAGUARO (*CARNEGIEA GIGANTEA*) IN THE SONORAN DESERT

Alejandro E. Castellanos, Reyna A. Castillo, Adrian Quijada

The giant saguaro (*Carnegiea gigantea*), an icon of the Sonoran Desert due to its uniqueness in the landscape, has had a role as a delimiter of the Desert's boundaries and plant communities (Shreve and Wiggins 1964). The saguaro is a long-lived perennial cactus in which many different biotic interactions have been characterized, such as its dependence on nurse plants during establishment, bird nesting and insect presence in its trunk, and bat pollination of flowers and bird dispersion of seeds (Steenbergh and Lowe 1969, 1977; Turner et al. 1969; Turner et al. 1966). Even diseased, necrotic and dead saguaro stems create habitats for insects. Given its importance in saguaro performance, biotic interactions may be the explanation for saguaro population decline and recovery at different times and places (Alcorn and May 1962; Steenbergh and Lowe 1969, 1977; Turner 1990).

Declines in saguaro forests have been noticed in different parts of the Sonoran Desert and at least one study has proposed a correlation between increased saguaro mortality and epidermal browning (Turner and Funicelli 2000). Although its causes have not been clearly identified, epidermal browning refers to a series of symptoms in saguaros, the most conspicuous being changes in color of aboveground tissues over time from green to yellow and brown (Duriscoe and Graban 1992; Evans et al. 1995; Turner and Funicelli 2000), decreasing UV-B protection, photosynthesis and gas exchange (Evans et al. 1994b; Lajtha et al. 1997). As the saguaro is a dominant and keystone species of the Sonoran Desert, changes in its population dynamics will likely have an effect on the functioning of this desert ecosystem.

Termites are important components in desert ecosystem function. Their role in cellulose decomposition and nutrient recycling has been well studied in North American deserts (Schaefer and Whitford 1981; Whitford 2002). In most cases, it has been shown that desert termites are restricted to underground nesting and feeding on woody and dead plant materials. Most of the forty species in the Sonoran Desert are specialists to particular plant species (Smith 2000), and those limited to saguaro, were found only on its lignified base (Olson 2000).

In the past, termite activity on live tissues has been reported anecdotally, and mostly in urban settings (Jones and Nutting 1989). There are no reports or studies of termite activity on living tissues of saguaro and most other desert plants. Population density and/or control procedures of *Heterotermes aureus*, *Gnathamitermes tubiformans* (subterranean termites), and other termite species have been reported in live tissue of several grass and desert plants, but without any quantification of damage (Allen et al. 1980; Bodine and Ueckert 1975; Spears et al. 1975; Ueckert et al. 1976).

In this paper, we report for the first time the presence of termites on aboveground living green tissues of saguaro. We studied termite presence on a number of sites and over several years in order to increase our understanding about the role and causes of this previously undocumented phenomena as well as its contribution to the ecology of saguaro populations throughout the Sonoran Desert.

METHODS

Saguaro populations were sampled from Mesquite–Palo Verde plant communities within the Central Gulf Coast subdivision of the Sonoran Desert (Brown 1982; Shreve and Wiggins 1964) in Sonora, Mexico. The sites were located at 29°22'15" lat N and 112°00'29" long W (Figure 1). The associated natural vegetation showed little evidence of disturbance, and consisted of a mixture of trees (*Prosopis glandulosa*, *Cercidium microphyllum*, *Bursera microphylla, Olneya tesota, Pachycereus pringlei*) and shrubs (*Fouquieria splendens*, *Lophocereus schotti, Stenocereus thurberi, Larrea tridentata, Ambrosia dumosa*, *Encelia farinosa* (species name follows Shreve and Wiggins 1964). The nearest climatological records available were obtained from Puerto Libertad, Sonora, a coastal town, approximately 60 km from the farthest site. Puerto Libertad has a mean annual temperature of 19° C and average annual precipitation of 83.8 mm (14-year average). Winter rainfall is an important and significant percentage (40.9 %) of total annual rainfall.

Fieldwork was performed in December 1989, March 1990, January 2001, and May and August 2003. Saguaro populations were sampled using point-centered quarter transects of 700-1500 m length. Sampled points were taken every 50 m, and at each point, the four nearest saguaros were measured for height, diameter, vigor, presence or absence of termite activity (nesting tubes) along their ribs, number of ribs with such activity, and height of termite tubes on saguaro living tissues. We reported saguaro vigor based on tissue color; green tissue was considered healthy, yellow was intermediate, and brownish color unhealthy. For most analyses, saguaros were grouped in three size classes: saplings (up to 1 m), juveniles (1 to 2.5 m) and adults (above 2.5 m). In January 2001, as it was evident that termites were notoriously present on aboveground tissues of a diverse number of desert species, we sampled saguaros and other plant species in the same community for termite activity on living tissues.

At each date, we sampled aboveground nesting tubes for species identification. Although a number of other insect and arthropod species were found along the exfoliating bark tissues at the base of saguaros, we sampled only those found inhabiting the aerial nest remains on saguaro green tissues. Specimens identified as *Heterotermes aureus* (Paul Baker, pers. com.) were collected in August 2003 from aerial nesting tubes on affected green epidermal tissues of saguaro.

We used χ^2 statistical tests to identify the relationship between termite presence and vigor (or browning) in the sampled saguaro populations. Here we report only those analyses performed on data from 1989, 1990 and 2001. We used statistical software to perform our analyses (SPSS, SAS Institute) with a significance level of $p <= 0.05$ (Sokal and Rohlf 1995).

RESULTS

Presence of Termites on Aboveground Green Tissues of Saguaro

Our analysis at the study site focused on saguaros because at our first sampling dates (1989 and 1990) this was the species that conspicuously showed a presence of termites on aboveground living tissues (Figure 2). Presence of termite nesting — tubes were found most frequently in adult and juvenile saguaros and less in saplings, although the height of affected individuals went from a few centimeters to 8 to 10 m (Figure 3). Presence of termites on juvenile saguaros was most frequent in 1989, but not in 1990 when frequency was higher on mature individuals. A comparison between year and age group (Figure 2) resulted in highly significant statistical differences for presence of termites on adult saguaros in each year (1989, $\chi^2 = 15.29$; 1990, $\chi^2 = 27.55$; 2001, $\chi^2 = 25.12$; all significantly different $\chi^2 <= 0.001$).

Termite nesting tubes started at the bottom of saguaros and went, in most cases, up to the

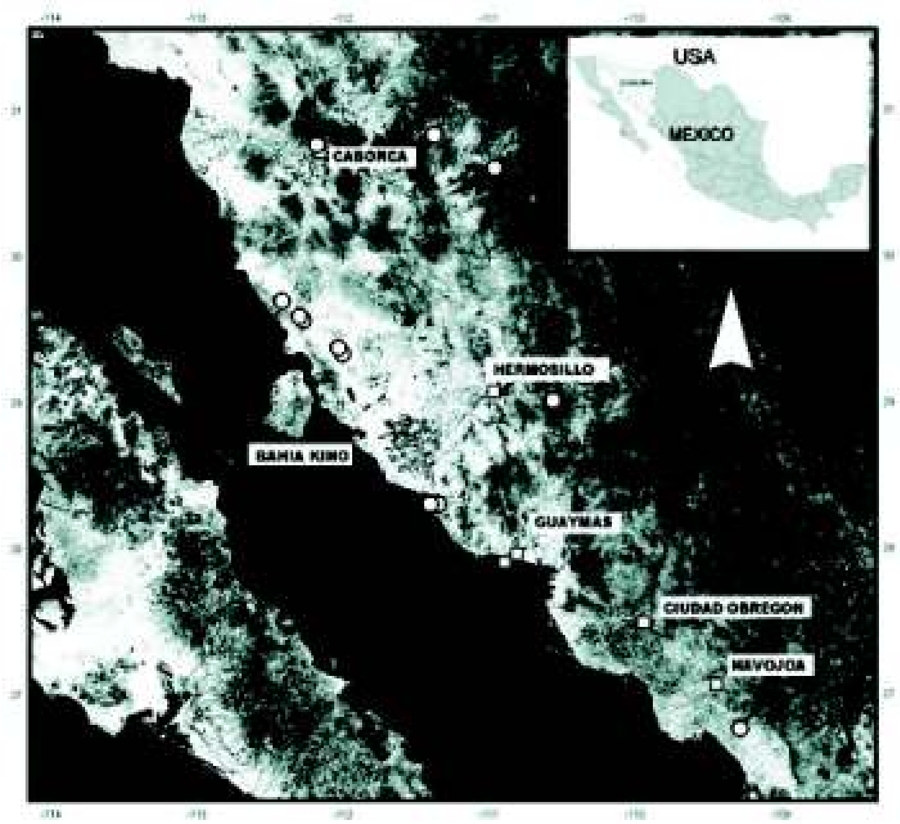

Figure 1. Location of sampled saguaro sites in Sonora (dots). Other locations in Baja California (near La Paz), Mexico and Arizona (east of Casas Grandes), USA, are not shown.

green epidermal tissues. Most adult individuals with termite presence had either some sort of epidermal damage or different degrees of epidermal browning from previous years. In saguaros, height of termite tubes was statistically and significantly correlated with height of browning surface area ($\chi = 0.8041$, $p <= 0.0001$; Table 1), although not all saguaros with browning in their tissues had termite nesting tubes on them, and some healthy saguaros had termites present only in their green living tissues. Healthy saguaros, apparently colonized for the first time by termites, had the shortest height of termite tubes along their ribs. Height of termite tubes was also positively correlated with number of affected ribs ($\chi = 0.7957$, $p <= 0.0001$), and height of saguaro ($\chi = 0.6668$, $p <= 0.0001$).

We did not notice a strong directional component on saguaro termite nesting tubes, although a formal geostatistical analysis was not performed. At our sites about 51% of all sampled individuals were affected by termite activity in 75% or more of their ribs, and a smaller percentage of saguaros had every one of their ribs affected to different degrees (data not shown).

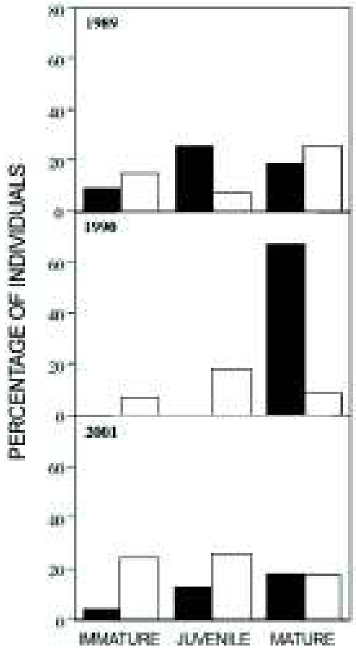

Figure 2. Percentage of saguaros with (black columns) and without (white) termite nesting tubes on aboveground green tissues. Data grouped for three age categories (see text) were significantly different $\chi^2 < 0.001$ in all years (1989, $\chi^2 = 15.29$; 1990, $\chi^2 = 27.55$; 2001, $\chi^2 = 25.12$).

Presence of Termites on Aboveground Tissues of Sonoran Desert Plant Species

We found widespread termite presence on saguaros over a large portion of their distributions in the Sonoran Desert (Figures 1 and 3a, b, c). as well as on *Pachycereus pringlei* (Figure 3d). During the 2001 field season, we also found termites in aboveground tissues of cacti such as cholla (*Opuntia fulgida*; Figure 3e), senita cactus (*Lophocereus schotti*) and pitahaya (*Stenocereus thurberi*; Figure 3f) as well as herbaceous and woody species such as *Fouquieria splendens*, *Ambrosia deltoidea*, *Ambrosia dumosa* and *Encelia farinosa* to name the most conspicuous in our sample (Table 2). In 2001, termites were found as high as 7–8 m in saguaro and cardon (Figures 3c and d).

DISCUSSION

Our study is the first to describe termite presence on aboveground green epidermal tissues of live saguaros. Previous descriptions of termite ecology in North American deserts have been restricted to underground nesting and feeding habits with decayed wood and dead plant materials (Schaefer and Whitford 1981). Termite presence on aboveground live tissue in Sonoran Desert plants has only incidentally been mentioned for species in urban and agricultural environments (Jones and Nutting 1989). There is only anecdotal references for native desert plants like *Opuntia*, *Acacia gregii*, *Dalea* and *Atriplex* (Jones and Nutting, 1989) from other North American deserts. Jones and Nutting (1989) mention that *Paraneotermes simplicicornis* was found on

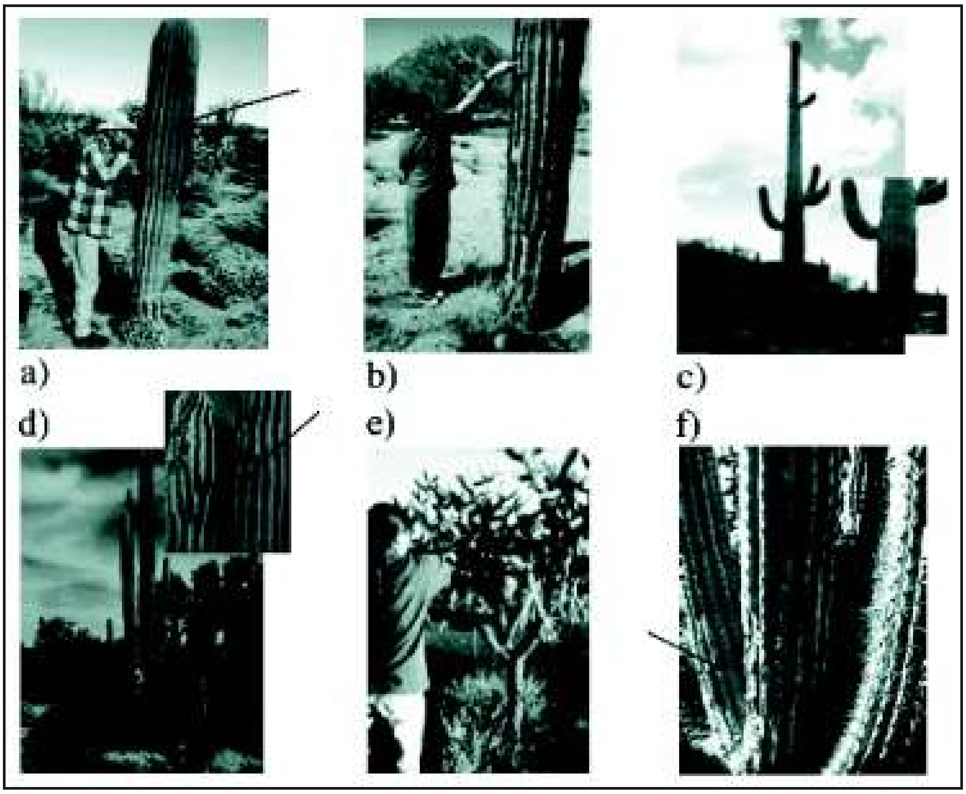

Figure 3. a) Termites along ribs in a young saguaro individual (study site); b) Adult saguaro with termites only on ribs (Organ Pipe Cactus National Monument); Termites can reach considerable heights in saguaro (c) and cardon (d), and have been found in cholla (e) and pitahaya (f) at different localities within the Sonoran Desert.

Table 1. Spearman non-parametric test for Height of termite tubes in live tissues as they correlated with Saguaro height, diameter, number of damaged ribs and height of browning in tissues. Highly statistical significance for p < = 0.0001.

Saguaro		ρ	p
Height of termite tubes	Height	0.6668	< .0001
	Diameter	0.2958	0.0206
	Damaged ribs	0.7957	< .0001
	Browning height	0.8041	< .0001

Table 2. Number and presence percent of termite tubes on live tissue of trees, shrub and sub-shrub species at the study site. Data are from three transects (900 * 2 m each) made in 2001.

Species	Termite presence %	Sample n
Trees		
Cercidium microphyllum	25.0	4
Olneya tesota	0	6
Shrubs		
Fouquieria splendens	54.4	54
Ambrosia dumosa	33.3	57
Lippia palmeri	28.6	14
Ambrosia deltoidea	23.3	129
Condalia globosa	16.7	12
Encelia farinosa	15.4	78
Hyptis emoryi	9.5	21
Krameria parvifolia	5.1	39
Larrea tridentata	0	33
Lycium spp	0	5
Jatropha cinerea	0	8
Cacti		
Ferocactus wislizenii	90.0	10
Pachycereus pringlei	68.5	89
Lophocereus schotti	49.1	57
Stenocereus thurberi	42.4	59
Carnegiea gigantea	33.5	243
Opuntia fulgida	25.9	27
Opuntia leptocaulis	46.7	15

cactus skeletons of chollas and *Carnegiea gigantea* (saguaro), but not on their live tissues.

Termites and Disturbance

Termite presence on living saguaro and above-ground tissues of desert species may be increasing within the Sonoran Desert. At our site in 1989, termites were noticed only on saguaro, but by 2003, they were present on shrubs and other cactus species (Table 2). Termites may not have been previously noticed on saguaro because termite tubes persist for only a short period of time during fall and early winter, they are washed away with light winter rains. Although termite activity typically ceases when temperatures are cooler than 9° C (Ueckert et al. 1976), we have no data on the physiological constraints of the species we found in our study. Given the large variability in the amount and distribution of termite presence in aboveground tissues in different years, it is possible that soil moisture and air temperature are factors that influence termite nesting tube presence.

There are a number of possible causes that may be influencing the increase of termite presence in aboveground tissues of plant species from Sonoran Desert ecosystems. Change in temperature and rainfall patterns either human (land-use change) or climatically (global change) induced may be important factors for increased termite activity above-ground. Termite activity increases during wet years (Bodine and Ueckert 1975) and with anthropogenic disturbance. Increased abundance of certain termite functional types has been noticed in deserts and the tropics after vegetation disturbance (Black and Okwakol 1997; Davies et al. 2003). In the tropics, disturbance has lead to termites nesting in the stems of live plants (Hegh 1922), often associated with sites with poor soil nutrient conditions (Black and Okwakol 1997).

Human disturbance is increasingly widespread in the Sonoran Desert. The plant communities at the sites we studied have been increasingly decimated in their populations of keystone species such as *Prosopis* spp (mesquite) and *Olneya tesota* (ironwood), which have been selectively and heavily harvested for fencing, firewood, charcoal, and crafts. Over the last 15-20 years, charcoal has dramatically increased as a profitable domestic and export business. The statistics on wood and charcoal production from our study region are unreliable, however there is evidence that extraction levels are considerable (Taylor 2006). Given the low rate of establishment and slow growth of desert trees, overexploitation of these key species is to be expected after a few years (Suzán et al. 1997), as shown in the absence or almost complete absence of these species from our vegetation sampling (Table 2). We think that as wood removal increases to meet demand, physical and biotic processes affected by diminished litter and dead material, such as termite dynamics, may become disrupted. Wood extraction may affect primary productivity, availability and seasonality of wood litter presence, alter decomposition dynamics (Nash et al. 1999), and indirectly alter termite behavior, perhaps triggering increased aboveground presence in saguaro and other desert plants. If this is the case, we should be seeing increased termite activity in areas where land-use patterns cause impoverished litter and dead root biomass input to the soil. We know very little about the causes and ecological and functional implications of aboveground termite activities.

Other natural or human-induced changes in rainfall and land cover may be responsible for increasing aboveground termite presence on other desert species (Table 2). Increased variability in temporal rainfall patterns and increasing temperatures will occur as global change progresses. Climate models for Sonoran Desert predict an increase in rainfall and temperatures during the autumn-winter season (SRAG 2000). Because termite activity increases with late summer and fall precipitation at our sites, a change in rainfall patterns and increased temperatures during fall and winter seasons could be already happening and help explain the increased presence of termites on live plant tissues over the years, and on saguaro and cardon from many distant locations from Baja California, Arizona (Castellanos, pers. obs.), and islands of the Gulf of California (Castillo, pers. obs.) in the Sonoran Desert.

Termites and Saguaro Browning

Presence of termites on living saguaro epidermal tissues has not been described and the consequences of their presence on saguaro physiology and population dynamics is yet unknown. We found however, important similarities between our observations of termite visible effects to living epidermal tissues of saguaro with those described as first occurring for epidermal browning (Turner and Funicelli 2000). We propose that termite effects on saguaro green epidermal tissues and epidermal browning may be related phenomena. At our study site, termite presence was correlated with some of the characteristics of tissue damage that had been ascribed to epidermal browning (Table 1). Compared to healthy saguaros with no spine damage (Figure 4a), spines with termite nesting tubes (Figure 4b) showed signs of loosening first the middle spine and damage at the base of the spine areole and along the rib (Figures 4b and c), with total spine loss apparently after several events. Spine loosening and fall is a first sign of saguaro browning (Turner and Funicelli 2000).

We observed other similarities between termite effects on saguaro epidermal tissues and saguaro browning. Browning spreads from ribs to adjacent epidermal tissues, a pattern

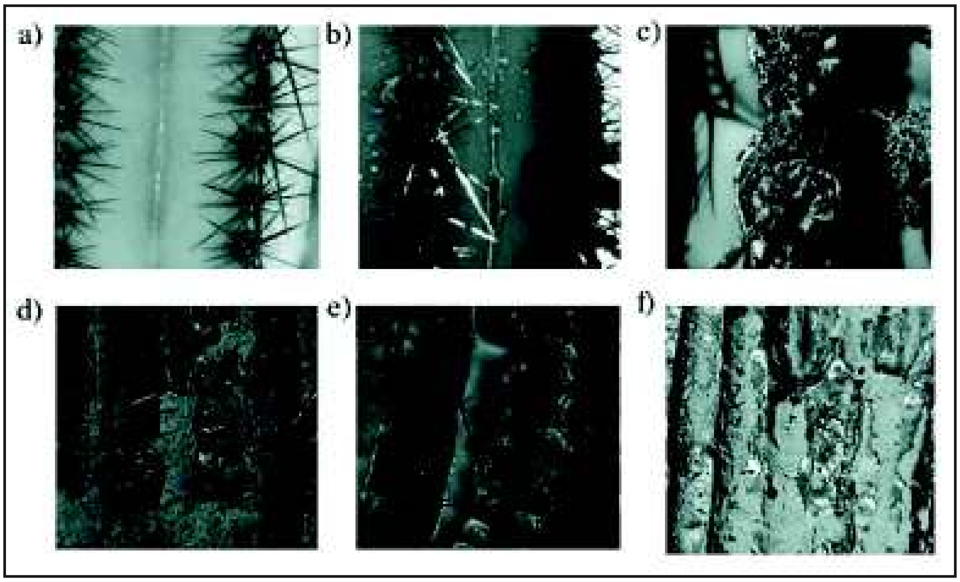

Figure 4. Saguaro browning correlates with termite activity. Healthy saguaro ribs and spines (a); Termite tubes along spines (b); Spine damage after termite presence (c); Termite damage spread to green tissue (d) (tubes were removed from region in the center of the photography to expose the kind of termite damage); Spread of termite tubes to all saguaro ridges and aerial tissues (e); Saguaro epidermal browning (f). Photographs were taken in 2001

similar to that found with termites initially climbing only along ribs and progressively spreading to adjacent green tissues (Figure 4d). Damage induced each year, either physically or possibly as a wounding response, will allow termites to spread further from lignified spines over the next years (Figure 4d). Progressive effects spreading from spine ribs to epidermal tissues (Figures 4c, d, and e) were associated with termites, with symptoms very similar to what has been reported for epidermal browning (Figure 1 in Turner and Funicelli 2000). During years with high termite aboveground activity, browning and termites were related phenomena as found in browned saguaros with termites spread all over them (Figure 4f). Since aboveground termite presence on epidermal tissues of saguaros differs from year to year (Figure 2), spread and damage may take decades.

Epidermal browning in saguaro does not yet have a known definitive causal agent. Several physical variables such as freezing (Steenbergh and Lowe 1977), air pollution (Stolte 1992), heat and UV-B load (Evans et al. 1994b; Evans et al. 1992; Turner and Funicelli 2000) have been proposed as causes of saguaro epidermal browning. Increased heat and UV-load on southern exposure saguaro stems seem to be related to the directional effects of browning found in some saguaro populations of the northern Sonoran Desert region (Evans et al. 1994a; Evans et al. 1992; Turner and Funicelli 2000). Termite effects on saguaros were visually well correlated with most previously described symptoms of saguaro browning. The symptoms we uncovered under termite nesting tubes on spines (Figure 4b), and scars left on epidermal tissues (Figure 4e), were similar to those previously associated with browning

(Turner and Funicelli 2000) and tissue hardening and lignifications of saguaro epidermal tissue (Evans et al. 1994b; Olson 2000). Although we did not specifically measure directional effects, at our sites there were no obvious directional patterns in the epidermal browning on saguaro tissues, since more than 75% of ribs were affected in at least 51% of affected adult saguaros. Some of the studied sites are at more southern, non-freezing latitudes and in regions with warmer temperatures than the locations where directional effects have been reported (McAuliffe 1993). If directional effects are present at more northern latitudes of saguaro distribution, that wouldn't cancel the possibility that increasing heat loads may benefit termite activity and aboveground growing conditions or that both effects could be related. Spine loss may diminish the cooling effects on epidermal tissues, and increase heat load, but this should be tested. As an end result, saguaro browning decreases photosynthetic carbon gain, and induces a positive feedback loop of diminishing physiological performance (Lajtha et al. 1997), inducing an early senescence process.

Termites and Sonoran Desert Ecosystem

In this paper we have described a previously undocumented and seemingly increasing phenomena of termite presence on aboveground plant species in the Sonoran Desert. We think that presence of termites aboveground may be an early warning signal that important changes are happening in Sonoran Desert ecosystems, and here we bring some evidence that such phenomena will be playing an increasingly important role in shaping the structure and function of species and ecosystems in this North American desert.

It is of outmost importance to determine the ecological and environmental factors that have enabled termites to spread aboveground, and to understand the ecological consequences of this increased termite activity. As a small glimpse of what could happen, we are amazed that such a sturdy plant as saguaro, a plant that can withstand years and possibly centuries of stressful physical conditions, may be so greatly affected by a small, almost inconspicuous insect.

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CONSERVATION OF AMPHIBIANS AND REPTILES IN NORTHWESTERN SONORA AND SOUTHWESTERN ARIZONA

James C. Rorabaugh

The 4.26 million hectare (10.5 mil ac) region of Sonoran Desert in southwestern Arizona and northwestern Sonora is surprisingly diverse in regard to its herpetofauna, owing to its varied landscapes and habitats: from the marine waters of the Gulf, the remnant riparian woodlands and marshlands along the Colorado, Sonoyta, and Gila Rivers, the volcanic slopes of the Sierra Pinacate, the arid and relatively barren dunes of the Gran Desierto (the largest dune system in the western hemisphere, Bowers 1998), to the broad desert valleys and mountains.

The region's rivers and wetlands have been dramatically altered by water diversions, upstream dams, groundwater pumping, levees and bankline structures, introduction of sport fishes and other non-native plants and animals, and development of the floodplains for agriculture and urban uses (Ohmart et al. 1988; Fradkin 1996; Felger 2000; Glenn et al. 2001). However, the desert lands are relatively intact, being too dry to support much livestock grazing and generally lacking minerals of sufficient quality for large-scale mining. Current uses of the desert lands, mainly aerial military training, border security, dispersed recreation, and wildlife management, have left relatively few scars on the landscape, although roads, trails, camps, and other disturbance near the border in Arizona — resulting from illegal border crossings and response by U.S. Border Patrol and other law enforcement agencies — have increased greatly in recent years (Milstead and Barns 2002; Rorabaugh et al. 2002a; Segee and Neeley 2006). With the exception of mountainous regions, pedestrian fences or vehicle barriers now span the border in the study area from San Luis east onto the Tohono O'odham Nation. These structures have created barriers not only to people and their vehicles, but to wildlife and cultures as well (Cordova and de la Parra 2007). Also of great concern in the desert lands is the spread of flammable non-native winter annual plants that are capable of fueling large fires.

This description of the herpetofauna emphasizes species or groups of species that are imperiled within the region or throughout their ranges as well as the conservation efforts that would facilitate the maintenance of these threatened, but important populations. Some are conserved by species-specific plans and actions, while others are afforded protection via land management practices, including protective land use designations. Conservation efforts are occurring within biological, cultural, political, and fiscal environments that in some cases constrain their effectiveness, but in others provide significant conservation opportunities.

STUDY AREA

This area of northwestern Sonora, Mexico, and southwestern Arizona, U.S., is bounded by the Colorado River on the west, the Gila River on the north, a line from Gila Bend, Arizona, to Bahia San Jorge, Sonora, on the east, and the Upper Gulf of California on the south; also included is a small portion of Baja California east of the Colorado River (Figure 1).

Common biological, climatic, geological, and cultural threads run through the study area that bind it into a discrete unit, despite a myriad of land management jurisdictions and an international border (Cornelius 1998). Elevations vary from sea level to 1,466 m (4,810 ft) at Ajo Mountain and 1,290 m (4,232 ft) at Pinacate Peak. Dunes and sandy flats of silica sands brought to the region by the Colorado River stretch from Yuma south and east through the Gran Desierto to Bahia San Jorge (Kresan 2007; Bowers 1998). The Pinacate Volcanic field covers about 2,000 km^2 (722 mi^2), while elsewhere northwest to southeast trending granitic and basaltic mountain ranges occur. Large management jurisdictions cover much of the landscape; they include the Barry M. Goldwater Range (BMGR, U.S. Department of Defense), Cabeza Prieta National Wildlife Refuge (CPNWR, U.S. Fish and Wildlife Service), and Organ Pipe Cactus National Monument (OPCNM, U.S. National Park Service); and in Mexico the Reserva de la Biosfera Pinacate y Gran Desierto de Altar (Pinacate Reserve, La Comisión Nacional de Áreas Naturales Protegidas (CONANP)) , and the Reserva de la Biosfera Alto Golfo de California y Delta del Río Colorado (Alto Golfo Reserve, CONANP).

The study area is relatively sparsely populated; the largest city is San Luis Río Colorado, with roughly 160,000 inhabitants (Schmidt 2005), followed by Yuma (77,515) and Puerto Peñasco (roughly 35,000). Smaller communities include Sonoyta (10,817), Somerton (7,266), Ajo (3,705), Gila Bend (1,980), and Wellton (1,829) (U.S. Census Bureau 2000, Border Environment Cooperation Commission 2005). Arizona communities grow in the winter months, often substantially, due to an influx of winter visitors, and the population of Puerto Peñasco can reportedly double on holiday weekends.

Floristically the area is largely represented by simple, sparse shrub communities, often dominated by creosote (*Larrea tridentata*), white bursage (*Ambrosia dumosa*), and other species of the Colorado Desert subdivision of Sonoran desertscrub (Brown and Lowe 1994; Turner and Brown 1982). Washes and slopes support a more diverse flora, both structurally and in species richness; diversity also increases with rainfall from west to east (Felger 2000; Turner and Brown 1982). Mountains and bajadas in the region's eastern portion are characterized by the more diverse flora of the Arizona Upland subdivision of Sonoran desertscrub (Brown and Lowe 1994).

Variability in precipitation brings about dramatic floristic changes, both seasonally and in the longer term. This is most apparent in wet winters that produce luxuriant ephemeral, herbaceous floras, but can also be seen in wet and dry cycles during which perennial cacti, shrubs, and trees may die back in large numbers or much regeneration occurs. A drought from 1931-34 in the Sierra Pinacate killed large numbers of trees and shrubs and they have yet to return to their prior abundance (Hayden 1998).

This region of the Sonoran Desert is particularly hot and dry. High temperatures combined with low relative humidity in summer result in high evaporation and transpiration rates. Yuma has a potential evapotranspiration-to-precipitation ratio of about 30, which is particularly challenging for plant survival and growth (Dimmitt 2002). Freezing temperatures are relatively rare (15-25 days a year at Yuma, and about one day at Puerto Peñasco) and becoming rarer (Weiss and Overpeck 2005), but occasional damaging freezes occur. Freezing temperatures in 1978 resulted in die back of elephant trees (*Bursera microphylla*) and organ pipe cactus (*Stenocereus thurberi*) at OPCNM (S. Rutman, pers. comm. 2005). Lows of -5.5° C (22.1° F) were recorded at Bahia Adair and Sierra del Rosario in December 1972 (May 1973).

Rainfall is bimodal (winter and summer) and highly variable; mean annual precipitation ranges from 40 mm (1.6 in) at San Luis Río Colorado to 267 mm (10.5 in) at Aguajita / Quitobaquito (Felger 2000; Comrie and Broyles 2002). Periodic severe drought contrasting with brief wet periods strongly influence plant and animal communities (Felger 2000; Rosen 2000). For instance, no

Figure 1. Study area and protection/management areas.

measurable precipitation fell in the Sierra del Rosario from September 1969 to August 1972, a period of 34 months (May 1973). Yet, winters can be relatively wet, and occasional monsoons or late summer-early fall rains may bring more than the annual average rainfall in a short period. From 24-26 September 1997, the remnants of Hurricane Nora dropped 86.6 mm (3.4 in) of rain on Yuma. Monsoon storms in the afternoons of July 27 and August 9, 1989 dropped a total of 151.6 mm (6.9 in) of rain on Yuma (National Oceanic and Atmospheric Administration 1989a,b), which is 217% of the mean annual rainfall (Holcombe et al. 1997).

Water is a "master limiting factor" in deserts (Pianka 1986). Net primary productivity, insect abundance, and lizard clutch sizes and frequency, body size, and density have been found in various studies to all be positively correlated with amounts of recent precipitation (Rosenzweig 1968; Turner et al. 1969, 1982; Pianka 1970, 1986; Parker and Pianka 1975; Anderson 1994; Dickman et al. 1999; Rosen 2000; Young and Young 2000). That said, timing of rainfall (summer versus winter), density dependent factors, predation, and potentially inter-specific competition can act to obscure these climatic-driven relationships (Turner 1977; Turner et al. 1982; Rosen 2000; Young and Young 2000).

Populations of longer-lived species, such as many larger snakes, desert tortoise (*Gopherus agassizi*), Gila monster (*Heloderma suspectum*), desert iguana (*Dipsosaurus dorsalis*), desert night lizard (*Xantusia vigilis*), and common chuckwalla (*Sauromalus ater*), vary less, as most adults of these species tend to survive drought, but reproductive output, growth, diet, and behavior often vary between wet and dry periods (Nagy 1973; Krekorian 1984; Smits 1985; Rosen 2000; Averill-Murray et al. 2002; Beck 2005). At OPCNM, Rosen (pers. comm. 2006) found that the distribution of snakes varied between dry and wet periods — in drought, snakes were typically found in drainages, where vegetation was more abundant and occasional runoff occurred, but in wetter periods snakes ventured more into the drier uplands and flats between the drainages.

In contrast to the desert areas, population dynamics of riparian, marine, agricultural, and urban herpetofauna are probably not limited by precipitation. Historically, amphibians and reptile populations in the riparian corridors of the Gila and Colorado rivers probably varied with periodic flood or low water events, the former of which were extreme in some years (Mueller and Marsh 2002). This is much less the case now, as these rivers are regulated by upstream dams and at least some flow in the study area is maintained by irrigation return flow, both of which tend to create much more stable conditions. Disturbance today in these two rivers is more likely to occur from periodic fire, and in the Gila River from about Highway 95 to Texas Hill, by channel-clearing activities conducted by the Wellton-Mohawk Irrigation and Drainage District.

AMPHIBIAN AND REPTILE INHABITANTS

The herpetofauna of the study area (Appendix 1) includes 12 amphibians (one salamander, six toads, one spadefoot, and four frogs) and 58 reptiles (nine turtles and tortoises, 20 lizards, and 29 snakes). One lizard, two turtles, two frogs, and one salamander are non-native introductions. Two introduced species, the tiger salamander (*Ambystoma mavortium*) and pond slider (*Trachemys scripta*), are probably maintained in the study area by continued introductions and may not maintain breeding populations.

Some species reported from the study area are not included in the Appendix. A pair of breeding mud turtles (probably Arizona mud turtle, *Kinosternon arizonense*) was collected at Quitobaquito, OPCNM in 1955 (Rosen and Lowe 1996), and the yellow mud turtle (*Kinosternon flavescens*) was reported from Yuma (Stebbins 1966) and collected on the Gila River near Fort Yuma (Van Denburgh 1922). The Arizona mud turtle occurs on Tohono O'odham Nation lands to the east of the study area as well as south in Sonora, and could have conceivably existed historically in the valley of the Río Sonoyta, Sonora (Iverson 1985; Jones et al. 2007). Today, yellow mud turtles occur from Cochise and Graham counties in southeastern Arizona east to northwestern Illinois (Ernst et al. 1994; Brennan and Holycross 2006). The disjunct nature of the Yuma records suggests misidentification, incorrect locality data, or an introduction (Ohmart et al. 1988; Mellink and Ferreira-Bartrina 2000). In any case this species and the Arizona mud turtle have apparently not persisted in the study area and therefore are not considered further. American alligators (*Alligator mississipiensis*) were introduced to the Colorado River probably before 1938 and persisted at least into the 1950s, although no evidence of reproduction was ever found (Glaser 1970; Vitt and Ohmart 1978). I also observed an alligator at Fortuna Pond, Gila River near Yuma (pers. obs., 1988), but the species has not persisted and thus was also not included. Baegert (1952) reported "alligators" at the mouth of the Colorado River in 1751, which may have been American crocodiles (*Crocodylus acutus*); however, Felger (2007) believed that report was not credible. In any case, the species is now extirpated from the coastal waters of Sonora (Rorabaugh 2008), and is also not considered further.

The information in the Appendix is based on a variety of sources, including literature, museum collections, my own personal experiences, and communications with others who have worked in the study area. The following literature was particularly valuable: Vitt and Ohmart (1978), Lowe et al. (1986), Ohmart et al. (1988), Gonzalez-Romero and Alvarez-Cardenas (1989), Rosen and Lowe (1996), Turner et al. (1997), Rosen (2000, 2007), Stebbins (2003), Brennan and Holycross (2005, 2006), Rorabaugh (2008), and species accounts in the Catalogue of American Amphibians and Reptiles.

Seventy species represents substantial diversity for an arid region of the Southwest. Arizona supports 128 species (Brennan and Holycross 2006), while Sonora (not including islands in the Gulf of California) is home to at least 178 species (Rorabaugh 2008). Hence, the study area includes 55% and 39% of the number of species found in Arizona and mainland Sonora, respectively.

CONSERVATION CONTEXT

About 50% of the 4.26 million ha (10.5 mil ac) study area is designated as biosphere reserves, national monument, or wildlife refuge, including the 0.94 million ha (2.3 mil ac) Alto Golfo Reserve, the 0.71 million ha (1.7 mil ac) Pinacate Reserve, the 0.35 million ha (0.86 mil ac) CPNWR, the 0.13 million ha (0.32 mil ac) OPCNM, and the 0.13 million ha (0.32 mil ac) Refugio Vaquito (part of which also lies within the Alto Golfo Reserve, Figure 1). The biosphere reserves include core protection zones (Zona Nucleo in the Alto Golfo Reserve, and Zonas Sierra el Pinacate and Sierra del Rosario in the Pinacate Reserve) where protective regulations are very strict; the remaining areas within the reserves are buffers with less stringent regulations. These buffer zones often overlay ejido (private cooperative) lands. The study area also includes the 0.75 million ha (1.85 mil ac) BMGR, which is primarily a military aerial training range. Much of the BMGR is off limits to the public, and only 2.5% of lands in the BMGR have been subjected to moderate to high severity military activities; another 7.5% have been affected to a lesser degree (U.S. Departments of the Navy, Air Force, and Interior 2006). These land use designations and accompanying restrictions and regulations provide substantial protection for the region's herpetofauna and its habitats.

The study area is rich biologically, and supports many imperiled faunal and floral species. Marshall et al. (2000) evaluated conservation priorities in the Sonoran Desert ecoregion and found the Pinacate/OPCNM/BMGR complex to contain more conservation targets (sensitive faunal and floral species) than any of the other 99 conservation sites they evaluated. The Colorado River delta ranked eighth on that list.

A major challenge to amphibian and reptile conservation has been a negative public perception. Characteristics often associated with these animals, such as "venomous, slimy, cold, lowly, and creepy", have evolved into quite a mythology of half truths and misconceptions. The end result is that many snakes are killed on sight, frogs and salamanders are avoided, and in general, amphibians and reptiles have not received the same affection or appreciation that colorful birds, big game species, sport fishes, or other charismatic or commercially significant species are afforded. Even in the scientific and conservation communities, amphibians and reptiles are relatively unknown compared to other vertebrate groups in the study area. Negative public perception is perhaps abating (e.g., frogs are now well represented in popular culture), but still remains a problem for conservation.

IMPERILED SPECIES

Thirty-seven of 70, or 53% of amphibian and reptiles species in the study area, are considered special conservation status species under the U.S. Endangered Species Act (8 species), Mexican regulations (36 species: 'Lista de Especies en Riesgo", SEMARNAT 2008), or are on the IUCN's Redlist (8 species, Appendix). Some species on the Mexican list are either introductions or their populations appear fairly secure in the study area. Most of these are "Pr" species, which is a category indicating possible threat, but not enough information is available to list the species as threatened or endangered. For instance, there is no indication that the western banded gecko (*Coleonyx variegatus,* "Pr"), zebra-tailed lizard (*Callisaurus draconoides*, "A" or threatened), long-nosed leopard lizard (*Gambelia wislizenii*, "Pr"), common kingsnake (*Lampropeltis getula,* "A"), coachwhip (*Masticophis flagellum,* "A"), nightsnake (*Hypsiglena chlorophaea,* "Pr"), and all six of the rattlesnakes (all "Pr") are threatened or endangered in any substantial way in the study area. The variable sandsnake (*Chilomeniscus stramineus,* "Pr"), saddled leaf-nosed snake (*Phyllorynchus browni,* "Pr") and Sonoran coralsnake (*Micruroides euryxanthus*, "A"), although of limited distribution in the study area, are additional species that are probably not threatened in the study area. Four "Pr" species, including the tiger salamander, Rio Grande leopard frog (*Rana berlandieri*), spiny softshell (*Apalone spinifera*), and pond slider, are only represented as introduced species, and in the study area do not warrant protection.

The only species that may warrant special status, but currently is not afforded one, is the Sonoran Desert toad. Although probably secure in the eastern portion of the study area (Rosen and Lowe 1996) and along the Gila River east of Dome Valley (pers. obs.), I am not aware of any documented observations or collections of the species along the Colorado River Arizona/Mexico in the study area, Yuma area, or Gila River west of Dome Valley since the 1940s (Vitt and Ohmart 1978; Jennings and Hayes 1994, pers. obs.). Yet Sonoran Desert toads may still persist in the Río Colorado valley of Sonora (Grismer 2002; pers. comm. with resident of Ejido Johnson, Sonora, 2007) and potentially at the Foothills or Fortuna Wash east of Yuma based on unconfirmed reports in the 1980s.

If we remove from special status designation the 15 species on the Mexican list that appear not to be significantly threatened in the study area, and the four introduced species, but add in Sonoran Desert toad, then a short list of 19 (27%) species would be considered imperiled. Grouping of these species by community types — marine, riparian/wetland, desert valleys, and desert bajadas and mountains, reveals an interesting pattern (Table 1): marine and riparian/wetland species are particularly imperiled when compared to desert species. Five of six marine species (all sea turtles) and six of 13 (46%) riparian/wetland species are imperiled, compared to 13% (4 of 31) of desert valley and 13% (5 of 39) of desert bajada/montane species. Another indication of threats is the presence of introduced species, of which five of six are riparian/wetland species.

Marine Species

Five species of sea turtles (Green, Hawksbill, Olive Ridley, Leatherback, and Loggerhead) are known from the Gulf of California (Table 1). All but the Hawksbill have been recorded in the Upper Gulf (Grismer 2002), but it likely visits the study area. Only the Olive Ridley has been known to nest in the Upper Gulf; Nabhan (2003) and Peggy Turk-Boyer (pers. comm. 2006) report nesting on beaches near Puerto Peñasco in the 1990s, and Seminoff and Nichols (2007) report evidence of nesting near El Golfo de Santa Clara in 2000. All five species are listed as threatened, endangered, or critically endangered on the U.S., Mexican, and IUCN lists, and all have declined in the Gulf of California. A long history of harvesting turtles, legally and illegally, and unintentional bycatch in nets and on longlines in the Gulf of California have contributed to that decline. But the threats to sea turtles are neither unique to the study area nor to the Gulf of California, as all five species are distributed throughout the warmer waters of the world, and turtles that visit the Gulf come from as far away as southern Mexico and Japan. Throughout their distributions, the Gulf's sea turtles are also dying from pollution-related disease; ingestion of debris and trash; intentional harvest of turtles for food, aphrodisiacs, and the jewelry and souvenir industry; incidental capture in nets; boat strikes; destruction or disturbance of beaches where sea turtles nest; and predation of nests by people and dogs.

Since 1991 all sea turtles in Mexico and its waters have been protected by presidential decree; however, the law is difficult to enforce and some poaching still occurs. For such prohibitions to be effective, an understanding of the need for conservation must be promoted at the community level. Several organizations are doing just that. Drs. Gary Nabhan and Jeffrey Seminoff and others have worked closely with the Seri (Coomcáac) people on the north-central Sonoran coast to recruit the Seri and local fisherman into sea turtle conservation. A training session co-taught by biologists and Seri elders for Seri youth "para-ecologists" introduced conservation techniques and simple monitoring protocols to promote conservation of the Gulf's sea turtles (Nabhan et al. 1999). Similarly, on the Baja peninsula, Grupo Tortuguero de las Californias — an alliance of communities, fishing cooperatives, NGOs, tourism outfitters, scientists, government agencies, and others — is working to promote the ecological, economic, and cultural role of sea turtles in the Gulf of California. CEDO (El Centro Intercultural de Estudios de Desiertos y Océanos) located in Puerto Peñasco, has developed educational and outreach programs

Table 1. "Short list" of imperiled species by community type.

Community[1]	Imperiled Species	Total No. Species	% Imperiled	% Introduced
Marine	Green Sea Turtle, Hawksbill Sea Turtle, Loggerhead Sea Turtle, Olive Ridley Sea Turtle, Leatherback Sea Turtle	6	83	0
Riparian/ Wetland	Sonoran Desert Toad, Lowland Leopard Frog, Sonoran Mud Turtle, Black-necked Gartersnake, Mexican Gartersnake, Checkered Gartersnake	13	46	42
Desert Valleys	Sonoran Green Toad, Western Narrow-mouthed Toad, Flat-tailed Horned Lizard, Yuman Fringe-toed Lizard	31	13	3
Desert Bajada/ Mountain	Desert Tortoise, Gila Monster, Common Chuckwalla, Rosy Boa, Sonoran Desert Toad	39	13	0

[1] Communities where species primarily occur or are most commonly encountered.

and promotes conservation of Gulf of California resources and species, including sea turtles. In addition, staff at the Alto Golfo Reserve work with fisherman and local communities to develop an understanding of the need for conservation of sea turtles and other species of the upper Gulf.

Riparian and Wetland Species

Thirteen species are obligate or primarily wetland or riparian species (Appendix, Table 1), including tiger salamander, Woodhouse's toad, Sonoran Desert toad, Great Plains toad, three ranid frogs, three turtles, and all three gartersnakes. Note that in the study area the black-necked gartersnake is only known from mesic canyons of the Ajo Mountains. All of the extant wetland species, except the black-necked gartersnake, can be found in agricultural ditches, canals, and fields, as well as along rivers or backwaters. The Sonoran Desert toad and occasionally Great Plains toad are also found at stock tanks, tinajas, and rain pools in the desert in the eastern portion of the study area.

Five of the 13 species are introduced, and of the other eight, 6 are considered imperiled (I included the Sonoran Desert toad). Two of the six imperiled species are almost certainly extirpated — Mexican gartersnake and lowland leopard frog — which have not been recorded in the study area since 1890 and 1942, respectively. These species were not found in recent investigations: Vitt and Ohmart (1978), Rosen and Schwalbe (1988), Clarkson and Rorabaugh (1989), Rorabaugh et al. (2002b). Nor have Sonoran mud turtles been found in the region since 1962, except on the Río Sonoyta, where they still persist. The Sonoran Desert toad is extirpated from the U.S. portion of the Colorado River, but may still persist along that river in Mexico (Grismer 2002), and still occurs in ephemeral waters and the Gila River corridor in the eastern portion of the study area. The high percentage of introduced species and imperilment of native wetland and riparian species is consistent with the status of other wetland and riparian species groups (Ohmart et al. 1988; Rosenberg et al. 1991; Mellink and Ferreira-Bartrina 2000; Mueller and Marsh 2002).

Although it is impossible to determine causes after the fact, predation by non-native American bullfrogs, potentially spiny softshell turtles, and a diversity of non-native fishes, is a likely cause of the demise of the lowland leopard frog, Mexican gartersnake, and Sonoran mud turtle on the lower Colorado and Gila Rivers. American bullfrogs and a variety of non-native fishes eat gartersnakes, frogs, and turtles, and each one alone may be capable of eliminating populations of lowland leopard frogs, Sonoran mud turtles, and Mexican gartersnakes (Hayes and Jennings 1986; Rosen and Schwalbe 1988, 2002). Red swamp crayfish (*Procambrus clarkia*) and Rio Grande leopard frogs were likely introduced after the extirpation of these native species (Inman et al. 1998; Platz et al. 1990), and thus did not contribute to their demise.

In addition to the many introductions of non-native predators, wetland habitats on the Colorado and Gila Rivers have been lost and degraded due to upstream dams and diversions, levees and bankline structures to control flows and flooding, introductions of non-native plants, groundwater pumping, and return agricultural flow, which is typically saline and carries with it pesticides and fertilizers (Ohmart et al. 1988; Garcia-Hernandez et al. 2001; Glenn et al. 2001).

Restoration of flows and some aspects of native wetland and riparian communities are possible along the big rivers (Ohmart et al. 1988; Pitt 2001). When completed, the Yuma East Wetlands Park, which straddles the Colorado River just east of Yuma, will encompass about 565 ha (1,400 ac) of wetlands and native riparian communities. Another 55 ha (135 ac) park and restoration area — "Yuma West Wetlands" — is close to completion nearby. These projects are excellent examples of restoration potential. Similarly, wetlands and riparian restoration has been accomplished at several sites along the Gila River in the study area with varying success (Rorabaugh 1995), and wetland and riparian restoration projects are occurring as well in the delta and on the

Río Hardy (J. Campoy, pers. comm. 2006). However, these projects probably do not benefit imperiled amphibians and reptiles because wetlands are rapidly colonized by non-native predators. Loss of native herpetofaunal diversity on the Colorado and Gila Rivers may be irreversible, although there is some potential for establishing highly managed and isolated refugia populations of lowland leopard frogs, Sonoran mud turtles, or other species. The recently completed Lower Colorado River Multi-Species Conservation Plan may provide opportunities for establishing such refugia — the Sonoran Desert toad and lowland leopard frog are considered evaluation species under the Plan (Lower Colorado River Multi-Species Program 2004).

In contrast to the situation on the big rivers, the Río Sonoyta and associated Quitobaquito, Quitovac, and sewage treatment ponds at Sonoyta present an opportunity to conserve and potentially restore a desert stream community. The Quitobaquito/Río Sonoyta Working Group, a bi-national coalition of agencies and biologists, has developed a proposal for comprehensive conservation for which they are seeking funding. The proposal includes community-based, ecologically sound planning to develop: (1) ecotourism and an urban park along the stream corridor, (2) aquifer conservation or restoration, (3) modernized infrastructure planning regarding sewage treatment, (4) landscape-level conservation planning and urban design, and (5) monitoring and educational programs for key resources. This proposal would help conserve the Sonoran (Sonoyta) mud turtle (*Kinosternon sonoriense longifemorale*) and other native species. A recent threat to the Río Sonoyta is a planned modernized sewage treatment plant to be located on ejido lands west of the town of Sonoyta. The plant would replace the existing sewage lagoons, which provide habitat for mud turtles. As of this writing, the disposition of the treated water that would exit the plant is uncertain. If returned to the river, it could bolster flows and benefit mud turtles and other native aquatic species; however, there is some potential that the ejido will use all or portions of the outflow for agriculture, with resulting reductions in riverine aquatic habitat. See Rosen et al. (this volume) for further information.

Desert Valley Species

Thirty-one species are considered inhabitants of desert valleys and flats. Of those, four are on the list of imperiled species (Table 2), including Sonoran green toad, western narrow-mouthed toad, Yuman fringe-toed lizard, and flat-tailed horned lizard. The Sonoran green toad is known only from a few localities from Why to Lukeville and breeding sites have not yet been documented (Rosen and Lowe 1996). The western narrow-mouthed toad is known only from an individual that was calling at Lukeville (Rosen and Lowe 1996). Both are expected in the Río Sonoyta Valley. In the study area, these species are at the western extremes of their ranges. Breeding sites may include cattle tanks or other artificial impoundments, as well as playas and intermittent reaches of the Río Sonoyta. A key conservation need for these species is locating and protecting any breeding sites in the study area.

The range of the Yuman fringe-toed lizard lies mostly within the study area, although it also occurs south along the coast from Bahia San Jorge to Bahia Tepoca. It is associated with and highly adapted to living in dunes, but I have also observed it in windblown sandy flats in the Yuma Desert. This species and its habitat are vulnerable to habitat degradation. In the Algodones Dunes, Imperial County, California, Luckenbach and Bury (1983) documented declines in plants, arthropods, mammals, and lizards (including the closely-related Colorado Desert fringe-toed lizard, *Uma notata*) in areas with relatively low levels of OHV use. In heavily used areas, virtually no plants or animals existed. However, the largest tracts of habitat for the Yuman fringe-toed lizard in the study area are either closed to public use, or vehicles are limited to existing routes. In Arizona, no off-highway vehicle (OHV) activity is allowed on the Mohawk Dunes, and the Yuma Dunes (on the BMGR) are in an area where public use is prohibited.

Military activities have had little or no impact on these areas, and Border Patrol or smuggler vehicle tracks are uncommon (pers. obs.). At Pinta Sands on CPNWR, a road traverses the northern end of the dunes and lava flow, but no vehicles are allowed off-road (although Border Patrol and smugglers drive off-road in this area). A dune south of County 19th Street and west of Avenue 4E near Yuma, where I have observed fringe-toed lizards, has been developed into a sand and gravel pit and is also impacted by OHVs and trash dumping; however, in regard to impacts to dune habitats, this is the exception to the rule. In Sonora, the largest and most extensive dunes lie within the Pinacate and Alto Golfo reserves. Increasing OHV activity in the Puerto Peñasco/Cholla Bay area impacts some fringe-toed lizard habitat, and a recently completed highway from Peñasco to El Golfo de Santa Clara is bringing additional visitors, their OHVs, and associated recreational impacts to remote portions of the Gran Desierto.

The flat-tailed horned lizard is known from mostly sandy flats and low dunes. In Arizona it occurs in the Yuma Desert west of the Butler Hills and south of the Gila River (Rorabaugh et al. 1987), and in Sonora from San Luis Río Colorado south and east to the Gulf of California and Bahia San Jorge (Rodriguez 2002; Rorabaugh 2008). Piest and Knowles (2002) estimated 89,522 ha (221,214 ac) of habitat existed historically in Arizona, of which 25,190 ha (62,246 ac, 28%) have been lost primarily to agricultural and urban development. No recent estimates of habitat loss are available for Sonora; however, Johnson and Spicer (1985) estimated 14% of the habitat in Sonora was threatened by human activities. Their estimate of occupied habitat in Sonora was conservative, hence the percentage of the lizard's habitat that was threatened at that time was probably an overestimate.

In the U.S., the status of the flat-tailed horned lizard has been the subject of much rule-making and litigation. It was first proposed for threatened status under the Endangered Species Act in 1993. The proposed rule has been withdrawn and reinstated by the courts on three occasions. The proposed rule was withdrawn, in part, due to the development of a multi-party conservation agreement and strategy, in which 196,425 ha (485,000 ac) were designated in five Management Areas, one in Arizona and four in California, to be managed for the long-term viability of the flat-tailed horned lizard (Rorabaugh et al. 2000; Flat-tailed Horned Lizard Interagency Coordinating Committee 2003). Implementation of the conservation strategy has been good, as documented by annual progress reports.

Despite recent reductions in illegal border activities, habitats along the entire U.S.-Mexico border in the Arizona portion of the study area are threatened by these activities and law enforcement response (Milstead and Barnes 2002; Kralovec 2006; Segee and Neeley 2006; Cordova and de la Parra 2007). The pedestrian fence that runs through flat-tailed horned lizard habitat east of San Luis probably is, to some extent, a barrier to movement of lizards across the border, but it is apparently not an absolute barrier. In May 2008, I observed several miles of this fence through the Yuma Dunes that had been undermined by wind erosion. Animals, and in some cases people, could pass under the fence, which posed no barrier to a flat-tailed horned lizard. Even in places where the fence was not undermined, I observed western whiptails running into burrows at the base of the fence that appeared to provide access to the other side. The fence has apparently reduced illegal cross-border traffic and associated OHV activity in the Yuma Desert Management area (Allen and Rorabaugh 2007).

Construction of the Area Service Highway was completed in 2009 along the western and northern boundaries of the Yuma Desert Management Area from a new port of entry at Avenue E on the international border to Araby Road at Interstate 8. It eliminated about 283 ha (699 ac) of flat-tailed horned lizard habitat along the road corridor, and isolated another 1,480 ha (3,657 ac) (U.S. Fish and Wildlife Service files). Although the project impacted habitat, it only represented a loss of about 2.7%

of current habitat in Arizona, and the highway and its right-of-way fence could serve as a defensible barrier against OHV and other intrusions into the Management Area.

In Sonora, much of the habitat of the flat-tailed horned lizard lies within the Pinacate and Alto Golfo reserves, although there is significant habitat north of the latter reserve and west of the former reserve, as well as habitat in the southeastern portion of the study area that is unprotected. As discussed for the Yuman fringe-toed lizard, OHV activity is occurring in the Puerto Peñasco/Cholla Bay area, and such activity is likely to increase in the Gran Desierto with the recent completion of the Peñasco to El Golfo de Santa Clara highway. Another recently completed highway, from San Luis Río Colorado to roughly El Doctor, also eliminated habitat and provides new access to the Gran Desierto. These types of activities degrade habitat and result in mortality of lizards (Flat-tailed Horned Lizard Interagency Coordinating Committee 2003). Due to road mortality, there will likely be a "dead zone" along the new highways, in which densities of reptiles are much reduced and some species may be absent (Boarman et al. 1992; Rosen and Lowe 1994). Grant et al. (2001) found 87 percent fewer flat-tailed horned lizards within 0.72 km (0.45 mi) of Highway 98 in California than in areas farther from the road.

A growing threat to valley species is invasion of non-native plants, particularly winter annuals. Mediterranean grass (*Schismus arabicus* and *S. barbatus*) is widespread and often abundant, and was first recorded in Arizona in the 1920s and '30s (Felger 1990). Sahara mustard (*Brassica tournefourtii*), a more recent introduction (Felger 2000), is often common in sandy flats and dunes. This species covered the Mohawk Dunes and surrounding areas during the wet winter of 2004-2005, and appears to be on the increase in the Yuma area. Also during the winter of 2004-2005, salad rocket (*Eruca vesicaria*) was the dominant vegetation in a swath along Interstate 8 from Gila Bend to west of Sentinel (~53 km), and was also prominent near Sonoyta. Additional non-native plants, such as Russian thistle (*Salsola tragus*), the perennial buffelgrass (*Pennisetum ciliare*), and many others are common locally, particularly in disturbed areas with relatively fertile soils (Brooks 1999; Wilson et al. 2002).

Probably the greatest effect non-native plants can have on the herpetofauna is increasing the fire frequency with subsequent major effects to vegetation communities. Historically, fire occurred only very rarely in Sonoran desertscrub (Schmid and Rogers 1988). Many Sonoran Desert plants are poorly adapted to fire and are readily killed. Desertscrub communities that burn, and particularly if they burn repeatedly, may take decades or centuries to recover (Schmid and Rogers 1988; Schwalbe et al. 2000; Narog and Wilson 2003), if such recovery is possible. In the spring of 2005, after the previous winter's luxurious growth of annual plants dried out, fires scorched at least 25,500 ha (63,010 ac) on the BMGR (Luke Air Force Base 2005) and 2,025 ha (5,000 ac) on CPNWR (C. McCasland, pers. comm. 2006). Fires burned especially hot in desert washes, killing palo verdes (*Parkinsonia floridum* and *P. microphylla*) and other trees, as well as saguaros (*Carnegiea gigantea*). Removing trees from this community would likely reduce or eliminate tree-dwelling species, such as ornate tree lizards (*Urosaurus ornatus*) and desert spiny lizards (*Sceloporus magister*), but would also reduce the availability of relatively mesic microsites that may be important for lizard and snake survival during drought (see discussion above).

Desert Bajada and Mountain Species

Five imperiled species occur primarily in desert mountain or bajada habitats, including desert tortoise, Gila monster, common chuckwalla, rosy boa, and Sonoran Desert toad (Appendix, Table 1). The latter species was discussed above under Riparian and Wetland Species, and is likely fairly secure where it occurs as a montane or bajada species in the eastern study area (Rosen and Lowe 1996). The common chuckwalla is widespread in montane areas, whereas the rosy boa is limited to mountains in the northeastern portion of the study area, the Gila Mountains, and perhaps elsewhere. The Gila monster and desert tortoise are more common in the study area's eastern portion, but occur as far west as the Gila Mountains (Appendix).

In general, montane habitats are much less affected by anthropogenic activities than desert flats and valleys. Urban and agricultural development, roads, OHV and most other recreational pursuits, military training, utility corridors, and other activities typically occur in the flats, rather than on hillsides or bajadas heavily dissected by drainages. Fire also does not burn as readily in montane habitats, where fuels are often discontinuous because of barren rock outcrops. The 2005 fires on the BMGR and CPNWR generally burned around mountain ranges and only rarely burned onto slopes.

The desert tortoise has been the subject of much conservation planning and implementation for more than two decades in Arizona (Howland and Rorabaugh 2002). The desert tortoise, including the Sonoran population (south and east of the Colorado River) and the Mojave population (north and west of the Colorado River), was petitioned for listing under the U.S. Endangered Species Act in 1985 and 1989, but only the Mojave population was listed as a threatened species (1990). The Sonoran population was petitioned again in 2008; and in 2009, the U.S. Fish and Wildlife Service found that it may warrant listing as a threatened or endangered species. The Mojave population occurs primarily in flats and valleys, while the Sonoran population occurs on bajadas and montane slopes.

The Arizona Interagency Desert Tortoise Team, which has included representatives from several land management agencies in the study area, developed a "Management Plan for the Sonoran Population of the Desert Tortoise in Arizona, 1996," which provides a number of management options for minimizing effects of human activities on the desert tortoise and its habitat, as well as research and monitoring recommendations. The plan is used by land managers in the development of land use plans, but its management guidance is not binding. A conservation agreement and strategy is in development for the Sonoran population in Arizona. If adopted, signators to the agreement would commit to implementing the guidance in the conservation strategy.

The common chuckwalla, the Gila monster, and rosy boa are desirable to herpetoculturists, and are often collected or poached. Gila monsters can bring $1,200 to $1,500 apiece on the black market. In Arizona, it is illegal under the Arizona Game and Fish Commission Order 43 to collect or possess a Gila monster; however, under the same order, limited numbers of common chuckwallas and rosy boas may be collected with a valid hunting license. No collection of these species is allowed in Sonora without a special permit. Goode et al. (2005) documented collection-related habitat destruction and declines in common chuckwalla populations in areas frequented by collectors on South Mountain near Phoenix. However, common chuckwalla populations persist and have been stable in five Phoenix mountain parks despite four of them being relatively small (less than 1,500 ha, or 3,706 ac), surrounded by urban development, and subjected to substantial recreational use and access (Sullivan and Flowers 1998; Sullivan and Sullivan 2008). Rosy boas may be impacted by collecting (Fisher 2003), which often occurs along paved roads through their habitat. However, even in heavily collected areas, such as Whitewater Canyon in Riverside County, California, rosy boas still persist (Spillman 2006). Hence, it may be difficult to extirpate a population of common chuckwallas or rosy boas via collecting or poaching alone, and in the remote regions of the study area, populations are probably relatively safe for now. Although some poaching occurs, collection is not known to be a significant threat to the Gila monster in the study area. Furthermore, the species is likely most abundant in protected areas, such as OPCNM.

Over a four-year period, Rosen and Lowe (1994) recorded snake mortality along a 44.1 km section of Route 85, which runs along the middle bajada through OPCNM from Why to

Lukeville. The number of snakes found dead was equivalent to the estimated snake population in a 5.0 km^2 (1.9 mi^2) area, or to eliminating all snakes within 65 m (213 ft) of the road. No rosy boas were found on the road during the study, but the authors presented evidence of it being collected on the road in previous decades. They suggested that its populations adjacent to the road had declined substantially due to road mortality.

CONCLUSIONS

The following conclusions target conservation priorities for imperiled amphibians and reptiles, but also address threats to the four major herpetofaunal communities in the study area. To maintain biodiversity, conservation often must focus on specific at-risk species and the sometimes very specialized habitats in which they occur. But taking a broader conservation perspective, an entire suite of species can be protected by targeting ecological communities. The most imperiled herpetofauna in the study area occur in communities that also support a variety of other sensitive or endangered plants and animals. If these communities can be protected, many of their imperiled species (herpetofauna and others) will be protected as well.

Recommended Actions

1) Conserve sea turtles in the Upper Gulf. Ultimately, if worldwide efforts to protect sea turtles are successful, all five species will probably continue to visit the Upper Gulf. Our focus locally should be to minimize or eliminate poaching and incidental bycatch, and to monitor sea turtle populations. Although significant threats remain, conservation of sea turtles in the Upper Gulf is achievable and much work has been accomplished towards that goal (Seminoff and Nichols 2007). Fishing regulations protective of sea turtles should be aggressively enforced in the Gulf of California, but there is also a critical need to work with local fishing communities and ejidos to build an understanding of the need for sea turtle conservation at the community level. The work of Drs. Nabhan and Seminoff, Grupo Tortuguero de las Californias, and CEDO, as well as outreach carried out by staff of the Alto Golfo Reserve, are models for this kind of work and should be supported and expanded.

2) Conserve the wetlands of the Río Sonoyta Valley. Unlike the Colorado and Gila Rivers, threats to the wetlands of the Río Sonoyta are manageable. Proposals by the Río Sonoyta/Quitobaquito Working Group should be funded and implemented. Furthermore, U.S. interests should continue to work with the Pinacate Reserve and others to find designs for the new wastewater treatment plant that will maintain flows in the Río Sonoyta and facilitate conservation of the sensitive species that depend upon it.

3) Breeding habitats of the Sonoran green toad and western narrow-mouthed toad should be located and protected.

4) Thorough surveys for special status riparian and wetland species should be conducted in the Río Colorado Valley. The status of the Sonoran Desert toad in the Foothills and Fortuna Wash should also be evaluated. Any breeding sites of this species should be protected.

5) Opportunities should be sought with the Alto Golfo Reserve in Sonora and through the Lower Colorado River Multi-Species Conservation Plan in Arizona to develop refugia populations of special status amphibians and reptiles of the Colorado and Gila Rivers, including those that have been extirpated. These managed wetland sites could potentially serve as refugia for a variety of native fishes, as well as native turtles, snakes, and amphibians.

6) Fires in Sonoran desertscrub should be aggressively suppressed, and feasible controls for non-native invasive plants should be developed and implemented. Aggressive suppression of fires can be an expensive management option, and may not be feasible in Sonora. Some plants with localized distributions in the study area, such as buffelgrass, can be mechanically controlled (Rutman and Dickson 2002); however, others will require

biological or other controls. Fire enhanced by invasive plants may be the most serious threat to biotic communities in desert valleys, and yet current control techniques are expensive and relatively ineffective or temporary.

7) Continue implementation of the Flat-tailed Horned Lizard Rangewide Management Strategy and Agreement, with an emphasis on bi-national coordination and cooperation. Protection of areas for the flat-tailed horned lizard also benefits other valley species, such as the Yuman fringe-toed lizard. An attempt should be made to bring the Border Patrol into the agreement as a signatory.

8) Finalize and implement the conservation agreement and strategy for the Sonoran population of the desert tortoise. This agreement and strategy should be a bi-national document.

9) Develop a bi-national working group to coordinate herpetofaunal conservation, monitoring, and research across jurisdictional boundaries north and south of the border. This group could perhaps examine herpetofaunal conservation needs and targets more thoroughly than I did here, and develop further recommendations for conserving the biodiversity of the area. This group could be a subcommittee of Partners in Amphibian and Reptile Conservation (PARC), and management recommendations could tier from and elaborate on PARC's "Habitat Management Guidelines for Amphibians and Reptiles of the Arid Southwest" (Woods et al. 2004). This group could also seek funding for key projects and conduct outreach to communities and stakeholders to build support for conservation actions.

10) Continue and strengthen management of protected areas. Additional staff, funding, and resources are needed in all protected areas to fully implement management plans, conduct public outreach, and enforce regulations.

11) Presence and distribution of the imperiled amphibians and reptiles listed in this chapter should be monitored. Additional monitoring of conservation management (including the implementation of plans and agreements), extent and trends in human impacts, climate change, and changes in biotic communities across the study area would be desirable. Feasible, consistent, and repeatable monitoring strategies that meet the needs of differing jurisdictions and plans could potentially be developed by the bi-national working group proposed in Recommended Action 9).

12) Conduct research to identify new tools for conservation or to improve the effectiveness of existing tools. In particular, new methods are needed to control non-native plant invasions in desertscrub. If effective means can be developed to control crayfish or bullfrogs in complex aquatic systems, some wetland habitats could potentially be restored for native amphibians and reptiles.

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Appendix. Checklist of the amphibians and reptiles of northwestern Sonora and southwestern Arizona.

Scientific and Common Names[1]	Distribution, Status, and Notes[2]
AMPHIBIANS	
Salamanders	
Ambystoma mavortium, Tiger Salamander, Ajolote, Salamandra Tigre	Collected at the Pozo Municipal, Puerto Peñasco, occasionally found in Colorado River region, probably due to escaped/released fish bait. ***Introduced***. **Pr**
Frogs and Toads	
Anaxyrus cognatus, Great Plains Toad, Sapo de las Grandes Planicias, Sapo	Gila River and associated croplands, Río Sonoyta and croplands, and occasional at impoundments in the eastern portion of study area. Rare on Colorado River.
Anaxyrus punctatus, Red-spotted Toad, Sapo Manchas Rojas, Sapo Pinto	Found widely at tanks, tinajas, and ponds particularly in mountains and in the eastern portions of the study area. Occasional in agriculture.
Anaxyrus retiformis, Sonoran Green Toad, Sapo Sonorense, Sapo	Breeds in ephemeral rain pools and cattle tanks in summer. Valley bottoms on eastern edge of study area from Lukeville to Why. **Pr**
Anaxyrus woodhousii, Woodhouse's Toad, Sapo de Woodhouse, Sapo	Colorado and Gila River valleys. Common in agriculture and along rivers.
Gastrophryne olivacea, Western Narrow-mouthed Toad, Ranita Olivo, Sapito	Recorded near Lukeville, may occur elsewhere in eastern edge of study area. Breeds in ephemeral pools in summer. **Pr**
Ollotis alvaria, Sonoran Desert Toad, Sapo Verde, Sapo Grande	Eastern portions of study area in Arizona and Sonora, as well as along the Gila River. May still occur at the Foothills and Fortuna Wash east of Yuma. Extirpated from the Colorado River, Arizona, but may still persist in the Río Colorado valley, Sonora, and Baja California.

continued

Appendix. Checklist of the amphibians and reptiles of northwestern Sonora and southwestern Arizona. *continued*

Scientific and Common Names[1]	Distribution, Status, and Notes[2]
Rana berlandieri, Río Grande Leopard Frog, Rana Leopardo	Colorado River valley, Sonora and Arizona, and Gila River valley – ***introduced*** from New Mexico or Texas in the 1960s or 1970s. Found in riverine (including Cienega de Santa Clara) and agricultural habitats. **Pr**
Rana catesbeianus, American Bullfrog, Rana de Toro, Rana Mugidora	Colorado and Gila River valleys, in riverine and agricultural habitats. ***Introduced***.
Rana yavapaiensis, Lowland Leopard Frog, Rana de Yavapai, Rana Leopardo	Historically found along Colorado and presumably Gila Rivers. Extirpated. **Pr**
Scaphiopus couchii, Couch's Spadefoot, Sapo de Espuela, Sapo	Breeds in ephemeral rain pools and cattle tanks in summer. Widespread, but absent from valleys of the Gran Desierto and the Yuma Desert.
Smilisca fodiens, Lowland Burrowing Treefrog, Ranita Minera, Rana	Breeds in ephemeral rain pools and cattle tanks during summer. Recorded near Why, may occur elsewhere in eastern edge of study area.
REPTILES	
Turtles	
Apalone spinifera, Spiny Softshell, Tortuga Verde	An ***introduced*** aquatic turtle of the Río Colorado and Gila River, as well as adjacent agricultural ditches and canals. **Pr**
Caretta caretta, Loggerhead Sea Turtle, Tortuga Caguama, Tortuga Perica	Large (to 1.1 m) and rare turtle of the Gulf of California. Not known to nest in Sonora. **P, EN, T**
Chelonia mydas, Green Sea Turtle, Parlama, Tortuga Negra,	Large (to 1.1 m) marine turtle of the Gulf of California. Most commonly encountered marine turtle on the coast of Sonora. Not known to nest in study area. **P, EN, E**
Dermochelys coriacea, Leatherback Sea Turtle, Laúd	Large (to 2.4 m, but typically < 1.0 m in the Gulf of California) and rare marine turtle. Not known to nest in study area. **P, CR, E**
Eretmochelys imbricate, Hawksbill Sea Turtle, Carey	Large (to 0.9 m, but most are 0.3-0.5 in the Gulf) marine turtle, which is more common in the southern portion of the Gulf. Not known to nest in Sonora. **P, CR, E**
Gopherus agassizii, Desert Tortoise, Tortuga del Monte, Galápago de Desierto	A large (to 0.4 m) terrestrial tortoise found in mountains and bajadas. Apparently absent from some ranges in western study area. **A, VU**
Kinosternon sonoriense, Sonoran Mud Turtle, Tortuga de Agua, Casquito de Sonora	Currently an aquatic stream and pond turtle of the Río Sonoyta and adjacent wetlands, including Quitobaquito. Likely extirpated from Colorado and Gila Rivers. **VU, C**
Lepidochelys olivacea, Olive Ridley Sea Turtle, Tortuga Golfina	Large (to 0.7 m) marine turtle of the Gulf of California. Nests rarely on beaches as far north as Puerto Peñasco and El Golfo de Santa Clara. **P, EN, T**
Trachemys scripta, Pond Slider, Tortuga Pinta	Occasional in aquatic habitats near Yuma. ***Introduced***. No evidence of breeding. **Pr**

continued

Appendix. Checklist of the amphibians and reptiles of northwestern Sonora and southwestern Arizona.
continued

Scientific and Common Names[1]	Distribution, Status, and Notes[2]
Lizards	
Aspidoscelis tigris, Tiger Whiptail, Huico Occidental	Throughout study area in valleys, mountains, and riparian woodlands.
Aspidoscelis xanthonota, Red-backed Whiptail, Huico, Huico de Dorso Rojo	Known from mountains in northeastern portion of study area. Not documented in Sonora, but likely occurs in one or more of the Sierras Cubabi, San Francisco, and Pinacate.
Callisaurus draconoides, Zebra-tailed Lizard, Cachora	Flats and valleys. Particularly common in sandy or gravelly flats and washes. **A**
Coleonyx variegatus, Western Banded Gecko, Cuija Manchada Occidental	Throughout valleys and bajadas in the study area, occasional in lower montane canyons. Nocturnal. **Pr**
Crotaphytus nebrius, Sonoran Collared Lizard, Lagartija de Collar, Cachorón	Rocky mountains and bajadas, throughout the study area.
Dipsosaurus dorsalis, Desert Iguana, Iguana, Iguana del Desierto	Throughout flats and bajadas. Particularly abundant in the valleys of the arid Gran Desierto and Yuma Desert.
Gambelia wislizenii, Long-nosed Leopard Lizard, Cachorón, Cachorón Mata Caballo	Flats and valleys throughout the study area. **Pr**
Heloderma suspectum, Gila Monster, Escorpíon, Escorpíon Pintado	Primarily a montane and bajada species, most common in the eastern half of the study area. Venomous. **A, VU**
Hemidactylus turcicus, Mediterranean House Gecko, Geco Pinto	This ***introduced*** nocturnal gecko is found in cities and towns, often in and around buildings at night. Occurs at Yuma, Gila Bend, and El Golfo de Santa Clara. Reported from San Luis Río Colorado. Likely occurs locally at Puerto Peñasco.
Phrynosoma goodei, Goode's Horned Lizard, Camaleón de Sonora	Widespread, but within the range of *P. mcallii*, typically found in coarser sands closer to mountains.
Phrynosoma mcallii, Flat-tailed Horned Lizard, Camaleón de Cola Plana, Camaleón del Gran Desierto	Arid, sandy flats and low dunes of the Gran Desierto and Yuma desert from Yuma southeast to Bahia San Jorge. **PT, A**
Phrynosoma solare, Regal Horned Lizard, Camaleón Real	Flats in eastern portion of study area. Absent from west of Crater MacDougal and Agua Dulce Mountains.
Sauromalus ater, Common Chuckwalla, Iguana,	Large-bodied lizard of rocky slopes and outcrops throughout the study area. **A**
Sceloporus clarkii, Clark's Spiny Lizard, Lagartija Espinosa de Clark, Cachora	Relatively mesic canyons in the Ajo and other mountains in the eastern edge of the study area. Often found in trees, sometimes on the ground or in rocks.
Sceloporus magister, Desert Spiny Lizard, Lagartija Espinosa del Desierto, Cachorón	Throughout the study area, except for treeless valleys in the Gran Desierto and Yuma Desert. Found on trees or rocks.

continued

Appendix. Checklist of the amphibians and reptiles of northwestern Sonora and southwestern Arizona. *continued*

Scientific and Common Names[1]	Distribution, Status, and Notes[2]
Uma rufopunctata, Yuman Fringe-toed Lizard, Cachora, Lagartija de Manchas Laterales	Patchily distributed in dunes and flats with fine, windblown sand from near Dateland to the Yuma Desert and south to the Gulf of California. **A**
Urosaurus graciosus, Long-tailed Brush Lizard, Cachorrita, Lagartija de Matorral.	Typically found on the branches of creosote, mesquite and other shrubs or trees in the valleys in the study area. Rare in eastern study area and distribution poorly known in Sonora.
Urosaurus ornatus, Ornate Tree Lizard, Lagartija de Árbol, Cachorita	Typically found on trees or rocks. Throughout study area, but patchy distribution in the western deserts. Common in riparian woodlands and urban landscaping. Absent from treeless valleys.
Uta stansburiana, Common Side-blotched Lizard, Cachora Gris	Widespread throughout the study area in flats and mountains.
Xantusia vigilis, Desert Night Lizard, Cuija, Salamanquesa	Isolated montane localities. Typically found under dead agaves, Yuccas, and Nolinas. Primarily nocturnal.
Snakes	
Arizona elegans, Glossy Snake, Culebra Brillante	Primarily a species of flats and valleys. Throughout the study area.
Chilomeniscus stramineus, Variable Sandsnake, Culebra de los Médanos, Coralillo	Primarily a burrowing species of sandy or gravelly arroyos with leaf litter. Probably absent from western valleys. **Pr**
Chionactis occipitalis, Western Shovel-nosed Snake, Culebra Palanaria Occidental	Flats and valleys throughout. Abundant in sandy flats and low dunes.
Chionactis palarostris, Sonoran Shovel-nosed Snake, Coralillo Falso	Eastern edge of study area from near Why south into Sonora in gravelly bajadas and sandy to rocky flats with relatively open vegetation.
Coluber bilineatus, Sonoran Whipsnake, Chirrionera, Alicante	Mountains and bajadas in northeastern portion of study area; also in Sierra Pinacate. Often arboreal.
Coluber flagellum, Coachwhip, Chirrionera, Alicante	Throughout, primarily in valleys and bajadas. Found primarily on the ground, but occasionally in trees and shrubs. **A**
Crotalus atrox, Western Diamond-backed Rattlesnake, Víbora Serrana, Cascabel	Species of bajadas, washes, and riparian areas. Common in the latter habitat. Absent from valleys of the western Gran Desierto and Yuma Desert. Highly venomous. **Pr**
Crotalus cerastes, Sidewinder, Cuernitos	Small (< 0.8 m) horned rattlesnake of sandy flats and bajadas throughout. Abundant in sandy western valleys. Highly venomous. **Pr**
Crotalus mitchelli, Speckled Rattlesnake, Víbora Blanca	Rocky mountains and bajadas in the Pinacate region of Sonora and throughout Arizona portion, except for most ranges at Organ Pipe Cactus NM. Highly venomous. **Pr**
Crotalus molossus, Black-tailed Rattlesnake, Cola Prieta, Cascabel	Rocky slopes and canyons likely throughout the study area. Highly venomous. Rarely encountered in western mountain ranges. **Pr**

continued

Appendix. Checklist of the amphibians and reptiles of northwestern Sonora and southwestern Arizona. *continued*

Scientific and Common Names[1]	Distribution, Status, and Notes[2]
Crotalus scutulatus, Mojave Rattlesnake, Cascabel	Valleys and bajadas, particularly in the east. Absent from western Gran Desierto (west of Sierra del Rosario) and Yuma Desert. Highly venomous. **Pr**
Crotalus tigris, Tiger Rattlesnake, Cascabel, Cascabel del Tigre	Small (< 0.9 m) rattlesnake of rocky slopes and canyons in eastern portions of study, especially at Organ Pipe Cactus NM. Highly venomous. **Pr**
Hypsiglena chlorophaea, Nightsnake, Culebra Nocturna	Mountains and bajadas, absent from valleys of the Gran Desierto and the Yuma Desert. **Pr**
Lampropeltis getula, Common Kingsnake, Culebra Real Común	Most common in riparian corridors and agriculture, likely absent from drier western ranges and valleys. **A**
Leptotyphlops humilis, Western Threadsnake, Culebrilla Ciega de Occidente	Probably more common in eastern portion of study area. Likely absent from arid valleys of the Gran Desierto and the Yuma Desert. Small, secretive, burrowing species.
Lichanura trivirgata, Rosy Boa, Boa Rosada	Montane species of the northeastern study area, but also the Gila and Tinajas Altas mountains and Sierra Pinacate. Likely occurs elsewhere. **A**
Micruroides euryxanthus, Sonoran Coralsnake, Coralillo, Coralillo Occidental	Eastern edge of study area. Organ Pipe Cactus NM, Agua Dulce Mountains, presumably mountains and bajadas in eastern study area in Sonora. Highly venomous. **A**
Pelamis platurus, Yellow-bellied Sea Snake, Alicante del Mar	Ranges throughout the Gulf of California, but does not breed in our area. Highly venomous, although it rarely bites.
Phyllorhynchus browni, Saddled Leaf-nosed Snake, Culebrita	Northeastern portion of study area in foothills and bajadas. Often in gravelly or sandy soils. **Pr**
Phyllorhynchus decurtatus, Spotted Leaf-nosed Snake, Culebrita	Typically found in sandy or gravelly soils in valleys and bajadas. Absent from western valleys.
Pituophis catenifer, Gophersnake, Cincuate, Víbora Sorda	Widespread, but likely absent from arid valleys in the western Gran Desierto and Yuma Desert. Common in riparian and agriculture.
Rhinocheilus lecontei, Long-nosed Snake; Coralillo Falso	Likely absent from arid valleys in the Gran Desierto and Yuma Desert. Elsewhere fairly common. Occasional in agriculture.
Salvadora hexalepis, Western Patch-nosed Snake, Culebra Chata	Throughout, but most common in valleys. Diurnal.
Sonora semiannulata, Western Groundsnake, Culebra de Arena	In urban, agricultural, and riparian habitats along the Río Colorado and presumably Gila River. Distribution elsewhere poorly understood.
Tantilla hobartsmithi, Smith's Black-headed Snake, Culebra Cabeza Negra del Suroeste	Mesic canyons in the Ajo Mountains, but also near Sonoyta. Reported from the Gila River at Wellton.
Thamnophis cyrtopsis, Black-necked Gartersnake, Culebra de Agua, Culebra Lineada de Bosque	Mesic canyons in the Ajo Mountains. Diurnal. **A**

continued

Appendix. Checklist of the amphibians and reptiles of northwestern Sonora and southwestern Arizona.
continued

Scientific and Common Names[1]	Distribution, Status, and Notes[2]
Thamnophis eques, Mexican Gartersnake, Culebra de Agua, Culebra de Agua Nómado Mexicano	A highly aquatic species, formerly occurred near Yuma and presumably elsewhere on the Colorado and Gila Rivers. Extirpated. **A, C**
Thamnophis marcianus, Checkered Gartersnake, Culebra de Agua, Sochuate	Marshy wetlands and agriculture along or near the Colorado and Gila Rivers near Yuma. Ciénega de Santa Clara and likely elsewhere in the Río Colorado Valley of Sonora. **A**
Trimorphodon biscutatus, Western Lyresnake, Víbora Sorda	Rocky hillsides and bajadas throughout the study area.

[1] Nomenclature based on Crother (2008), except that Spanish common names are taken from Liner and Casas-Andreu (2008) or are names used locally. [2] Status corresponds to Mexico's 'Lista de Especies en Riesgo" (SEMARNAT 2008), including **P** = in danger of extinction, **A** = threatened, and **Pr** = species of special protection; IUCN's Redlist, including **CR** = critically endangered, **EN** = endangered, **VU** = vulnerable, and **NT** = near threatened; and U.S. Endangered Species Act, including **C** = candidate for listing and **PT** = proposed threatened, **T** = threatened, and **E** = endangered.

OBSERVATIONS ON THE STATUS OF AQUATIC TURTLES AND THE OCCURRENCE OF RANID FROGS AND OTHER AQUATIC VERTEBRATES IN NORTHWESTERN MEXICO

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The aquatic vertebrate fauna in the arid southwestern United States is highly imperiled by the combined action of habitat destruction, habitat modification, introduction of exotic species, and introduced diseases and parasites (Minckley and Deacon 1991; Rinne and Minckley 1991; Rosen and Schwalbe 2002a). Although much less completely documented, it appears that similar processes are more recently (Unmack and Fagan 2004) becoming manifest in arid northwestern Mexico (Hendrickson et al. 1980; Hendrickson 1983; Contreras-Balderas and Escalante Cavasos 1984; Miller et al. 2005). Although severe in Mexico, the problem appears to be developing later than in the U.S., with similar ecological symptoms apparently time-lagged by about 4 decades. (Unmack and Fagan 2004). Armed with this knowledge, perhaps Mexico might abate and mitigate the catastrophic ecological situation that is occurring in the U.S.

The status of aquatic, perennial-water herpetofauna in Mexico is poorly known and documented, and no published details are available in arid northwestern Mexico for this assemblage, which shares many species, habitat characteristics, and conservation problems with the aquatic herpetofauna of the U.S. Southwest. In connection with a survey of mud turtles (genus *Kinosternon*) to obtain additional material for an ongoing genetic study at localities in Sonora and northwestern Chihuahua, we had the opportunity to conduct a rapid assessment of occurrence and status of aquatic herpetofauna. We focused on the turtles and, especially, ranid frogs (family Ranidae), which are impacted by exotic species and disease throughout the American West (Rosen 2008; Lannoo 2005). Based on long-term familiarity with this ecological system and its components in Arizona and New Mexico, our surveys allowed us to assess habitat conditions and introduced species such as bullfrogs, crayfish, and non-native fishes known to be affecting native frogs in adjoining parts of the U.S. (Hayes and Jennings 1986; Rosen et al. 1995; Rosen and Schwalbe 2002b). Here we present the results of this autumn 2005 survey, and compare them to species status and habitat conditions in the Sonoran Desert and Madrean regions of the United States.

METHODS

Sampling and Identification

During the period 22 September through 11 November 2005 we sampled 39 localities in Sonora and northwestern Chihuahua (Figure 1, Table 1). The targeted localities were chosen based on museum records for mud turtles (genus *Kinosternon*), with additional sites sampled whenever time and access permitted along the extensive survey routes. Sites were sampled using a combination of baited hoop traps, dipnetting, seining, and visual encounter survey (Crump and Scott 1994) for periods of 0.5-13.25 hours. Although the objective was to obtain blood samples from turtles for a continuing phylogeographic study (Rosen 2003), and much time was spent traveling between the widely scattered localities, sites reported here were sampled as thoroughly as possible for fishes, amphibians, reptiles, and crayfish. However, since only single site visits were made, our data do not represent an exhaustive sampling of the aquatic fauna.

We made efforts to capture, identify, and obtain photographic vouchers for all aquatic species observed. This was not always possible, and some taxa could not be reliably identified from our photographs. For leopard frogs, we assigned species based on geographic range indicated by Frost and Bagnara (1976), which largely corresponded to our estimates based on our gestalt (field-based) identifications. Reptiles that were not captured but were tentatively identified with binoculars are indicated with a "?" in the tables. Although specimens could not be collected, all crayfish we observed appeared to be the exotic northern crayfish (*Orconectes*

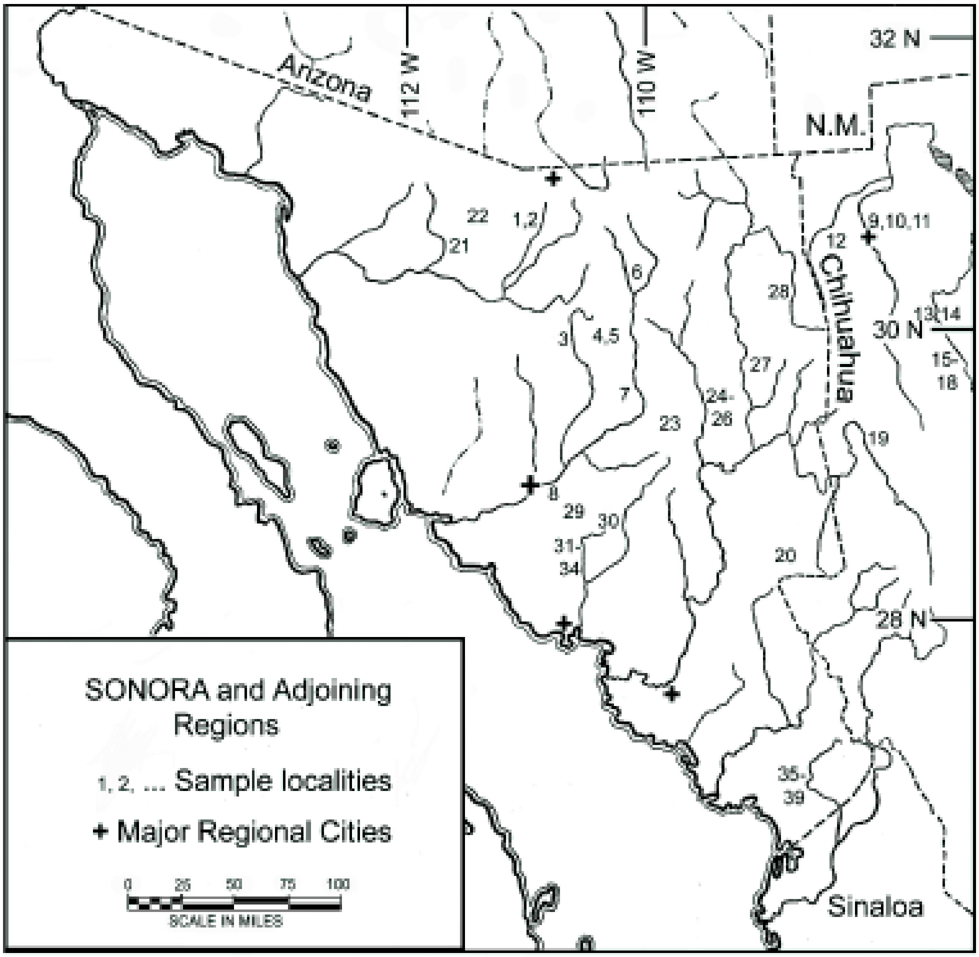

Figure 1. Localities sampled for turtles and other aquatic vertebrates during fall 2005.

virilis), as in most of Arizona and previously reported for Chihuahua (Hobbs 1989).

Fishes were identified in hand and from voucher photographs, and confirmed with reference to Miller et al. (2005). Although we suspect that most of the cichlid fishes we observed were redbelly tilapia (*Tilapia zillii*), except at Alamos and in Ojo de Agua on Río Mátape, and are reasonably certain all were non-native, we could not confirm cichlid identifications and therefore report all cichlids as "*Tilapia* sp." Similarly, topminnows were identifiable as *Poeciliopsis occidentalis* (or *P. sonoriensis*) based on the presence of dark males; we made no attempt to treat the problem of accompanying all-female species, and list all our records under the genus name.

Names of animals discussed in text and tables are collated in Table 2. We have utilized common names as in Crother (2001), Liner (1994), Schwalbe and Lowe (2000), and Miller et al. (2005) with slight modifications for clarity and conciseness, as follows. We retain the generic names *Bufo* and *Rana*, following Pauly et al. (2009). For *Kinosternon sonoriense*, we use the name, "Sonoran Mud Turtle", rather than "Sonora Mud Turtle" because the latter is a recent misnomer that misleads regarding the distribution of the species, which is clearly associated with the Sonoran biogeographic region but not restricted to or centered on the state of Sonora.

Relative Abundance and Ranking

For numerical analysis of abundance patterns, we converted categorical abundance values to ordinal ranks (Tables 3 and 4). The methodological design and ordinated categories used in this rapid assessment follow from experience surveying for and categorizing abundance of aquatic herpetofaunal taxa in Arizona (Rosen and Schwalbe 1988, 2002b; Rosen 1987). This ensures that within-study comparisons among sites are un-biased and reflect similar observations reported for Arizona by the senior author.

Here, details are provided to make clear the observational bases underlying the ranked values for abundance to facilitate comparison to other and future studies. Survey times (Table 1) were matched, as nearly as possible, to the needs presented by habitat complexity and extent. In all cases, environments were searched for visible (resting, sun-basking, under-cover hiding, and surfacing) animals; clear water was searched visually for visible fish and tadpoles. If appropriate, each site was sampled using a long-handled dipnet (2 m handle, 4 mm mesh) including random sweeps and directed capture to identify animals. Trapping (Table 1) was carried out for turtles and large fishes for the time periods indicated in the table. Deeper waters were seined (25 ft x 6 ft deep, 4 mm mesh bag seine) when feasible to capture large fish for identification and when low water clarity prevented observations of fish relative abundance. However, most species identifications of larger fish taxa were confirmed based on captured small conspecifics.

For springs and small ponds, the entire perimeter was walked and searched, and dipnetting was carried out systematically in suitable habitat cover. Similar methods were used in larger systems, except that (a) lotic systems or large reservoirs were not sampled in their entirety, but only within 1-3 km of the coordinates given in Table 1, (b) searches were made widely to encompass maximal habitat diversity within available time, (c) auspicious habitat, based on prior experience, was accorded a majority of search time, while (d) apparently suboptimal habitat was spot-sampled to avoid allowing pre-conceived ideas about habitat to go unchecked under the potentially different circumstances of Sonora compared to Arizona.

In a rapid assessment survey, direct, numerical data on abundance and population density cannot be collected. Experience has shown that these assessments, with ordinal ranking of abundance, have great value for resource managers and subsequent surveyors (e.g., Holycross et al. 2006 use of Rosen and Schwalbe 1988). The ranked categories are defined as follows: 0 (absent) = none seen; 1 (rare) = one or a very few (generally less than four) specimens seen compared to taxon-specific expectation (see below); 2 (uncommon) = few seen (e.g., generally 8 or less), and generally less than expected for abundant populations observed in Arizona; 3 (common) = individuals seen in moderate to low numbers over extensive portions of the sample area, and total numbers generally 9 or greater for abundant species like frogs or involving schools of fish; 4 (abundant) = consistently observed individuals throughout extensive portions of sample area, and generally always present in suitable habitat; 5 (super-abundant) = species visible in high numbers throughout sampling area, at densities exceeding those seen under usual circumstances for the taxon, and in numbers totaling in the teens (turtles), hundreds (ranid frogs or larger fish species), or thousands in extensive schools (tadpoles, smaller fish species, and juvenile fish). Naturally uncommon or rarely observed

Table 1. Localities surveyed, survey time, and sampling methods (V = visual encounter survey; T = baited hoop net; D = dipnetting) for turtles and other aquatic animals during Fall 2005 in Sonora and Chihuahua..

Location		UTM (NAD-27)			Elev.	Sampling		
No.	Locality Description	Zone	Easting	Northing	(ft.)	Date	Time	Method
1	Son., Río Magdalena - Teranate	12R	507832	3398832	NA	09/22/05	2:00	V, D
2	Son., Río Magdalena - bridge to Teranate	12R	513072	3404692	NA	09/22/05	0:45	V, D
3	Son., Rió San Miguel de Horcasitas near Cucurpe	12R	528002	3354356	NA	09/22/05	2:00	V, D
4	Son., Rancho Agua Fria wash, Saracachi Ciénega	12R	541549	3357976	NA	09/23/05	1:00	V
5	Son., Saracachi Ciénega	12R	539026	3358469	NA	09/23/05	8:00	V, T, D
6	Son., Río Sonora just N of Arizpe	12R	583972	3358173	NA	09/24/05	1:00	V, D
7	Son., Sierra Aconchi at Agua Caliente Spring Canyon	12R	569694	3301863	NA	09/24/05	2:45	V, D
8	Son., Presa Molinito, Rió Sonora E of Hermosillo	12R	526392	3231339	NA	09/24/05	1:15	V, D
9	Chih., Río Casas Grandes Hwy bridge N Casas Grandes Viejo	13R	217822	3364072	4813	10/11/05	2:25	V, T, D
10	Chih., Río Casas Grandes, tajo W Nuevo Casas Grandes	13R	217321	3368690	NA	10/12/05	2:40	V, D
11	Chih., Casas Grandes, Rancho La Princesa house pond	13R	217532	3368366	NA	10/12/05	1:45	V, D
12	Chih., Río Piedras Verdes ca. 1.7 mi SE of Colonia Juarez	12R	783651	3354182	NA	10/12/05	3:49	V, D
13	Chih., Galeana, Angostura pool/spg near Ojo de Arreys	13R	250247	3327924	4900	10/13/05	6:00	V
14	Chih., Galeana, Angostura town, bulldozed pond & vicinity	13R	249745	3326672	4900	10/13/05	0:30	V, D
15	Chih., Río Santa Maria, Buenaventura, S of Chih Hwy 28	13R	261048	3303204	5131	10/14/05	2:00	V, T, D
16	Chih., Río Santa Maria, Buenaventura, rastro N Chih Hwy 28	13R	260339	3304324	5110	10/14/05	1:15	V, T, D
17	Chih., floodplain acequia pond ca. 4 mi S Buenaventura	13R	262484	3300382	NA	10/14/05	0:30	V, D
18	Chih., Río Santa Maria irr. headgate, ca. 5 mi S Buenaventura	13R	263772	3296396	NA	10/14/05	0:30	V, D

continued

species, or those for which our sampling methods or seasonality were insufficient to permit estimates of relative abundance, were categorized as absent (0) or present (+); these observations are included for future reference and were not used in the analyses presented in this paper. Although it is admittedly impossible to precisely specify the way ordinal ranks were assigned, we have little doubt that experienced observers, accustomed to assigning such values in the field, would produce roughly similar and consistent relative abundance values.

In order to summarize the ordinal abundance data into broader measures reflective of overall fish abundance patterns (native fish abundance, exotic fish abundance, exotic predatory fish abundance) we created indices by summing the ordinal ranks for these categories. From these, standardized indices of the relative dominance of native versus exotic fish

Table 1. *continued*

Location		UTM (NAD-27)			Elev.	Sampling		
No.	Locality Description	Zone	Easting	Northing	(ft.)	Date	Time	Method
19	Chih., Río Papagochic at Yepomera, at Chih Hwy 16	13R	221193	3218796	6349	10/14/05	2:30	V, T, D
20	Son., Yecora, stream in meadow 0.4 mi S of Mex Hwy 16	12R	703736	3138788	5075	10/15/05	4:45	V, T, D
21	Son., Río Altar, Presa Cuatemoc	12R	450785	3416147	NA	10/22/05	0:30	V
22	Son., Río Altar at Tubutama bridge	12R	455537	3417098	2050	10/22/05	1:49	V, D
23	Son., tank along Mex Hwy 14 W of Moctezuma	12R	617942	3293168	3545	10/27/05	1:00	V, D
24	Son., Río Moctezuma S of Jecori	12R	621269	3310352	NA	10/27/05	3:30	V, D
25	Son., Río Moctezuma at presa near Mex Hwy 14	12R	625987	3296664	2048	10/28/05	0:30	V, D
26	Son., Río Moctezuma N of Jecori (Jamaica)	12R	619951	3315235	NA	10/28/05	4:45	V, T, D
27	Son., Río Bavispe, N of Huasabas	12R	665423	3314947	1809	10/28/05	12:15	V, T, D
28	Son., Río Bavispe, S of Bavispe	12R	699744	3367785	3284	10/30/05	13:15	V, T, D
29	Son., La Colorada (presa just N of town)	12R	540865	3186789	1267	11/05/05	1:08	V, D
30	Son., Río Mátape at Hwy 16 near San Jose de Pima	12R	563683	3176913	1180	11/05/05	2:14	V, D
31	Son., Río Mátape ca. 4 mi S of San Jose de Pima	12R	562640	3173996	NA	11/05/05	0:45	V, D
32	Son., Rancho Ojo de Agua, NE of La Misa	12R	567439	3149138	826	11/05/05	12:00	V, T, D
33	Son., isolated spring just NW Punta de Agua, vic. La Misa	12R	558735	3145084	773	11/06/05	0:50	V, D
34	Son., laguna below dam at Punta de Agua (nr La Misa)	12R	558739	3144330	NA	11/06/05	0:30	V, D
35	Son., Sierra de Alamos, aguaje SE of Rancho La Sierrita	12R	704379	2985841	1520	11/09/05	0:45	V, D
36	Son., Alamos, Rancho Las Cabras	12R	708143	2987805	NA	11/10/05	0:45	V, D
37	Son., Alamos, tank nr Río Cuchujaqui, SSE Las Uvalamas	12R	707428	2977582	NA	11/11/05	1:25	V, D
38	Son., Alamos, pool along El Chinal Rd 4.2 mi S Las Uvalamas	12R	706211	2977489	NA	11/11/05	0:30	V, D
39	Son., Alamos, concrete well tank at (S of) Rancho Las Sierrita	12R	703997	2984964	1770	11/11/05	0:30	V

Table 2. Scientific and common names of animals referred to in text and tables. Asterisk indicates the common name given differs from cited sources.

Scientific Name	English Name	Spanish Name	Family
Bufo alvarius	Sonoran Desert Toad	sapo grande sonoriense *	Bufonidae
Hyla arenicolor	Canyon Treefrog	ranita de canon	Hylidae
Pachymedusa dacnicolor	Mexican Leaf-frog	rana verduzca	Hylidae
Smilisca fodiens	Lowland Burrowing Treefrog	ranita excavador *	Hylidae
Smilisca baudini	Mexican Treefrog	rana trepadora	Hylidae
Leptodactylus melanonotus	Sabinal Frog	ranita sabinal	Leptodactylidae
Gastrophryne olivacea	Great Plains Narrow-mouthed Toad	ranita boca cónica *	Microhylidae
Rana catesbeiana	American Bullfrog	rana de toro *	Ranidae
Rana magnaocularis	Big-eyed Leopard Frog	rana leopardo ojos grandes *	Ranidae
Rana tarahumarae	Tarahumara Frog	rana de Tarahumara	Ranidae
Rana yavapaiensis	Lowland Leopard Frog	rana leopardo de Yavapai *	Ranidae
Orconectes virilis	Northern Crayfish	cangrejo norteño	Cambaridae
Catostomus bernardini	Yaqui Sucker	matalote Yaqui	Catastomidae
Catostomus wiggensi	Opata Sucker	matalote opata	Catastomidae
Lepomis cyanellus	Green Sunfish	pez sol	Centrarchidae
Micropterus salmoides	Largemouth Bass	lobina negra	Centrarchidae
cichlid sp.	unknown cichlid	mojarra no conocido	Cichlidae
Tilapia zillii	Redbelly Tilapia	tilapia	Cichlidae
Agosia chrysogaster	Longfin Dace	pupo panzaverde	Cyprindae
Agosia sp.	Mexican Longfin Dace	pupo mexicano	Cyprindae
Campostoma ornatus	Mexican Stoneroller	rodapiedras mexicano	Cyprindae
Cyprinella formosa	Beautiful Shiner	carpita Yaqui	Cyprindae
Cyprinus carpio	Common Carp	carpa comun	Cyprindae
Gila ditaenia	Sonora Chub	carpa sonoriense	Cyprindae
Gila eremica	Desert Chub	carpa del desierto	Cyprindae
Pimephales promelas	Fathead Minnow	carpita cabezona	Cyprindae
Rhinichthys osculus	Speckled Dace	carpita pinta	Cyprindae
Cyprinodon eremus	Quitobaquito Pupfish	cachorrito del Sonoyta	Cyprindontidae
Ameiurus melas	Black Bullhead	bagre torito negro	Ictaluridae
Gambusia affinis	Western Mosquitofish	guayacon mosquito	Poeciliidae
Poeciliopsis occidentalis	Gila Topminnow	guatapote de Sonora	Poeciliidae
Trachemys yaquia	Yaqui Slider	jicotea Yaqui	Emydidae
Kinosternon hirtipes	Rough-footed Mud Turtle	casquito de pata rugosa	Kinosternidae
Kinosternon integrum	Mexican Mud Turtle	casquito de burro	Kinosternidae
Kinosternon sonoriense	Sonoran Mud Turtle	casquito de Sonora	Kinosternidae
Thamnophis cyrtopsis	Black-necked Gartersnake	culebra lineada de bosque	Natricidae
Thamnophis eques	Mexican Gartersnake	culebra de agua Mexicana *	Natricidae

at individual sites were constructed by dividing their abundance indices by total abundance index for all fish.

Statistical Tests and Assumptions

Two-sample tests and non-parametric analysis of covariance (ANCOVA on the ordinal rank values; Quade 1967, Shirley 1981, Marascuilo and McSweeney 1977) were performed using SAS-JMP version 5.1 on a personal computer. Sample sizes were not large, and we therefore performed visual checks of graphical material for approximate normality and homogeneity of slopes for parametric two-sample and

ANCOVA tests, respectively. The ANCOVA is presented as a means to summarize the dataset: this study was conducted under uncontrolled, natural conditions with many operative factors and possible, unknown covariates. The ANCOVA has heuristic value for understanding the dataset numerically, but its result is interpreted as a preliminary evaluation and hypothesis regarding the relative impact of exotic fishes versus bullfrogs on native ranid frog abundance.

In this analysis we have assumed that native leopard frogs originally occurred in all regions and major waters sampled, an assumption justified by examination of museum records in the University of Arizona herpetology collection, as well as in the literature (Frost and Bagnara 1976; Platz and Frost 1984). This does not imply that these frogs are or were equally abundant within each region, but only that it was potentially possible to find native ranid frogs in the each of the regions, had these regions not been differentially occupied by exotic species. Our experience and the more extensive museum voucher record in Arizona and New Mexico support this assumption. One area we visited during 2005, Río Sonoyta, has never yielded leopard frog specimens, and we believe they were not present in historic times, and have therefore excluded it from the ranid frog analysis. This site will be reported on elsewhere (Rosen et al., this volume).

RESULTS

We observed 16 species of aquatic herpetofauna (Table 3), defined to include those species requiring perennial water or at least using it occasionally for breeding. We also observed crayfish, in Chihuahua only (Table 3), and at least 14 species of fishes (Table 4).

Aquatic Reptiles

Although all historic museum localities that we revisited were considered suitable for mud turtles, we found mud turtles at only 8 of 15 (53 %) of them. Not all of the other visited sites were considered suitable for mud turtles: some were isolated and semi-perennial, concreted springs, or very large reservoirs, and these were considered unsuitable (i.e., non-habitat) and, in the case of large reservoirs, were impractical to survey adequately in any case. Of the non-historic, but apparently suitable areas sampled, 12 of 17 (71 %) were occupied, not significantly different from the proportion of historic localities where we found turtles ($\chi^2 = 2.0$, $p > 0.1$), indicating, not unexpectedly, a wider distribution of mud turtles than defined by the museum localities.

Major impacts on turtle populations were apparent in the Guzman Basin (Ríos del Carmen, Santa Maria, and Casas Grandes) of northwestern Chihuahua. Río Casas Grandes supported many exotic species reported or suspected to impact the Sonoran mud turtle (Rosen and Schwalbe 2002a; Rosen 2008), including bullfrogs, crayfish, and common carp. Habitat desiccation and modification was widespread, and we could not capture any mud turtles in this region. Similarly, near Galeana, Chihuahua, drought and agricultural water use were reported to have completely desiccated all major streams, springs, and cienegas. We found only two terrestrially active rough-footed mud turtles at a recently desiccated historic locality at which turtles had previously (J. Iverson, pers. comm. 2009) and recently (S. McGaugh, pers. comm. 2005) been very abundant. Although drought conditions were widespread in the region, local people we interviewed indicated the widespread failure of springs was a recent phenomenon, and they attributed it to groundwater pumping for agriculture. Thus, although aquatic turtles are persisting in the Guzman Basin (Table 3), we were able to locate little suitable habitat for sampling during our 1.5-day survey effort.

In Sonora, most of the flow of major streams including the Río San Miguel de Horcasitas, Río Sonora, and Río Moctezuma was being diverted by small, established or temporary, diversion dams and levees, and almost all water deep enough for the Sonoran mud turtle was localized as a result. Small habitat areas remained at the diversion structures, or in widely scattered scour pools adjoining or near the main channel. Although we captured turtles in some of these streams, it was apparent that

Table 3. Herpetofauna, and crayfish, observed at localities surveyed during Fall 2005 in Sonora and Chihuahua. Symbols are as follows: r = rare, u = uncommon, c = common, a = abundant, s = super-abundant. A + indicates "present", without estimate of relative abundance. Question mark indicates the species was observed but identification was not confirmed by capture.

Locality Number	*Rana yavapaiensis*	*R. magnaocularis*	*R. tarahumarae*	*R. catesbeiana*	*Hyla arenicolor*	*Smilisca fodiens*	*S. baudini*	*Leptodactylus melanonotus*	*Gastrophryne olivacea*	*Kinosternon sonoriense*	*K. hirtipes*	*K. integrum*	*Trachemys scripta yaquia*	*Chrysemys picta*	*Thamnophis cyrtopsis*	*T. eques*	*Orconectes* cf. *virilis*	Total Species
1	-	-	-	u	-	-	-	-	-	-	-	-	-	-	-	-	-	1
2	-	-	-	u	-	-	-	-	-	-	-	-	-	-	-	-	-	1
3	u	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1
4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
5	s	-	-	-	-	+	-	-	-	a	-	-	c	-	-	-	-	4
6	u	-	-	-	-	-	-	-	-	u	-	-	-	-	-	-	-	2
7	u	-	u	-	c	-	-	-	+	u	-	-	-	-	+	-	-	6
8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
9	-	-	-	c	-	-	-	-	-	-	-	-	-	-	-	-	c	2
10	-	-	-	a	-	-	-	-	-	u?	-	-	u?	+	-	-	-	4
11	-	-	-	a	-	-	-	-	-	-	-	-	-	-	-	-	-	1
12	-	-	-	u	-	-	-	-	-	a	-	-	-	-	-	-	u	3
13	-	-	-	-	-	-	-	-	-	-	u	-	-	-	-	-	-	1
14	-	-	-	c	-	-	-	-	-	-	-	-	-	-	-	-	-	1
15	-	-	-	u	-	-	-	-	-	-	c	-	-	-	-	-	c	3
16	-	-	-	c	-	-	-	-	-	-	a	-	-	-	-	-	c	3
17	-	-	-	c	-	-	-	-	-	-	-	-	-	-	-	-	u	2
18	-	-	-	u	-	-	-	-	-	-	-	-	-	-	-	-	c	2
19	-	-	-	-	-	-	-	-	-	-	a	-	-	-	-	-	u	2
20	-	a	-	-	-	-	-	-	-	s	-	-	-	-	-	-	-	2
21	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
22	-	-	-	a	-	-	-	-	-	s	-	-	-	-	-	+	-	3
23	u	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1
24	c	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1
25	a	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1
26	u	-	-	-	-	-	-	-	-	r	-	-	-	-	-	-	-	2
27	c	-	-	-	-	-	-	-	-	a	-	-	a	-	-	-	-	3
28	r	-	-	-	-	-	-	-	-	c	-	-	-	-	-	-	-	2
29	-	r	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	2
30	-	u	-	-	-	-	-	-	-	-	-	a	-	-	+	-	-	3
31	-	u	-	-	-	-	-	-	-	-	-	a	-	-	-	-	-	2
32	-	a	-	-	-	-	-	-	-	-	-	a	-	-	-	-	-	2
33	-	a	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1
34	-	-	-	-	-	-	-	-	-	-	-	u	-	-	-	-	-	1
35	-	c	-	-	-	-	-	-	-	-	-	c	-	-	-	-	-	2
36	-	-	-	-	-	-	-	+	-	-	-	a	-	-	-	-	-	2
37	-	a	-	-	-	-	-	+	-	-	-		-	-	-	-	-	2
38	-	-	-	-	-	-	-	-	-	-	-	a	-	-	-	-	-	1
39	-	u	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	2
Total Localities	10	9	1	12	1	1	1	2	1	10	4	7	3	1	3	1	7	74

Table 4. Fishes observed at turtle survey localities surveyed during Fall 2005 in Sonora and Chihuahua. Symbols are as in Table 3. Details for determination of abundance categories and species identity are in text.

	Native Fish Species							Exotic Fish Species								
Locality Number	*Agosia chrysogaster*	*Campostoma ornatum*	*Catostomus bernardini*	*C. wigginsi*	*Gila ditaenia*	*G. eremica*	*Poeciliopsis* sp.	*Ameiurus melas*	*Cyprinus carpio*	*Lepomis cyanellus*	*Gambusia affinis*	*Micropterus salmoides*	*Pimephales promelas*	*Tilapia* sp.	Unidentified Fish	Total Species
1	a	-	-	-	c	-	a	c	-	r	-	-	-	-	-	5
2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	a	1
3	a	c	-	u	-	u	a	-	-	-	-	-	-	-	-	5
4	u	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1
5	-	c	-	c	-	c	a	-	-	-	-	-	-	-	-	4
6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	u	1
7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
8	-	-	-	-	-	-	-	s	u	-	a	-	-	a	-	4
9	-	-	-	-	-	-	-	-	c	c	-	-	c?	-	-	3
10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	c	1
11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	c	1
12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	u	1
13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
15	-	-	-	-	-	-	-	c	-	-	-	-	-	-	c	2
16	-	-	-	-	-	-	-	-	-	-	c	-	-	-	c	2
17	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
18	-	-	-	-	-	-	-	-	-	-	c	-	-	-	-	1
19	-	-	-	-	-	-	-	-	-	-	-	-	-	-	u	1
20	-	-	-	-	-	-	-	-	-	u	-	-	-	-	a	2
21	-	-	-	-	-	-	-	-	-	-	-	-	-	a	a	2
22	-	-	-	-	-	-	-	-	-	-	-	-	-	a	a	2
23	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
24	a	-	-	-	-	-	c	-	-	-	-	-	-	-	u	3
25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	?	0
26	a	-	-	-	-	-	c	-	-	-	-	-	-	-	-	2
27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	s	1
28	-	-	c	-	-	-	-	-	c	u	-	a	-	-	a	5
29	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
30	-	-	-	-	-	-	a	-	-	-	-	-	-	c	u	3
31	-	-	-	-	-	-	-	-	-	-	-	-	-	r	-	1
32	-	-	-	-	-	-	-	-	-	-	-	-	-	c	u	2
33	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
34	-	-	-	-	-	-	-	-	-	-	-	-	-	a	-	1
35	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
36	-	-	-	-	-	-	-	-	-	-	-	-	-	c	-	1
37	-	-	-	-	-	-	-	-	-	-	-		-	-	-	0
38	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
39	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
# Occurrences	5	2	1	2	1	2	6	3	3	4	3	1	1	8	16	

Figure 2. A large pool behind a diversion dam on Río Bavispe north of Huasabas, in which Yaqui Sliders (upper right) were abundant. Photographs by P. C. Rosen, 29 October 2005.

diversions simplified the channels, leaving them almost uniformly very shallow. Stream depletion by agricultural diversion at small or medium-sized dams was observed at localities 3, 6, 8, 18, 21, 24-27, and 30, and probably at locality 31.

We never observed the large Yaqui slider, which is found in deep water environments (unpubl. obs. 2006-2009, Figure 2), in these situations. This form of habitat modification affects it severely, even in larger streams such as Río Bavispe, although habitat suitable for it has been created behind some of the medium-sized diversion dams.

In areas with such diversions, most habitat suitable for Sonoran mud turtles had been lost. Sonoran mud turtles were rarely observed in the main stream channel, except in pools at the diversion itself. They occurred primarily in marshy backwaters produced by inflow scour and off-channel scour pools. By contrast, we found the Mexican mud turtle abundant under a wide variety of conditions, including streams impacted by water diversion, such as Río Mátape (Figure 3).

Black-necked gartersnakes (*Thamnophis cyrtopsis*) were observed at three localities, but Mexican gartersnakes (*T. eques*) were found at only one locality — the ciénega at the bridge crossing at Tubutama on Río Altar — where three were found in under two hours of sampling despite the presence of exotic cichlids and bullfrogs. Most of our survey effort took place under conditions too cool for high

Figure 3. Shallow stream micro-habitat in Río Mátape Basin occupied by the Mexican Mud Turtle. Photographs at Rancho Ojo de Agua, by P. C. Rosen, 5 November 2005.

activity of gartersnakes, and therefore we have not evaluated gartersnake status except to provide presence data (Table 3).

Aquatic Frogs

We found the introduced American bullfrog at 3 of 4 sites in the Concepción basin (Río Altar and Río Magdalena) in northwestern Sonora near Arizona, and 9 of 10 sites in the endorheic Guzman Basin in northwestern Chihuahua, both near the United States. In contrast, no bullfrogs were seen in the interior of Sonora and Chihuahua (0 of 25 sites). Leopard frogs showed the opposite pattern, being seen only, and regularly, in the interior (19 of 25 sites, with a mean relative abundance of 1.9 ± 0.31 SE). This pattern is highly significant (χ^2 = 38.3, $p < 0.001$).

We detected similar numbers of fish species at bullfrog and non-bullfrog sites (1.58 versus 1.44 species / site), but there were more exotic fish species detected at bullfrog versus non-bullfrog sites (1.33 ± 0.26 versus 0.85 ± 0.22; t = 1.41, P < 0.09) and fewer native fish species (0.25 ± 0.25 SE versus 0.59 ± 0.25 SE; P > 0.2). Similarly, using the index derived from rank abundance values, exotic fish were more prominent, and again non-significantly, at bullfrog versus non-bullfrog sites (3.08 ± 0.77 versus 2.13 ± 0.70; t = 0.92, P < 0.19). However, considering the index of exotic species dominance (the summed abundance ranks for exotic fishes / summed abundance ranks for all fishes) exotic fish were significantly more dominant at bullfrog versus non-bullfrog sites (0.54 ± 0.10 SE versus 0.33

± 0.08 SE; t = 1.72, P = 0.049). Crayfish abundance was more strongly and positively associated with bullfrog occurrence (1.33 ± 0.41 SE versus 0.07 ± 0.07 SE; t = 2.99, P < 0.01); as such, the bullfrog and crayfish effects cannot be statistically separated in this dataset.

To further explore the relative weights of bullfrog presence-absence and measures of exotic fish predominance, we regressed the exotic fish measures (species richness, index of abundance, and index of dominance) against the rank-abundance values for leopard frogs in the upland regions from which bullfrogs and crayfish were absent. For fish species richness, these data yielded no significant or nearly significant correlations, whereas there was a significant correlation between the index of exotic predatory fish abundance and ranked leopard frog abundance (r = 0.406, n = 24, P = 0.049; for the index of exotic predatory fish dominance this statistic was marginally significant: r = 0.366, n = 24, P = 0.078).

To attempt to express, in a single analysis, the relative importance of the bullfrog-crayfish and exotic fish associations with leopard frog abundance, we computed the analysis of covariance of the leopard frog abundance using bullfrog plus crayfish presence-absence as a category and the abundance index for exotic predatory fishes as the covariate. This analysis also suggested that bullfrog-crayfish presence was a stronger effect ($P < 0.0001$) than exotic predatory fish (P = 0.03; Table 5), although crayfish and bullfrog effects could not be statistically separated.

In the interior of Sonora, native leopard frogs were often seen in moderate to high abundance, especially where native fishes predominated. The most spectacular example was at Saracachi Ciénega, in the Río Sonora basin. This largely intact, extensive headwater marsh of Río San Miguel de Horcasitas supported 2 turtle species, 5 fishes, and at least 4 anurans (Tables 3 and 4; an additional two anurans, the Couch's spadefoot [*Scaphiopus couchii*] and red-spotted toad [*Bufo punctatus*] were also observed), including thousands of adult and subadult lowland leopard frogs. This species count is especially notable because all aquatic vertebrate taxa observed at Saracachi were native, with several of them occurring in remarkable abundances. The widespread presence of native leopard frogs in the bullfrog-free interior of Sonora (Table 3) was notably observed even in places (e.g., upper Río Bavispe) where non-native fishes were diverse and numerically predominant (Table 4).

DISCUSSION

Status of Aquatic Turtles

Observations of habitat conditions made during our survey indicated that aquatic turtle species in northwestern Mexico were being impacted by water diversions. Simply put, the water was so shallow in reaches downstream from these diversions that certain species would not be expected, and were rarely or never detected, in the diversion-modified habitat. Diversions of this kind were seen wherever canyon bottoms were broad enough for small-scale farming; this included most of the stream areas accessible in our survey. Although this impact is undoubtedly smaller in remote, rugged canyons, such canyon-bound, scour-prone environments are also less suitable for turtles than the slower, deeper, more productive waters of fertile lowlands. We believe that none of the aquatic turtles we studied are rare or threatened in Sonora and northwestern Chihuahua, but that all have likely been affected to some degree by habitat loss.

Water diversion impacts on individual turtle species can be judged by interspecific variation in habitat needs and predation resistance known or inferred for members of the turtle assemblage. For example, the large Yaqui slider would be highly vulnerable to predation and collection by humans without deep water for escape; we have seen it at many localities across Sonora, but never in shallow-water environments. Similarly, the Sonoran mud turtle is generally uncommon or rare in the Sonoran Desert region where it lacks deep water, available shelter in tree roots or undercut banks, and often with muddy substrata; predation has been noted when shallow water exposes this species to medium-sized stream-

Table 5. Analysis of covariance of leopard frog (*Rana yavapaiensis, R. magnaocularis*) abundance in northwestern Mexico in relation to American bullfrog (*R. catesbeiana*) and northern crayfish (*Orconectes virilis*) presence/absence and predatory exotic fish abundance.

Summary of Fit

R2	0.40
R2 – adjusted	0.35
Root Mean Square Error	1.28
Mean of Response	1.33

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	39.0	13.0	7.9
Error	35	57.6	1.6	Prob > F
C. Total	38	96.7		0.0004

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob > |t|
Intercept	2.25	0.285	7.87	< .0001
Bullfrog-Crayfish Presence / Absence	-1.94	0.446	-4.34	0.0001
Predatory Exotic Fish Abundance	-0.25	0.110	-2.24	0.0319
(Bullfrog P/A) x (Predatory Exotic Fish - 1.26)	0.25	0.247	1	0.3256

Effect Tests

Source	DF	Sum of Squares	F Ratio	Prob > F
Bullfrog-Crayfish Presence / Absence	1	31.07	18.87	0.0001
Predatory Exotic Fish Abundance	1	8.23	5.00	0.0319
(Bullfrog-Crayfish) x (Predatory Exotic Fish) interaction	1	1.64	0.99	0.3256

side predators (Rosen, unpublished observations at Tule Creek, Yavapai County, Arizona). We expect that the rough-footed mud turtle, which is morphologically similar and has similar habitat utilization, will be affected like the Sonoran mud turtle. The Mexican mud turtle provided a telling contrast. This relatively large mud turtle is able to close remarkably tightly within its shell, and this apparently permits it to remain active, and to persist as populations, in shallow waters rarely utilized by other regional *Kinosternon*. The sight of these animals clambering over sand in scant centimeters of water depth can be strikingly reminiscent of the terrestrial capability afforded terrestrial box turtles (*Terrapene*) by their tight shell closure. Based on these considerations, and the occurrence and abundance we observed during the survey, we rate turtle susceptibility to water diversions as follows: Yaqui slider > Sonoran mud turtle ≈ rough-footed mud turtle > Mexican mud turtle.

Our survey covered little of the level terrain of the Altiplano or lowland plains, where impacts of habitat modification and introduced animals are most potent (Hendrickson et al. 1980; Juárez-Romero et al. 1991; Miller et al. 2005). Our observations in the Guzman Basin and in the lowland reservoirs we examined in Sonora (Presa Molinito and Presa Cuatemoc) suggest that turtles and other aquatic herpetofauna are indeed suffering severe impacts from habitat desiccation and modification in broad valleys and on the coastal plain. However, we subsequently (2006) observed Yaqui sliders in canals on the heavily agricultural Yaqui River floodplain west of Ciudad Obregón.

Native and Non-native Fishes

Even without intensive fish sampling, patterns important for conservation biology were evident that are consistent with broader patterns for Mexico described in Miller et al. (2005). Non-native fishes are now dominant in a number of major waters: the current terminus of Río Sonora at Presa Molinito near Hermosillo, the two areas we sampled in Río Altar, the upper Río Bavispe near Bavispe, and the Guzman Basin in Río Casas Grandes and Río Santa Maria. Native fishes predominated in many other waters, including Río Magdalena and throughout most of the interior highlands of Sonora (Table 4).

Most of our records of non-native fishes in the Río Yaqui Basin are similar to those reported by Hendrickson et al. (1980) based on surveys nearly three decades earlier, but our records add the green sunfish (*Lepomis cyanellus*) at Yecora. Rinne and Minckley (1991) suggested that non-native fish invasion in Mexico may be 2-3 decades lagged behind that in the U.S., whereas Unmack and Fagan (2004) estimated a 4-5 decade lag comparing the Río Yaqui Basin to the Gila River Basin of the United States. Our analysis does not help discriminate between these estimates, but does demonstrate that the highlands of the Yaqui and other basins are considerably less impacted by the invasion of exotics than surrounding lowland aquatic environments.

A review of the published literature (Hendrickson 1983; Campoy-Favela et al. 1988; Hendrickson and Juarez-Romero 1990; Abarca et al. 1995; Miller et al. 2005) suggests that the following exotic fish locality records, in addition to green sunfish at Yecora, are also new: non-native African cichlids (*Tilapia* sp.) abundant in mainstem Río Altar at Tubutama (two localities), at Quitovac (Rosen et al., this volume), and in Río Mátape (Juarez-Romero et al. 1988); and black bullhead catfish (*Ameiurus melas*) in Río Magdalena below Imuris, Sonora.

Introduced Species and Native Ranid Frogs

Some other records for exotic species in the study region are also new. Most of the observed bullfrog localities are new records, and the apparent absence of this frog throughout most of Sonora was unexpected, based on experience in Arizona. Exotic crayfish (*Orconectes* cf. *virilis*), previously reported in Chihuahua (Hobbs 1989), were only observed in Guzman Basin streams and at Yepomera, Chihuahua. All of the exotic species recorded on this survey may be continuing to spread. Tracking, understanding, and working toward a solution to this problem is a critical element for native biodiversity conservation in the region.

The frequency of leopard frog observations during our surveys, and the observed abundances, suggested better population status in Sonora than in Arizona. The remarkable superabundance of leopard frogs at Saracachi Ciénega is described below; elsewhere, leopard frog abundances were consistently moderate to high in all areas where habitat appeared suitable, except in lowlands where multiple exotic species were predominant. Even in marginal habitat conditions or isolated waters, we often found leopard frogs. These results resemble 1971-1976 observations by John Frost in Arizona (Frost, unpublished field notes, P. Fernandez, pers. comm. 1996), but since then equivalent abundances of native ranid frogs have not been reported in Arizona. We did not find leopard frogs in major reservoirs, as expected based on previously known effects of exotic fish species that were typically dominant in the reservoirs.

It was also surprising to find native leopard frogs persisting even at the upper Río Bavispe where non-native fishes have dominated the system for several decades (Hendrickson et al. 1980; Leibfried 1991; Abarca et al. 1995). Mechanisms permitting native leopard frogs to persist as they have in Sonora deserve investigation, and the rate at which these frog populations may be declining should be evaluated.

The lack of observed co-occurrence of leopard frogs with introduced bullfrogs and crayfish in northwestern Sonora was not unexpected, although it was more similar to results for the Chiricahua leopard frog in southeastern Arizona (Rosen et al. 1995; Rosen and Schwalbe 1995, 2001, 2002b) than for the lowland leopard frog in Arizona (Sartorius and Rosen 2000). Although many authors have recognized bullfrogs as a primary cause of ranid frog declines in the American West, others have suggested that non-native fishes may have stronger negative impacts (Hayes and Jennings 1986; Adams 1999, 2000).

The results of our analysis of covariance (Table 5) suggest that bullfrogs or bullfrogs together with crayfish may have greater impact than exotic fishes on leopard frogs. Perhaps exotic fish impacts are intensifying (e.g., Unmack and Fagan 2004) and will become progressively more important. Predatory native fishes that may be replaced by exotics might have already limited leopard frog populations under original conditions, so exotic fishes may not alter the predation and competitive regimes for leopard frogs in the ways bullfrogs might. The bullfrog may also be vectoring the emerging amphibian disease chytridiomycosis (Garner et al. 2006), but this pathogen is widespread in Sonora even in large regions where bullfrogs are absent (Hale et al. 2006), so disease transmission by bullfrogs seems an unlikely explanation for bullfrog impacts in Sonora.

Two alternative ecological mechanisms strengthening bullfrog impacts may include: (1) not only do adult and large juvenile bullfrogs prey on native ranids, but bullfrog tadpoles can be strong competitors with other ranids (Kupferberg 1997); and (2) bullfrogs and leopard frogs are phylogenetically related and hence ecologically similar in myriad ways, including subtle aspects of habitat and microhabitat utilization, competition, and predation susceptibility. As an example, leopard frogs utilize peripheral or semi-perennial pools in river bottoms where interactions with fish are minimal, but bullfrogs are also able, and likely, to invade such sites.

Perhaps, however, the apparent priority of bullfrog impacts reflects the current restriction of bullfrogs in our survey areas to lowland regions that are heavily impacted by anthropogenic habitat modification and have high diversities of other exotics, particularly crayfish, which have known impacts on Southwestern ranid frogs (Fernandez and Rosen 1996). We suspect, based on their observed abundances, and based on their occurrence in assemblages of exotics with abundant species known to impact leopard frog populations, that crayfish may not have been primary impacts causing leopard frog population losses in northwestern Mexico. However, further investigation involving fieldwork and experimental conservation will be required to clarify this issue.

An Exemplary Site: Saracachi Ciénega

We have visited most, if not all, major ciénegas in the U.S. Southwest, as well as several in northernmost Sonora: most of these sites have been ecologically dominated by exotic fishes and bullfrogs for two or more decades, and many have been severely degraded by anthropogenic erosion (Hendrickson and Minckley 1985). We therefore found our observations at Saracachi Ciénega, at Rancho Agua Fria, to be remarkable in several ways. The site is largely intact, with little evidence of erosion. Structurally, it may be the most natural, least impacted major ciénega remaining in the Southwest; we believe there is no equivalent ciénega example remaining in the U.S., either from the standpoint of aquatic vertebrate species diversity or the absence of exotic aquatic vertebrates. No ciénega in the U.S. Southwest supports such high diversity of native fishes (maximum 3 species, at Empire Ciénega) and aquatic turtles (1 species, Sonoran mud turtle, being the norm). Other ciénegas in northern Sonora, such as those at Cocospera and Los Fresnos, are already invaded by bullfrogs (J. Rorabaugh, T. Jones, pers. comm. 2006).

The abundance of leopard frogs at Saracachi equaled or exceeded the superabundance of bullfrogs found in comparable Arizona ciénegas (Rosen and Schwalbe 1995),

Figure 4. Lowland Leopard Frog egg-laying site with extensive, moderately vegetated shallows at Saracachi Ciénega, Sonora, 23 September 2005. Photograph by P. C. Rosen.

including extreme examples observed at Arivaca and San Bernardino National Wildlife Refuge (Schwalbe and Rosen 1988). This supports inferences that valley bottom ciénega wetlands originally were critical parts of the original leopard frog population of southern Arizona, and may have supported core abundances that drove regional metapopulation source-sink and related dynamics. We observed 24 egg masses during our single reconnaissance at Saracachi, during what is usually the secondary breeding season for the lowland leopard frog (Collins and Lewis 1979; Frost and Platz 1983; Sartorius and Rosen 2000). Leopard frog reproductive success was apparently supported by extensive shallow, productive waters with open aquatic vegetation maintained by moderate livestock grazing on the un-incised ciénega bottomland (Figure 4). These observations of leopard frogs therefore carry implications for recovery prospects for threatened species (USFWS 2002). Saracachi Ciénega offers outstanding opportunities for basic and conservation-oriented ecological research, and deserves high conservation priority.

Modes of Persistence of Native Aquatic Vertebrates in Arid Northwestern Mexico

The persistence and abundance of leopard frogs as well as native fishes in northwestern Mexico appears to be associated with the delayed and — thus far, compared to impacts in the United States — relatively limited impact of the biological invasion by non-native predatory fishes (Unmack and Fagan 2004) and crayfish and bullfrogs. However, the regional persistence of native taxa in our dataset is markedly uneven: in the lowlands near Hermosillo, Sonora, and Casas Grandes, Chihuahua, we observed aquatic vertebrate faunas in much the same degraded condition found over most lowland areas in the U.S. Southwest (Campoy-Favela et al. 1989; Juárez-Romero et al. 1991; Varela-Romero et al. 1992a & b for related examples). Near Altar, Sonora, we believe degradation like that seen in the U.S. was currently underway at the time of our survey, and unpublished reports regarding headwater ciénegas in the San Pedro and Santa Cruz river basin in northern Sonora (J. Rorabaugh, D. Duncan, pers. comm. 2006-2009) point toward this same conclusion.

The parallel, but time-lagged, buildup of exotics in the Gila River Basin and in interior highlands of Sonora (Unmack and Fagan 2004) is not a simple lock-step with time-lag, but reflects two pairs of divergent forces: (1) the smaller number of major dams in interior Sonora in tandem with habitat modification by small-scale water diversions, and (2) the less intensive and extensive government involvement in propagation and dispersal of exotic aquatic vertebrates in northwestern Mexico compared to the U.S. Southwest. The example of exotic species problems in the U.S., and the difficulties they create for biodiversity conservation, may motivate proactive conservation programs in Mexico at an earlier stage of development of the exotic species advance (e.g., Varela-Romero et al. 2004).

Whereas dams create habitat, refugia, and source populations favoring exotic species, shallow, heavily flood-affected waters favor native aquatic species (Meffe 1984; Minckley and Meffe 1987; Sartorius and Rosen 2000). Although the widespread diversion of waters from streams onto small arable floodplain lands in Sonora has negative impacts on turtles, as described above, it also keeps many stream reaches shallow, flood-prone, and thus unsuitable for a number of exotic species that would otherwise likely be having greater impacts on native aquatic species. It seems plausible that the large- and small-scale patterns of water diversion described above might be combined with environmentally foresightful governmental policy to prevent the U.S. exotic species biodiversity catastrophe from being replayed in the highlands of northwestern Mexico.

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SUMMARY

A total of 39 localities were sampled in Sonora and northwestern Chihuahua during a 24-day rapid assessment survey conducted in tandem with mud turtle genetics sampling during fall 2005. Mud turtles were generally abundant, and were captured at 8 of 15 historic localities and 12 of 17 newly sampled localities with potentially suitable habitat (Sonoran mud turtle, 4 of 9 historic, plus 6 of 9 newly sampled sites; rough-footed mud turtle, 4 of 5 historic; and Mexican mud turtle, 1 of 2 historic plus 6 of 8 new localities). Although the Sonoran mud turtle probably had not been extirpated from any major locality, river diversions for agriculture restricted it to localized deeper-water micro-sites in some localities. The rough-footed mud turtle was impacted by desiccation of springs near Galeana, Chihuahua, whereas the Mexican mud turtle appeared tolerant of shallow water. The endemic Yaqui Slider was recorded at only 2 localities, and in many areas water diversion has probably eliminated much of its habitat. Exotic crayfish were found only in Chihuahua. Exotic fishes were dominant in certain major waters, whereas native fishes predominated in many others. Although native leopard frogs widely co-occurred with exotic fishes, their abundance was negatively correlated with measures of exotic fish abundance, most strongly involving the predominance of exotic predatory fishes. Exotic American bullfrogs occurred at most localities in northwestern Chihuahua, where crayfish also occurred

widely, and northwestern Sonora, and neither bullfrogs nor crayfish were detected in interior Sonora. Native Lowland and Big-eyed Leopard Frogs had a pattern opposite that of bullfrogs and crayfish, and were found at 19 of 25 localities sampled in interior Sonora, suggesting a particularly strong negative impact of bullfrogs, and possibly crayfish, on leopard frogs. As in native fishes, impacts of exotic species on aquatic herpetofauna in northwestern Mexico appear to have lagged behind the impacts of exotics and habitat modification in adjacent areas of the United States, but our observations indicate substantial impacts that are very likely expanding. We note sites with outstanding habitat characteristics, some, particularly Saracachi Cienega, deserving special protection.

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CHALLENGES TO NATURAL RESOURCE MONITORING IN A SMALL BORDER PARK: TERRESTRIAL MAMMALS AT CORONADO NATIONAL MEMORIAL, COCHISE COUNTY, ARIZONA

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Since 1916, the responsibility of the U.S. National Park Service (NPS) has been to provide for public enjoyment of America's greatest natural and cultural resources while simultaneously conserving these resources for future generations. Although NPS has long recognized the value of long-term monitoring (e.g., Robbins et al. 1963), only a few long-term data sets exist for any national park. In the early 1990s, in response to criticism that most parks do not even know what species they have, let alone how park ecosystems may be changing over time (National Research Council 1992), NPS initiated a service-wide Inventory and Monitoring (I&M) Program that was greatly expanded with the Natural Resource Challenge beginning in 1999.

NPS management policy for natural resources ultimately directs that management of parks be based on knowledge of resources and their conditions (NPS 2006). A major purpose of this policy is to monitor (and manage) biological diversity — in other words, to document trends in the inherent integrity of the entire natural community, not just one or more individual species (NPS 2006, Chapter 4.1). Although the level of preservation required in parks — explicit protection of even the smallest scrap of petrified wood or living flower — may impact field work (for example, in the collection of voucher specimens), it provides the conceptual framework for monitoring.

Unfortunately, failure to monitor biological diversity is also an important backdrop for monitoring in the Park Service. NPS and other land management agencies have been criticized for their failure to prevent, and even recognize, the loss of species from protected areas. These failures are explicit in studies that report high extinction rates of native mammals (Newmark 1995), amphibians (Drost and Fellers 1996) and plants (Drayton and Primack 1996) in parks, and implicit in inventories and studies of park biodiversity. The need for inventory and monitoring programs is thus grounded in public expectations that NPS will be proactive in recognizing and preventing damage to all natural resources under the agency's care, not simply high profile, threatened, or endangered species.

Nevertheless, financial realities, including the ability to retain and rehire specialized biologists, mean that it is impossible to monitor all park resources all of the time. Due to fluctuations in NPS funding, many monitoring programs designed for parks in the past have been discontinued or were never implemented. Thus there is a great need to develop monitoring that can be maintained when funding declines, yet adequate to detect important ecological changes.

Coronado National Memorial is a National Park Service (NPS) interpretive site of approximately 1900 ha that was established because it overlooks the probable route of Francisco Vasquez de Coronado, an early Spanish explorer of North America. Located on the Mexico-United States boundary at the junction of several major biogeographic provinces, the Memorial supports a rich flora and fauna, but has also been greatly impacted in recent years by human traffic along the international border, as well as wildfire, cattle grazing, and development outside park boundaries. Monitoring to provide information for management is considered essential at the Memorial, as in many small parks, but is one of many management priorities.

The goal of our study was to conduct a thorough and repeatable inventory of terrestrial mammals and to make recommendations for long-term monitoring that would be relevant for small national park units. During an intensive, one-year inventory phase (1996–1997), we used multiple techniques to confirm as many of the memorial's terrestrial mammal species as possible. To develop data to inform monitoring decisions, we then continued to monitor mammals for seven additional years (1997–2003) using infrared-triggered cameras and, in particular, annual small mammal trapping on two large permanent plots.

STUDY SITE

Coronado National Memorial is located at the south end of the Huachuca Mountains, on the Mexico-United States border (Figure 1). The memorial contains 1900 ha in the upper watershed of Montezuma Canyon and ranges in elevation from approximately 2,386 m to 1,471 m. The steep northern and western portions of the memorial are predominantly oak woodland (Ruffner and Johnson 1991), while the less steep eastern portion is primarily semi-desert grassland. Little surface water is present. The complex geology includes metamorphosed sedimentary deposits, volcanic deposits, and more recent sedimentary deposits (Doe 1986), including limestone outcrops that form underground chambers. A small portion of the memorial was grazed by cattle during our study. The Huachuca Mountains are one of a number of "sky island" ranges in southeastern Arizona, southwestern New Mexico, and Mexico that include biota from several biogeographic provinces, including the Sierra Madre Occidental to the south, the Rocky Mountains to the northeast, the Sonoran Desert to the west, and the Chihuahuan Desert to the east (Van Devender and Reina 2005).

METHODS

Detecting presence and absence of terrestrial mammals can be difficult due to their diverse lifestyles, including nocturnal and underground habits. In addition, small mammals may be very specific in their microhabitat requirements, while larger species, especially carnivores, may occur naturally at very low population densities. To detect as many species that occur in the memorial as possible, we used a wide variety of techniques as outlined below.

Small mammal trapping

We trapped small mammals using extra large Sherman and Tomahawk brand live traps for small mammals using standard methods (for details see Swann et al. 2007). During the 1996–1997 inventory, we established 65 plots of 25 traps each in areas that represented the geographic, topographic, and vegetative diversity of the memorial (Figure 2), including burned and unburned oak woodland areas, wet seeps, cattle tanks, riparian corridors, high and low elevation grasslands, grazed and ungrazed semi-desert grassland areas, and areas altered by human activity. At each grid we placed traps 10 m apart in a square or rectangular pattern and trapped for one to four nights, marking mammals captured on each night.

To evaluate the sample size and cost of annual monitoring of small mammals we established two grids of 100 traps each (Figure 2). One grid was randomly located in semi-desert grassland below 1524 m; this grid was dominated by non-native grasses, particularly Lehmann's lovegrass (*Eragrostis lehmanniana*). The second was randomly located on a south-facing slope in oak savanna above 1921 m and was dominated by native grasses such as bullgrass (*Muhlenbergia emersleyi*) and small trees including Emory oaks (*Quercus emoryi*). Individual animals were

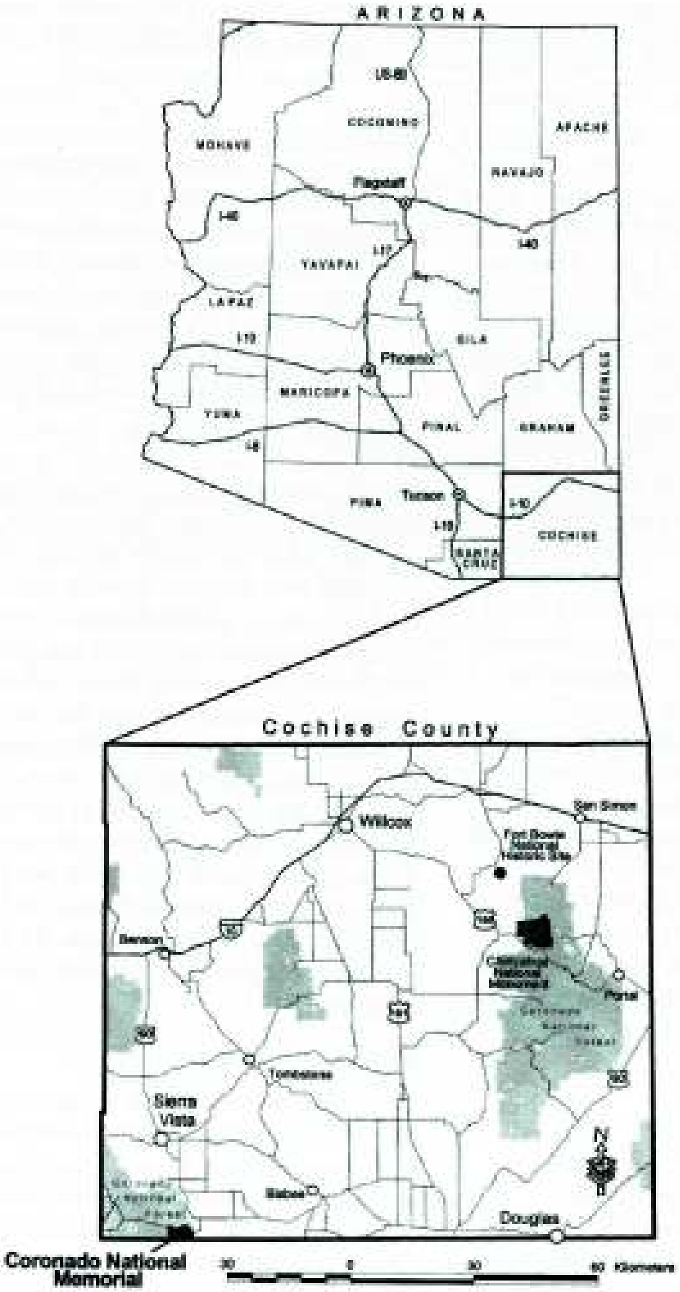

Figure 1. Location map of Coronado National Memorial, Cochise County, Arizona. From Schmidt et al. 2007.

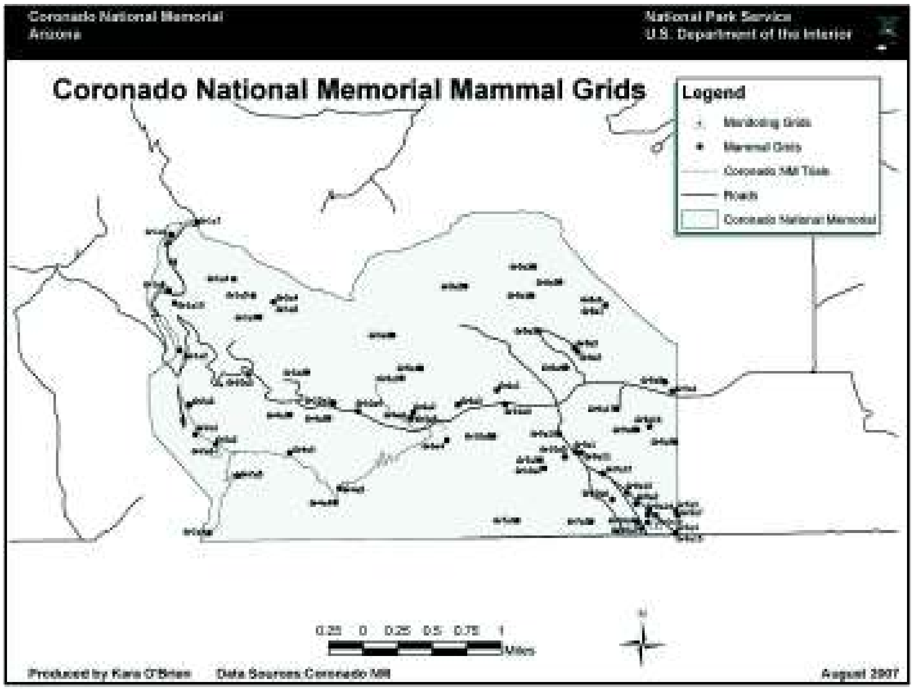

Figure 2. Map of Coronado National Memorial, showing locations of mammal trapping grids used during this study. Long-term monitoring grids (trapped 1997-2003) were 2a6 (Joe's Canyon grid, oak woodland, southwest section) and 9a18 (Grassland grid, semi-desert grassland, southeastern section). All others were inventory grids.

uniquely marked using permanent color pens in order to develop a capture history for each and each grid was annually trapped for 3–6 nights during late October – early December from 1997 through 2003. Abundance on each grid was estimated using the Program CAPTURE for closed populations (Otis et al. 1978). CAPTURE chooses a model based on the data given; we generally chose this model to estimate abundance unless the null model was chosen and a model based on behavior, heterogeneity or time was available with only a slightly lower rating.

Infrared-triggered photography

Infrared-triggered photographs of large and medium-sized mammals were obtained using the model 1500 Trailmaster camera system (Goodson and Associates, Inc., Lenaxa, KS), where a single infrared beam is emitted by a transmitter and detected by a receiver; a photograph is taken when this beam is broken by an animal. We placed camera units in vegetated areas that were protected from visitors and illegal border crossers, and represented the geographic diversity of the memorial (Figure 3). Cameras were set for intervals of two weeks or more at a natural water source, or baited with sardines, cat or other carnivore lure, a visual lure, or some combination of these. We recorded all changes of film and bait used, and map coordinates were obtained using GPS. Animals in each photograph were identified to species if possible, and times and dates recorded.

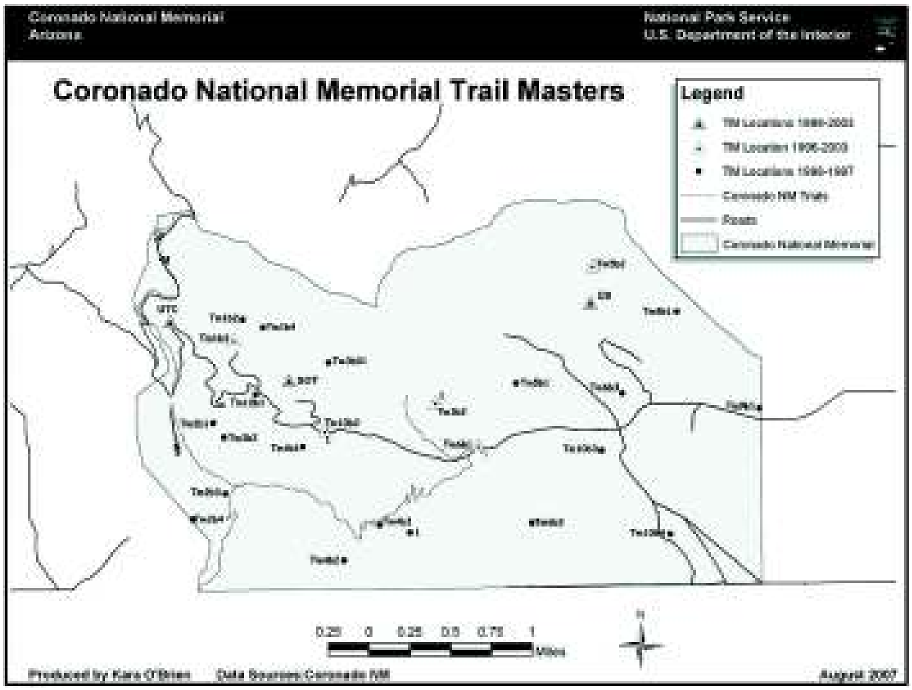

Figure 3. Locations of infrared-triggered (Trailmaster) cameras used during this study.

As with small mammal trapping, we conducted an extensive inventory at 25 locations for one year (1996–1997), then continued photography at a selected smaller number of sites through 2003.

Observations

To supplement records of mammal distribution and relative abundance, we recorded all mammals observed during field work on this and a related study of herpetofauna (Swann and Schwalbe 2007) during 1996–1997. Park staff continued to look for and document new species during 1998–2003. We looked for mammals while driving on a road transect, conducting trapping and habitat analysis, and under boards and other materials. We recorded date, time, species, and location associated with each animal observed.

Species identification and permits

Specimens or photographs of difficult-to-identify mammals were brought to the University of Arizona Mammal Collection and confirmed by Yar Petryszyn, Assistant Curator. Research was conducted under permits to CRS from Coronado National Memorial and the Arizona Game and Fish Department and followed University of Arizona animal handling protocols (Institutional Animal Care and Use Committee, Control #94-067).

RESULTS

We confirmed 45 terrestrial mammals at Coronado National Memorial during 1996-2003, including three non-native species — feral dog (*Canis familiaris*), feral cat (*Felis catus*) and house mouse (*Mus musculus*). Species were confirmed by voucher photos, specimens, or observations where a specimen previously existed, or (in three cases) by reliable observations only. We believe that two other species occur at the memorial, but did not document them during 1996–2003: mule deer (*Odocoileus hemionus*), which were reliably observed by park staff prior to our study and are probably occasional visitors; and eastern cottontails (*Sylvilagus floridanus*), which we believe we observed and photographed, but for which a voucher specimen is required for unambiguous identification.

We confirmed a number of species not previously confirmed for the memorial and, except for one species of pocket gopher — Southern pocket gopher (*Thomomys umbrinus*, for which we observed sign in appropriate habitat — we observed all species confirmed in a previous inventory (Petryszyn and Cockrum 1979).

Small mammal trapping.

We trapped small mammals during the inventory phase, September 1996 – December 1997 for a total of 4628 trap nights. We made 540 captures for a mean trap success of 11.7%. We captured 416 individuals of 17 species (Table 1). A few species were captured throughout the memorial, but many were confined to either high or low elevations; a few were captured in special habitats such as wet seeps or open desert habitat.

On the 100-trap oak savanna grid near Coronado Peak, we captured 412 individuals of 11 species during 3,700 trap nights during 1997–2003. On the lower grassland grid just north of Montezuma Canyon near the east boundary, 478 individuals of 14 species were captured during 3,800 trap nights. Over seven years, on both grids combined, we trapped 890

Table 1. Species of small mammals and numbers captured (captures – minus recaptures) at Coronado National Memorial during the intensive inventory (1996-1997) and long-term monitoring (1997-2003). **Note that the desert shrew was not trapped during the inventory phase, but one individual was hand-captured and photo-vouchered.*

Species	1996-1997 Inventory	1997	1998	1999	2000	2001	2002	2003
Desert shrew *(Notiosorex crawfordii)*	0*	0	0	1	0	0	0	0
Hispid pocket mouse *(Chaetodipus hispidus)*	23	1	0	4	1	5	2	1
Rock pocket mouse *(C. intermedius)*	2	0	4	3	0	8	5	8
Silky pocket mouse *(Perognathus flavus)*	0	0	0	0	1	2	1	0
Sonoran Desert pocket mouse *(C. penicillatus)*	51	3	0	0	0	0	4	1
Unknown pocket mouse	0	0	0	0	0	0	0	1
Ord's kangaroo rat *(Dipodomys ordii)*	2	0	0	0	0	0	0	9
Banner-tailed kangaroo rat *(D. spectabalis)*	1	0	0	0	0	0	0	0
Merriam's kangaroo rat *(D. merriami)*	5	0	0	0	0	0	0	0
House mouse *(Mus musculus)*	0	0	0	0	0	1	0	0

individuals of 19 species (Table 1). Two species trapped during the intensive inventory — Merriam's kangaroo rat (*Dipodomys merriami*) and banner-tailed kangaroo rat (*D. spectabalis*) — were not trapped on the monitoring grids during 1997–2003, and four species trapped during the monitoring effort — spotted ground squirrel (*Spermophilus spilosoma*), silky pocket mouse (*Perognatus flavus*), house mouse, and desert shrew (*Notiosorex crawfordi*) — were not trapped during the inventory in 1996–1997. In addition, we captured a number of species in areas where they had not been previously trapped, including several low elevation "grassland" species, such as Northern pygmy mice (*Baiomys taylori*), on the high elevation oak savanna grid.

Abundance and species richness on the two grids varied greatly among years (Table 2, Figure 4). For example, on the grassland grid estimated abundance ranged from a low of 46 in 1997 to a high of 192 in 2000. Abundance of cotton rats (*Sigmodon* spp.) was higher during 2000 and 2001 than during 1997–1999 or 2002–2003 (Figure 5). Increases in rodent abundance, and especially in abundance of Arizona cotton rats (*S. arizonae*) the dominant species on the grassland grid) appeared to be correlated with higher than normal summer rains in 1999 and very high rainfall in 2000 (Figure 6).

Infrared-triggered photography

During the inventory of September 1996 – December 1997, three Trailmaster cameras were used for approximately 1142 nights at 25 locations (Figure 3). During this period, 379 photographs of 17 mammal species were obtained (Figure 7). Cameras were often not operational because a roll of film had been completely exposed or an equipment malfunction had occurred; we estimate the cameras

Table 1. *continued*

Species	1996-1997 Inventory	1997	1998	1999	2000	2001	2002	2003
Northern pygmy mouse *(Baiomys taylori)*	34	7	5	15	26	30	18	23
White-throated woodrat *(Neotoma albigula)*	50	8	9	13	10	12	8	20
Southern grasshopper mouse *(Onychomys torridus)*	15	4	10	10	22	14	6	9
Deer mouse *(Peromyscus maniculatus)*	5	2	0	0	3	3	3	13
White-footed mouse *(P. leucopus)*	26	9	4	26	6	3	2	3
Brush mouse *(P. boylii)*	80	3	7	3	15	23	4	28
Unknown white-footed mouse	3	0	0	1	0	0	0	1
Fulvous harvest mouse *(Reithrodontomys fluvescens)*	16	14	4	12	13	15	10	14
Western harvest mouse *(R. megalotis)*	8	7	8	1	4	10	8	11
Unknown harvest mouse	0	0	1	0	2	0	0	0
Arizona cotton rat *(Sigmodon arizonae)*	27	4	3	10	39	69	11	8

Table 2. Abundance estimates for small mammals on two long-term monitoring plots at Coronado National Memorial, 1997-2003. JC = Joe's Canyon grid (oak woodlands). GR = semi-desert grassland. Estimates were derived using mark-recapture based on CAPTURE; we used model selected by CAPTURE unless null model was selected and another model scored within 10 percentage points, in which case we chose the other model. M(o) is null model, M(h) is heterogeneity model, M(b) is behavior model, M(t) is time model, and M(bh) is combined behavior and heterogeneity.

Plot	Year	All Species					Cotton rats (*Sigmodon* spp.)				
		#Cap	Model	Est	SE	CI	#Cap	Model	Est	SE	CI
JC	1997	56	M(o)	66	4.62	61-79	18	M(o)	21	2.59	19-31
	1998	38	M(h)	67	3.91	52-97	11	M(o)	11	0.85	11-14
	1999	60	M(b)	89	21.14	68-164	5	M(th)	5	0.42	5-7
	2000	53	M(h)	102	11.54	82-129	5	M(o)	5	0.39	5-5
	2001	88	M(bh)	114	15.02	98-162	17	M(h)	18	1.31	17-24
	2002	30	M(t)	39	4.78	34-53	8	M(o)	11	3.19	9-24
	2003	87	M(h)	137	15.08	116-176	15	M(h)	19	3.63	16-33
GR	1997	27	M(h)	46	7.48	36-66	7	M(h)	15	4.5	10-29
	1998	35	M(h)	68	11.8	52-100	7	M(o)	8	1.73	9-27
	1999	45	M(b)	65	17.48	50-132	11	M(th)	14	3.60	12-29
	2000	100	M(h)	192	18.45	163-235	44	M(b)	63	16.00	49-123
	2001	119	M(bh)	174	18.17	149-222	64	M(b)	102	28.72	75-205
	2002	74	M(bh)	82	8.64	75-117	24	M(bh)	34	7.75	27-62
	2003	79	M(bh)	118	15.39	98-161	9	M(h)	24	6.12	16-44

were operational for a total of approximately 640 nights.

During the monitoring period of January 1998 – January 2004 (excluding 2001 and 2002, when we did not operate cameras), Trailmaster cameras were used at 9 locations (Figure 3), and we estimate that cameras were operational for approximately 972 nights. During this period, 1028 photographs of 18 native species (plus feral dogs) were obtained (Figure 7). One species photographed in 1996–1997, the common raccoon (*Procyon lotor*), was not photographed during 1998–2004; two species not photographed during 1996–1997 — Virginia opossum (*Didelphis virginiana*) and Arizona gray squirrel (*Sciurus arizonensis*) — were photographed during 1998–2004.

Observations

Three species — desert shrew, feral cat, and Botta's pocket gopher (*Thomomys bottae*) — were documented during the inventory by hand-capture or collection of a dead individual. Three species — Arizona gray squirrel, southern pocket gopher, and black-tailed jackrabbit (*Lepus californicus*) — were not trapped or photographed but were observed (or, in the case of the pocket gopher, their sign in appropriate habitat was observed) by researchers. Two additional species — American badger (*Taxidea taxus*) and mule deer — had been recently observed by expert staff but were not observed, captured, or photographed during the period.

During the monitoring phases, no new species were observed. Of the five species observed but not otherwise documented during or just prior to the 1996–1997 inventory, one species (Arizona gray squirrel) was confirmed by infrared-triggered photography and one (American badger) was confirmed by roadkill in 2004. Three species (southern pocket gopher, black-tailed jackrabbit and mule deer)

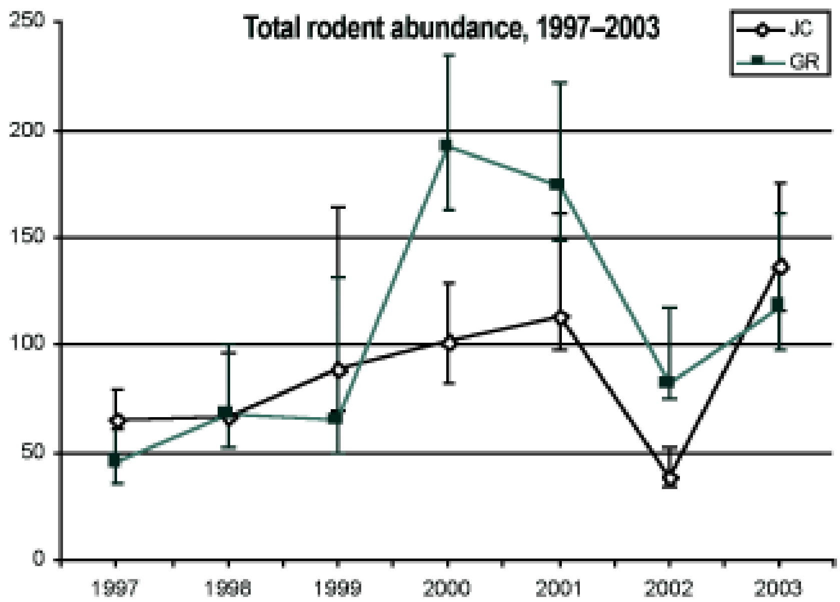

Figure 4. Estimated abundance and 95% confidence interval of small mammals on Joe's Canyon (oak woodland) and Grassland (semi-desert grassland) monitoring grids at Coronado National Memorial, 1997–2003.

known to occur at the memorial remain undocumented.

DISCUSSION

Species diversity and inventory completeness

Coronado National Memorial has a great diversity of mammals compared to other parks in southern Arizona, especially considering its small size. For example, the Rincon Mountain District of Saguaro National Park is more than 14 times larger than Coronado, but has the same number (45) of confirmed species (Swann and Powell 2006). In addition to the terrestrial mammals we studied, Coronado also has many bats (6 confirmed and 17 possible species; Swann et al. 2007). This diversity is probably due to a number of factors, including the memorial's location in the Huachuca Mountains at the northern end of the Madrean mountains; connectivity with other natural areas, including Coronado National Forest, the San Pedro River, and undeveloped areas in Mexico; and the presence of areas of ungrazed semi-desert grasslands with high grass cover. In addition, small parks such as Coronado may have higher diversity per unit area because their mammalian fauna include most of the habitat generalists — e.g., species like desert cottontail and mountain lion (*Puma concolor*) — that occur in larger parks. Mammal diversity is a significant natural resource value at the memorial that is worthy of preservation.

We believe that we detected most terrestrial mammals at the memorial, given our long-term effort using multiple methods, although we failed to confirm two other species (mule deer and eastern cottontail) that probably also occur. We did not detect seventeen native species that occur or have occurred historically within the Huachuca Mountains (Hoffmeister 1986) and nearby valleys. These include species which

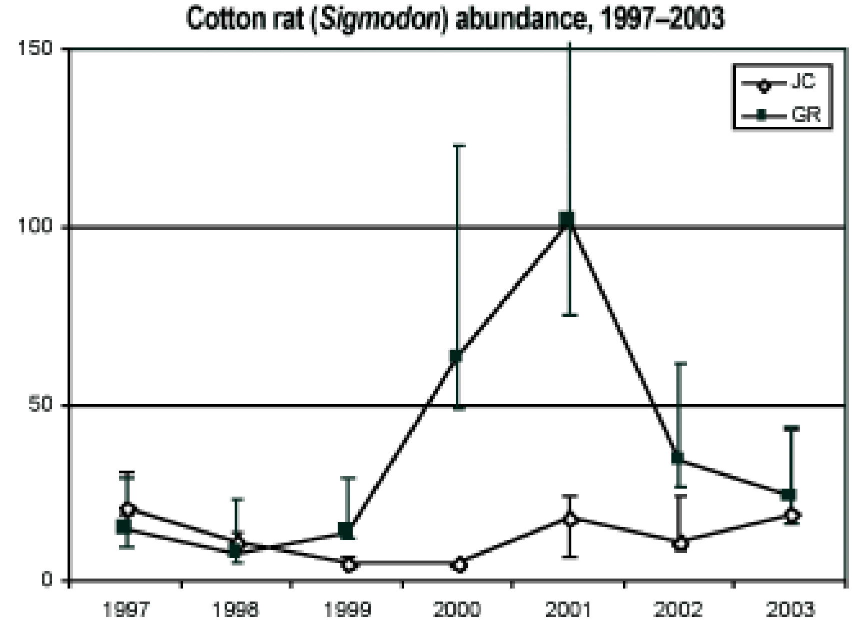

Figure 5. Estimated abundance and 95% confidence interval of cotton rats (*Sigmodon* spp.) on Joe's Canyon (oak woodland) and Grassland (semi-desert grassland) monitoring grids at Coronado National Memorial, 1997–2003. Most cotton rats on the Joe's Canyon grid were yellow-nosed cotton rats, and most on Grassland grid were Arizona cotton rats.

have been found very close to the memorial and are likely to occur there (e.g., common porcupine [*Erithizon dorsatum*]) from time to time; species which occur nearby but are unlikely at our site due to lack of suitable habitat, e.g., round-tailed ground squirrel (*Spermophilus tereticaudus*); species which are certainly not resident but range widely and may pass through the memorial from time to time, e.g., jaguar (*Panthera onca*); and a few species which are now certainly extirpated in the area, e.g., gray wolf (*Canis lupus*). Swann et al. (2000) provides detailed species accounts for all known and potential species, including summaries of historic and museum records.

Comparison with past studies

Our study confirmed a number of rodent species not confirmed by an earlier inventory (Petryszyn and Cockrum 1979). Although their study was shorter and involved fewer trap nights than ours, Petrysyn and Cockrum (1979) trapped in similar areas and did not detect several grassland species, such as pygmy mice, three species of kangaroo rats, and three species of cotton rats. Indeed, the yellow-nosed cotton rat (*Sigmodon ochrognathus*), one of the most abundant rodent species at both higher and lower elevations, was never trapped by Petryszyn and Cockrum (1979).

The most plausible explanation for these differences, in addition to reduced effort, is that grasses in the low elevation grasslands south of East Montezuma Canyon Road, which were very robust during our study, were sparse in 1977–78 due to heavy cattle grazing and low rainfall. Although grazing occurred in the memorial during our study, it had been absent from this area for at least 8 years when our

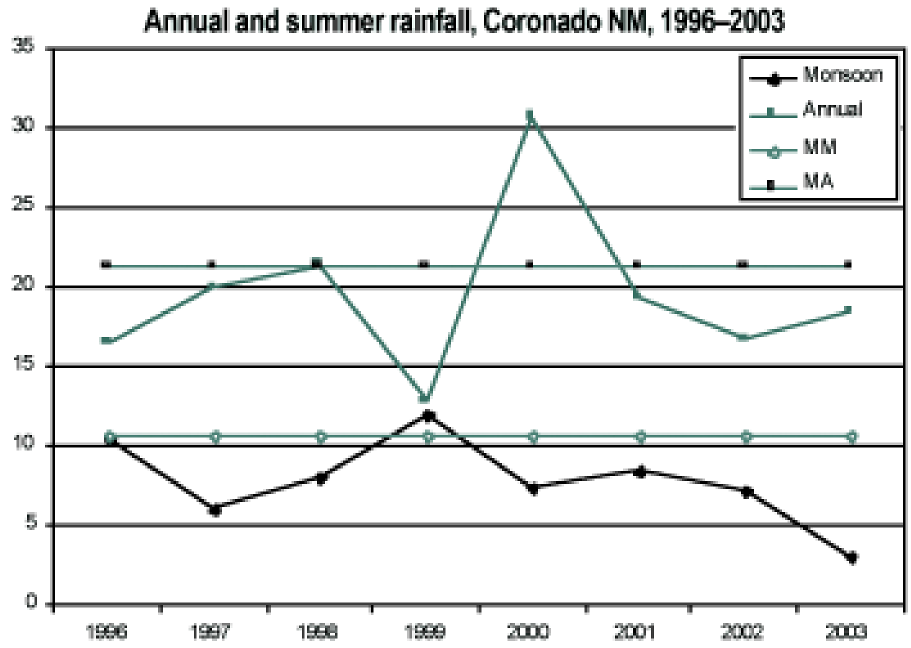

Figure 6. Annual and summer rainfall totals, Coronado National Memorial, 1996-2003. MM = Mean monsoon, MA = Mean annual. "Monsoon" is rainfall total during June, July, August, and September. Source: National Weather Service.

inventory began (E. Lopez, Coronado NM superintendent, pers. comm.). Our long-term semi-desert grassland grid was dominated by the non-native Lehmann's lovegrass, but nonetheless had a very high abundance and richness of native rodents.

Another major change that has occurred at Coronado during recent decades has been the loss of trees (particularly conifers) and the resultant growth of high elevation grasses since the severe Peak Fire of June 1988 (Ruffner and Johnson 1991). Our oak woodland monitoring grid was located in an area of thick native grasses that had completely burned during the Peak Fire. This vegetative change may also be related to the cessation of grazing at higher elevations. The resulting increase in grass seed crop has clearly been favorable to small rodents. It will be interesting to track changes in the species diversity of these oak savannas if they become revegetated with oaks and piñon pine.

Monitoring implications

Although monitoring is essential if the NPS is to fulfill the important mission of preserving biodiversity on its lands, monitoring of vertebrates can be time-consuming and expensive. Many mammal species are difficult to observe and count, and their populations often fluctuate greatly due to natural causes. Monitoring is particularly difficult in small park areas where human and financial resources may be more variable and limited than in larger parks (Swann 1999). Coronado does not have any threatened and endangered terrestrial mammals, so our study examined the costs and benefits of two other methods proposed for monitoring terrestrial mammals, annual trapping of small mammals and repeated

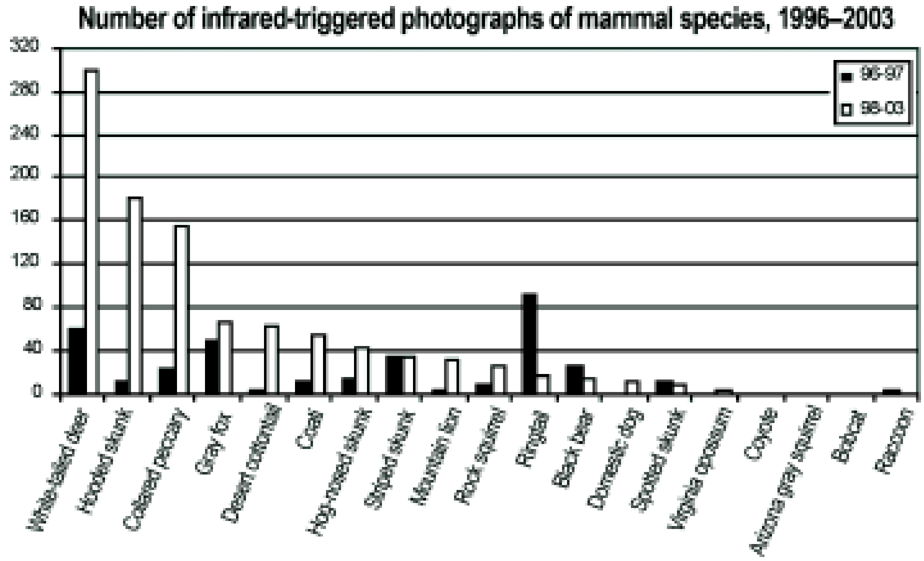

Figure 7. Number of photographs of 19 species of mammals detected by infrared-triggered (Trailmaster) cameras during inventory phase (1996-1997) and long-term monitoring (1998-2003).

inventories of the terrestrial mammal community as a whole.

Annual trapping of small mammals is often recommended for monitoring programs for various reasons, including documentation of changes in prey base and overall environmental conditions. In our study, annual monitoring clearly provided many economic and non-economic benefits, including a demonstration of the dynamic nature of mammal communities at the memorial. As seen in other studies in semi-desert grasslands (e.g., Heske and Brown 1990), abundance of grassland rodents varied among years and appeared to respond to changes in precipitation. We observed a large increase in Arizona cotton rats, normally associated with riparian grasslands, during the very wet period during 1999–2000. The 1997–2003 trapping effort also gradually increased our detection of very rare species in the memorial and added new species.

Non-economic benefits of our effort included opportunities to work with volunteers in the field and a higher profile for research in the park. Like many parks, Coronado relies on volunteers for many daily tasks, and many volunteers in visitor contact positions increased their knowledge of natural resources by assisting with trapping efforts.

Our economic costs during the period were minimal, but this was because of continuity in personnel and a high reliance on volunteers. One of us (BA) was employed by the memorial during most of this study and was able to assist with mammal trapping, recruit park volunteers, secure park funds to pay two of us (DES and MB) for short periods to process mammals, coordinate infrared-triggered camera efforts, and coordinate security arrangements directly with law enforcement staff. However, staff changes at the memorial were one factor in our decision to discontinue monitoring in 2003, as by that time there were higher priority issues at the memorial than monitoring non-threatened or endangered mammals.

Border security, not an issue when we started the inventory in 1996, became the overriding issue at the memorial during 1998 (and remains so as of this writing). During 1998–2003 we were unable to set or check traps before or after sunset, which greatly reduced the number of traps we could set within our budget, which in turn reduced power to detect significant trends. In addition, our data suggest that small mammals are probably not a good indicator for impacts associated with the international border; mammals were abundant during periods where border crossings and enforcement activities were high.

Efficiency of intensive inventories in describing the mammal community

Another goal of this study was to assess how completely the mammal community could be described with an intensive, relatively short-term effort (approximately one year). For small parks such as Coronado, monitoring mammal diversity through periodic (repeat) inventories has been proposed as a cost-effective approach to long-term monitoring (Swann 1999). The advantage of repeat inventories is that they do not require permanent staff (indeed, our intensive inventory was conducted through a cooperative agreement with the University of Arizona). Repeat inventories may provide insight into important changes that are occurring, such as the loss of native species. But due to the difficulty of detecting rare species, there is a danger that short inventories may fail to adequately describe the community in a way that is adequate for long-term monitoring.

During the inventory phase of our study we confirmed or reliably observed 42 species; during the monitoring phase we trapped, photographed, or observed all but three of these species; collected or photographed two of the five observed species; and confirmed an additional three species. Thus, if mule deer and eastern cottontail are excluded, and reliable observations included, the 1996–1997 inventory documented 42 of the 45 species (93.3%) known to occur at Coronado during the entire 1996–2003 period. This high percentage suggests that for monitoring long-term changes in diversity of mammals, at least, inventories of short duration can be reasonably complete if they are of sufficiently high intensity and are designed to be repeatable.

However, the species we detected only in the monitoring phase are obviously rare at the memorial and therefore may be of greater management interest. Long-term studies of many taxonomic groups (see summary in Rozensweig 1995) indicate that known species richness in an area increases over time, though at a declining rate. Species detected only after significant effort probably exist in small populations or expand their ranges to include the memorial during years with favorable environmental conditions. For this reason, estimation of species richness, or at least use of species accumulation curves, should be part of the inventory process.

Monitoring recommendations

National Park Service programs to monitor mammals often emphasize estimating population size of threatened or endangered species such as Florida panthers, or common species such as deer mice, but are not concerned with monitoring other species. Threatened or endangered species often must be studied for legal reasons, and long-term studies of single species (Gibbons 1990; Pierson and Turner 1998) have given tremendous insight into their natural history and endangerment factors. Nevertheless, understanding changes in abundance of selected species is no substitute for data on trends in the presence and distribution of all species in the park. Loss of species from national parks and other natural areas due to human impacts is a major concern (Newmark 1995) yet one that few monitoring programs are designed to measure. In addition to tracking potential changes in abundance of common species, monitoring must provide information on species that may be in danger of extirpation because of their rarity or loss of specialized habitat.

Our study suggests that intensive inventories may be a useful and more sustainable tool for monitoring mammals in small national parks and natural areas than annual monitoring. Inventories designed to be repeated every 10-20 years can allow assessment of overall changes in species richness as well as in the individual status of different species. To be effective, repeat inventories should take a systematic approach to sampling all species in the area of interest and include trapping and use of infrared-triggered cameras or similar technology in all vegetation communities.

Like all monitoring approaches, repeated inventories may be helpful in detecting many types of ecological changes, both positive and negative. Comparison of our results with Cockrum and Petryzyn (1979) suggests that native species diversity may be increasing at Coronado and that the memorial may be a refugium for many mammals, including not only grassland rodents, but also hunted animals such as deer and predators such as mountain lion. Because of this, the memorial may also play a future role in the return of species which are presently extirpated from the area. Black-tailed prairie dogs (*Cyonomys ludovicianus*), which occurred near the memorial earlier in this century, occur in Mexico less than 4.8 km (three miles) south of the Huachucas (Ecological Center of Sonora 1994) and could naturally recolonize the memorial in the future. Coronado, as part of the Greater Huachuca Mountains–San Pedro River area, similarly provides habitat for jaguars, ocelots (*Leopardus pardalis*), and gray wolves moving northward, should these species increase in number. On the other hand, future development of a border fence could restrict movements of animals. The memorial by itself is not large enough to sustain populations of large species such as mountain lions, black bears (*Ursus americanus*), and coatis (*Nasua narica*), so habitat loss in the San Pedro Valley could lead to local extirpation of these species.

While monitoring of mammal diversity through repeated inventories should be a priority, it goes without saying that other research and monitoring should occur whenever possible. In addition to small mammals, efforts should be made to study selected mammal species intensively, measuring abundance as well as parameters such as reproduction and survival. Long-term studies of species that are of management interest at Coronado, such as ringtails (*Bassariscus astutus*), skunks, or pygmy mice, are extremely rare, and would benefit not only NPS but other land management and wildlife conservation agencies.

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THE SMALL MAMMAL COMMUNITY ASSOCIATED WITH IRONWOOD *(OLNEYA TESOTA)*

Helí Coronel-Arellano and Carlos A. López-González

One of the most studied assemblies (Fauth et al. 1996) are the small mammals in the North American deserts. Through these studies, mechanisms have begun to be proposed to understand the structure of a community; this is in part because of the relative simplicity of the microenvironments present in arid zones (Shepherd and Kelt 1999; Kelt et al. 1999; Giannoni et al. 2001). In arid environments the association of small mammals with vegetation is important because they modify it directly (Kelt et al. 1999); one of the main functions of the community of small mammals is to generate changes in the distribution and structure of the vegetation, mainly of herbs and shrubs because these are their main sources of food (Curtin et al. 1999; Price and Correll 2001; Sassi et al. 2004).

Small mammals are one of most abundant groups in North American deserts and their coexistence has been attributed to processes that imply differences in the use of microhabitat and variation in food availability (Kelt et al. 1999). In relation with microhabitat use, it has been established that rodents with bipedal locomotion (e. g. *Dipodomys*) are species that prefer to forage in areas with low cover and sparse vegetation (Thompson 1982; Hallet 1982). Regarding the species with quadruped locomotion (e.g. *Chaetodipus*, *Perognathus* and *Peromyscus*), they concentrate their foraging in areas with dense vegetation and cover which protect them from predators (Hallet 1982; Kotler 1984).

Rodents in arid zones act as seed dispersers and they feed mainly on plants (Brown et al. 1979; Price and Correll 2001; Folgarait and Sala 2002). It is important therefore, to evaluate the degree of association between rodents and plants on the community level. The legume ironwood (*Olneya tesota*) has been broadly studied in both the United States and the state of Sonora, México. It is the most abundant species of the coast of the Gulf of California and the plains of Sonora (Nabhan and Behan 2000). The ironwood, an extremely hard wood (hence the name), has remarkably slow growth (it has been estimated that some trees are 800 years old) and can grow to heights exceeding 15 meters. (Tewksbury and Petrovich 1994; Nabhan and Behan 2000).

Ironwood is considered one of the main Sonoran Desert nurse species, because under its canopy microenvironments are created which increase the germination and establishment of different seedlings (Búrquez and Quintana 1994). Nurse trees protect various species of plants like saguaros and other columnar cacti from sun radiation, high temperatures, and water stress (Búrquez and Quintana 1994; Tewksbury and Petrovich 1994).

The majority of ecological studies have been focused on the association of ironwood with the seedlings that use it as a nurse species, leaving aside the relationship that it has with the fauna. Of the few existing studies of the relationship with fauna, it has been determined that the presence of ironwood, palo verde and acacias increases the richness of bird species up to 63.7%, and in absence of such vegetal association, owls and woodpeckers disappear from the community (Nabhan and Behan 2000).

Tewksbury and Petrovich (1994) carried out counts of bird nesting sites in the canopy of the ironwood and they compared it with other types of bushy vegetation *(Acacia, Bursera, Colubrina, Condaliopsis, Jatropha, Prosopis* and *Cercidium, Zizyphus* and *Jaquinia)*. The authors studied the numbers of animals and their activity in sites with ironwood (e.g., bedding places and direct observations). These authors found a larger number of nesting sites in ironwood (27) than in the rest of trees and bushes (19). In regard to the activity of other animals, they found a relationship between the canopy cover and the increase of usage from mammals and reptiles. Observations show that the birds, mammals and reptiles use with major frequency habitat associated with ironwood trees (Tewksbury and Petrovich 1994).

There is no reliable inventory of the fauna associated with ironwood, because the information available is the product of questionnaires sent to different researchers. From this questionnaire, the probable fauna associated with *O. tesota* are 25 species of ants, 25 orthopterans, 188 bees, 12 anura, 19 lizards, 24 serpents, 57 birds, and 64 mammals (Nabhan and Behan 2000).

Regarding mammals, the species that may have a major use of ironwood sites are the ones belonging to the order *Rodentia*; one of the main groups that feeds on and harvests seed in North American deserts. McAuliffe (1984) registered consumption of ironwood seedlings by pocket mice (*Perognathus* sp.), packrats (*Neotoma* sp.) and ground squirrels (*Spermophilus* sp.). Nevertheless, the conditions that favor the frequency and quantity of seed depredation is unknown.

Due to the fact that ironwood in the Sonoran Desert is one of the main nurse species and is under anthropogenic pressure, it is necessary to evaluate the relationship that this tree has with rodents. Therefore, the objectives of this work were: (1) to determine if the community of small mammals selects sites with ironwood, (2) to describe and compare the richness, structure and composition of the community of small mammals, and (3) to determine if the abundance of rodents has a relationship with the cover and structure of the vegetation.

STUDY AREA

The study area was located within the Sonoran Desert in the state of Sonora, México. We conducted sampling at four localities (Figure 1). The first study area was San Judas Ranch, located at coordinates 29˚22'43" north latitude and 111˚06'37" west longitude. The second was the Pozo Hondo Ranch, located at Hermosillo municipality at 29°43'05" north latitude and 111°25'11" west longitude and at an altitude of 638 meters above sea level. The third study area was Las Glorias Ranch, with location at 29°38'05" north latitude and 111°29'12" west longitude.

These three study areas are located in the "plains of Sonora" of the Sonoran Desert (Turner and Brown 1994). The climate of these locations is classified as "very dry semi-hot with rains in summer." The average annual temperature is 21.8° C, the highest temperatures are in the months of July (31.6° C) and August (30.6° C) and the lowest temperatures are in the months of December and January (13.5° C and 12.7° C respectively); the average annual precipitation is 278.4 mm, the major quantity of rain (66.3 and 67.4 mm) occurring in the months of July and August (Instituto Nacional de Estadística, Geografía e Informática 2000).

The higher canopy of the vegetation is dominated by *Olneya tesota*, it is also characterized by *Fouquieria macdougalii*, *Bursera confusa*, *Cercidium praecox*, *C. microphyllum* and *Prosopis*; the most common cactus species are *Lophocereus schottii*, *Stenocereus thurberi* and *S. alamosensis*. Regarding the shrubs, *Encelia farinosa* is the most abundant. There are also large size bushes such as *Mimosa laxi-*

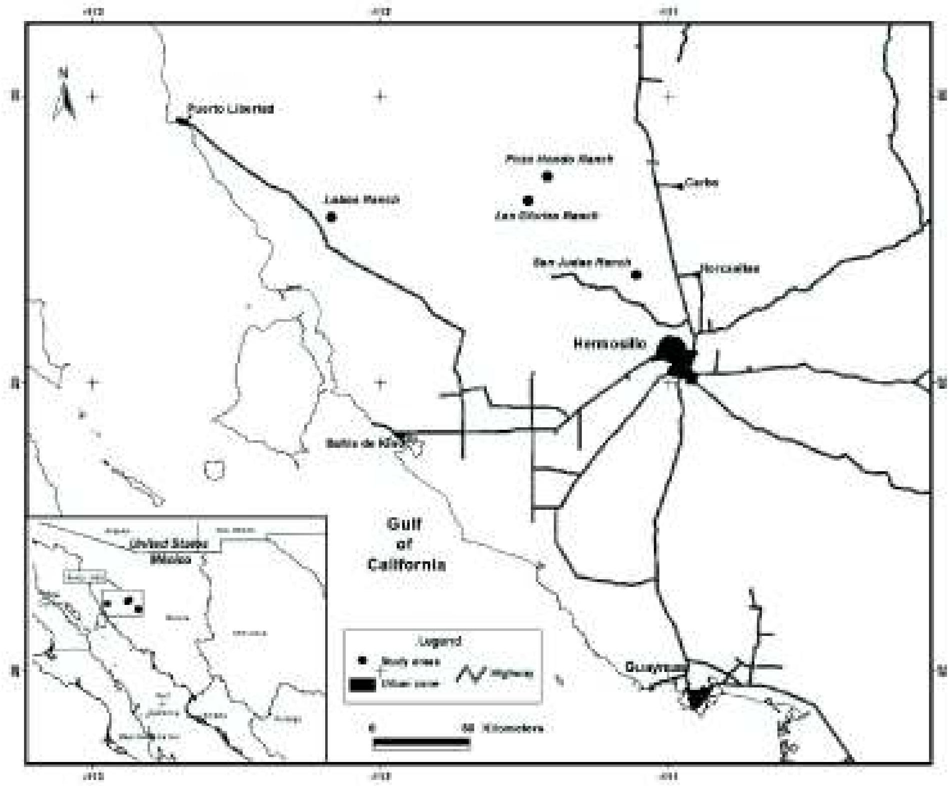

Figure 1. Localities sampling in the Sonoran Desert.

flora, *Guaiacum coulteri*, *Phaulothamnus spinescens* and *Randia thurberi* (Turner and Brown 1994).

The last place that we studied is Lobos Ranch, located at 50 kilometers to the south-east of Puerto Libertad in the municipality of Pitiquito Sonora, at 29°34'36" north latitude and 112°10'10" west longitude, elevation 198 meters above sea level. This place is located in the "central gulf coast" (Turner and Brown 1994). This private property has 22,800 hectares and is managed for hunting and forest exploitation. Forest management includes the extraction of rubber, charcoal, mesquite wood, and jojoba seeds. The climate of this location is semi-hot with cool winter. The average annual temperature is 20° C and the average annual precipitation is 250 mm. This property consists of 95% plains with small hills in the center (Information Systems and Automation 2005). The main vegetation elements are bushes such as *Jatropha*, *Euphorbia*, *Fouquieria splendens*, *Larrea tridentata* and small trees like *Cercidium microphyllum*, *Olneya tesota* and *Bursera;* other bushes with a minor representation are *Encelia farinosa*, *Solanum* and *Ambrosia*, the representative cactus in the area is *Lophocereus schottii* (Turner and Brown 1994).

METHODS

Capture of Organisms

At each study area, we selected 20 sites with ironwood and 20 sites without ironwood. Within each site we captured small mammals by placing Sherman traps of three different

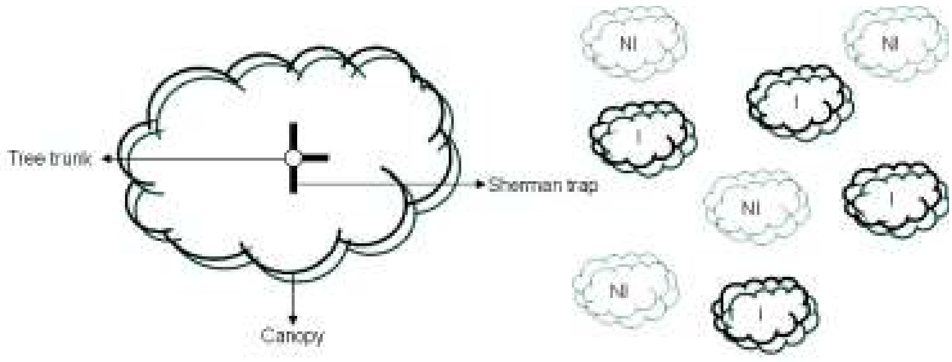

Figure 2. Spatial diagram of Sherman traps in vegetation sites, where I = Ironwood, NI = No Ironwood.

sizes (small, medium and large) in a circular pattern, taking as center one ironwood or the absence of it (Figure 2; Coronel et al. 2005). We baited the traps with oats mixed with peanut butter and vanilla. The captured organisms were identified to species, sexed, weighed and released. The identification of the captured organisms was made using species keys present in MacMahon (1994), Álvarez-Castañeda and Patton (2000) and Whitaker (2002).

The relative abundance of each species was calculated dividing the number of individuals by the sampling effort (Nichols and Conroy 1996).

Association with Ironwood

To establish if there were any differences in selection by the small mammal community at sites with ironwood, we used a two-way ANOVA. Also, the species diversity was compared in sites with and without ironwood by ways of the equity index of Shannon-Weaver using a paired t-test (Zar 1999).

Community Analysis

We described species richness at each site, by counting the number of species of small mammals at the four study areas. The Margalef index (D_{mg}) was also calculated for each site. To evaluate the efficiency of the sampling, we calculated a species accumulation curve, using as effort the 511 locations where the traps were placed. This analysis was elaborated with data of two places (Pozo Hondo and Lobos ranches). To construct the curve three non-parametric estimates of alpha diversity, were used $Chao_2$, Jackknife of first order and Bootstrap; the estimate $Chao_2$ is recommended when dealing with small sample size and it is calculated as $Chao_2 = S + (L^2 / 2M)$ where, S = the total number of species, L = number of species that occur only in one sample (unique species) and M = is the number of species that occur in two samples.

The Jackknife estimate of first order is based on the number of species that occur only in one sample (L); this estimate reduces the subestimation of the real number of species in the area of study and is calculated as follows: $Jackknife\ 1 = S + L\,(m - 1/m)$, where S = is the total number of species, L = number of species that occur only in one sample (unique species), m = number of samples. The third estimate used was Bootstrap which is calculated as follows: $Bootstrap = S + \Sigma\,(1 - p_j)^n$. This estimate is based on p_j, the proportion of sampling units that contain each species *j*, but it appears that this estimate is less precise than the prior two (Magurran 2004). To calculate the alpha diversity values we used the algorithms of the program Estimates 7.5.0 (Colwell 2004).

To analyze the structure of the community, abundance rank curves were created to determine abundant and rare species in the sampled sites. These curves were constructed calculating the abundance logarithm of each species and are graphed (on the *x* axis) ordering from the most abundant species to the least abundant. This type of curve allows one to observe the dominance or evenness of the different species within the community. When a community is highly equitable the curve of the table is horizontal. On the other hand when there is a high dominance species the curve has a vertical form. To analyze the heterogeneity we calculated the index of equity of Shannon-Weaver and Pielou (*J´*). This last one measures the proportion of the observed diversity in relation to the maximum expected diversity. Its values go from 0 to 1, this last value is achieved when all the species abundance is equally distributed in the community (Magurran 2004).

Structure of the Microhabitat

Additionally, in the sites where traps were located (with or without ironwood), we quantified canopy cover by measuring two distances: from the tree or shrub to the north (D1) and another to the east direction (D2); the canopy cover was calculated with the following formula of area: A =0.25 * 3.1416 * D1* D2. To determine if there are differences in cover between sites with and without ironwood a t-test was applied. To establish if canopy cover has an effect on the number of captured rodents, a simple linear regression was made. The analysis of cover was made with 256 sites per treatment.

In the sites where the traps were located, the distance to the nearest tree and shrub was measured, using the point-quarter sampling method (Brower et al. 1998); to establish if there were significant differences between the distances to the nearest tree and bush of the sampling sites, a t-test (Zar 1999) was applied to each case. To determine if the structure of the vegetation (distance to the nearest tree and bush) of the sampled sites had an effect on the number of captured organisms, a Pearson correlation was made for each case (Zar 1999). The previous analyses were made with 200 sites per treatment.

RESULTS

The sampling effort was 6,732 trap nights. A total of 599 rodents were captured, concentrated in three families, seven genera and 10 species. The relative abundance of each species of rodent was different. The most abundant rodent was the spiny pocket mouse (*Chaetodipus baileyi)*, followed by the kangaroo rat (*Dipodomys merriami),* desert pocket mouse *(C. penicillatus)* and the white-throated woodrat *(Neotoma albigula)*. The least abundant rodents were two species of *Peromyscus* (Table 1).

Association with Ironwood

We found no preference for sites with ironwood, because there were no significant differences in the treatments with or without ironwood (F = 0.012, df = 1, P = 0.9130), nevertheless, a significant difference between the abundance of the species (F = 8.823, df = 9, P = 0.0001; Figure 3) was found.

Species diversity in the sites with ironwood was higher (H'= 1.50) in comparison with the sites without ironwood (H'= 1.26), nevertheless, there was not a significant difference in the diversity between both treatments (t = 0.276, df = 598, P = 0.05).

When diversity was analyzed between sites, Las Glorias and Lobos, the diversity of rodents was higher in areas with ironwood (Las Glorias H'= 0.8019; Lobos H'=1.624) than in areas without ironwood (Las Glorias H'= 0.7785; Lobos H'= 1.573). For the San Judas and Pozo Hondo ranches, diversity was higher in the areas without ironwood (San Judas H'= 0.7646; Pozo Hondo H'= 1.297), than in areas with ironwood (San Judas H'= 0.6588; Pozo Hondo H'= 1.072).

Community Analysis

The site with higher specific richness (D_{mg}) was Lobos Ranch, followed by San Judas, Pozo Hondo, and Las Glorias ranches. In addition, sites that presented a higher diversity and

Table 1. Species richness and relative abundance of small mammals captured.

Family	Species	AIW*	PIW*	Total	Relative Abundance
Heteromyidae	*Perognathus flavus*	18	12	30	0.0045
	Chaetodipus baileyi	148	158	306	0.0455
	Chaetodipus penicillatus	31	35	66	0.0098
	Dipodomys merriami	66	49	115	0.0171
Muridae	*Neotoma albigula*	18	37	55	0.0082
	Peromyscus maniculatus	1	0	1	0.0001
	Peromyscus eremicus	3	9	12	0.0018
	Peromyscus boylii	0	1	1	0.0001
	Onychomys torridus	5	3	8	0.0012
Sciuridae	*Spermophilus tereticaudus*	3	2	5	0.0007

*AIW = Ironwood absence, *PIW = Ironwood presence.

dominance were Lobos and Pozo Hondo ranches (Table 2).

The estimates of alpha diversity $Chao_2$ and Bootstrap predicts that there are seven species of rodents in the Pozo Hondo and Lobos ranches, while the estimate of first order Jack-knife predicts eight species (Figure 4).

The rank-abundance curves (Figure 5) showed in the four ranches a high dominance of the family *Heteromvidae*, represented mainly by the species *Chaetodipus baileyi* and *Dipodomys merriami*. The species *Chaetodipus baileyi* was the dominant species in three sites (Lobos, San Judas and Las

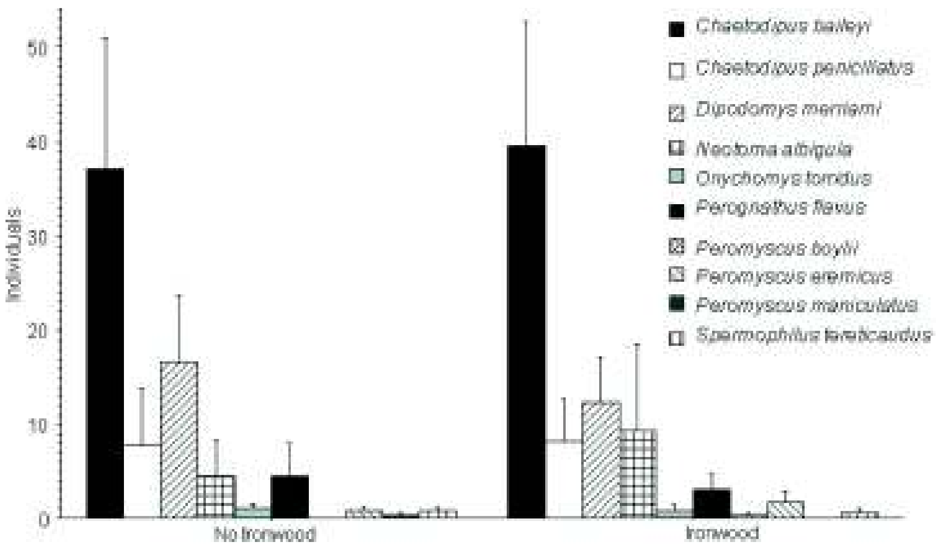

Figure 3. Number of individuals by species between treatments (with or without ironwood).

Table 2. Species, number of individuals and diversity indexes for the study areas.

Species	Lobos	San Judas	Pozo Hondo	Las Glorias
Spermophilus tereticaudus	4	1	0	0
Dipodomys merriami	65	13	19	18
Chaetodipus baileyi	129	90	2	85
Chaetodipus penicillatus	47	2	5	10
Perognathus flavus	23	5	0	2
Neotoma albigula	53	0	2	0
Onychomys torridus	5	0	2	0
Peromyscus eremicus	3	1	6	0
Peromyscus boylii	1	0	0	0
Peromyscus maniculatus	1	0	0	0
Number of Individuals	331	112	36	115
Total Number of Species	10	6	6	4
Margalef Index	1.551	1.060	1.395	0.632
Shannon-Wiener Index	1.637	0.721	1.392	0.797
Pielou Index	0.711	0.313	0.605	0.346

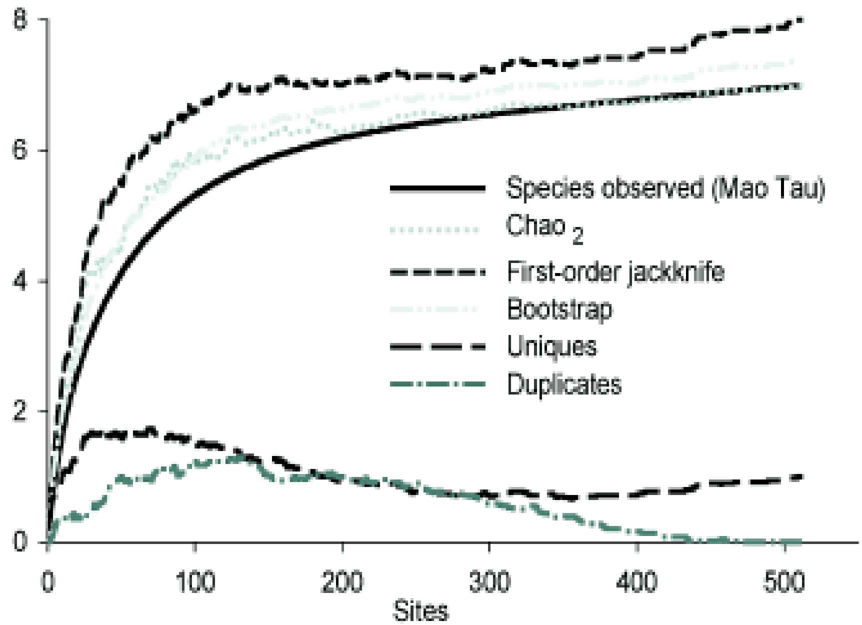

Figure 4. Species accumulation curve of rodents using three non-parametric estimates of alpha diversity.

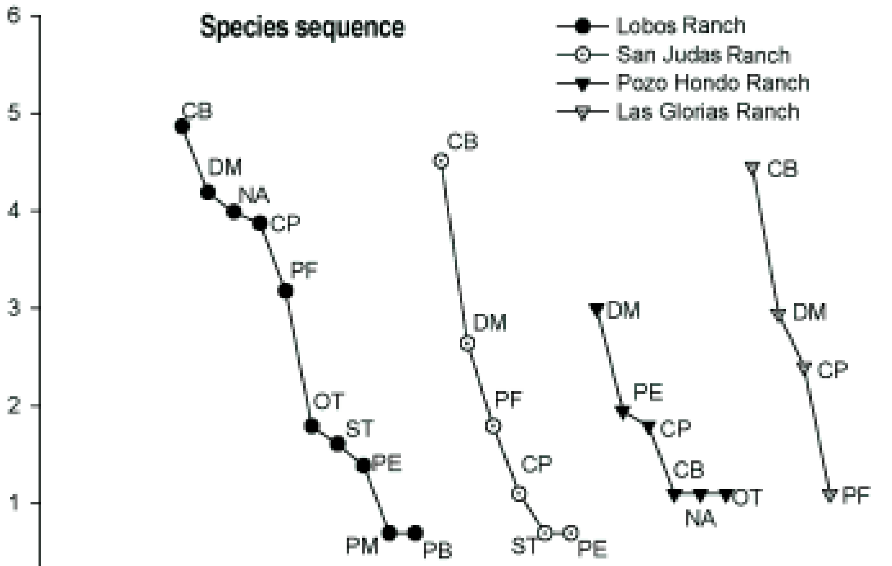

Figure 5. Rank-abundance curve for the species of small mammals in the four study sites. Where CB corresponds to *Chaetodipus baileyi*, DM to *Dipodomys merriami*, NA to *Neotoma albigula*, CP to *Chaetodipus penicillatus*, PF to *Perognathus flavus*, OT to *Onychomys torridus*, ST to *Spermophilus teriticaudus*, PE to *Peromyscus eremicus*, PM to *Peromyscus maniculatus* and PB to *Peromyscus boylii.*

Glorias ranches), while in Pozo Hondo Ranch the dominant species was *Dipodomys merriami*.

Structure of the Microhabitat

Average cover was higher on sites with ironwood (x =14.36, SD = 21.76, n = 256) than on sites without ironwood (x = 6.16, SD = 10.23, n =256; t = 5.46; df = 510; P = 0.0001). In addition, we found a negative association between cover and number of animals captured (r = 0.651, df = 26, P = 0.0002; Figure 6). *Dipodomys merriami* presents a higher number of captures in areas with reduced cover (r = 0.669, df = 9, P = 0.0342; Figure 7).

Average distance between trees on sites with ironwood (x = 12.94; DE = 8.84; n = 200) and without ironwood (x = 13.12; SD = 9.11; n =200) was not significantly different (t = -0.2, df = 398, P = 0.8414). Nevertheless, we found that shrub distance was higher (t = 4.14, df = 398, P = 0.0001) on sites with ironwood (x = 3.76; SD = 1.61; n = 200) than on sites without ironwood (x = 3.10; SD = 1.58; n = 200). Regarding the correlations, a relationship between the distances to shrubs and captures was not found (r^2 = -0.0732; P = 0.059), but we did find a relationship between distance to trees and small mammal captures (r^2= -0.732; P = 0.010).

DISCUSSION

The species with higher number of captures were the ones belonging to the family *Heteromyidae* and the species *Neotoma albigula*. These results coincide with those reported in other studies of small mammals in the Sonoran Desert (Duncan 1990; Petryszyn and Russ 1996).

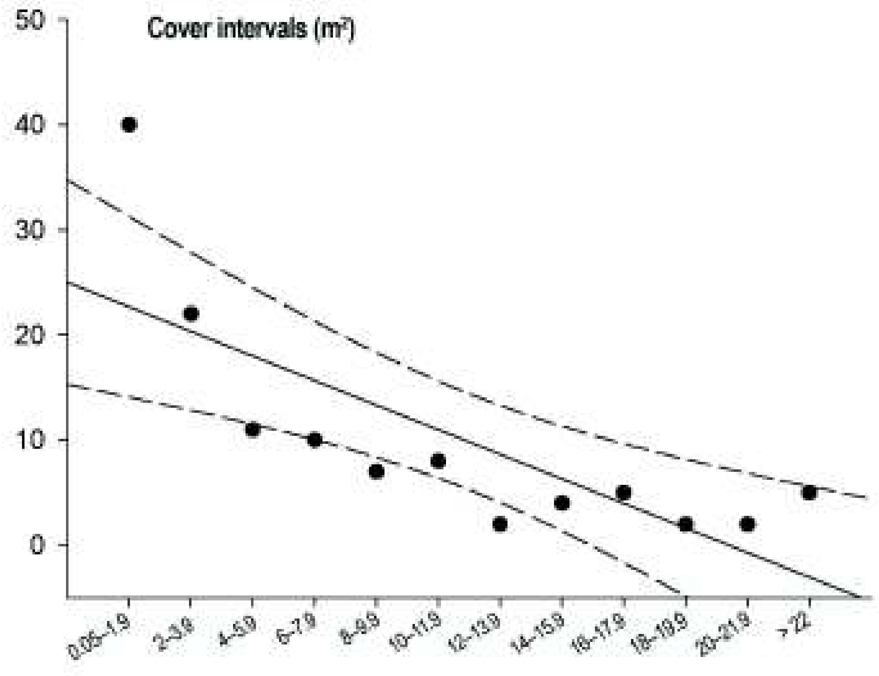

Figure 6. Simple lineal regression of the ranks of cover and number of captured individuals.

In this study we found that ironwood was not selected as a nurse species by the community of small mammals, because there were no differences in the abundance between the treatments (with and without ironwood), also, we found that the diversity in both treatments was similar, so these results differ with those reported for perennial seedlings and birds. Other authors have found that in sites with ironwood the diversity and species abundance is higher when compared with sites without *O. tesota* (Tewksbury and Petrovich 1994; Nabhan and Behan 2000).

Regarding the evaluation of the sampling by the curves of accumulation of species, the different estimates of alpha diversity $Chao_2$, Jackknife of first order and Bootstrap predict between seven and eight species per site. From the previous supposition in three sites (Pozo Hondo, San Judas and Las Glorias) we documented 100% of the diversity of small mammals, while for Lobos we documented 80%, nevertheless, in this site we counted only one record of *Peromyscus boylii* and *P. maniculatus,* which may mean that these individuals have an erroneous identification and belong to the species *Peromyscus eremicus* (Table 1).

In this study, we found a high dominance by the species *Chaetodipus baileyi* which can be explained by this species preference for areas with trees and bushes of large size (Paulson 1988), characteristics that were presented at all study sites.

The rank-abundance curves (Figure 5) show that *C. baileyi* was the dominant species in three sites, followed by *D. merriami*, which can mean that these two species are in direct competition; as has been observed in other studies, where *C. baileyi* excludes *D. merriami* (Paulson 1988).

Despite the fact that the ironwood did not explain the presence of small mammals, it was

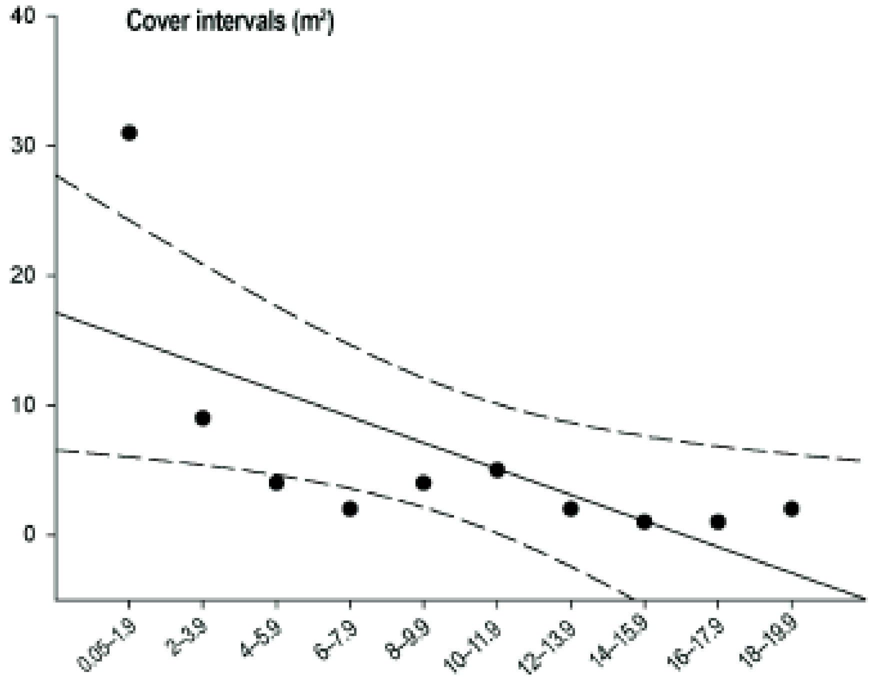

Figure 7. Simple lineal regression of cover and captures of *Dipodomys merriami.*

found that the structure of the habitat (cover of the canopy and distance to trees) has an influence on the abundance of rodents, as we found a higher usage of sites with small cover (0.05 to 11.9 m^2) and small distances to trees (6 to 15 m), which may indicate that the documented species in this study concentrate their foraging activity on sites with closed vegetation structure, which reduces the detection from predators (i.e., owls, coyotes, kit fox, or snakes), because closed areas or sites are suitable to reduce the risk of predation (Thompson 1982; Kotler 1984; Brown et al. 1988).

The relationship that we found of a higher number of captures of *Dipodomys merriami* in open sites has been reported in other studies and it has been attributed to the biped locomotion of this heteromyid, which favors its ability to escape from predators (Brown and Lieberman 1973; Price 1978; Hallet 1982; Thompson, 1982).

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FINDING THAT 4-STAR DINER OR HOW BATS MIGHT "ANTICIPATE" PRODUCTIVE FORAGING AREAS

Debbie C. Buecher, Ronnie Sidner, and John L. Koprowski

Riparian corridors, particularly in the American Southwest, are critical habitat for many plant and animal species (Ohmart and Anderson 1982). The structural complexity of streamside landscapes often contains tremendous biodiversity — often contributing much greater diversity than their proportion of land area (Neary et al. 2005). Unfortunately, riparian environments are often at risk due to anthropogenic pressures such as water extraction, cattle grazing, urbanization, mining, and timber harvest (Steiner et al. 2000). These impacts have caused riparian landscapes to dwindle to less than 1% of the area known in the late 19th century (Ffolliott and Thorud 1974). As well as a reduction and degradation of historic riparian environments, the introduction of exotic species has added additional pressure to the quality of these landscapes. Because of concern for native species impacted by these changes, studies have been conducted to evaluate resource use across taxa (Greier and Best 1980; Hunter et al. 1988; Anderson 1994; Ellis et al. 2000). Riparian landscapes are also important foraging habitat for bats and may provide their only access to drinking water (Grindal et al. 1999; Holloway and Barclay 2000). We used a Sonoran Desert riparian corridor to define and quantify the associated bat community. Our study is an effort to provide land management agencies with critical information necessary to make informed decisions regarding wildlife in an arid region.

Historically it has been difficult to study and monitor habitat use by nocturnal mammals, due to the inability to observe behavior in low light levels. An assessment of peer-reviewed literature indicated a paucity of research publications, particularly on bats and rodents in Arizona (Koprowski et al. 2005). In addition, because body mass of most temperate bats is ≤ 15 grams, Aldridge and Brigham (1988) found advances in radio-transmitter technology (i.e., miniaturization) necessary to allow for the effective monitoring of bats during their study of night-time foraging. Due to the labor-intensive nature of these studies, there is still only a limited understanding of how individuals use their environment. Studies examining broad landscape questions among multiple species are still prohibitively expensive. On the other hand, due to use of biosonar by bats for spatial orientation and to forage for food (Griffin 1958), recent advances in acoustic technology have given us another tool to monitor bats across landscapes. This study began as an investigation of bat use along a Sonoran Desert riparian corridor but serendipitously gave us some greater insight into how bats perceive and perhaps even anticipate food resources in heterogeneous environments.

STUDY SITE

Sabino Canyon is a Sonoran Desert riparian corridor administered as a recreational area by Coronado National Forest, U.S. Department of Agriculture. This rugged canyon system, just north of Tucson, Arizona, is in the front range of the Santa Catalina Mountains. These mountains lie on the northeastern edge of the Sonoran Desert and rise to 2791 m above the 728 m desert floor. The Santa Catalinas are composed of hard metamorphic granites and the mid to lower reaches of Sabino Canyon are characterized by dramatic vertical cliffs (Bezy 2004). This popular oasis is situated in the Arizona Upland subdivision of the Sonoran Desertscrub Biome (Turner and Brown 1994). Although the Forest Service has closed the area to private vehicles, they provide areas to hike, picnic, and bicycle, plus a tram system transports visitors 5.6 km along the bottom of the canyon. The proximity of Sabino Canyon to a large metropolitan area (~ 800,000 residents) ensures heavy visitation (> 1.4 million visitors/year) to this scenic attraction. In addition, two major forest fires (Bullock Fire 2002 and Aspen Fire 2003) in the upper watershed of this canyon have applied further pressure on a resource already impacted by recent years of drought (Swetnam and Betancourt 1998). Annual precipitation for Tucson is approximately 300 mm/year, with the surrounding mountain ranges getting up to 750 mm/year. The Sonoran Desert has a bimodal rain pattern, with about 50% of the annual precipitation occurring during December–February, producing snow above 1500 m. The rest of the precipitation generally falls during July–September as intense summer monsoon storms. Sabino Creek begins high in the Santa Catalina Mountains (1800 m elevation) in mixed conifer forest and has one of the larger watersheds in the Santa Catalina Mountains (~ 92 km^2), resulting in Sabino Creek flowing for longer periods than other canyons. During snow melt or summer monsoons the canyon can flood, but the normal pattern of precipitation produces moderate to low flows for approximately 8 months of the year. Early summer and late fall are the creek's driest periods. During these months the water often sinks into the channel's sandy floor, flows underground, and is inaccessible to wildlife. The banks of Sabino Creek support deciduous riparian vegetation dominated by cottonwood (*Populus fremontii*), willow (*Salix gooddingii*), ash (*Fraxinus pennsylvanica*), walnut (*Juglans major*), and sycamore (*Platanus wrightii*) (Minckley and Brown 1994). The steep slopes of Sabino Canyon are dominated by saguaro (*Carnegiea gigantea*), prickly pear and cholla cacti (*Opuntia* spp.), palo verde (*Cercidium* spp.), and brittle bush (*Encelia farinosa*) (Turner and Brown 1994).

METHODS

Passive Acoustic Sampling

The recent availability of portable, field- robust yet affordable ultrasonic bat detectors has made evaluation of activity patterns much easier to conduct than previously (Murray et al. 1999; Johnson et al. 2002). In addition bat detectors have greatly increased our knowledge of how bats use a resource (Hayes 1997; Vaughn et al. 1997; Humes et al. 1999; Kalcounis et al. 1999). During 2005 we conducted monthly passive (i.e., researcher absent) acoustic sampling in an effort to compare bat use between two environments. Our sampling protocol involved deploying 4 Anabat II frequency division bat detectors (Titley Electronics, Ballina, N.S.W. Australia) simultaneously each month, January through December, in two different habitats along Sabino Creek. We chose two sites from the lower canyon to represent riparian environments with deciduous streamside vegetation (Minckley and Brown 1994). We anticipated that this habitat, characterized by dense vegetation, could support greater insect biomass for foraging bats. We selected two additional sites in a more arid, open habitat with less vegetation. These upper sites were chosen where Sonoran desertscrub extends from the hillsides to the canyon floor. The null hypothesis for this study was that bats would use both habitats equally, and the alternative hypothesis was that bats would prefer the lower riparian area due to its additional foraging resources. Locations of the four sites were: Site 1, ~ 300' above Sabino Canyon Dam; Site 2, a pool area just upstream from Shuttle Stop #1; Site 3, just upstream from Tram Bridge #7; and Site 4, just upstream from the concrete foundation for Anderson Dam (Figure 1). Sites 1 and 2 were categorized as "Riparian" sites and Sites 3 and 4 as "Desertscrub" sites (Figure 2). We sampled on a monthly basis (except October), plus we sampled twice in January, July and September.

Each month we synchronized internal clocks in each detector unit and programmed internal timers to turn the sampling equipment on 30 minutes prior to sunset, running continuously all night and turning off 30 minutes past sunrise. The afternoon prior to sampling, we set equipment at each site in a locked, waterproof housing designed by T. Messina (http://home.earthlink.net/~nevadabat/). Because the microphone system for the Anabat II is sensitive to moisture, we placed the microphone at a 45° angle downward to a horizontal 11 x 11 cm plexiglass reflector placed on top of a 2 m high PVC pole (Livengood et al. 2003). The next morning we downloaded data (i.e., sound files of bat calls labeled with date/time stamps) onto a laptop computer. We used the number of call files as a measure of bat activity and evaluated echolocation calls using Anabat6, Analook and Anamusic software (O'Farrell et al. 1999). With this system we sampled simultaneously at 4 sites per night

Figure 1. Map of Lower Sabino Canyon showing the sites used for the comparative acoustic sampling study. Sites 1 and 2 are in riparian deciduous vegetation and Sites 3 and 4 are in Sonoran desertscrub.

Figure 2a. Riparian sampling site above Sabino Canyon Dam.

Figure 2b. Desertscrub sampling site above Bridge #7.

per month, allowing us to evaluate and compare resource use and determine where bats are most active along the canyon bottom.

RESULTS

During 14 nights of acoustic sampling in 2005, we passively recorded approximately 35,000 files of bat calls. Often Anabat detectors will record more than an individual bat's call on the same file, however we used the number of files as a general measure of overall activity at each site. Figure 3 shows the calls by sampling period distributed throughout the year. The bat detector placed at Site 1 recorded a total of 7,234 files, the detector at Site 2 recorded 5,436 files, the detector at Site 3 recorded 12,354 files and the detector at Site 4 recorded 9,823 files. We expected that the greatest level of foraging activity, reflected by the number of call files, would be along the lower portion of Sabino Creek (Sites 1 and 2) where dense deciduous riparian vegetation exists to support greater insect biomass.

However, we found that the upper reaches of the canyon (Sites 3 and 4) often had greater bat activity. In addition, the Anabat detector just upstream from Bridge #7 (Site 3) had the greatest number of calls of all sites along Sabino Creek. These results support neither our null hypothesis nor our alternative hypothesis and required a new evaluation of the habitat parameters along Sabino Creek.

DISCUSSION

The outcome of this study was unexpected and required further analysis to explain the results. We expected greater foraging by bats, reflected in the number of calls, along riparian stretches of Sabino Creek with characteristically dense vegetation. However, we believe that the differences that occurred, particularly the high levels of foraging activity above Bridge #7, are real and explainable when we use additional scientific disciplines during analysis.

Physics and Meteorology

When we review basic laws of physics, we know that warm air is less dense than cold air, causing warm air to rise; whereas cold air sinks (Geiger 1957; Halliday and Resnick 1966). Additionally, topography has a huge influence on the microclimate in valleys or canyons (Geiger 1957), particularly in the mountainous, semi-arid American Southwest. During the day the basin floor heats up, causing hot air to rise and move up-canyon. On a warm summer day, warm up-slope currents influence the microclimate of the valley and will move small bits of dust and detritus up-canyon. As the warm air rises to higher elevations, the air loses heat

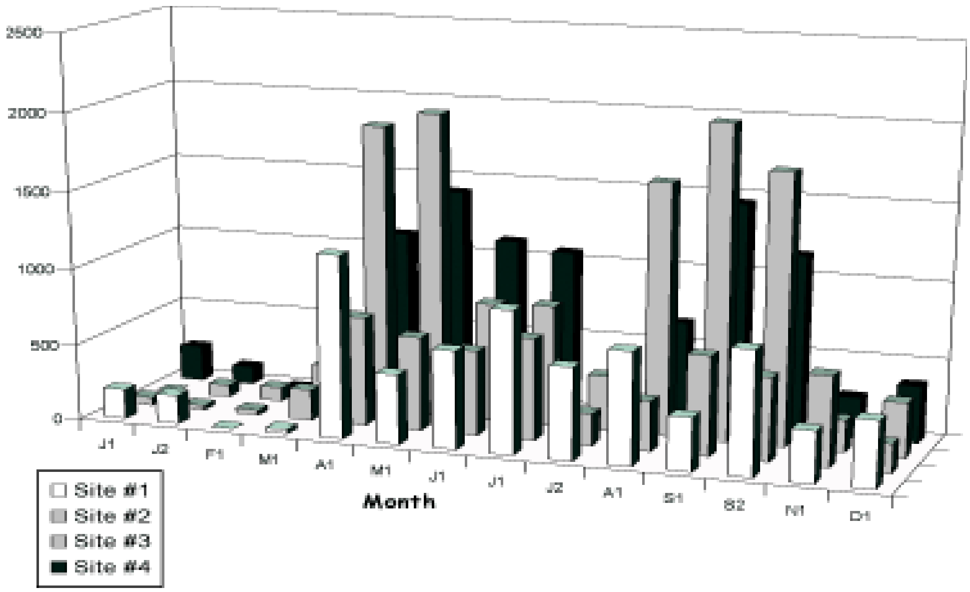

Figure 3. Plot of monthly totals of the acoustic calls of bats by sampling site.

due to adiabatic cooling, and this cooler air mass sits on the "cushion" of rising warmer air. However, once the sun sets, the "engine" that drove this phenomenon reverses and the cold air sitting in the upper watershed on the mountain, being heavier, settles and flows down-canyon much like a river of cold water (Geiger 1957). This can be observed at night when crossing a dry arroyo or streambed where the air temperature at the flow-line of the canyon floor is often colder than the surrounding terrain.

Hydrology

Combining physics and hydrology, the flow of water down valleys can be modeled using computer software packages (HEC 2 Manual 1990) to predict where water will be slowed or impounded by topographic irregularities. These variable landscapes can affect flow velocities and create currents that produce side eddies in the channel. These circular currents can capture leaves and detritus in small vortices along the side of the main flow, and actually move this debris upstream along the backside of a circular eddy until fluctuation in the current occurs that changes the flow regime (Rouse 1978). A practical application of this phenomenon is seen in guidebooks available to kayakers and river-runners that show the safest way to maneuver rapids in rivers. These hydrologic models might also allow us to evaluate other "fluids," such as cold-air drainage, under similar topographic constraints. We suggest that after sunset, cold air moves along canyon floors much like water flows downhill and will create eddies in the air column just as eddies occur in the water flow (Geiger 1957). The cool air will be more dense than an equal amount of warm air flowing up- canyon during the day and will capture dust and detritus in eddies.

Entomology

Flight for insects is an effort to counteract forces acting in opposition (i.e., gravity and drag) to desired motion. A method to evaluate insect flight through air uses a proportional relationship of inertial to frictional forces (Chapman 1998). Forces acting on a flying insect include “lift” created by wing movements, “drag” or friction of the medium because of the insect’s mass and shape, plus “thrust,” a function of the wings lifting the insect up and forward (Brodsky 1994). “Drag” is the force acting in opposition to forward movement (Drag = $0.5\ C_D\ \rho\ S\ V^2$), where ρ = the density of the medium, V = the velocity of the medium, S = the area of the insect perpendicular to the direction of movement and C_D = the Drag Coefficient (Chapman 1998). The Drag Coefficient depends on the shape of the insect (i.e., how streamlined its presence is to air resistance), the insect’s surface texture (smooth creating less drag than rough) and its Reynolds Number. The Reynolds Number (Re) is a dimensionless value that measures the relative importance of the speed and size of an insect to the density and viscosity of the medium through which the insect is flying ($Re = \rho Vl / \mu$; Chapman 1998), where ρ = the density of the medium, μ = the viscosity of the medium, V = the speed of the insect, and l = the size of the insect. Generally, the larger the insect, the larger the Reynolds number because the viscosity becomes less critical as the size of the insect increases (Brodsky 1994; Lehmann 2002). However, for prey-sized insects (≤ 5 mm), flight may be influenced by the air’s density and — particularly for nocturnal insects flying along a cooler canyon bottom — could be equated to swimming through molasses. It is in this way that insects may be at the mercy of airflow patterns and the fluid nature of air (Lewis 1965), allowing bats to predict where to forage efficiently on patchy food resources.

Extensive research in Europe to model insect infestations between crop fields provides an example of how insects are distributed by winds (Lewis 1970; Landon et al. 1997). Lewis showed that smaller insects (< 3 mm^2) drift along with the breeze — like inert particles and are often retained in eddy zones. However, larger insects (> 4-5 mm^2) will actually use eddies as a refuge and will also accumulate in shelter zones or eddies in the flow. In England this often occurred along hedgerows; however any break or protection from the main flow of the wind will provide an opportunity for insects to accumulate (Lewis 1965). Epila (1988) also showed that insects are poor “aeronauts” and, once airborne, are at the mercy of the wind until they encounter a wind shelter or shadow that affords protection. These studies may prove helpful when determining why bats are congregating in larger numbers at a particular site along Sabino Creek.

Mammalogy

Insectivorous bats often cope with heterogeneous patches of prey, both temporally and spatially (Barclay 1991; Brigham 1991). Research has shown that bats often anticipate productive feeding areas, given their spatial memory and knowledge of the landscape (Bell 1980). It is not unexpected that bats foraging along Sabino Creek would anticipate pockets of prey that occur dependably due to topographic irregularities along the canyon bottom. These would actually be more predictable than the heterogeneous emergence patterns of insects during the summer months.

Disciplines Combined

When we investigate the topography along Sabino Canyon at Site 3, where we saw the greatest foraging activity, we observe that a prominent rocky ridge projects into the canyon cross-section from the west (Figure 4). As Sabino Creek flows under the bridge just upstream from Bridge #7, it turns slightly and flows parallel to the paved road. However, when the main flow of the creek hits the ridge of rock at Bridge #7, it forces the creek to make an abrupt 90° bend to the east. This likely produces a large eddy in the flow regime and essentially traps insects in a protected column of air upstream of the ridge. This could explain the high number of foraging calls and suggests that bats are able

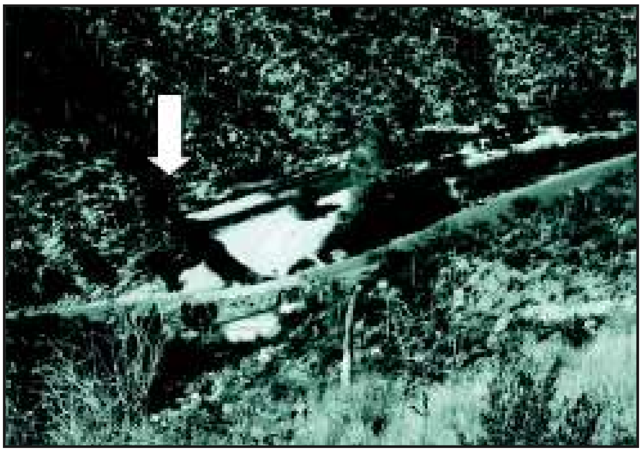

Figure 4. Note granite ridge extending into Sabino Canyon flow-line.

to take advantage of rich food resources, particularly if they are not as patchy as ephemeral insect swarms.

MANAGEMENT IMPLICATIONS

Three primary factors characterize the distribution of bats across the landscape: availability of appropriate roosts, accessibility to drinking water and adequate food resources (Racey and Entwistle 2003). Resource managers often focus on preservation of bat populations through appropriate management of day roosts, especially maternity colonies and hibernacula (Brady 1982; Brigham 1993; Thomas et al. 1990; Tuttle 1977). Although this has proven critical in maintaining healthy bat populations, proper land management policies must also consider availability of other limiting resources. When protecting bat populations, habitat associated with roosts must guarantee continued accessibility to food and drinking water.

Our study used a multi-discipline approach to evaluate how bats locate food at a landscape level, given the heterogeneous nature of these resources (Buecher 2007). This approach shows promise in predicting the presence of bats at the scale at which these animals must evaluate their habitat. Hopefully, these data will provide resource managers with additional insight and information critical to determining resource use by bats along an invaluable riparian corridor. Given the many pressures on this unique environment, this study will provide Forest Service personnel with information necessary when making decisions regarding the protection and conservation of this resource.

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ADVANCING LARGE CARNIVORE RECOVERY IN THE AMERICAN SOUTHWEST

Tony Povilitis and C. Dustin Becker

By passing the Endangered Species Act (ESA) of 1973, the United States Congress committed the nation to restoring endangered species by protecting their ecosystems from "economic growth and development untempered by adequate concern and conservation" (USC 1973). Since then, the science of conservation biology has confirmed the act's core imperative by demonstrating the tight connection between ecosystem conservation and the recovery of endangered species populations. However, economic interests have increased their political influence on government to a point where ecosystem conservation is difficult even when it is essential for species recovery. Povilitis et al. (2006) cite examples of species that are "bureaucratically imperiled" because public agencies have failed to uphold the ESA by circumventing ecosystem conservation in deference to economic interests. The San Diego ambrosia (*Ambrosia pumila*), Pacific fisher (*Martes pennanti pacifica*), humpback chub (*Gila cypha*), Florida panther (*Puma concolor coryi*), leatherback turtle (*Dermochelys coriacea*), Mexican wolf (*Canis lupus baileyi*), and jaguar (*Panthera onca*) are a few of many bureaucratically imperiled species. Bureaucratic practices that stymie recovery of endangered species include withholding protective listing under the ESA, failure to develop adequate recovery goals and plans, and failure to implement agreed-upon conservation plans.

We discuss how wildlife agencies responsible for the recovery of the Mexican wolf and the jaguar in the southwestern United States have faltered in their efforts to recover these species. In both cases, deference to stakeholders with economic interests or ideological opposition has hampered efforts of the U.S. Fish and Wildlife Service (USFWS) and cooperating state wildlife agencies to fully implement the ESA. After reviewing historical and contemporary reasons for why these species are endangered, we discuss a number of actions that could make it easier for agency professionals, conservation organizations, and citizen wildlife advocates to achieve large carnivore recovery.

MEXICAN WOLF

Mexican wolves once ranged from the borderlands of the American Southwest to central Mexico numbering in the thousands, but by the early 1930s they had been extirpated in the United States primarily as a result of a campaign led by the U.S. Bureau of Biological Survey (Brown 1983; Robinson 2005) and partner agencies. On behalf of the livestock industry, the Biological Survey's successor agency, the USFWS, extended the extermination program south of the border and all but eliminated Mexico's wolves by the mid-1970s. In 1976, the Mexican wolf joined four other wolf subspecies on the U.S. Endangered Species list (USFWS 2003). Only the timber wolf's existence in the Great Lakes region was certain at that time, whereas any wild Mexican wolves in the Southwest were presumed wanderers from Mexico.

After the ESA listings, concern arose that individual wolves that could not be identified to subspecies in the lower 48 states would lack legal protection under the ESA. In response, the USFWS ruled that the problem could be “handled most conveniently by listing only the species name” (USFWS 1978); consequently, Mexican wolf and other subspecies were consolidated into a generalized gray wolf listing. USFWS offered its “firmest assurance” that it would continue to recognize and conserve valid subspecies of gray wolf (USFWS 1978) because the ESA calls for recovering imperiled subspecies and populations, as well as full species (USC 1973). The likelihood that subspecies, like the Mexican wolf, carry ecologically relevant adaptations and the potential to become a unique new species are compelling biological reasons underlying that mandate (O’Brien and Mayr 1991).

Edward Nelson and Edward Goldman of the Biological Survey first identified the Mexican wolf as a unique subspecies and named it for their fellow employee, Vernon Bailey (Nelson and Goldman 1929). Goldman delineated the northern range of *C. l. baileyi*, approximately at today’s U.S. Interstate 10 in Arizona and New Mexico (Young and Goldman 1944). Other mammalogists reaffirmed *baileyi* as a distinct subspecies and confirmed Goldman’s boundary line (Hall and Kelson 1959; Nowak 1995). The uniqueness of the Mexican wolf has also been corroborated by genetic studies (Wayne et al. 1992; Hedrick et al. 1997), with Garica-Moreno et al. (1996) concluding that Mexican wolves are the “most distinct grouping of North American wolves supporting their distinction as an endangered subspecies.”

In 1980, biologists suggested that the two extinct southwestern subspecies that occurred just to the north and east of the Mexican wolf’s range (the Mogollon mountain wolf and the Texas gray wolf) could be consolidated taxonomically with *C. l. baileyi* (Bogan and Mehlop 1980). They found the two most distinct southwestern subspecies to be *baileyi* and *youngi* (the southern Rocky Mountain wolf), and believed that the Mogollon wolf represented an intermediate form between the two (Bogan and Mehlop 1983). The USFWS adopted their view (USFWS 1982) and recognized an area extending approximately 200 miles to the north of Goldman’s boundary line as a “zone of subspecies intergradation” (USFWS 1996). This interpretation of Mexican wolf taxonomy and geographic range allowed the choice of what was apparently the least politically sensitive area in the Southwest for a reintroduction attempt — a 17,752 square kilometer portion of the Gila and Apache National Forests in east-central Arizona and west-central New Mexico, now known as the Blue Range Wolf Recovery Area (USFWS 1996).

Twenty years after the Mexican wolf was placed on the U.S. Endangered Species list a lawsuit filed by wildlife advocates prompted USFWS to begin releasing Mexican wolves back into the wild from the only existing source, a captive population. The goal for the Blue Range Wolf Recovery Area (BRWRA) was to establish a single population of at least 100 wild wolves in 9 years (by 2006) (USFWS 1996). This was an important initiative but well short of the widely accepted recovery goal in conservation biology of inter-connected, multiple populations within a species’ natural geographic range.

To meet the requirement for multiple populations, the USFWS Recovery Team for gray wolves in the Southwest has suggested introducing Mexican wolves well beyond their historic range to the north, in northern New Mexico, northern Arizona, and Colorado (Draper 2004). Their apparent rationale is that these areas have larger blocks of habitat with less potential for livestock and development conflicts than the “Sky Island” mountain ranges of southern Arizona and New Mexico. Unfortunately, this approach jeopardizes the future of the Mexican wolf as a subspecies in violation of the ESA requirement to conserve valid subspecies. If introduction of the Mexican wolf proceeds north, hybridization and genetic swamping by the northern gray wolf are likely. Wolves transplanted to the

Yellowstone region from western Canada have flourished and are dispersing south, with a confirmed report of a wolf reaching central Colorado (Gebhart 2004). Mexican wolves would also probably lose territories when confronted by northern wolves, as they are on average 44% smaller (J. Oakleaf, USFWS, pers. comm.; USFWS 2003).

Even in the absence of northern wolves, Mexican wolves placed to the north of the BRWRA would face a different evolutionary environment from their original range. For example, the historic northern limit of the Mexican wolf's range corresponds with a major shift in prey. To the south, Coues white-tailed deer (*Odocoileus virginianus couesi*) and collared peccary (*Tayassu tajacu*), both among the smallest of North American ungulates, are prevalent (Hall 1981). On the other hand, large-bodied elk (*Cervus elaphus*), abundant to the north, are absent over most of the Mexican wolf's original range (Leopold 1959; Hoffmeister 1986). Policy regarding regional boundaries for recovery of subspecies should not ignore evolutionary biology—the process by which genetic distinctiveness develops. Isolation by distance, climate, and habitat on a continental scale, along with prey specialization by wolves in different regions explains variability in genetic structure of wolf populations in North America (Carmichael et al. 2001; Geffen et al. 2004).

By 1998, when the USFWS began releasing Mexican wolves in the BRWRA, policy had firmly pitted wolf restoration against perceived limits of social and political tolerance (USFWS 1998; Robbins 2005). The policy was and continues to be heavily influenced by opponents of large predator recovery. Mexican wolves that depredate livestock are translocated or killed. On the other hand, no reductions in livestock numbers or distribution, or changes in livestock husbandry practices are required to better accommodate wolves. Unlike in Yellowstone National Park and central Idaho, where northern gray wolves were successfully reintroduced in the mid-1990s, the BRWRA lacks a large, core area of livestock-free habitat where Mexican wolves are lightly managed or left alone (USFWS 1996; Bangs et al. 1998). Moreover, unlike wolf recovery programs elsewhere in the western U.S. (USFWS 1994), Mexican wolves are not allowed to colonize public lands beyond BRWRA area boundaries (USFWS 1998). Finally, initial releases of captive-born wolves were limited to a "primary recovery zone" comprising part of the smaller Arizona portion of the BRWRA (USFWS 1996). These policies hampered the program's ability to release wolves in suitable areas lacking wolves, for replacement of lost mates, or for genetic enhancement (Bergman et al. 2004).

The USFWS (1996) anticipated that the BRWRA wolf population would grow to around 83 wolves and 15 breeding packs by the end of 2005 (year 8 of the program) and that the need to release wolves from captivity would end after 2002. In contrast, at the end of 2005, the USFWS estimated that there were 35 to 59 wolves in 5 breeding packs in the BRWRA (AZGFD 2006). This shortfall occurred despite the release of 90 captive wolves, including 18 released in 2004 and 2005. Removals for management purposes (58) and human-caused mortality (31) largely explained the high mortality of collared wolves, averaging 64% annually from 1998 to 2003 (AMOC 2005). Most removals were of wolves moving outside the BRWRA boundary (36%) or depredating livestock (24%), and most mortality involved illegal gunshot (61%), showing that policy constraints on the Mexican wolf program had not deterred poaching.

Empirical data collected by USFWS biologists from 1998–2003 (USFWS 2004) provide estimates of annual survival (S=0.36) and births per individual (B=0.44). When used in a simple linear population viability analysis (PVA): $Nt + 1 = (Nt * S) + (Nt * B*S)$, where Nt is the initial population and Nt+1 is the population a year later, it is obvious why wolf recovery is failing. Even with an optimistic estimate of a starting population of 50 Mexican wolves of reproductive age, the population declines to near zero in 7 years without new releases (Figure 1). While it is clear that mortality rates are excessive because of removals, translocations, and illegal shooting of wolves, the cause of the low birthrate is uncertain but may be related to biological conditions on the recovery area (USFWS 2004). Wolf pack productivity and pup mortality in the BRWRA are important research areas (USFWS 2004). Still, if management policies are not changed to allow for improved survival, a self-sustaining population of Mexican wolves will not be achievable.

In 2005, USFWS imposed additional restrictions on wolf recovery through the interagency Adaptive Management Oversight Committee (AMOC 2005), chaired by the Arizona Game and Fish Department (AGFD). Additional restrictions were advanced at closed meetings arranged by a U.S. Congressman between USFWS officials and opponents of the Mexican wolf reintroduction program (Soussan 2005). These added restrictions included a moratorium on new releases of captive-bred wolves in 2006 (if the number of breeding pairs in the wild were to reach six or more on December 31, 2005), and automatic removal or killing of wolves known or likely to have been involved in three livestock depredation incidents in a single year, regardless of their genetic significance to the population or any subsequent cessation of depredations. AMOC also sought authority for Arizona and New Mexico to permanently remove wolves that prey on livestock or create locally unacceptable impacts on native ungulate populations once the Mexican wolf population reached 125 individuals (AMOC 2005). Under current policies, it is unlikely that the population will attain that size.

While policy makers have the technical data for making adaptive management changes, they fail to fully address what is biologically required for Mexican wolf recovery, apparently to minimize political conflict. A successful recovery program will require policy changes to enhance survival of BRWRA wolves by reducing control activities

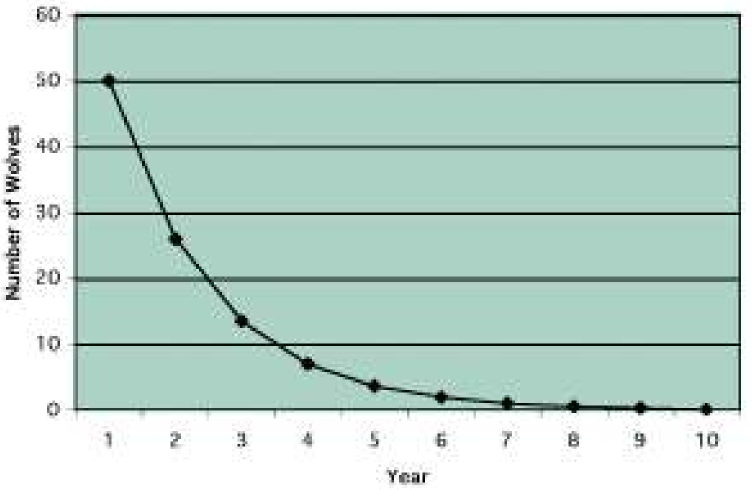

Figure 1. Population viability of 50 Mexican wolves based on empirical values for annual survival (S) and births per individual (B) (S = 0.36; B = 0.44) (USFWS 2004). Extinction of the wild population results in the absence of continued release of wolves from captive stock.

involving their capture and relocation or removal. Recovery of the Mexican wolf will ultimately depend on policy changes in favor of reestablishing the subspecies within its original range to the south.

JAGUAR

The northern end of the jaguar's geographic range historically included much of Arizona, New Mexico, Texas, and perhaps parts of southern California and Louisiana (Hall 1981; Valdez 2000). The jaguar was known by the Papago, Pima, Yavapai, Hopi, Apache, and other Native Americans of the Southwest (Daggett and Henning 1974; Brown and López 2001). Bounties offered by Spanish authorities may have significantly diminished jaguar presence in the Southwest prior to American settlement (Matthiessen 1987). Later, hunting, trapping, and poisoning by hunters, ranchers, and U.S. government agents depleted jaguar numbers, with over 60 animals reportedly taken in Arizona and New Mexico alone during the last century (Brown and López 2001). While jaguars were apparently extirpated from Texas by 1948 (Nowak 1975), the animals continue to be recorded in southern Arizona and New Mexico, with two or three identified individuals photographed in recent years.

As with the Mexican wolf, habitat loss and fragmentation are a threat to the jaguar (Johnson and Van Pelt 1997; USFWS 1997). In Arizona and New Mexico, the most favorable jaguar habitat includes mountain ranges, canyons, and washes, interconnected by undeveloped riparian areas, wash complexes, and mesquite grasslands (Sierra Institute 2000). Jaguar habitat is jeopardized by land development, road construction, and depletion of springs and surface waters, especially along the base of mountain ranges, major wash complexes, and riparian areas.

In response to the killing of a jaguar by an Arizona rancher, a petition was filed in 1992 to list the jaguar as endangered in the United States (Povilitis 1992). The USFWS had listed the jaguar 20 years earlier, but protection applied only to animals south of the U.S. border (USFWS 1972). In 1979 the USFWS acknowledged the oversight and its intention to rectify the matter "as quickly as possible" (USFWS 1979). Two years after receiving the 1992 petition, the agency issued a proposed rule for U.S. listing of the jaguar, and, upon legal action taken by the Center for Biological Diversity and a subsequent U.S. District Court order, completed the listing process in 1997 (USFWS 1997). However, the USFWS did not designate critical habitat, arguing that identification of critical habitat would likely make jaguars more vulnerable to illegal killing, and suggesting that critical habitat for the species is not determinable. In response, the petitioners asked USFWS to reconsider its decision since designation of large blocks of habitat (as opposed to localized areas) required for this wide ranging carnivore would not aid would-be poachers. They further explained that essential features of jaguar habitat were in fact known (i.e., concealing vegetation and topography, adequate prey base, perennial or seasonal water sources, limited risk from poaching and human disturbance, and spatial requirements based on body size and diet), and demonstrated how these features could be used to identify and map core and connecting habitat for jaguar in southern Arizona and New Mexico (Sierra Institute 1999). In rejecting critical habitat, the USFWS also claimed that the U.S. cannot be considered "essential to the conservation of the species" as "the key to the species' conservation in the northern part of its [global] range lies closer to the core of the species range in Mexico" (USFWS 1999). It assured that Section 7 of the ESA prohibits federal agencies from taking actions likely to jeopardize the continued existence of a listed species, including activities which impact habitat. In contrast, the petitioners reasoned that the "jeopardy" issue would be ignored by agencies given the jaguar's sparse presence, that conservation of the species in the U.S. was the issue at hand, and that responsible federal and state agencies need to understand which areas are of salient importance for habitat monitoring, protection, and restoration.

The USFWS decision on critical habitat was legally challenged, and a new ruling was required by a court-approved settlement agreement. In 2006, the USFWS again opposed the protection of critical habitat but dropped the argument that designation was not determinable or prudent because it would make jaguars more vulnerable to poaching (USFWS 2006). Instead, it presented a three-part argument as to why critical habitat designation would not be beneficial because "jaguar conservation does not require habitat within the United States": first, they reasoned, the Southwest currently does not have the essential physical and biological features for jaguar since there are few recent reports of the animals and no confirmed females or cubs (a non sequitur); second, "loss of or threats to [habitat] features in the United States...is not limiting the recovery of the species" (contrary to previous USFWS assessments of this threat [e.g., USFWS 1997]); and third, "the range of the jaguar in the United States is not enough area to provide for the conservation (i.e., recovery) of the jaguar or even make a significant contribution to the conservation of the jaguar" (a position that ignores the ESA's focus on the U.S. and the urgent need to conserve the integrity of the greater ecosystem for the northernmost jaguar population that extends into the U.S. from Sonora, Mexico). With this second critical habitat ruling, the USFWS jacketed the jaguar in a classic Catch-22: no need for habitat conservation because there are too few jaguars, but without such conservation the fewer jaguars there will be. Immediately after the critical habitat decision, the Center for Biological Diversity filed a notice of its intent to sue the USFWS for ESA violations, namely failure to designate critical habitat for the jaguar and failure to develop a recovery plan for the species (Augustine 2006).

In 1997, a Jaguar Conservation Team (JAGCT) led by the AGFD was created in lieu of a federal recovery process. The JAGCT stemmed from a formal agreement by federal and state agencies and a number of counties in southern Arizona and New Mexico to adopt the AGFD's jaguar conservation strategy (Johnson and Van Pelt 1997). The initiative was conceived with the intent to convince the USFWS that the ESA listing of the jaguar in the United States was not needed (Shroufe 1997; Brown and López 2001). The JAGCT pledged to address threats to the jaguar by providing for conservation "consistent with the intent of the Act" (Johnson and Van Pelt 1997). JAGCT's accomplishments include a jaguar bibliography, collaboration on research, a capture risk assessment, educational materials and school curriculum, and reports on potential habitat (Van Pelt 2006). On the other hand, JAGCT's promise to undertake habitat conservation has been entirely unfulfilled. Under the conservation strategy, the team was to provide "land management cooperators with guidelines for assessing impacts of current and planned actions on the jaguar and its currently known or suspected habitat" (Johnson and Van Pelt 1997). Cooperators, in turn, were to "evaluate the potential impact on jaguars and jaguar habitat of each new project" while JAGCT would recommend how to address impacts and concerns. The JAGCT would also "encourage public and private land managers to conserve or enhance suitable or potentially suitable jaguar habitat, including corridors connecting those habitat blocks, to ensure that the jaguar's current and future habitat needs (including natural dispersal and habitat expansion) are appropriately addressed." State wildlife agencies would pursue formal agreements with public land agencies and private landowners to get the job done. These and other habitat objectives, most slated for completion by 1999, were not met.

JAGCT's neglect to advance habitat conservation appears to be in deference to members and work group participants concerned that concrete measures might ultimately conflict with ranching and property rights interests. At the same time JAGCT existence has succeeded in keeping the politically reluctant USFWS from developing a recovery plan (ESA Section 4) for the jaguar. The prognosis for genuine conservation through policy change is not promising: In 2006, the AGFD and the New Mexico Department of Game and Fish (NMDGF) revised the original 1997 "Conservation Assessment and Strategy for the Jaguar in Arizona and New Mexico" under which the JAGCT was to operate (AGFD and NMDGF 2006a). The new draft document lacked measurable recovery goals, failed to recognize loss or degradation of habitat as a clear threat to the jaguar in the United States, was less specific about conservation measures, lacked time schedules for implementation, and would only be implemented depending on "funding, personnel availability, and other responsibilities of the individual signatories." It ignored important previous work of JAGCT's Habitat Subcommittee (for example, on habitat conservation guidelines) or simply rehashed the 1997 document's call for tasks (for example, assessment of impacts to jaguar habitat) that were to have been completed long ago. In short, JAGCT's new 2006 framework was weaker and only "strategic in nature, not a detailed implementation plan" (AGFD and NMDGF 2006b)

Ironically, while touting the "metapopulation concept for species persistence and an ecosystem approach for habitat conservation" the new JAGCT document failed to apply these key concepts despite numerous efforts by participant conservationists to encourage and assist the team in doing so. When queried on the matter by conservationists, the responsible agencies, instead of outlining actions, simply removed these principles from a later draft of the plan (AGFD and NMDGF 2006c).

The AGFD and the NMDGF appear to hold ambiguous concepts of habitat conservation for the jaguar. For example, in responding to a public comment in favor of keeping ranchers and farmers on the land to prevent subdivision, the agencies acknowledged "the importance of habitat loss (including fragmentation) through subdivision or other causes relative to jaguar conservation," elsewhere noting that "habitats must remain sufficiently intact (and barrier-free) and otherwise suitable for jaguars...to allow them to travel and sustain themselves in Arizona and New Mexico" (AGFD and NMDGF 2006b). In contrast, in replying to criticism that JAGCT had not delivered as promised on habitat conservation, the agencies asserted that "habitat protection or enhancement [in Arizona and New Mexico] is not needed for jaguars," and that as "evidenced by presence of mountain lions and bears...habitat and prey base exist in sufficient quantity and quality to sustain carnivores, including the jaguar" (AGFD and NMDGF 2006b). We believe these contradictory statements by state wildlife agencies on jaguar habitat and its conservation reflect pressures to present politically "balanced," as opposed to scientifically credible, assessments.

By April 2006, livestock and property rights interests had taken even greater control of the JAGCT when the team allowed a large number of sympathetic state soil and water conservation districts to vote on important habitat decisions along with the smaller pre-existing slate of members, mostly representing higher levels of government (e.g., state wildlife and agricultural departments, and regional or state offices of federal natural resource agencies). An outcome was *de facto* exclusion of potential habitat areas in New Mexico from JAGCT's program. In response to a conservationist's concern about such "block voting," the state wildlife agencies conceded the issue "might warrant further discussion and consideration" (AGFD and NMDGF 2006b).

BUREAUCRATIC REFORM

Historically, the Mexican wolf and the jaguar were persecuted under institutionalized anti-predator campaigns sponsored by the U.S. Government for the benefit of the livestock industry. Both species ultimately required legal action from private entities to prompt agency measures under the ESA. Requiring large blocks of habitat configured for movement and dispersal, large carnivores face a regional landscape increasingly rendered unfavorable to them by economic activities and development.

Public wildlife agency staff understand fully that current human population growth and development patterns in the states in question, and that a host of related stressors on wildlife will lead to further habitat loss and degradation, declines in water availability, and increased disturbance and displacement (e.g., AGFD 2005). Mexican wolf and jaguar recovery cannot be achieved until federal and state wildlife agencies enact policy and programmatic changes (Povilitis et al. 2006) that engage them in regional-scale habitat conservation for these species. The changes would involve collaborative planning for land development, highway design and modification (for safe wildlife passage), and international border security in order to protect key habitat areas and connecting corridors. As lead government agencies responsible for wildlife recovery, the USFWS, the AGFD, and the NMDGF would promote primacy or co-equal status for endangered carnivores on public lands (e.g., reduction of livestock and road densities where needed), and provide candid assessments of on-the-ground recovery progress, or lack thereof. Politically-based substitutes for habitat conservation measures would be avoided. For example, repeated calls for more research on jaguars and their habitat (Johnson and Van Pelt 1997; AGFD and NMDGF 2006a) in lieu of on-the-ground habitat conservation measures do not advance species recovery. Lastly, we believe that agency officials would accomplish better recovery by avoiding concessions to economic interests that undermine the effectiveness of habitat conservation programs.

How can agency professionals end bureaucratic imperilment of endangered carnivores while at the same time protecting themselves from political retaliation? First, they can call upon professional organizations for support, favorable publicity, and, if need be, whistle-blowing protection. Examples of these organizations include the Society for Conservation Biology, a group concerned with public policy as well as conservation science (Meffee et al. 2006), and the Public Employees for Environmental Responsibility, a national alliance of scientists, law enforcement officers, land managers, and other professionals dedicated to upholding environmental laws and values. Second, they can work closely with federal, state, and local political leaders who support the ESA and other wildlife laws and who would exert their influence, when needed, on behalf of those who steadfastly work to implement those laws. Third, wildlife officials can employ professional facilitators to lead stakeholder meetings to avoid direct political attacks, improve *ad hoc* decision making, and ensure that meetings stay focused on species recovery and the means to achieve it.

Many individuals and private conservation organizations have fought arduously for Mexican wolf and jaguar recovery. Nevertheless, they have had little success. A stronger, more unified public voice to overcome bureaucratic obstacles to wildlife recovery is needed to accomplish real recovery. We suggest the creation of carnivore-recovery oversight groups (CROGS) whose mission would be to promote ecosystem-based recovery planning, to publicly expose any agency misdoings, and to garner the political support needed to advance species recovery. CROGS would commission scientifically-based (and peer-reviewed) recovery plans that would set program standards by way of example and be ready in anticipation of an end to (or at least a lessening of) bureaucratic obstructionism and an improved political climate for species conservation. To stimulate public interest and concern, CROG leaders would discuss Mexican wolf and jaguar conservation through popular articles, editorials, talk radio, news releases, and other media and would engage individuals in state and federal wildlife agencies and elected officials in respectful dialogue or joint discussions.

As federal and state agencies have increasingly embraced community-based initiatives (Brunner et al. 2002), the ability of local economic and political interests to override conservation science has grown proportionally, undermining in many instances the greater public interest in recovering endangered wildlife. Endangered species management can be co-opted by stakeholders for private interests (Becker 2002). Being "caught in the middle" of what appears to be a democratic process of opposing values and goals can prevent wildlife agencies from attaining their stated conservation goals. Agency officials have an ethical and professional obligation not to abandon species recovery objectives, and to engage stakeholders in genuine community-based initiatives to fulfill the nation's commitment to endangered species recovery.

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CONSERVATION GENETICS OF BLACK BEARS IN THE SKY ISLANDS OF ARIZONA AND NORTHERN MEXICO

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Black bears (*Ursus americanus*) were first described in Arizona in the early 1800s. From the 1930s to the 1950s black bears were classified as predatory species (Hoffmeister 1986) and some populations were nearly extirpated. From 1958 to 1968 bears were classified as small game and received some protection. In 1968 their status changed to big game (Hoffmeister 1986). From the 1950s until 2001, the black bear population in Arizona was stable (*n* = 2,500-3,500) (Cunningham et al. 2001; McCracken et al. 1995).

Reduction in bear numbers is of increasing concern to their long-term survival in Arizona (LeCount and Yarchin 1990). Bear populations that are unintentionally reduced significantly often take years to recover (Miller 1990) due to delayed reproductive maturity (first breeding at 3-7 years) and low reproductive rate (2 cubs every 2 to 6 years) (LeCount 1982a, 1983; Kolinosky 1990).

Concerns for black bears in Arizona include harvest numbers, anthropogenic use of land that could threaten population connectivity, and inaccurate population estimates. From 1964 to 1989 a mean of 239 bears were harvested annually (6.8% of the maximum population estimate), which increased to 368 bears in 2001 (10.5% of the maximum population estimate).

Since the 1980s, the Arizona black bear season length has been based on the number of females harvested within a given game management unit. When the harvest objective of 5% of total females is reached, the bear season is closed in that area. However, in the 1970s greater than 5% females in some populations were harvested (R. Olding and T. Waddell, Arizona Game and Fish Department, unpubl. data). Also, the black bear population in east-central Arizona was over harvested in the 1980s with 15% adult annual mortality affecting recruitment by reducing the breeding age of females and, therefore, reducing the number of cubs available for replacement (LeCount 1982b). Additionally, liberal hunting seasons in the sky islands (i.e., isolated mountains surrounded by desert and grassland ecosystems) combined with limited habitat available, have produced low population numbers in Coronado National Forest in southern Arizona (R. Olding and T. Waddell, unpubl. data).

In Mexico, black bears are listed as endangered (Servheen et al. 1999). There are records of black bears in Sonora, Chihuahua, Coahuila, Nuevo León, Zacatecas, and Durango (Sierra-Corona et al. 2005). However there is not much information on current black bear populations in Mexico. The published information is mainly from populations in the northern Sonora and Coahuila (Doan-Crider and Hellgren 1996; Sierra-Corona et al. 2005; Onorato et al. 2004), and bear occurrence is not well documented in other parts of Mexico. Although little scientific information is available for Mexico, it is known that black bears have lost at least 30% of their historical range in Mexico (Pelton et al. 1997). The main factors threatening black bear survival in northern Mexico are habitat loss and poaching (MacCracken et al. 1995); in addition the poor economy prevents enforcement of poaching and habitat destruction regulations. The lack of information about migration patterns and connectivity among populations within Mexico and neighboring Arizona further hampers potential conservation and management efforts. To enhance conservation, biologists and managers should concentrate their efforts on sky islands.

SKY ISLANDS

Primary habitats for black bears are coniferous and broadleaf deciduous woodlands in Arizona and northern Mexico. These habitats occur on mountains that rise from the desert and are isolated from each other. Of necessity black bears periodically move through the desert lowlands to other sky islands (LeCount and Yarching 1990).

Sky islands of the desert Southwest have produced population isolation in many species occupying the region resulting in morphological and genetic differentiation of flora and fauna. Morphological diversity has been demonstrated in lemon lily (Linhart and Premoli 1993), snails (Bequaert and Miller 1973), beetles (Ball 1966), the jumping spider (Maddison and McMahon 2000), mountain spiny lizards (Stebbins 1985), canyon treefrog (Barber 1999), and the Mt. Graham red squirrel (Riddle et al. 1992).

Molecular genetic studies have been used to investigate the mechanisms of sky island isolation and how they affect population structure of the species that inhabit them. Genetic differentiation has been studied in terms of isolation due to biogeography barriers, distance to the source of migrants, and sky island size with respect to population structure. Also, genetic analyses have been useful to estimate whether time of speciation is concordant with island formation. Molecular studies have not been reported in the literature for large mammals in the sky islands. And there is no knowledge of how sky island size, configuration, distance from other sky islands, and proximity to barriers affect connectivity (gene flow) of large mammals such as black bears.

Factors, such as distance, that influence the dispersal of plants, insects, reptiles, and small mammals could have little or no effect on black bears due to their capacity for long distance dispersal up to 230 km. Also, barriers such as rivers or patches of desert that affect smaller species could have little effect on bear movement. However, a combination of distance and unsuitable habitat (e.g., human use of desert lowlands including housing developments in the valleys between mountain ranges, recreational use of the land, agricultural land use, summer home developments, and highways) may cause significant barriers for black bears (Schenk 1996) and disrupt the connectivity among bear populations.

North of the Mogollon Rim in Arizona is an area of continuous bear habitat that extends from west of Williams southeastward to the Arizona-New Mexico border. This area has the greatest number of black bears in Arizona and the bears appear to move large distances (Cunningham et al. 2001). This northern population could potentially be the source of bears for at least some of the sky islands in southern Arizona and northern Mexico. We examined this possibility by using molecular DNA techniques to study the population structure of black bears on sky islands in Arizona (i.e., Mogollon Rim, Four Peaks-Mt. Ord, Nutrioso Mountains) and Mexico (Sierra San Luis, Sierra Madre Occidental).

STUDY TECHNIQUES. PREVIOUS STUDIES

Bear populations are difficult to inventory and monitor because the animals occur in low densities and are secretive by nature. A variety of techniques have been used to obtain population numbers, density, and movement estimates for bears. Direct observation can be used to estimate small population sizes and trends as with the brown bears in Glacier, and Yellowstone National Parks (Hayward 1989). Capture-mark-recapture (Kolenosky 1986) and radio telemetry (Vashon et al. 2003) have been the most commonly used techniques. Recently, molecular markers in combination with non-invasive sampling techniques have provided an inexpensive and efficient alternate method to obtain information about species and populations.

Where paleontological and morphological data have revealed inconclusive results, molecular DNA techniques have been useful in delineating evolutionary relationships of the eight species of bears. The giant panda is the most ancestral, followed by the spectacled bear. This was determined using six gene segments of mitochondrial DNA (Waits et al. 1999). The American and Asiatic black bear are closely related, and the youngest group includes brown and polar bears.

During the Pleistocene, the most recent glaciation, deciduous forests occurred mainly in eastern and western refugia in North America. Mitochondrial DNA studies of black bears have confirmed the existence of these two refugia by identifying two major groups (i.e., clades): one east of the Rocky Mountains (including the southern Rocky Mountains), and another west of the Rocky Mountains (California and southern British Columbia), with an area of contact where both clades are present in northern British Columbia and Alberta (Wooding and Ward 1997). This suggests that, at least in part, the extant patterns of diversity in black bears is due to post Pleistocene colonization followed by woodlands retreating to higher elevations in the southwestern United States.

Analysis of population genetic structure in black bears has identified evolutionary history and level of genetic differentiation among populations (Peacock et al. 2007; Robinson 2007). Genetic structure of black bear populations has been examined in several studies using nuclear DNA microsatellite loci (highly variable regions of nuclear DNA that are not usually contained within genes) fragment analysis and mitochondrial DNA (maternally inherited extra-nuclear DNA) sequence analysis.

Microsatellite DNA variation has been used in black bears to understand how fragmentation affects population structure and management decisions. For example, black bears on Newfoundland Island, Canada, had lower levels of genetic variation than mainland populations (Paetkau and Strobeck 1994). In Florida, black bears have currently at least eight genetically distinct subpopulations from what once was a large single population (Dixon et al. 2007). Louisiana black bears showed a significant population differentiation between the coastal and inland populations (Triant et al. 2004). Microsatellite loci were useful to detect the origins of black bear populations after reintroduction programs from Minnesota and Manitoba to Arkansas and Louisiana. Bears from Ozark and Ouachita in Arkansas and inland Louisiana descended from reintroduced bears; whereas, bears from southeastern Arkansas and coastal Louisiana were genetically unique and isolated populations (Csiki et al. 2003). Mitochondrial DNA has also been useful in detecting population isolation, for example, black bears in the Kenai Peninsula and adjacent coastal populations are not closely related, showing the lack of connectivity between the peninsula and coastal populations (Robinson et al. 2007). Finally, a lack of connectivity has been confirmed between the Alexander Archipelago black bears and the mainland bears of southeast Alaska (Peacock et al. 2007; Stone and Cook 2000). In contrast, a lack of differentiation has been observed in one bear study. Black bears from northern Sierra Madre Oriental in Mexico and western Texas show connectivity between them via desert corridors (Onorato et al. 2004).

Genetic analyses have been useful in examining phylogenetic relationships and level of connectivity among bear populations. The earliest studies using allozymes were mostly uninformative due the little genetic variability detected. Microsatellite loci and mtDNA control region sequences, used more recently in black bear population studies, have revealed substantial genetic variation. Genetic data has been used to develop augmentation plans in conservation planning and bear management (Waits et al. 2001).

METHODS

We collected hair, scat and tissue samples from bears in Arizona (Mogollon Rim, Four Peaks-Mt. Ord, Nutrioso Mountains) and Mexico (Sierra San Luis, Sierra Madre Occidental). The samples from the Mexican populations were collected from field studies, using non-invasive techniques. In Arizona samples collected included scats, hair and tissues from hunted animals and from other field studies that involved handling of bears. We extracted DNA using QIAGEN's DNeasy tissue or scats kits (for instructions visit http://qiagen.com/literature/genomlit.asp) and amplified mitochondrial DNA and six microsatellites using polymerase chain reaction (PCR) (Paetkau et al. 1995). A detail of the laboratory methodology we used in this study is described in Paetkau et al. (1998). We checked for errors and quality control according to Paetkau (2003).

Mitochondrial DNA

Mitochondrial DNA is maternally inherited, and is very useful to detect historical evolutionary lineages. We amplified a 310 base pairs (bp) region of the mitochondrial DNA Control Region (CR). For details see Varas et al. (2006).

Nuclear Microsatellites

Microsatellite loci are useful to resolve recent population structure (i.e., determination of the two alleles present for an individual at one genetic locus). The number of alleles and heterozygosity (i.e., the state where the two alleles at a genetic locus are different) are indicators of how variable the populations are. We amplified and genotyped six microsatellites: G1A, G10B, G1D, G10C, G10M, G10X (Paetkau and Strobeck 1994, 1998) for all Arizona and Mexico populations in this study.

Analysis

Mitochondrial DNA

We edited and aligned sequences using Sequencher 4.6 (Gene Codes Corporation, 2006) and PAUP 4.0 (Phylogenetic Analysis Using Parsimony; Swofford 2002), to resolve phylogenetic relationships among the sequences. In our analyses, we included sequences from Onorato et al. (2004), Wooding and Ward (1997) and one sequence of *Ursus americanus Kermodei* (Paetkau and Strobeck 1996). We performed parsimony and distance analysis using PAUP 4.0 (Swofford 2002).

Microsatellites

We tested departures from Hardy-Weinberg equilibrium and genetic differentiation in Genepop 3.4 (Raymont and Rousset 1995). The Fixation Index (F_{ST}) is an indicator of connectivity among populations with $F_{ST} = 0$ indicating the populations are fully connected, and $F_{ST} = 1$ indicating there is no connection between populations.

RESULTS

Mitochondrial DNA

Preliminary results show five mitochondrial DNA haplotypes (i.e., unique set of mutations within a region of DNA). Two haplotypes are shared with bears from western New Mexico in roughly the same frequencies. These same two haplotypes were also shared with bears from the Rocky Mountains (Wooding and Ward 1997). The other three haplotypes were rare and found in only one population from this study. No sharing was observed between haplotypes from this study and the single haplotype found in south central New Mexico, or with the two haplotypes found in southern Texas and the Sierra Madre Oriental in Mexico.

Nuclear Microsatellites

The number of alleles ranged from two to nine per locus and the heterozygosity ranged from 0.17 to 0.42. Randomly mating closed populations should conform to Hardy-Weinberg equilibrium, whereby observed and expected heterozygosities do not differ significantly. The observed versus expected heterozygosity indicated our populations conformed to Hardy-Weinberg expectation at four microsatellite loci but not at two loci. Considering all loci together, only the Four Peaks-Mt. Ord population deviated from Hardy Weinberg equilibrium. The F_{ST} values in this study were highest (0.1131) between the Mogollon Rim in Arizona and the Sierra Madre Occidental in Mexico. The range in F_{ST} values was 0.0002 to 0.1131 and the average F_{ST} was 0.0477.

DISCUSSION

Our mitochondrial DNA data shows that black bears from Arizona are more closely related to black bears in western New Mexico and along the Rocky Mountains (east of the Rocky Mountain clade) than to bears in the western group (California) presented by Wooding and Ward (1996). This is reasonable because there is a geographical connection between northern Arizona (Mogollon Rim) and the southern Rocky Mountains, and because black bears in Arizona are separated from California by a long stretch of desert. Our results indicate the Arizona/Mexico populations are not closely related to populations further east than western New Mexico. This pattern of diversity likely represents historical dispersal since the last glaciation.

Black bears in the sky islands in Arizona and in the Sierra Madre Occidental in northern Mexico are closely related. Mitochondrial DNA and microsatellites show the Arizona sky islands and Sierra Madre Occidental populations share mtDNA haplotypes and many microsatellites alleles. Therefore, we could consider the sky island region in Arizona and northern Mexico one connected population in terms of management and conservation.

Preliminary mitochondrial data shows that there is a moderate level of gene flow among the sky islands in Arizona and Sierra Madre Occidental in Mexico, with the highest F_{ST} value being 0.1131 between the populations in the Sierra Madre Occidental and the population on the Mogollon Rim in Arizona (the populations separated by the longest distance). These results suggest that the primary factor influencing gene flow among bear populations is the distance between populations. Therefore, neighboring populations are less differentiated than distant ones.

Black bears in the two studied Mexican populations, Sierra Madre Oriental (Coahuila/Sierra el Burro) (Onorato et al. 2007), and the Sierra Madre Occidental (Sierra San Luis) (Varas et al. 2006), are not closely related. It seems likely that these populations were historically separate and have not experienced significant gene flow since the last glaciation. This means that there are at least two different black bear lineages occurring in Mexico.

Our results indicate a connected population of black bears in the sky islands in Arizona and the Sierra Madre Occidental in northern Mexico. Black bears are moving among these sky islands within and between the U.S. and Mexico. Management options need to consider genetic differentiation and levels of gene flow among populations, and to strive to maintain genetic variability of population to promote long-term survival of wildlife. The increased militarization on the border may be disrupting and reducing the movement of bears across the border. Also, the addition of an impermeable fence across the border would stop bear migration between the United States and Mexico. Arizona populations may be the only source of migrants to the endangered black bear population in Sonora, Mexico. Habitat connectivity between Texas and Mexico has allowed dispersal between populations in Coahuila, Mexico (source population) and Texas (subpopulations) (Doan-Crider and Hellgren 1996, Onorato at al. 2007). As a result this enhances the long-term viability of the metapopulation in Big Bend National Park, Texas provided that the border remains open to bear migration. Two-way movement between source populations and subpopulations is vital to the survival of the black bear in the desert Southwest.

Challenges are huge in terms of preserving the connectivity among populations in the sky islands. This connectivity is vital so that large mammals in general have the genetic variability they need to adapt to the fast changing environment. International cooperation, binational agreements, and education of the public are the keys to maintaining the rich biodiversity we have in this unique sky island ecosystem.

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RECOVERY EFFORTS FOR THE SONORAN PRONGHORN IN THE UNITED STATES

Ryan R. Wilson, Paul R. Krausman, and John R. Morgart

The goal of listing a species as endangered under the Endangered Species Act (ESA) is to recover that species from the threat of extinction (Yoakum 2004a). An amendment to the ESA in 1978 requires a recovery plan be developed for all endangered species (Clark 1994), outlining the steps that are required for the recovery of the species and designating criteria for delisting (Scott et al. 1996). Recovery plans and efforts made to recover endangered species alone do not always make a difference (Scott et al. 1996), as many species with revised recovery plans are more imperiled than they were when their original recovery plan was written (Tear et al. 1995). Reviewing recovery efforts for a species is important to determine what has worked and what has not, and to provide insight into endangered species recovery that may improve the recovery process for other species (Clark et al. 1994).

The Sonoran pronghorn was on the first list of endangered species in 1967 (U.S. Fish and Wildlife Service 1967), six years before the enactment of the ESA. The subspecies is still listed as endangered and until 2003 was probably more imperiled than when originally listed. Reviewing recovery efforts for Sonoran pronghorn is now appropriate because the Final Revised Recovery Plan for Sonoran Pronghorn (U.S. Fish and Wildlife Service 1998) stated that if actions in the plan were completed successfully, then downlisting to threatened was anticipated for Sonoran pronghorn by 2005; an action that did not happen.

In this chapter we review the history of the Sonoran pronghorn as an endangered species and outline the conservation and recovery efforts initiated for the subspecies before and after its listing in 1967. We limited our review of Sonoran pronghorn recovery efforts to those initiated for the U.S. subpopulation; two other subpopulations occur in Sonora, Mexico, and are functionally separated by a highway and agricultural developments (Arizona Game and Fish Department 1981).

REASONS FOR ENDANGERMENT

Sonoran pronghorn were historically distributed in the U.S. from the Imperial Valley, California, east to the Altar Valley, Arizona, and from near the Gila River in the north to the international boundary with Mexico in the south (Wright and deVos 1986). The current distribution of Sonoran pronghorn is almost entirely limited to Cabeza Prieta National Wildlife Refuge (CPNWR), Organ Pipe Cactus National Monument (OPCNM), and the Barry M. Goldwater Range (BMGR) (Hervert et al. 2000).

The Sonoran pronghorn numbers, which likely numbered in the thousands in the mid-19th century, declined rapidly by the end of that century due to over-harvest and loss of habitat (Yoakum 2004b). By 1907 they were already rare along the U.S.-Mexico border (Mearns 1907). This led to the appointment of a special game warden to patrol the international border with Mexico to protect pronghorn and bighorn sheep (*Ovis canadensis*) from poaching (Leopold 1959).This appointment, however, only lasted a few years and likely had little impact on the population. Unlike other populations of pronghorn in North America, Sonoran pronghorn did not increase in numbers during the 1900s (Yoakum 1968). Estimates (better classified as "guesstimates" because the populations were not systematically sampled) of Sonoran pronghorn numbers in the U.S. during the 1900s varied between 100 and 200 and never exceeded 250 (U.S. Fish and Wildlife Service 1998).

Even with hunting of Sonoran pronghorn banned for nearly 60 years (U.S. Fish and Wildlife Service 1998) and the preservation of large areas of Sonoran pronghorn habitat (610,000 ha; Hervert et al. 2000) in the late 1930s and early 1940s (Phelps 1978), the population never increased, indicating other factors limited the population. The most commonly cited suggestion for the ultimate cause of the population's endangerment is loss of habitat due to the creation of roads and other barriers to movement, in addition to overgrazing by livestock (U.S. Fish and Wildlife Service 1982; Wright and deVos 1986; U.S. Fish and Wildlife Service 1998). The drying of the Gila and Sonoyta rivers in Arizona and Sonora, respectively, may also have contributed to the decline in numbers of Sonoran pronghorn (Carr 1972). Sonoran pronghorn may have used these areas during dry periods as sources of succulent and nutritious forage and drinking water (Arizona Game and Fish Department 1981), although multiple waters were developed for Sonoran pronghorn in the 1950s and 1960s (Morgart et al. 2005).

RECOVERY AND CONSERVATION EFFORTS

Following listing of Sonoran pronghorn under the Endangered Species Preservation Act in 1967, the Arizona Game and Fish Department initiated a study to collect biological information on the subspecies (Arizona Game and Fish Department 1981).

The Sonoran Pronghorn Recovery Team first met in 1975 (U.S. Fish and Wildlife Service 1998) producing the first recovery plan for Sonoran pronghorn in 1982 (U.S. Fish and Wildlife Service 1982). The recovery team set a recovery goal of maintaining an average population of 300 Sonoran pronghorn in the U.S. over a 5-year period. If this goal could be met and the recovery team believed that major threats to the subspecies were eliminated, the U.S. Fish and Wildlife Service would consider delisting the Sonoran pronghorn (U.S. Fish and Wildlife Service 1982). Little was known, however, about the subspecies' basic life history characteristics (e.g., survival and mortality rates, home range size, seasonal movements, habitat selection, productivity, and recruitment estimates).

The recovery team recognized that inadequate knowledge of methods to increase the numbers or range of Sonoran pronghorn was a serious problem inhibiting its recovery. The recovery team also stated that while it could be possible to transplant Sonoran pronghorn to other areas as a means of increasing the overall population, at that time there was inadequate knowledge of suitable transplant sites, capture methods, or numbers of animals required to successfully establish a new population (U.S. Fish and Wildlife Service 1982). The 1982 recovery plan did not outline a proposed method for reaching the recovery goal. Therefore, the objective set forth in the plan was to maintain Sonoran pronghorn numbers until techniques were developed to reach the recovery goal.

Actions proposed in the 1982 recovery plan to maintain Sonoran pronghorn numbers included: population surveys, maximize public ownership of habitat, preserve existing habitat (i.e., minimizing human disturbance and cattle trespass), determine life history, modify limiting factors (e.g., predation, forage quantity and quality, and water) when they are determined, establish a captive breeding population for transplant stock, and reestablish Sonoran pronghorn in historic habitat.

The first conservation action with the potential to increase Sonoran pronghorn numbers was the removal of cattle on most of the current Sonoran pronghorn range in the late 1970s and early 1980s (1978 on OPCNM, 1983 on CPNWR, and 1986 on BMGR; O'Gara and McCabe 2004). On ranges in good ecological condition, cattle and pronghorn do not normally compete for forage (Yoakum et al. 1996), however, on marginal pronghorn habitat (Yoakum 2004a) cattle may compete with pronghorn (Ellis 1970). Cattle may also change the vegetation associations so the landscape supports fewer pronghorn (Wagner 1978). Removing livestock from the current range of Sonoran pronghorn may have benefited pronghorn, however, reverting the areas to better habitat for native ungulates may take decades (Valone et al. 2002) or may even be impossible (Van Auken 2000).

Between the mid-1980s and 1990s, three studies on life history characteristics of Sonoran pronghorn were conducted (Wright and deVos 1986; Hughes 1991; Hervert et al. 2000). In addition, three water developments were created for Sonoran pronghorn (Morgart et al. 2005), all fences were removed from guzzlers and drinkers on CPNWR to facilitate their use by pronghorn, OPCNM modified their boundary fences with CPNWR to facilitate pronghorn movements, and the first full-time ecologist was employed at CPNWR (U.S. Fish and Wildlife Service 1998). Various studies were also conducted to determine what effects military operations on BMGR might have on pronghorn behavior and survival (see Krausman et al. 2005 for a review).

In 1992, a systematic population monitoring program was initiated to conduct biennial population surveys (Snow 1994). At the time, Sonoran pronghorn were the only endangered mammal in Arizona that had not been intensively surveyed, and prior to 1992, there had not been a range-wide population survey (Snow 1994). Therefore, as late as 1992 the population status of Sonoran pronghorn in the U.S. was not known. Prior to 1992, there had been periodic attempts to estimate pronghorn numbers in the U.S., but they were not true estimates and therefore their reliability is unknown. Since 1992, the entire range of Sonoran pronghorn in the U.S. has been surveyed biennially to obtain population estimates.

In 1996, a population viability analysis (PVA) was used to model the probability of Sonoran pronghorn becoming extinct given population status and conditions present in 1996 (Hosack et al. 2002). The PVA also examined the sensitivity of the remaining Sonoran pronghorn population to varying estimates of population parameters and frequency of severe droughts. Using an estimate of 100 animals in the population at the start of the modeling exercise, the probability of extinction in the next 50 years was 12%. Results of the PVA also revealed that populations with numbers < 100 have a 10-65% increased risk of extinction (Hosack et al. 2002). An increase in the frequency of catastrophic droughts (i.e., severe enough to cause > 50 % mortality of the population) caused greater population fluctuations, an increase in loss of genetic variation, and a decreased population growth rate. More importantly, the PVA revealed that reduced fawn survival (i.e., < 25%) might affect the population more than reduced adult survival (i.e, < 78% for males and < 90% for females) (Hosack et al. 2002).

The second Sonoran Pronghorn Recovery Plan was written in 1998 (U.S. Fish and Wildlife Service 1998) and updated the recovery criteria based on the results of the PVA (Hosack et al. 2002) and the three studies on Sonoran pronghorn life history (Wright and deVos 1986; Hughes 1991; Hervert et al. 2000). The new recovery criteria stated that Sonoran pronghorn would be considered for downlisting when there are 300 Sonoran pronghorn in one U.S. population, and a second population is established in the U.S. that remains stable over five years, or when numbers are determined to be adequate to sustain a viable population (U.S. Fish and Wildlife Service 1998). The 1998 recovery plan also stated that if actions presented in the plan were successfully completed, Sonoran pronghorn were anticipated to be downlisted to threatened by 2005. The plan also acknowledged that significant aspects of Sonoran pronghorn life history were not known and that this hampered the ability to estimate a delisting date and possibly to develop effective recovery actions.

The 1998 recovery plan, like the one in 1982, mentioned that captive breeding and the possibility of reintroductions to areas of historic range should be further investigated. The 1998 recovery plan also called for the investigation of habitat modification (i.e., forage plots, water catchments, chain fruit cholla [*Opuntia fuligida*] establishment), land-use restrictions in areas of high pronghorn use, and further research on limiting factors.

By the beginning of 2002, none of the actions that were to be investigated in the 1998 recovery plan (i.e., forage plots, captive breeding, reintroductions, land-use restrictions) had been implemented. However, by the end of the year, many of those proposed recovery actions were implemented or were being implemented because nearly 80% of the Sonoran pronghorn population in the U.S. perished after a severe drought in 2002 (Bright and Hervert 2003).

Hervert et al. (2001) suggested the creation of forage enhancement plots in key areas of Sonoran pronghorn habitat to increase fawn survival by providing lactating females and foraging fawns access to more succulent and nutritious forage during times of the year with limited rainfall. Since 2002, four forage enhancement plots have been established (one in 2002, three in 2005). Each of the forage enhancement plots also provides a source of free-standing water for Sonoran pronghorn (Figure 1). There are plans to expand three of the existing forage enhancement plots prior to summer 2006 (Arizona Game and Fish Department, unpublished report). Additionally, the 2002 drought spurred the creation of 6 emergency water catchments for Sonoran pronghorn between 2003 and 2004 (Morgart et al. 2005). Two additional emergency waters were created in February 2006 within CPNWR in the Sierra Pintas and Pinta sands, (Arizona Game and Fish Department, unpublished report).

Following the 2002 drought, plans were made to implement a captive-breeding program for Sonoran pronghorn (Arizona Game and Fish Department 2003). The plans for a captive-breeding facility for Sonoran pronghorn were modeled after a facility developed for captive-breeding of peninsular pronghorn in Mexico (Cancino et al. 2005). The Sonoran pronghorn captive-breeding facility (enclosure) was built in 2003 and is located on CPNWR (Figure 1). The enclosure encompasses 260 ha and is sectioned into two halves to manage the genetic diversity of the captive population. Forage enhancement plots (Hervert et al. 2001) and drinkers were created in the enclosure (Figure 1) to enhance the natural forage available to captive pronghorn and provide water throughout the year.

Captive breeding began in early 2004 when two females from Sonora (January capture) and 1 male from the U.S. subpopulation (April capture) were captured and transported to the enclosure. Four additional females from the U.S. subpopulation were captured and released into the enclosure in December 2004. At the time of capture, ultrasound revealed that all four females were pregnant; most with twins. By mid-March 2005, all six females gave birth, increasing the total captive population to 17 animals. However, in July 2005, four fawns (three female, one male) died from unknown causes, and in November 2005, 1 adult female died of unknown causes. On 2 December 2005, supplemental feeding of *ad libitum* alfalfa hay was initiated within the enclosure after captive individuals began to look emaciated due to poor forage conditions within the enclosure.

In December 2005, three adult females were captured within the U.S. and transported to the enclosure and placed in the then unoccupied section (i.e., southern half). Also, during the December 2005 captures, two adult females were captured and fitted with radio-collars and re-released, to assist in population monitoring efforts and other research. Four additional Sonoran pronghorn (one male, three female) were captured in Sonora in January 2006 and transported to the southern half of the enclosure. Ultrasound revealed that all three of these females were pregnant upon

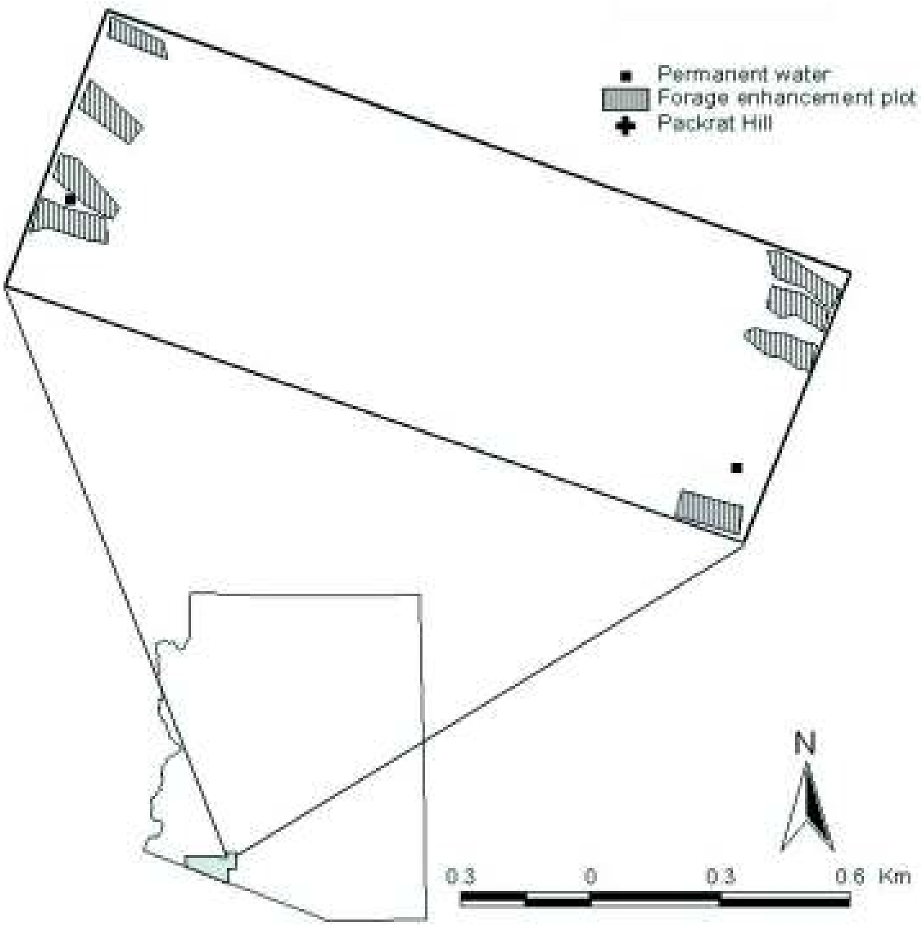

Figure 1. Location of forage enhancement plots and waters in the currently occupied portion of the Sonoran pronghorn captive breeding enclosure on Cabeza Prieta National Wildlife Refuge, Arizona, 2005.

their release. Approximately one month after their release, one of the Mexican females in the southern half of the enclosure died of unknown causes. Between February and March 2006, females in the enclosure gave birth to eight fawns; three sets of twins and two singletons (Arizona Game and Fish Department, unpublished report).

One of the goals of the Sonoran pronghorn captive breeding program is to produce healthy individuals so a second population of Sonoran pronghorn can be established in the U.S. (U.S. Fish and Wildlife Service 1998). To determine where a future reintroduction might occur, a habitat evaluation study was conducted (O'Brien et al. 2005). Six areas outside of the current distribution of Sonoran pronghorn were identified as potential habitat for a reintroduced population (O'Brien et al. 2005). However, the models used in the study only contained coarse vegetation and landscape features (i.e., slope, aspect, biome, distance to wash, and soil type) so future ground-based studies should be conducted to further evaluate the identified areas (O'Brien et al. 2005).

Another conservation effort, enacted in 2002 in response to the catastrophic drought and mentioned in the 1998 recovery plan, were temporary land-use closures on CPNWR, portions of OPCNM, and surrounding Bureau of Land Management (BLM) lands from 15 March until 15 July each year to limit disturbance from recreationists to Sonoran pronghorn during fawning. While disturbance of Sonoran pronghorn during fawning could be detrimental to individual productivity (Phillips and Alldredge 2000), the effectiveness of this conservation measure is likely reduced because of the increase in numbers of illegal immigrants and the subsequent increase in border law enforcement activity (Goodwin 2000). This is further supported by studies that document pronghorn being more easily disturbed by recreationists than other species of large mammals (Taylor and Knight 2003) and showing no signs of habituation to continued disturbance (Fairbanks and Tullous 2002).

Another action enacted to benefit Sonoran pronghorn was the retirement of the Cameron Grazing Allotment on BLM land south of Ajo, Arizona, in September 2004 (T. Hughes, BLM, pers. comm.). This allotment is known Sonoran pronghorn habitat — the removal of cattle and the subsequent removal of fences may allow more pronghorn to use the area. This action might also increase the number of Sonoran pronghorn that can be supported on their current range by increasing access to available habitat and allowing more flexibility in responding to seasonal rainfall events.

DISCUSSION

Recovery efforts for the Sonoran pronghorn over the last three decades have focused on studying the subspecies' natural history and potential impacts of military operations (Krausman et al. 2004, 2005); little habitat manipulation to benefit Sonoran pronghorn occurred until recently (U.S. Fish and Wildlife Service 1998). O'Gara and McCabe (2004) suggested that listing as endangered under the ESA has not hastened the recovery of the Sonoran pronghorn. To effectively conserve an endangered species, reasons why the species is imperiled and what factors contribute to this imperilment must first be determined (Scott et al. 1996), which requires knowledge of a species' natural history.

Biologists and managers lacked information on basic life history characteristics of Sonoran pronghorn until the studies of Wright and deVos (1986), Hughes (1991), and Hervert et al. (2000) were completed. Estimates of survival and mortality rates and of productivity and recruitment are important for endangered species management because they allow biologists to determine potential factors limiting population growth. Biologists can then develop strategies to increase survival and recruitment to stimulate population growth even if the limiting factors are only proximate causes of the species' endangered status (Mills et al. 2005). Knowledge of home range size, seasonal movements, and habitat use are also needed for effective management of endangered species because they identify the minimum area needed to maintain an individual, habitat requirements, and important areas that need to be protected for survival of the species (Hervert et al. 2005). This information can then be used to more effectively implement habitat management by considering habitat preferences of the species (Hervert et al. 2005), and to find potential habitat for future reintroductions.

Knowledge of a species' natural history, however, will not facilitate recovery unless concomitant recovery actions can minimize or eliminate limiting factors. Implementation of recovery actions is probably the most challenging part of the recovery process (Culbert and Blaire 1989). Until these basic life history data were known, efforts to manage the proximate factors of Sonoran pronghorn endangerment were not suggested and implemented. Both the 1982 and 1998 Sonoran pronghorn recovery plans discussed further research into implementing habitat management actions and captive breeding (U.S. Fish and Wildlife Service 1982, 1998), however these actions were not initiated until the middle of a severe drought, during which there was an 80% reduction of an already small population (Bright and Hervert 2003).

Prior to 2002, much had been said about potential negative impacts of a severe drought on the remaining Sonoran pronghorn in the U.S.. The results of the 1996 PVA (Hosack et al. 2002) suggested that an increased frequency of catastrophic droughts increased the probability of extinction over the next 100 years by 46%. It was, therefore, recommended that management actions that reduce the impacts of drought on a population be implemented (provisioning of food and water) to reduce the chances of the population going extinct (Hosack et al. 2002).

Hosack et al. (2002) noted that it may also be beneficial to establish a captive population to guard against the extinction of the remaining U.S. subpopulation of Sonoran pronghorn. The 1998 recovery plan stated that "actions that result in a decrease in mortality rates for adults and juveniles would be expected to provide the most drastic benefits for Sonoran pronghorn." (U.S. Fish and Wildlife Service 1998:26). An extreme drought provided the impetus for the initiation of recovery efforts mentioned in 1982, 1998, 2001, and 2002 (U.S. Fish and Wildlife Service 1982, 1998; Hervert et al. 2001; Hosack et al. 2002).

Forage enhancement plots and captive breeding may provide the best tools for protecting the remaining Sonoran pronghorn in the U.S. from extinction. Vegetation manipulation is a common management technique for increasing the number of pronghorn that can be supported on an area (Yoakum et al. 1996), but this is the first time it has been implemented to help increase Sonoran pronghorn numbers. Because one goal of Sonoran pronghorn recovery is to increase the population size, it is important to initiate management actions that assure adequate forage is available (Yoakum 2004a). One of two situations requiring the manipulation of habitat to increase pronghorn numbers occurs when food, water, or cover are limiting factors (i.e., forage and water in the case of Sonoran pronghorn; Fox et al. 2000) and the possibility exists for improvement of those factors (Yoakum and O'Gara 2000). Forage enhancement plots (Hervert et al. 2001) will hopefully increase survival and recruitment by allowing individuals to meet their nutritional demands, especially during periods of drought, pregnancy, and lactation (Fox et al. 2000; Koerth et al. 1984; Hervert et al. 2001).

Forage enhancement plots are still an experimental management tool as there have been no studies that show the plots are increasing survival and recruitment of Sonoran pronghorn. However, some information may be gained on Sonoran pronghorn use of forage enhancement plots by the two animals radio-collared in December 2005. The size and number of forage enhancement plots that will be adequate to enhance forage for the population is unknown and a study to quantify the increase in forage quality and quantity has not been conducted.

Studies have indicated that supplemental feeding of wild ungulates is either ineffective or detrimental to the management of those populations. In a supplementally fed population of white-tailed deer (*Odocoileus virginianus*), as density increased so did neonatal mortality of fawns born to two- and three-year-old females (Ozaga and Verme 1982). Also, in other studies of deer, when limited food is provided to starving individuals in a patchy environment, adult males usually dominate other deer in obtaining forage (Ozaga 1972; Grenier et al. 1999). Similar observations have been made of adult and yearling male Sonoran pronghorn in the enclosure chasing away females from feeding stations (Arizona Game and Fish Department, unpublished report). Supplemental feeding of elk (*Cervus elaphus*) did not increase fecundity, but may have influenced sex ratios at birth in favor of males (Smith 2001). These studies present possible implications of forage enhancement plots for Sonoran pronghorn. While the potential exists for forage enhancement plots and supplemental feeding to be positive, they may not be effective. Therefore, a study should be conducted to determine the effects of forage enhancement plots on forage quantity, quality, and water content. Until such a study is conducted, forage enhancement plots should continue to be operated.

The Sonoran pronghorn captive breeding program has potential to aid in the conservation and recovery of the subspecies in the U.S. In addition to serving as a source of stock for supplementing the existing wild subpopulation, the program will be able to provide a source of animals for translocations to portions of historic range. The 1998 recovery plan (U.S. Fish and Wildlife Service 1998) suggested that the most effective recovery effort for Sonoran pronghorn may be expanding the current range of Sonoran pronghorn. The 1982 recovery plan (U.S. Fish and Wildlife Service 1982) also discussed translocation of Sonoran pronghorn as a way to increase their numbers.

Other endangered species recovery programs have been successful at rearing individuals in captivity for translocations to reestablish populations in historic habitat (Stüwe and Nievergelt 1991). The captive breeding facility for peninsular pronghorn (Cancino et al. 2005) has been successful in rearing large numbers of individuals for eventual release into historic habitat, but the release of animals into habitat took longer than initially expected. Raising Sonoran pronghorn in a large enclosure in their habitat likely increases the chances that they will exhibit natural behaviors once released and, therefore, will increase the chance of successful future reintroductions, as has been demonstrated with black-footed ferrets (*Mustela nigripes*) reared in a naturalistic captive environment (Vargas et al. 1999). The Sonoran pronghorn captive breeding facility could also be a useful tool for increasing genetic diversity, especially after nearly 80% of the U.S. population perished in 2002. This will be accomplished by capturing and transferring Sonoran pronghorn from Mexico into the enclosure (Arizona Game and Fish Department 2003).

The ability to save an endangered species becomes more limited when fewer animals exist. Tear et al. (1995) recommended that aggressive and proactive efforts need to be initiated sooner rather than later for the conservation of endangered species. In the case of Sonoran pronghorn, funding for their conservation has recently increased, likely due to the near extinction of the U.S. subpopulation. Additionally, the amount of research on Sonoran pronghorn has increased as there were more peer-reviewed publications on Sonoran pronghorn from 1996 to 2005 (n = 17) than from 1926 to 1995 (n = 10) (Krausman et al. 2005). It is important to review past recovery efforts for Sonoran pronghorn to determine past successes and shortcomings of the recovery program. Managers should then focus on maximizing the effectiveness of the current recovery efforts by investigating their efficacy (Jarman and Brock 1996) and by implementing future recovery efforts experimentally (Sinclair 1991). More effective recovery efforts will aid in reaching the eventual goal of recovery and serve as a model for the recovery of other threatened and endangered species.

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CURRENT STATUS OF MOUNTAIN LIONS AND URBAN ISSUES IN TUCSON, ARIZONA

Kerry L. Nicholson, Lisa Haynes, and Paul R. Krausman

Mammalian carnivores, including mountain lions (*Puma concolor*; Leopold 1933) that are wide ranging and exist at low densities, are of particular concern (Wilcox and Murphy 1985; Noss et al. 1996; Gittleman et al. 2001). Typically carnivores that can live sympatrically with humans are relatively small (10 kg) and are usually not perceived as an imminent threat to humans. Larger carnivores such as coyotes (*Canis latrans*), bobcats (*Lynx rufus*), wolves (*C. lupus*), black bears (*Ursus americanus*) and mountain lions are perceived in a negative light by the public (Kellert 1985; Riley and Decker 2000; Teel et al. 2002). This negative view, however, is changing. Public opinion that once considered carnivores as vermin to be eradicated (Russo 1964; McCulloch 1986) is shifting to one that recognizes the ecological role that mountain lions play in the wildlife community (Noss et al. 1996; Teel et al. 2002). For example, mountain lions were viewed as a threat to ranching and free- ranging ungulate populations, thus, bounties were put on mountain lions along with hunting campaigns to eliminate them from the landscape (Russo 1964; McCulloch 1986). Some of these views still exist, but changes in tolerance levels towards mountain lions have allowed populations to increase. As a result mountain lions increasingly are encountering human dominated environments that often lead to increases in conflict between mountain lions and humans, their pets, and livestock. However, there is still a lack of understanding of basic lion ecology by the public, which has led to intense political pressures often based on narrow and erroneous assumptions (Casey et al. 2002).

Mountain lions have broad geographic distribution, from sea level to > 4,500 m in elevation (Logan and Sweanor 2001) and have the ability to persist in almost any habitat that offers adequate prey and cover (Cougar Management Guidelines Working Group 2005). With increasing human expansion, mountain lions are threatened with habitat loss, fragmentation, and potential inbreeding problems (Beier and Barrett 1993; Beier 1993, 1995). Our objective was to review the status of mountain lions around Tucson, Arizona and evaluate lessons scientists have learned about urban wildlife management.

METHODS

We obtained information on other current mountain lion studies from personal contact with scientists. We conducted a literature search of urban wildlife issues near Tucson and selected pertinent information for evaluation.

RESULTS

Mountain Lion-Human Conflict

Mountain lions are persecuted whenever there is an attack on humans; attacks have increased in the U.S. since 1985 (Beier 1991), the most recent occurring in April 2006 in the Flagstaff Mountains, Colorado. In the U.S., Beier (1991) conducted a thorough review of historical and unprovoked attacks on humans. From 1909 to 1970 there were 3 attacks from lions on humans. During 1970-1991 there were 10 deaths and at least 44 nonfatal mountain lions attacks (40% of the attacks were by sub-adults or yearlings; Beier 1991). The rise in human attacks in North America may be due to a number of factors, one being fragmentation of lion habitat that increases the likelihood of encounters with humans and pets (Mansfield and Weaver 1989; Beier 1991; Torres et al. 1996). Frequent encounters could also be due to the increased outdoor activities of humans in lion habitat (Beier 1991; Torres et al. 1996).

Attacks by sub-adult mountain lions are common. Young mountain lions are learning to support themselves without assistance from their mothers and are often exploring unfamiliar territories (Seidensticker et al. 1973; Beier 1991). These stresses can lead a young lion to encounter a greater number of humans (Beier 1991; Cougar Management Guidelines Working Group 2005).

In March 2004 in the Sabino Canyon Recreation Area, a popular hiking area in northeastern Tucson at the foothills of the Catalina Mountains, mountain lions were reportedly encountering humans (*Arizona Daily Star*, 3 March 2004). It was theorized that pressure from an extreme drought and fire in 2002, supplemental feeding of collared peccaries (*Pecari tajacu*), and lack of hunting pressures had resulted in mountain lions moving into this region and being observed during daylight hours (Perry and deVos 2005). The resulting controversy over actions taken by the Arizona Game and Fish Department (AGFD) to remove the habituated animals was covered by local newspapers over the next 9 months (*Arizona Daily Star* March 2004, 14 December 2004). As a result of these incidences AGFD initiated research to inform the public of the life history and population status of mountain lions in Arizona (Perry and deVos 2005). The research focused on urban mountain lions in the Tucson, Payson, and Prescott areas.

The recently published Cougar Management Guidelines (2005) outlines ways to reduce the chances of negative encounters and to help agencies evaluate and respond to these encounters. One of the first recommendations was for people to recognize and distinguish between natural and dangerous mountain lion behaviors. People are directed to avoid encounters whenever possible. Agencies and managers are directed to have a plan of action prior to any encounter. These plans should account for investigating reports, level of response, tolerance for specific behaviors, removal, and how to respond when a lion does attack humans (Cougar Management Guidelines Working Group 2005).

Effects of Urbanization

The International Union for Conservation of Nature (IUCN) Cat Specialist Group has called for increased research of wild cats in urban settings, because urbanization is one of the gravest threats to wild cat species worldwide (Nowell and Jackson 1996).

Within the past decade, researchers have initiated several studies of mountain lions in urbanized settings throughout the western U.S. One of the first lion studies conducted in an urban setting was in the Santa Ana Mountains in Southern California (Beier and Barrett 1993). The lions in Southern California encountered a variety of anthropogenic threats, (e.g., vehicular-caused mortalities, occluded and degraded corridors) and direct encounters with humans (Beier and Barrett 1993). Other studies in California have examined the influences of roads and topography on lion movements (Dickson et al. 2005), the efficacy of underpasses and wildlife crossings (L. Lyren, U.S. Geological Survey, pers. comm.), mountain lion / human interactions in Cuyamaca State Park east of San Diego after a lion attacked and killed a park visitor (Sweanor et al. 2004), the effects of rodenticide (anticoagulant "rat" poisoning) that are killing coyotes and bobcats (Recod and Marsh 1988; Riley et al. 2007), and habitat fragmentation and corridor use (Sauvojot and Riley 2002; Riley et al. 2004). Research has begun to model effects of urbanization on mountain lions including efforts to model individual-based movements to evaluate connectivity for mountain lions (J. Tracy, Ph.D. candidate, Colorado State University, pers. comm.), and use least-cost-path analysis to model corridors and connectivity (Newel and Beier 2004).

Other states are also beginning to research urbanization impacts on mountain lions. In Washington state, researchers initiated Project CAT, which conducts field studies of mountain lions, while incorporating students from all grade levels (K-12) in the study and analysis (Koehler and Spencer 2004). In Utah, Stoner and Wolf (2004) examined lion movement patterns, feeding behavior and habitat use in high and low density planned communities. In northern Arizona projects are underway with the U.S. Geological Survey (USGS) examining mountain lion movements near Flagstaff (Mattson et al. 2006).

Several analyses of gene flow and metapopulation genetic structure in mountain lions have been conducted. Molecular genetics have been used in evaluating the impacts of urbanization on wildlife such as determining the effect of landscape barriers on gene flow in mountain lions. A study that encompassed Arizona, New Mexico, Colorado, and Utah found evidence of a north-south partitioning that roughly equated to Interstate Highway 40 (McRae et al. 2005). Patterns of genetic structure in California found evidence of historic patterns based on natural landscape features (Ernest et al. 2003). In Wyoming, there was little evidence of metapopulation structure, suggesting a genetically mixed, panmictic population (Anderson et al. 2004). These genetic studies provide the basis for various geographic regions that can be used to detect changes in the future due to anthropogenic factors.

Studies that specifically examine mountain lion movements within urban landscapes are limited and most thus far are based on sighting locations or locations obtained on an irregular basis. Current research is underway using global positioning systems (GPS) and satellite technology and obtaining locations on a more frequent basis, but results of many of those studies have not been published. Many states maintain records of human interactions/conflicts and depredations of mountain lions; while these data are informative, additional data will be needed.

In Florida, urban development spread and fragmented habitat so much that the genetic viability of the Florida panther (*Puma concolor coryi*) came into question. Natural dispersal was no longer a viable option to maintain genetic diversity in the Florida panther population (Land and Lacey 2000). The Florida panther was listed in the endangered species act in 1967 (Land and Lacey 2000). Concerns began to rise over genetic health and population size due to the small ($n = 30$) population (Lotz 2005). Eight female mountain lions from Texas were translocated to Florida for genetic restoration (Land and Lacey 2000). About half of the presently known occupied panther range in south Florida occurs on private land where agricultural and urban development are increasing (Maher 1990; Cox et al. 2006). Human development has effectively fenced in the Florida panther, creating a small population where extinction now has a high probability of occurrence. Without significant management information, the population appears to occupy all areas with suitable panther habitat and may be close to reaching its carrying capacity (Lotz 2005). Primary mortality sources for the panther stem from intraspecific aggression and deaths from vehicles (Lotz 2005). The panther population is so isolated and restricted by development that if attempts are made to disperse, the amount of pavement necessary to cross to reach more suitable habitat increases the likelihood of collision. If the panthers choose not to disperse, they compete with each other for limited available resources. The Florida panther has become so isolated that manipulation by humans, such as future translocations is likely the only way for the population to survive (Land and Lacey 2000). Is this the future of all mountain lions adjacent to urban centers?

The effects of development on wildlife need to be considered if wildlife are to remain and coexist with humans. Bighorn sheep (*Ovis canadensis*) provide an example of what can happen when conservation efforts do not consider animal movement or land needs (Bleich et al. 1996). One goal for the Pusch

Ridge Wilderness, Santa Catalina Mountains, Arizona, was to provide protected habitat for desert bighorn sheep (Krausman 1997). Society wanted bighorn sheep, and wanted to be able to have the experience of viewing bighorn sheep. However, during development of management plans, little or no thought was given to corridors linking other mountains, which are a necessity for the survival of sheep populations (Krausman 1997). Due to continuing development, humans created a building and housing barrier around Pusch Ridge Wilderness, which effectively fenced the sheep and reduced available habitat (Krausman 1997). The bighorn sheep conservation goal failed. There are no sheep in the Pusch Ridge area and none have officially been documented in the Catalina Mountains since the late 1990s. Now that desert bighorns have declined, we must question the management strategies for the area. If the mountains surrounding Tucson had been managed by conserving numerous habitat patches and allowing for potential dispersal, would there be a viable population of bighorn sheep in the Santa Catalina Mountains? This is the same question that needs to be asked for any animal that society would like to maintain. It is a pivotal question for the sustainability of mountain lions.

Tucson Mountain Lion Research

Tucson, due to its rate of development, provides an ideal location to study mountain lion movements and interactions with urbanization. Located in the Sonoran Desert, Tucson is situated within a valley: the Santa Catalina Mountains to the northeast, the Tortolita Mountains to the northwest, the Tucson Mountains to the west, the Rincon Mountains to the east, and the Santa Rita Mountains to the south. There are several parks and wildlife reserves, including Coronado National Forest and Saguaro National Park, adjacent to the greater Tucson metropolis. Tucson is a major metropolitan area with a population > 900,000 people (> 2,500 people / 1.6 km²; http://www.fedstats.gov/qf/states/ 04/0477000. html).

In 2005, an intensive study initiated by AGFD and the University of Arizona using GPS technology attempted to answer some crucial questions and issues about mountain lion responses to urban situations. Some of the objectives were to examine use of urban areas, movement rates through various landscapes, least-cost-path corridor analysis, individual-based movement models, and intraspecific interactions of mountain lions. The first lion was captured in May 2005. Collared and released, it was subsequently killed by another lion within a week of release. In August 2005, a second lion was captured in the back yard of a private landowner bordering the Santa Catalina Mountains and fitted with a spread spectrum satellite collar (Telonics, Inc., Mesa, Arizona) that recorded a location every 4.25 hours. The 989 locations obtained from the male lion's collar indicated that this mountain lion used the Coronado National Forest in the Santa Catalina Mountains, the Tortolita Mountains, Picacho Peak Mountains, the Ninety-six Hills and the Black Mountains, surrounding and within 60 km of Tucson. We collected data from 10 August 2005 until 10 April 2006. The home range (159,000 ha) incorporated several large parcels of land that are slated for development, including parcels near Biosphere II and land between the Tortolita and Black mountains, which has been approved for development within the next 5 years (K. Baldwin, Pima Parks and Recreation, pers. comm.). The land will have approximately 5,000 new homes and businesses associated with new community development. The mountain lion's habitat already incorporates some developed areas and active living communities (Figure 1). Movements between the Santa Catalina Mountains and the Tortolita Mountains crossed Oracle Road on numerous occasions and were on the edge of several expanding communities.

DISCUSSION

Human development and habitat fragmentation is inevitable as population numbers increase. In Arizona, three interstate highways (I-10, I-8, and I-40) cut across the state. The Central Arizona Project (CAP) is a canal system from the Colorado River through Phoenix and south

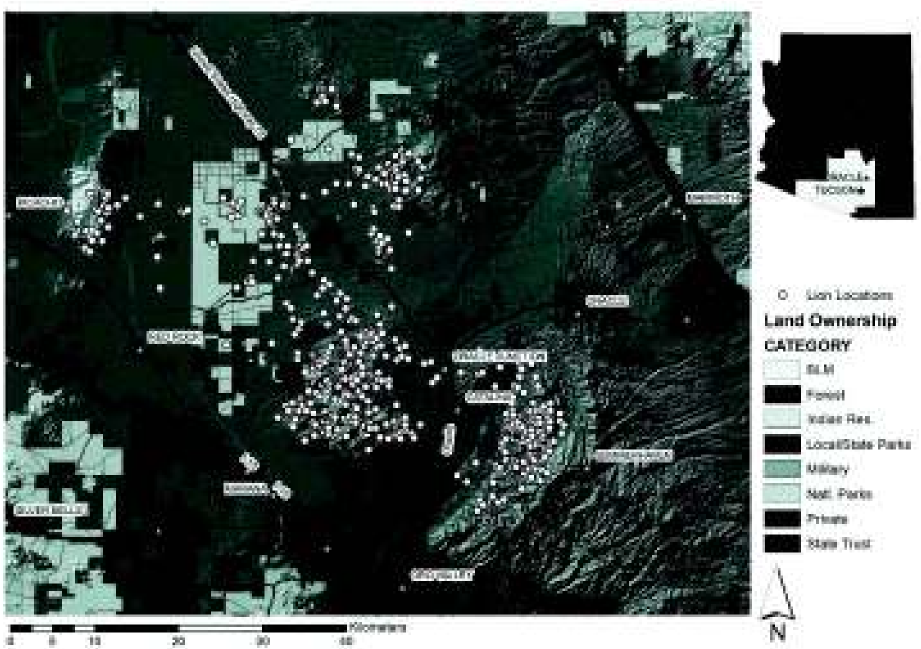

Figure 1. Mountain lion locations of a single male northeast of Tucson, Arizona, August 2005-April 2006.

to Tucson forming another major barrier to translocation. There is a project to erect a barrier between Arizona and Mexico to prevent illegal immigration of humans (*Arizona Daily Star*, 12 March 2006). These man-made structures are potential barriers to wildlife as well and could eventually stop the connectivity necessary for wildlife persistence in the border region. If society wants mountain lion populations to persist in Tucson there will need to be changes in decision making and management. Managers may need conservation strategies that go beyond traditional land acquisition by government and include economic programs to preserve critical landscapes on private land. Bighorn sheep in Pusch Ridge (Krausman 1997) and the Florida panther (Land and Lacey 2000; Lotz 2005) are examples of wildlife situations where forethought, commitment, and follow-through may have prevented problems that society now encounters. Arizona has the ability to begin planning with the knowledge gained from the mistakes in other regions of the country. Currently, Pima County has initiated the Sonoran Desert Conservation Plan which will integrate natural resource protection and land use planning. Also, the Arizona Wildlife Linkage Workgroup is a collaboration of agencies and others to identify potential landscape corridors around Arizona, and to develop detailed plans for some of these potential corridors, namely ones of high importance and at high risk of impairment by highways, urbanization, and other threats. Models are used to design corridors for multiple focal species, and efforts would benefit from empirical data on how mountain lions respond to habitat features in their activity and travel in Arizona landscapes (P. Beier, Northern Arizona University, pers. comm.).

Future studies need to examine lion use of urban areas, inter-mountain movements, human interactions and response practices. Mountain lions readily and easily move between several mountain ranges or across borders and therefore unimpeded pathways must be available for persistence of this species. Studies that document how lions interact with urbanization are important, but unless action is taken to implement the findings, mountain lions will get cut off by urbanization and will thereafter not have a viable future.

ACKNOWLEDGMENTS

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Social & Cultural Issues

MODELING AIRBORNE MINERAL DUST: A MEXICO – UNITED STATES TRANS-BOUNDARY PERSPECTIVE

Dazhong Yin and William A. Sprigg

Air pollution is common in the modern world. Emissions from factories, power plants, and vehicles change the natural composition of Earth's atmosphere constantly. Rapid economic development and industrialization make the problem worse. The most harmful components of air pollution are ground-level ozone and fine airborne particulates. Ozone is a colorless, odorless gas and a powerful oxidant. Airborne particles may consist of different chemical species such as sulfate, nitrate and toxic organics. When entering the human respiratory system, they react with tissues, enter the blood system, and create health problems (Kaiser 2005). Epidemiological studies find consistent evidence that concentration levels of particulate matter with aerodynamic diameter less than 10 μm and 2.5 μm (PM10 and PM2.5) are associated with mortality and morbidity related to all causes, especially to cardiovascular and respiratory illnesses (Burnett et al. 2000; Chock et al. 2000; Goldberg et al. 2003; Kelsall et al. 1997; Kwon et al. 2001; Moolgavkar 2000, 2003; Ostro et al. 1999; Pope et al. 2002; Roemer and van Wijnen 2001; Samet et al. 2000; Smith et al. 2000a, 2000b; Styer et al. 1995).

In the arid and semi-arid Southwestern United States, because of readily available erodible soil, wind-blown dust contributes significantly to air particle pollution. Airborne dust events made up 26%, 33%, 21% and 9% of the total air pollution episodes, 47, 66, 78 and 81 in Texas for 2002, 2003, 2004 and 2005, respectively. Thus, it is imperative to include wind-blown dust in the study of air pollution and its health consequences in the American Southwest.

Climate variability, rapid population growth and urbanization in the Southwest create a constantly changing landscape and vegetation pattern. These changes directly affect the reservoirs of dust available to be lifted into the atmosphere. In this study, we considered two dust storms which occurred in the bordering states of New Mexico and Texas, United States, and Chihuahua and Coahuila, Mexico, using a numerical dust transport model, the Dust Regional Atmospheric Modeling (DREAM) system (Nickovic et al. 2001). Dust sources were identified and divided into areas within the U.S. and Mexico in the model domain. For these two dust storm cases, contributions from source areas in the two countries to dust particle pollution were calculated by the model. Model results demonstrated the relative importance of U.S. and Mexico dust sources to dust air pollution in the Southwest U.S. and Northern Mexico. Results suggest that coordinated efforts in ecological system protection and resource management are needed in the U.S. and Mexico to control harmful particle air pollution.

MODEL AND MODEL SETUP

Model

In DREAM, a dust module, simulating dust production, advection, diffusion, and deposition, is coupled online with the National Centers for Environmental Prediction (NCEP) operational weather forecast Eta model (Messinger et al. 1988; Janjic 1994). The Eta model uses primitive equations based on the hydrostatic approximation. It can be executed with the finest resolution of about 10 km. It is a grid-point model, with which partial differential equations are represented by finite-difference schemes. Schemes are designed to fulfill computational requirements and physical constraints of the real atmosphere. Horizontally, the model uses a semi-staggered E grid (Arakawa and Lamb 1977). Using the E grid yields good performance in simulating small-scale processes such as gravity-inertia disturbances. The method that provides a proper behavior of the model with variables on the E grid is developed for strong physical forcing such as orography influence, convection, and turbulence. Vertically, the model uses a step-mountain representation (Mesinger et al. 1988). The vertical coordinate of the model is defined by

$$\eta = \left(\frac{p - p_T}{p_{sfc} - p_T} \right) \eta_{srf}$$

where

$$\eta_{srf} = \frac{p_{ref}\left(z_{sfc}\right) - p_T}{p_{ref}\left(0\right) - p_T} .$$

P_T is the pressure at the top of the model atmosphere, p_{sfc} and z_{sfc} are the pressure and the height of the model bottom boundary, p_{ref} is a reference pressure, pressure of the standard atmosphere (United States Committee on Extension to the Standard Atmosphere 1976). The mountains in the model are represented as grib-box mountain blocks. The non-slip bottom boundary conditions used at the vertical sides of the mountains in the model provide efficient simulation of the mountain's blocking/splitting/channeling effects. The second-order nonlinear advection scheme (Janjic 1984) conserves important parameters such as mass, energy and squared vorticity.

Vertical turbulent mixing in the surface layer is simulated using Monin-Obukhov similarity theory. The Mixing above the surface layer is modeled using Mellor-Yamada 2.5 level turbulence scheme (Mellor and Yamada 1982). A nonlinear fourth order lateral diffusion scheme is used to control the level of small-scale noise. The radiation parameterization is based on the radiative transfer model developed at the Goddard Space Flight Center (GSFC), National Aeronautics and Space Administration (NASA) (Chou et al. 1999, 2001). The revised Betts-Miller deep and shallow cumulus convection scheme is used to represent moisture processes causing excessive precipitation events (Betts and Miller 1986; Janjic 1994). The Oregon State University (OSU) scheme is used to model land surface processes including surface hydrology.

Airborne dust concentrations are simulated with a set of mass conservation equations for dust particles of four size bins. Table 1 lists the four dust categories in the model and their corresponding physical properties. The dust particles of these four categories are released from their distinctive soil components as listed in Table 1. Inter-particle interactions are not considered in the model.

Table 1. Four dust categories and their particle properties.

Dust category	Size bin (μm)	Typical particle radius (μm)	Particle density (kg/m^3)	Associated soil component
1	0~3.4	0.73	2500	Clay
2	3.4~12	6.10	2650	Small silt
3	12~28	18.00	2650	Large silt
4	> 28	38.00	2650	Sand

Table 2. MODIS land cover categories.

MODIS category	Description
0	Water
1	Evergreen Needleleaf Forest
2	Evergreen Needleleaf Forest
3	Deciduous Needleleaf Forest
4	Deciduous Broadleaf Forest
5	Mixed Forest
6	Closed Shrubland
7	Open Shrubland
8	Woody Savannas
9	Savannas
10	Grasslands
11	Permanent Wetlands
12	Croplands
13	Urban and Built-up
14	Crops, Natural vegetation Mosaic
15	Permanent Snow/Ice
16	Barren/Sparsely Vegetated

The amount and location of dust particles lifted into atmosphere are determined by land cover types, soil texture types, soil moisture conditions and surface wind drag. In DREAM, the land cover product from Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the NASA satellite Terra was used as the land cover dataset. MODIS land cover data used in our modeling studies identifies 17 categories (Table 2) in the International Geosphere-Biosphere Program vegetation classification scheme. The classification was produced using a supervised approach (Hodges et al. 2001). A decision tree algorithm (Quinlan 1993) and a boosting technique (Freund et al. 1995) were used to improve classification efficiency and accuracies. The MODIS data represents land cover conditions of 2001 with 30-second spatial resolution. The dust source areas have land cover category 16, which is barren and sparsely vegetated. Model soil texture was obtained from the Food and Agriculture Organization / United Nations Educational, Scientific, and Agricultural Organization (http://www.fao.org/ag/agl/agll/wrb/wrbmaps/htm/soilres.htm) soil map data with 134 categories and 2-minute spatial resolution.

Surface vertical dust fluxes are calculated according to Shao et al. (1993) wind tunnel experiments. Where the frictional velocity u_* is greater than the threshold frictional velocity u_{*t}, a dust flux F_s is

$$F_s = const \times u_*^3 \left[1 - \left(\frac{u_{*t}}{u_*}\right)^2\right]$$

The threshold friction velocity depends on soil wetness and dust particle sizes of each dust category. When the soil moisture is less than the maximum amount of the absorbed water of a soil type w',

$$u_{*t} = U_{*t} = const \sqrt{2 g r_p \frac{\rho_p - \rho_a}{\rho_a}}$$

where g is the gravitational acceleration, r_p is the particle radius, ρ_p the particle density, and ρ_a the air density. When w is greater than w',

$$u_{*t} = U_{*t} \sqrt{1 + 1.21 (w - w')^{0.68}}$$

The dust flux of an individual dust category is calculated using F_s and the fraction of desert surface, the fractions and the dust productivity factors of the clay/sand/silt components of the soil texture type in a grid cell.

The dry deposition of dust particles is based on the Georgi (1986) scheme, which includes deposition processes by surface turbulent and Brownian diffusion, gravitational settlement, and interception and impaction on the surface roughness elements. The wet removal of dust particles is calculated using the model precipitation rate.

Model Setup

The model domain covers the Southwest U.S. and Northern Mexico. The domain center is located at (35°N, 109°W). The grid spacing in north-south direction is 1/9 degree of latitude. From sea level to 100 hPa, there are 24 eta layers. The approximate heights above sea level (ABS) of the layer centers are as listed in Table 3.

Table 3. Height of 24 half eta levels.

Half eta level	Height (m ABS)
1	15022.83
2	13561.76
3	12257.34
4	11079.29
5	10006.64
6	9024.08
7	8120.08
8	7285.66
9	6513.69
10	5798.42
11	5135.13
12	4519.92
13	3949.52
14	3421.18
15	2932.59
16	2481.81
17	2067.16
18	1687.28
19	1341.00
20	1027.38
21	745.65
22	495.24
23	275.71
24	86.82

Model runs were carried out with all dust sources in the domain (referred as all source runs hereafter) and with no dust sources in Mexico (referred as no-mx source runs).

CASES

Dust storm events in the Southwest U.S. are usually associated with weather patterns starting with forming of a cold front and surface low pressure center over the Pacific Ocean, west of the U.S. Pacific Northwest. The strong cold front system pushes southeastward, and moves through the southwestern U.S. and northern Mexico. During Dec 08 to Dec 10, 2003 (hereafter referred as dust storm Case 1) and Dec 15 to Dec 17, 2003 (Case 2), two similar synoptic systems passed the Southwest U.S.

As shown in Figure 1, the cold front stretched from Montana through Idaho to mid California at 12Z (1200 Greenwich Mean Time) Dec 14, 2003. New Mexico and Arizona were under high pressure control. The cold front moved out of the Southwest at 12Z Dec 16, 2003 (Figure 1b). The system brought strong gusty winds to southern New Mexico, western Texas and northern Mexico. Figure 2 shows the surface Meteorological Aerodrome Report (METAR) wind gusts at 19Z Dec 15, 2003. Wind gusts below 11.2 m/s (25 mile/hour) are not marked in this figure. The areas of southern New Mexico and western

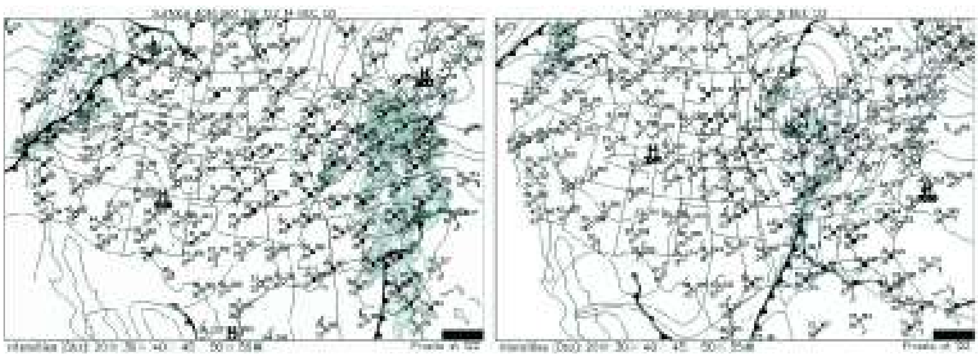

Figure 1. (a) Surface map for 12Z (1200 Greenwich Mean Time) Dec 14, 2003;
(b) Surface map for 12Z Dec 16, 2003 (www.weather.unisys.com).

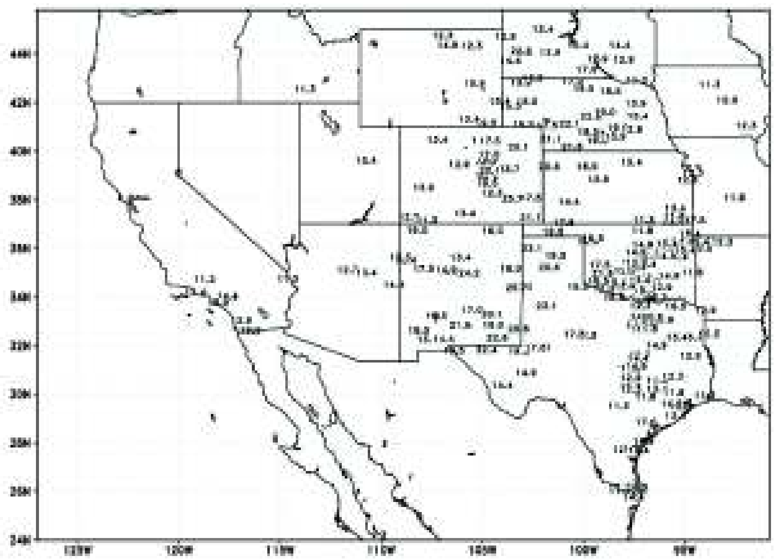

Figure 2. METAR wind gusts at 19Z Dec 15, 2003 (m/s).

Texas had the strongest wind gusts, more than 20 m/s.

These gusty winds caused saltation and sandblasting (Alfaro et al. 1997) over the loose soil areas and sent dust particles into the atmosphere. Satellites observed large plumes of dust in southern New Mexico, western Texas and northern Mexico during Case 1 and Case 2 periods. Observed visibilities in the same area dropped to less than 2 miles. A large dust plume covered the Texas panhandle. During the Case 2 period, visibilities as low as a quarter of mile were reported at Lubbock, Texas.

EVALUATION OF MODEL RESULTS

Model runs with all dust sources were verified against observations to assure the quality of modeled data. Modeled meteorological fields were compared to measurements and analysis products from surface synoptic, surface METAR and upper-air radiosonde. The modeled dust field patterns and dust concentrations were evaluated against satellite images and the surface PM2.5 and PM10 observations from U.S. Environmental Protection Agency (EPA) Air Quality System (AQS).

Performance statistical metrics were calculated in the model evaluation in addition to graphical comparisons, site against site time series and vertical profile comparisons. Table 4 lists the statistical metrics and their definitions.

Since both dust storms occurred in southern New Mexico, western Texas and northern Mexico, the PM2.5 data from 40 observational sites in New Mexico and Texas were used in the model evaluation. Table 5 lists the latitude and longitude of these sites. Figure 3 locates some of the sites. Unfortunately, no PM2.5 measurement data were available in northern Mexico. Only limited PM10 data were available in New Mexico and Texas. Since statistical representations require sufficient data samples, the statistical metrics were calculated for surface meteorological variables such as surface wind speed, wind direction, and surface temperature (data from total 758 sites available), and for surface PM2.5, due to the available amount of data.

Table 4. Statistical metrics and their definitions.

Mean modeled	$\frac{1}{N}\sum_{i=1}^{N} M_i$	M_i modeled value at each site
Mean observed	$\frac{1}{N}\sum_{i=1}^{N} O_i$	O_i observed value at each site
Mean Bias	$\frac{1}{N}\sum_{i=1}^{N} (M_i - O_i)$	0 if perfect
Mean error	$\frac{1}{N}\sum_{i=1}^{N} \lvert M_i - O_i \rvert$	0 if perfect
Index of agreement	$1-\frac{\sum_{i=1}^{N}(M_i - O_i)^2}{\sum_{i=1}^{N}(\lvert M_i-\bar{O}\rvert+\lvert O_i-\bar{O}\rvert)^2}$	1 if perfect

Case 1

Weather patterns

Figure 4a is the surface map for 12Z Dec 09, 2003. The modeled precipitation pattern and locations (Figure 4b) are in agreement withthose of the weather radar returns shown in Figure 4a. The low center is located at Oklahoma and Texas in the modeling domain, so is the observed low center. High pressure dominates the Arizona, Utah and Nevada area in both Figures 4a and 4b.

At 500 hPa level, the observed low geopotential height center (Figure 5a) is located in

Table 5. PM2.5 observational sites.

Site no.	Site name	Latitude (degree)	Longitude (degree)
1	St. Teresa	31.86	-106.69
2	SPCY	31.80	-106.56
3	El Paso	31.77	-106.50
4	El Paso Sun/Metro	31.76	-106.50
5	Anthony	32.00	-106.35
6	Santa Fe	35.67	-105.95
7	Carlsbad	32.31	-104.27
8	Odessa 47	31.84	-102.34
9	Odessa 1014	31.87	-102.34
10	Lubbock	33.59	-101.85
11	Amarillo	35.21	-101.83
12	Laredo	27.60	-99.53
13	CPS Pecan Valley	29.41	-98.43
14	Calaveras Lake	29.28	-98.31
15	Mission	26.23	-98.29
16	Audubo	30.48	-97.87
17	Austin Northwest	30.35	-97.76
18	Corpus Christi Airport	27.77	-97.43
19	Haws Athletic Center	32.76	-97.34
20	Diamond Hill Fort Worth	32.81	-97.34

Table 5. *continued*

Site no.	Site name	Latitude (degree)	Longitude (degree)
21	National Sea Shore	27.43	-97.30
22	Denton	33.19	-97.19
23	Arlington Airport	32.66	-97.09
24	Grapevine Fairway	32.98	-97.06
25	Midlothian Wyatt	32.47	-97.04
26	Midlothian Tower	32.44	-97.02
27	Dallas Hinton St.	32.82	-96.86
28	Conroe	30.35	-95.43
29	Houston Aldine	29.90	-95.33
30	Clinton	29.73	-95.26
31	Houston	29.77	-95.22
32	Kingwood	30.06	-95.19
33	Houston Deer Park	29.67	-95.13
34	Channel View	29.80	-95.13
35	Seabrook Friendship Park	29.58	-95.02
36	Galveston Airport	29.26	-94.86
37	Hamshire	29.86	-94.32
38	Karnack	32.67	-94.17
39	Carrol St. Park	30.07	-94.08
40	Thomas Jefferson	29.92	-93.91

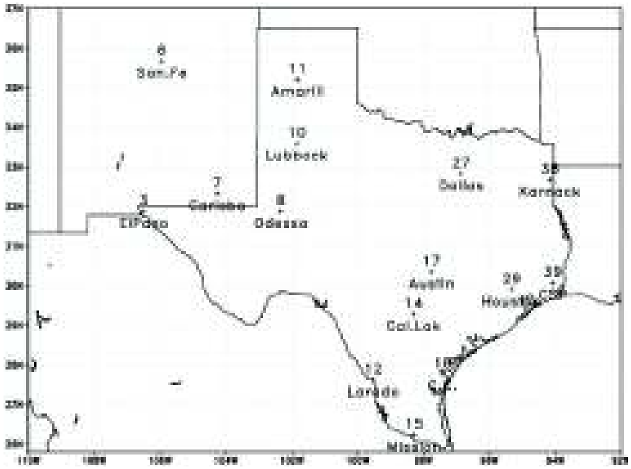

Figure 3. Locations of PM2.5 monitoring sites.

the Texas panhandle and bordering area of New Mexico and Colorado. A corresponding thermal low center is slightly west of the observed geopotential height low, located near the New Mexico and Colorado border. The model geopotential height and temperature fields (Figure 5c) are similar to the observations and the observed low centers are reproduced by the model.

Vertical profiles

The modeled wind, temperature and specific humidity for 12Z Dec 09, 2003 at Tucson airport are compared against radio-sonde data in Figure 6. In the figure, the dots represent observed values, and the lines modeled values. Modeled temperature and specific humidity lines follow the observations very closely. The modeled wind speed line follows the trend of the observations, except for

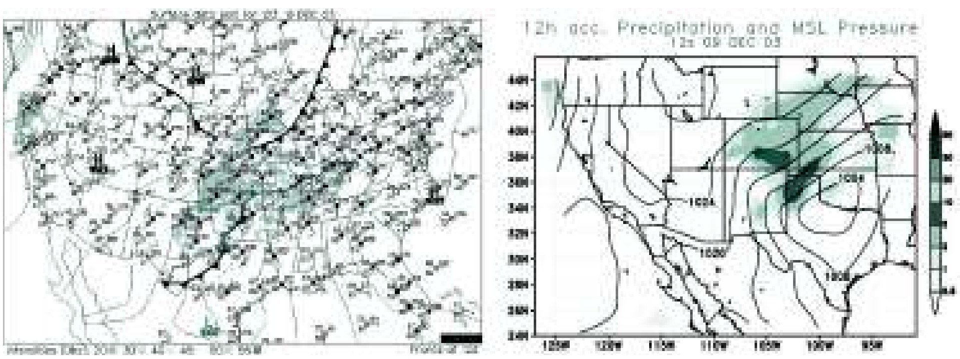

Figure 4. (a) Surface map; (b) modeled mean sea level (MSL) pressure (hPa) and precipitation (mm) pattern for 12Z Dec 09, 2003.

Figure 5. 500hPa (a) observed geopotential height (m); (b) observed temperature (°C); (c) modeled geopotential height (m) and temperature (°C) fields for 12Z Dec 09, 2003.

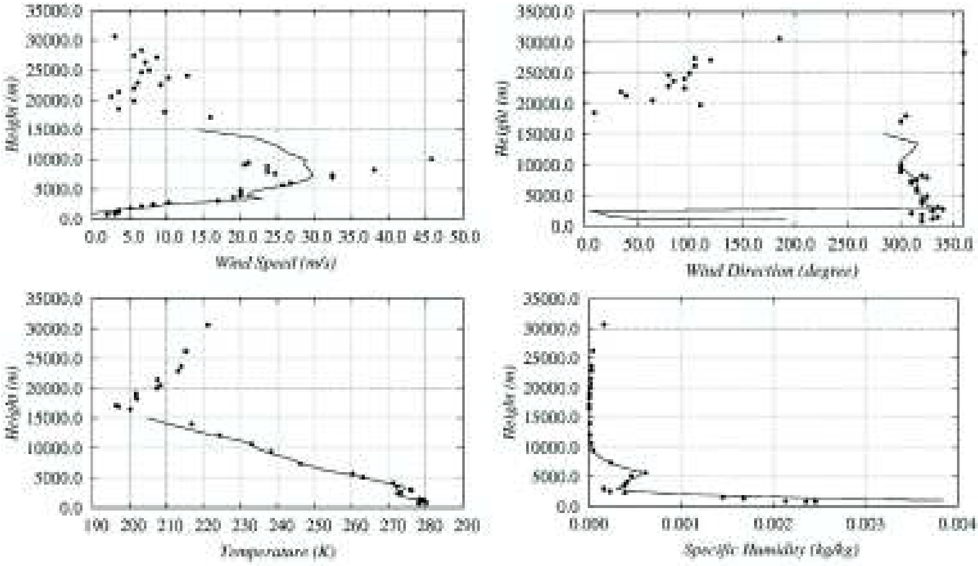

Figure 6. Modeled and observed vertical profiles at Tucson airport (32.12°N, 110.98°W) for 12Z Dec 09, 2003 (dots: observed values; lines: modeled values)

Table 6. Performance statistics of surface winds and temperatures.

	Wind speed (m/s)	Wind direction (degree)	Temperature (K)
Mean observed	5.36	222.29	278.39
Mean modeled	4.9	221.48	278.19
Mean bias	-1.17	-0.80	-0.22
Mean error	1.88	51.50	2.46
Agreement index	0.77	0.75	0.96

several observational points that are likely outliers. Modeled wind directions are similar to the observations. The modeled wind directions below several thousand meters show discrepancies against measurements, largely an artifact of the figure and plot. Wind directions more than 300 degrees are not significantly different from wind directions near tens of degree. Model biases are reasonable.

Performance statistics of modeled surface winds and temperatures. The performance statistics for modeled surface winds and temperatures were calculated using modeled and observed values at 758 sites in the modeling domain. The number of data samples is 27,587 in calculating surface wind statistics.

As listed in Table 6, the mean model biases of wind speed, wind direction, and temperature for Case 1 are -1.17m/s, -0.80 degree, and -0.22K. The agreement indices are 0.77, 0.75, and 0.96, respectively. These numbers indicate that the model performed well in simulating surface winds and temperatures.

Dust patterns

The model dust concentration distribution for 22Z Dec 09, 2003 is given in Figure 7. Compared to satellite observed dust at about the same time as shown in Figure 5a, the dust plume in the western Texas area is reproduced by the model.

PM2.5 and PM10 series. The modeled and observed PM10 and PM2.5 concentration time series during Case 1 at two sites are given in Figure 8. Both modeled PM10 and PM2.5 time series follow the observed trends well. The modeled PM10 and PM2.5 peak hours match the observed peak hours. However, the modeled peak PM10 has quite a large discrepancy against the measured value. It is about one third of the observed peak. The model PM2.5 peak concentration is in better agreement with the measured one.

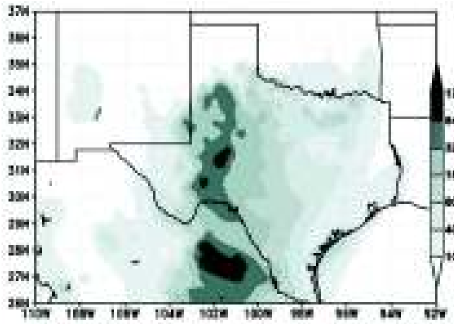

Figure 7. Modeled surface layer dust concentration distribution (μg/m3) for 22Z Dec 09, 2003.

Performance statistics for surface PM2.5. The performance statistics of modeled PM2.5 concentrations at 40 measurement sites (Table 5) are listed in Table 7. The mean bias of the modeled PM2.5 is -2.72. The relative bias to

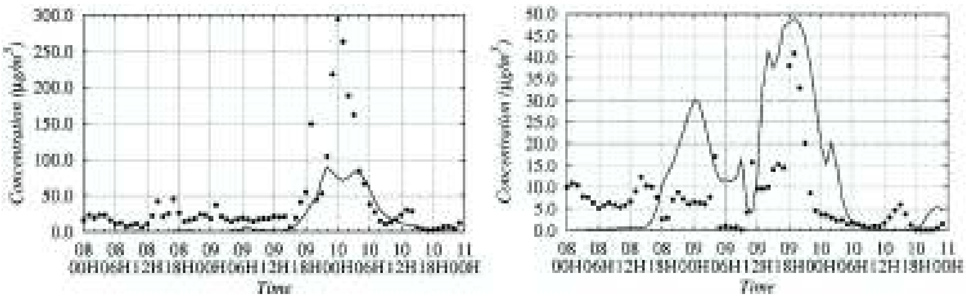

Figure 8. Modeled and observed (a) PM10 concentrations at Lubbock, Texas; (b) PM2.5 concentrations at Calaveras Lake, Texas (dots: observed values; lines: modeled values).

Table 7. Performance statistics for PM2.5.

Mean observed ($\mu g/m^3$)	Mean modeled ($\mu g/m^3$)	Mean bias ($\mu g/m^3$)	Mean error ($\mu g/m^3$)	Agreement index
6.65	3.93	-2.72	7.05	0.43

the observations is about 41%. The agreement index of the model PM2.5 is 0.43.

Case 2

Weather patterns

Figure 9a is the modeled MSL pressure field and precipitation. The modeled high pressure center location is the same as shown in Figure 1b. The precipitation area behind the cold front is also captured by the model. At 500 hPa, the modeled trough of the geopotential height field (Figure 9b) influences New Mexico, Texas and northern Mexico, and matches 500 hPa analysis shown in Figure 9c. The model 500 hPa cold center and thermal trough (Figure 9b) are similar to the analysis in Figure 9d.

Vertical profiles

The modeled wind, temperature and specific humidity vertical profiles at Tucson airport for

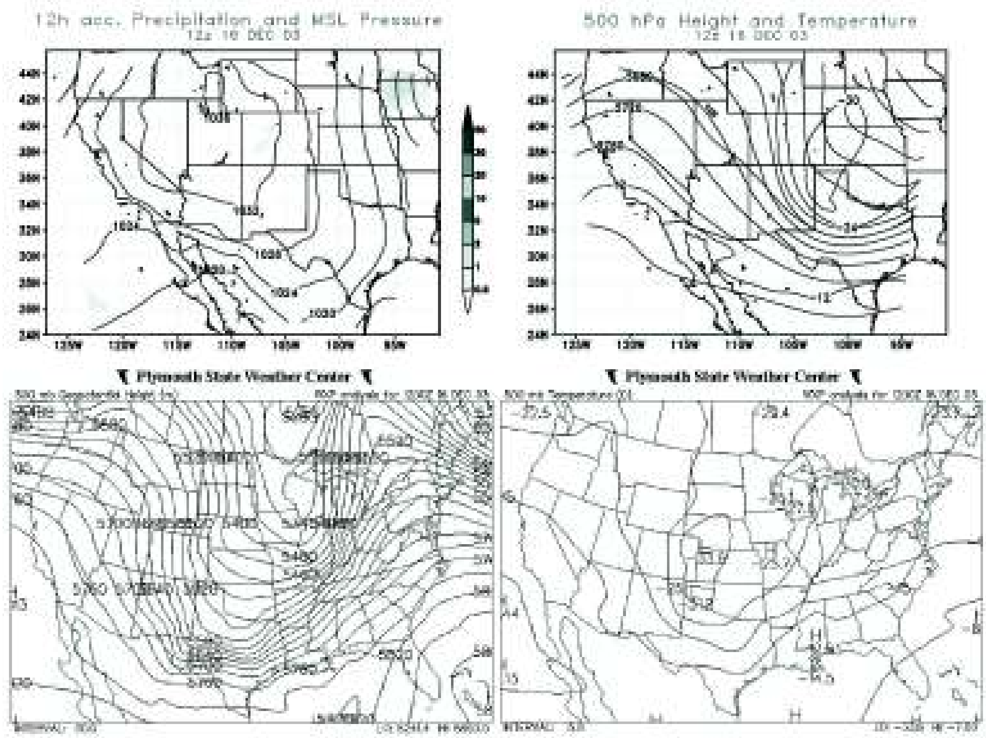

Figure 9.(a) Modeled mean surface pressure (hPa) and precipitation (mm); (b) modeled 500 hPa geopotential height (m) and temperature (°C); (c) 500 hPa geopotential height (m) analysis; (d) 500 hPa temperature analysis (°C).

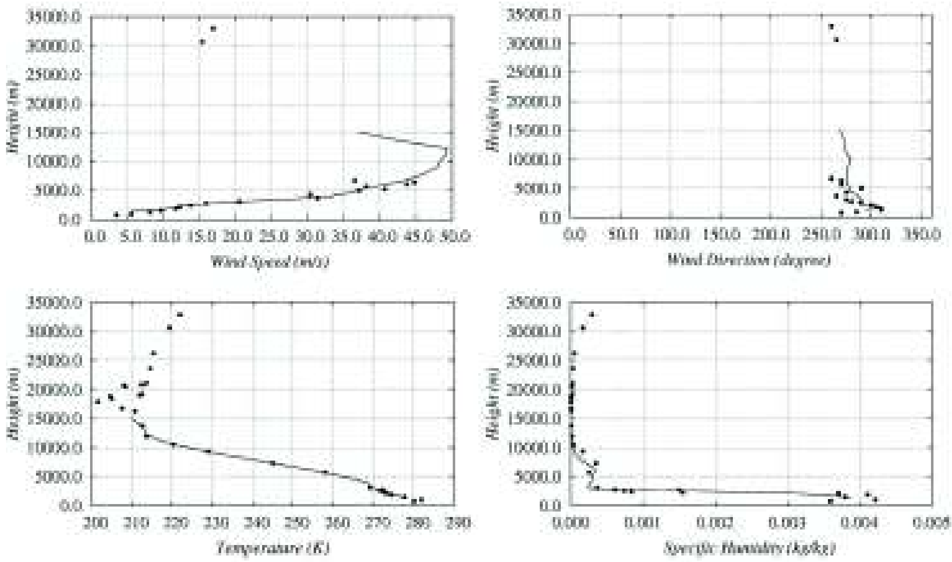

Figure 10. Modeled and observed vertical profiles at Tucson (32.12ºN, 110.93ºW) for 12Z December 15 (dots represent observed values and lines represent modeled values).

12Z Dec 15, 2003 are compared with the observed profiles in Figure 10. Both modeled wind speeds and directions agree with the observations. The modeled temperature and specific humidity also match with the measured values.

Performance statistics (Table 8) are calculated with modeled and observed surface wind and temperature at the same measurement sites as for Case 1. The mean biases of model wind speed, wind direction, and temperature are -1.16 m/s, -1.02 degree, and 0.72 K. The agreement indices are good, especially that of the modeled surface temperature.

Dust patterns

The modeled dust concentration distribution for 20Z Dec 15, 2003 (Figure 11) is comparable to the dust observed by the satellite.

PM10 and PM2.5 time series. The time series of modeled PM10 and PM2.5 concentrations at Cameron and Odessa, Texas follow the observed trend (Figure 12). The modeled time series reproduced dust peaks for both PM10 and PM2.5 concentrations during Case 2. The modeled PM10 peak hours occurred several hours later that the observed peak. The PM2.5 peak hours are in agreement with the

Table 8. Performance statistics of modeled surface wind and temperature.

	Wind speed (m/s)	Wind direction (degree)	Temperature (K)
Mean observed	5.53	231.40	276.74
Mean modeled	4.37	230.38	277.48
Mean bias	-1.16	-1.02	0.72
Mean error	2.03	47.85	2.67
Agreement index (dimensionless)	0.75	0.76	0.95

measurements. Peak PM10 and PM2.5 concentrations are close to the observed values.

Performance statistics of modeled surface PM2.5 concentrations. The statistics listed in Table 9 show that the agreement index of the modeled PM2.5 for Case 2 is better than that of Case 1. The agreement index increases to 0.57 from 0.43. The mean bias is -3.97 μg/m³, which is about 45% of the mean observed values.

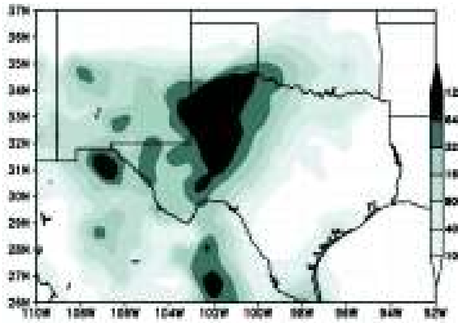

Figure 11. Surface model dust concentrations (μg/m³) for 20Z Dec 15, 2003.

CONTRIBUTIONS OF MEXICO DUST SOURCES

Changes of modeled dust concentrations were calculated from all source model results to no-Mexico source model results. Differences and changes of episode-average concentrations, domain-average concentrations and PM2.5 concentrations at 40 measurement sites (Table 5) before and after Mexican sources were excluded in the model domain show the contributions of Mexican dust sources to the dust pollution during these two dust storm events.

Case 1

Episode-average concentrations in the dust storm area: The episode-average modeled dust concentrations in the dust storm area were calculated with all source model results and with no-Mexico sources model results, respectively. DREAM outputs dust concentrations of four dust categories every hour. In the following context, total dust includes all four dust categories. PM10 and PM2.5 include only particles with diameters less than 10 μm and 2.5 μm. In the episode-average concentration calculation, the sum of the concentrations of all vertical layers in each grid cell in the area was calculated first. Then the averages of these concentrations using hourly model outputs from 00Z Dec 08 to 23Z Dec 10, 2003 were calculated. The episode-average concentrations for Case 2 were computed in the same manner.

Episode-average dust concentrations are significantly different for all source model results and no-mx (no-Mexico) source results. The maximum total dust in this domain dropped from 2171.71μg/m³ to 1202.28μg/m³

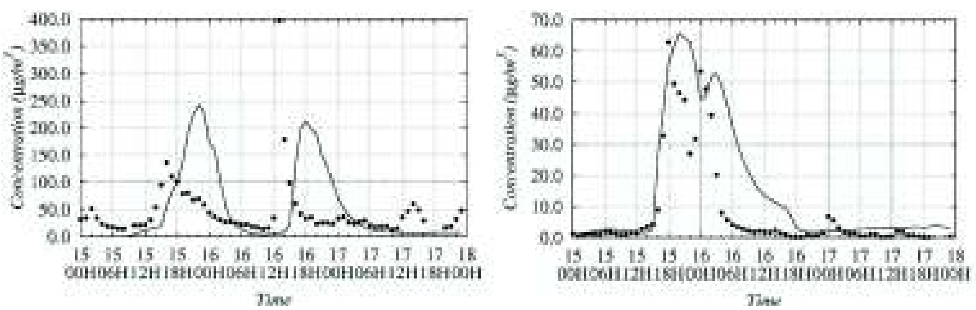

Figure 12. Modeled and observed (a) PM10 concentrations at Cameron site, Texas (25.89ºN, 97.49ºW) and (b) PM2.5 concentrations at Odessa 1014.

Table 9. Performance statistics of modeled surface PM2.5 concentrations.

Mean observed ($\mu g/m^3$)	Mean modeled ($\mu g/m^3$)	Mean bias ($\mu g/m^3$)	Mean error ($\mu g/m^3$)	Agreement index
8.66	4.70	-3.97	8.13	0.57

from all source model results to no-mx results. The maximum PM10 and PM2.5 changed from 813.57μg/m³ and 227.98μg/m³m, to 400.49μg/m³ and 110.46μg/m³. The mean changes of total dust, PM10 and PM2.5 were 135.65μg/m³, 57.81μg/m³ and 16.51μg/m³. The relative concentration changes of total dust, PM10, and PM2.5 range from 100% to 0%, with mean relative concentration changes in the domain as 42.04%, 41.97% and 41.85%.

Domain-average concentrations in the dust storm area: Similar to episode-average concentrations, the modeled concentrations of all vertical layers in each grid cell in the area were added together first. Then the averages of these concentrations in all cells of this domain were computed for every hour from 00Z Dec 08 to 23Z Dec 10, 2003.

The maximum and minimum domain-average total dust concentration differences due to excluding Mexican sources ranged between 438.00μg/m³ and 0.005μg/m³. The maximum and minimum PM10 and PM2.5 differences were 161.00μg/m³ and 0.002μg/m³, 44.7μg/m³ and 0.001μg/m³. The mean difference of total dust, PM10 and PM2.5 were 138μg/m³, 58.6μg/m³, and 16.8μg/m³. The average relative changes for total dust, PM10 and PM2.5 were 42.8%, 43.2% and 43.2%.

PM2.5 at 40 sites: The PM2.5 concentration changed it's range from 0 to near 45μg/m³. The percentage change could exceed 90%. This means that at some sites in New Mexico and Texas, most of the PM2.5 concentrations arrive from sources in northern Mexico.

Case 2

Episode-average concentrations in the dust storm area. As in Case1, spatial patterns of dust concentration changed when desert dust sources in northern Mexico were excluded in the model. The values of the concentrations also changed considerably. The maximum and mean concentrations of total dust changed from 1320.71μg/m³ and 260.77μg/m³, to 1318.71μg/m³ and 173.48μg/m³. The maximum and mean PM10 concentrations changed from 360.98μg/m³ and 106.68μg/m³ to 360.03μg/m³ and 67.32μg/m³. The maximum and mean concentrations of PM2.5 changed from 98.28μg/m³ and 30.58μg/m³, to 97.99μg/m³ and 19.12μg/m³. The mean relative change of total dust, PM10, and PM2.5 concentrations were 34.51%, 33.70% and 33.57%.

Different than Case 1, the maximum concentrations of total dust, PM10 and PM2.5 changed very little. This demonstrates that the sources inside the U.S. contributed most to the peak concentrations in the domain. However, Mexican sources still contributed to nearly 33% of overall concentrations in the domain.

The domain-average dust concentrations during Case 2 had but one peak, while those of Case 1 had two peaks. The maximum and minimum changes in total dust concentration due to excluding Mexican sources were 360μg/m³ and 16.3μg/m³, with an average change of 87.8μg/m³. Maximum and minimum PM10 and PM2.5 concentration changes were 136μg/m³ and 38.4μg/m³, and 11.6μg/m³ and 3.7μg/m³. The average PM10 and PM2.5 concentration changes were 39.6μg/m³ and 11.5μg/m³. The average relative changes for total dust, PM10 and PM2.5 were 42%, 43%, and 43.3%.

PM2.5 at 40 sites: The PM2.5 concentrations at 40 sites show a slightly bigger change from all dust source model results to no-mx source model results. The PM2.5 changes range from 0 to about 60μg/m³. The relative changes could exceed 90%.

CONCLUSIONS

In the arid and semi-arid U.S. Southwest, wind blown dust is an important part of airborne particle pollution. In this work, DREAM model results were used to study the contributions from wind blown dust sources in northern Mexico to the dust pollution in this region.

The modeled meteorological variables, weather fields, dust concentration distributions, and PM10 and PM2.5 concentrations of DREAM runs using all dust sources were verified against observational data. The evaluation showed that the modeled meteorological fields and PM concentrations were reasonably good.

The changes and differences of modeled dust concentrations between model results with all dust sources and model results excluding Mexico dust sources were calculated. The differences of episode-average dust (including dust with particles of all sizes, PM10 and PM2.5) concentrations in the dust storm area, the domain-average dust concentrations in the same area, and PM2.5 concentrations at 40 monitoring sites in New Mexico and Texas, showed that sources in Mexico contribute substantially to airborne dust pollution.

According to changes in episode-average concentrations during Case 1, excluding sources in Mexico halved maximum total dust, PM10 and PM2.5 concentrations. Because maximum concentrations are critical in determining a pollution episode, sources in Mexico played major roles in Case 1, where the mean contribution of Mexican sources to airborne dust concentrations was about 42%. During Case 2, maximum episode-average dust concentrations changed very little when Mexican sources were excluded; the mean relative contribution from Mexican sources was about 34%. The mean relative difference that Mexican sources made to domain-average dust concentrations was approximately 43%, about the same for both cases.

The modeled PM2.5 concentrations at the monitoring sites in New Mexico and Texas ranged from 0 to near 60 μg/m³ when changing from all source model results to no-mx source results. At some sites in New Mexico and Texas, most of the PM2.5 concentrations were contributed from dust sources inside Mexico.

The above results show that airborne dust pollution in the U.S. Southwest and surrounding area is linked closely to dust sources in the two countries. Working on ecosystem protection and management inside the U.S. without considering contributions from Mexico is insufficient to control pollution in the Southwest. People in both countries need to coordinate their efforts in order to control air pollution in this region.

ACKNOWLEDGMENTS

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OPEN SPACE PROTECTION AS A MEANS OF URBAN CONTAINMENT: A CASE STUDY FROM COLORADO

David Pesnichak

> *In America, with its superabundance of cheap land, simple property laws, social mobility, mania for profit, zest for practical invention, and Bible-drunk sense of history, the yearning to escape industrialism expressed itself as a renewed search for Eden. America reinvented that paradise, described so briefly and vaguely in the book of Genesis, called it Suburbia, and put it up for sale.*
>
> — Kunstler 1993, *The Geography of Nowhere*

Most of the southwestern United States is grappling with the lure of grand prosperity while dreaming of a simpler, smaller past. Cheap land and a strong regional tradition emphasizing property rights over government regulation has directed much of the growth outward, creating sprawling cities and far-flung suburban communities that threaten to undermine the long-term viability of the cities themselves (Cooper 1997). In order to shed some light on this issue, I investigated how urban containment policies that utilize the protection of open space have affected three cities in Colorado and analyzed how such programs have helped these communities factor in the vision of keeping open space an important part of their growth. More specifically, I took the lessons learned from Fruita, Durango and Boulder, and compared those lessons with the historic and present situation in Montrose in order to examine whether an urban containment program that incorporates open space protection could help other western communities in maintaining growth with significant open space.

As is evidenced by the ever-escalating costs of basic goods and fossil fuels, it has become painfully obvious that all cities are members of the ever-growing global economy: an economy which is now so large that society can no longer safely pretend it operates within a limitless ecosystem. Developing an economy that can be sustained within the finite biosphere now requires new ways of thinking (Daly 2005). There are a myriad of bygone cities from South America, Europe, Africa and Asia, as well as North America (such as the Anasazi who once inhabited much of what is now southwestern U.S.), that are now ruins because their population outgrew their available resources. It leads one to wonder whether they were not able to change their thinking with the times, were not paying attention, or that changes just came on them too quickly. In this modern era, both water and oil are without doubt the most finite and important resources to the survival of a city infected with urban sprawl in the West.

According to Kunstler (2001), cities are at the mercy of events halfway around the world. If the international oil markets suffer even moderate disruptions in the years ahead, much of the U.S. will find itself in deep trouble. Hosansky (1999) reports that more than 80 percent of trips in this country are made in private vehicles and traffic tie-ups cost motorists at least $74 billion every year in wasted time and fuel. Montrose is no exception; according to the 2000 U.S. Census over 87 percent of work commutes within the City of Montrose were made in private vehicles and the median commute time was among the highest in the study group (Figure 1). Available clean water is becoming more problematic every year, with periodic droughts happening regularly in the West (Brown 2006).

In addition to being intrinsically tied to the politically and geologically sensitive energy source of oil and putting more pressure on depleted water sources, sprawl also eats up valuable open space, worsens air and water pollution and destroys Americans' sense of community. Yet, developers and land-rights advocates call growth management policies intrusive social engineering and say sprawl is unstoppable — a sign of American prosperity and an efficient market responding to the growing demand for a piece of the American dream (Cooper 2004).

There is a constant struggle between private property rights and what is perceived as the overall public good. Planners are caught in a vise between the knowledge that growth must occur somewhere and the reality that adding more people doesn't necessarily make better places (Williamson 2004). Creating better places however, is what planning is all about. According to Kunstler (1993) the future will require us to build better places or the future will belong to other people in other societies. The economic status quo cannot be maintained long into the future. If radical changes are not made, we face loss of well-being and possible ecological catastrophe. The main idea behind sustainability is to shift the path of progress from growth, which is not sustainable, toward development, which presumably is (Daly 2005). Duane, Plater-Zyberk and Speck (2000) offer that the problem with suburbia is that, in spite of all its regulatory controls, it is not functional: it simply does not efficiently serve society or preserve the environment.

Cooper (1997) emphasizes that despite a hands-off approach from the federal government, state and local governments are acting on their own to conserve green space with smart growth initiatives to limit new development, and citizen-run, non-profit land trusts are sprouting up all over the country to buy up open land. Although such enthusiasm exists for defining communities and preserving open space in Colorado, without regional or statewide planning efforts, we now have situations like Boulder where, according to Eric Bergman of the Colorado Office of Smart Growth, sprawl just leapfrogged outside Boulder. So you now have a pocket of smart growth with the sprawl all around it. Despite the argument that such urban sprawl is an efficient market responding to the growing demand for a piece of the American dream, Boulder arguably remains one of the most attractive places to live in the U.S. precisely due to the easily accessible protected open

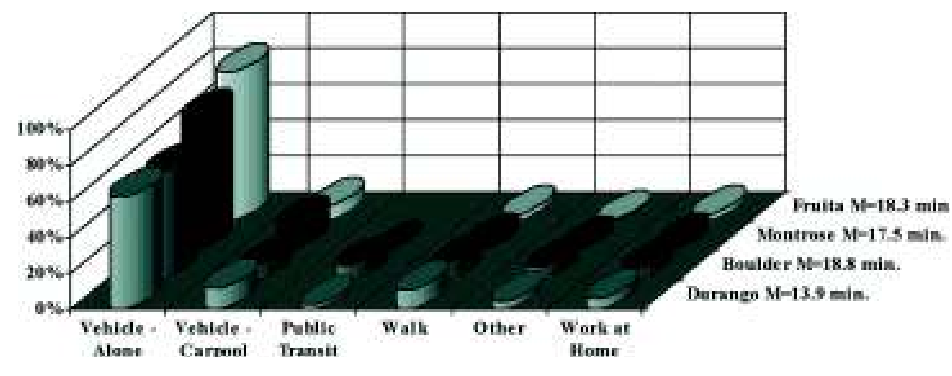

Figure 1. The commuting habits of the residents of the cities in the study as collected by the 2000 U.S. Census.

space harmoniously coexisting with a stimulating urban center—and this pattern was not a free market creation, but the result of smart growth policies.

In the midst of all the new development occurring in Colorado it seems the staunchest land rights advocates are those who stand to profit the greatest from urban sprawl. According to Environment Colorado, an advocacy group out of Denver, 10 acres of valuable open space and agricultural land are being developed every hour. Most Coloradans continue to support proposals to curb development, but big developers and the Colorado Association of Home Builders are pushing to further reduce the ability of local governments to enact enforceable growth plans (Environment Colorado, 2005). In addition, there are huge dollars at stake with urban containment and open space issues, and the interests that are against or contrary to this kind of plan and idea are those who are making big bucks out of development. In the meantime however, a significant portion of the Montrose and Colorado communities are able to see a larger picture (Ron Stewart, August 2005, pers. comm.).

In a 2004 City of Montrose Household Survey, two of the three top problems perceived to be facing the Montrose community were traffic congestion and too much growth (Moorman, 2004). In addition, in a 2005 Montrose Parks and Recreational Needs Assessment, two of the five highest unmet needs and highest importance issues to the residents of Montrose were a lack of Natural Areas/Wildlife Habitats and Greenway Areas along the Uncompahgre River (Leisure Vision 2005). According to Graham Billingsley, it is imperative to ask: What have we got? What do we want to keep? And what do we need to bring in that we are missing? In the results of the 2004 Household Survey and the 2005 Parks and Recreation Needs Assessment, these answers have been clarified: less traffic, slower growth, unimproved open spaces, wildlife habitat, and greenway areas along the Uncompahgre River. And according to Mayor Erica Lewis-Kennedy, we have to keep the open spaces around Montrose. If we are going to maintain our quality of life, we have to have open space or it will just be another Anywhere USA (July 2005, pers. comm.).

The necessity for more open space and decreased sprawl goes even further than social viability, livability and constituent desires. According to the Transit Cooperative Research Program (TCRP) Report 74, sponsored by the Federal Transit Administration, by developing with growth-control measures in place versus traditional or uncontrolled growth, the residents of the U.S. could save $12.6 billion in infrastructure costs and 155 million gallons of water and sewer demand per day between 2000 and 2025. In addition, in the same period, the U.S. could save 188,300 roadway lane miles and another $110 billion in road construction costs by using growth control measures (Burchell et al. 2002). A study conducted by the University of Colorado determined that future sprawling development in Delta, Mesa, Montrose, and Ouray Counties would cost taxpayers and local governments $80 million more than smart growth between 2000 and 2025. It is inevitable that the costs of building and servicing infrastructure for new sprawling development is ultimately subsidized by the whole community (Coyne 2003). Sprawled residential growth does not do a city any good because in the long run it costs more than it generates. In a Cost of Community Services Study (COCS) conducted by the American Farmland Trust, residential development costs were found to be a dollar fifteen cents for every dollar raised in taxes whereas working and open space land costs an average of only thirty-six cents per dollar raised.

In addition, the Governor’s Commission on Saving Open Spaces, Farms & Ranches has reinforced these findings. Coloradoans place tremendous value on their open spaces, farms and ranches because open space is essential to the state’s quality of life. It is, in fact, one of the principal reasons many Coloradoans decide to make this their home (Harris et al. 2000). However, Colorado can also be a difficult place when citizens can’t reach agreement on whether or how they want to manage growth and/or protect open space. This leads to the phenomenon of having places like Boulder, with incredibly strict control, surrounded by areas that are not doing much at all (Cooper 1997).

With the complex and decentralized system of open space protections and growth management regimes throughout the U.S. and Colorado, it is difficult to assess the cumulative effectiveness of the various programs. However, there has been a strong surge of interest in open space programs in the last few years, especially in rapidly urbanizing areas. Unfortunately our understanding of the impact of open space protection programs on metropolitan growth is sketchy at best. It is clear that open space acquisition programs clearly affect metropolitan growth patterns, but the form it takes is different in every metro area (Hollis and Fulton 2002).

The solutions may be complex, and not supported by everyone, but as urban sprawl and what Kunstler calls the 'geography of nowhere' is unmistakably taking hold within the city of Montrose and even in the surrounding countryside outside the city limits, Montrose is struggling to define itself as an environmentally and economically attractive place to live, work and play. The sense that the task before the Montrose community is too large and insurmountable is overshadowed by the responsibility of elected officials to bring the community vision of smart growth and protected open spaces into reality.

METHODS

Interview List

This study was based on literature review and extensive interviews with local planners and politicians in Boulder and Boulder County; Fruita and Mesa County; Durango, Montrose, and Montrose County. The individuals and the date of their interview were:

- Steve Aquafresca, Mesa County Land Trust; July 22, 2005;
- Allan Belt, Montrose County Commissioner; August 8, 2005;
- Eric Bergman, Colorado Dept. of Local Affairs, Office of Smart Growth; August 4, 2005;
- Graham Billingsley, Director of Boulder County Planning Dept.; August 5, 2005;
- Bennett Boeschenstein, City of Fruita Community Development Director; July 22, 2005;
- Virginia Castro, Durango City Councilor; June 15, 2005;
- Dennis Erickson, City of Montrose Parks Planner & President of Montrose Chamber of Commerce; July 28, 2005;
- Erica Lewis-Kennedy, Mayor, City of Montrose; July 26, 2005;
- Renee Parsons, Durango City Councilor; June 15, 2005;
- John Schneiger, Former Montrose City Manager; July 26, 2005;
- Randy See, Community Organizer, Western Colorado Congress; July 25, 2005; and
- Ron Stewart, Director of Boulder County Open Space; August 5, 2005.

Definitions

Open Space

This project utilized the definition of open space described by Hollis and Fulton (2002): land that is not devoted to urban development, especially if that land is located in a metropolitan region. The actual uses of lands that are set aside for open space are quite varied. Using this definition, open space is any land that is not already devoted to development through subdivision, covenants, speculation or intent. Examples of such open spaces are agricultural lands, ranch lands, recreation areas, national forests, protected river ways, parks and protected wetlands.

Urban Containment

This project utilized the definition of urban containment presented by Fulton, Martin and

Pendall (2002): a set of land-use regulations that prohibit urban development outside a certain boundary. This paper looks at the various options and proven methods of urban containment that simultaneously incorporate "push" and "pull" factors. According to Dawkins and Nelson (2004): urban containment has two fundamental purposes: (1) to promote compact and contiguous development patterns that can be efficiently served by public services; and (2) to preserve open space, agricultural land, and environmentally sensitive areas that are not currently suitable for urban development. They recommended that urban containment programs be based on the following seven objectives. A containment program should:

1) Accommodate long-range urban population growth requirements consistent with state and local goals and policies;
2) Fulfill local needs for housing, employment opportunities, and livability;
3) Provide public facilities and services in an orderly and economic manner;
4) Maximize efficiency for land uses in or at the fringe of existing urban areas;
5) Consider all environmental, energy, economic, and social consequences;
6) Preserve farm, forest, and other resource land; and
7) Ensure the compatibility of proposed urban uses with nearby resource activities.

Dawkins and Nelson (2004) demonstrate that urban containment plans can be divided into four basic types that represent a combination of either strong or weak boundaries and either restricted or accommodated development. The four categories are summarized as follows:

1) **Weak-Restrictive.** Cities that utilize this approach have an inward-focused growth management strategy with an unclear ultimate urban form. These growth management plans are composed of weak containment measures, but they adopt restrictive policies toward containing growth. Examples of Weak-Restrictive communities are Aspen, Colorado, and Bloomington, Indiana.
2) **Strong-Restrictive.** Cities that utilize this approach have a self-determined urban form, but no regional strategy. These growth management plans have strong containment but do not place high priority on meeting regional development needs. Examples of Strong-Restrictive communities are Boulder, Colorado, and San Luis Obispo, California.
3) **Weak-Accommodating.** Cities which utilize this approach have limited open space protection, weak planning statutes, and plans that minimize facility costs. These growth management plans employ weak urban containment measures, principally through lax management or rural development within the county or region. These plans do, nonetheless, attempt to accommodate development pressures. Examples of Weak-Accommodating communities are Lincoln, Nebraska, and Cookeville, Tennessee.
4) **Strong-Accommodating.** Cities that utilize this approach have a desire to balance open space with growth pressures and to shape metropolitan urban form. These growth management plans contain development through spatial growth limits combined with aggressive open space preservation. These plans also meet projected growth needs to accommodate development pressures. Examples of Strong-Accommodating communities are Portland, Oregon, and Tucson, Arizona.

According to Fulton, Martin, and Pendall (2002), every metropolitan area in the U.S. has some form of urban containment. Although Montrose does not explicitly have an official urban containment plan, it does have a loosely coordinated, state-required, 201 Sewer Service

Boundary, large tracts of federally controlled land to its east and west, and a recently re-adopted land use Intergovernmental Agreement (IGA) with Montrose County. As with many land use IGAs, the agreement between the City and County of Montrose provides the city with a first right of refusal for development occurring near the cities boundaries. With these regulations, it could be argued that the City of Montrose falls into the Weak-Accommodating category which is characterized by large-lot land preservation and infrastructure goals, an emphasis on infrastructure and land supply, as well as moderate intergovernmental coordination. Communities that use these plans typically have low per capita income, low population density and are common in states with no local planning mandate.

An Effective Open Space as Urban Containment Program

Unlike Oregon, Washington, Vermont, or Florida, Colorado does not have a statewide land use plan. In the absence of a Colorado state land use plan to use as a benchmark, I measured an 'effective' open space program as a means of urban containment in relation to the jurisdiction's community vision as stated in their respective comprehensive or master plan. I also focused on the opinions of local officials whom I interviewed to back up my analysis of what makes a successful or unsuccessful program. The determination of an effective program is therefore subjective.

CASE STUDIES

Durango, Colorado

The community vision for Durango is a community living in harmony with its natural environment; where residents and visitors can enjoy a historic small town atmosphere, the Animas River, and easy access to exceptional cultural, educational and wilderness opportunities (Carlisle et al. 1997). Durango is a community that clearly benefits from the federal open lands surrounding the community. According to Virginia Castro, a Durango City Councilor, the aesthetic value and the air quality that the open spaces and the National Forest provide really help maintain a clean environment in the area. Once those things start diminishing, it just follows that the economic viability of the city goes with it. Renee Parsons, Durango City Councilor, agrees that the open spaces surrounding the community are very attractive and economically very good for the city. However, according to a May 19, 2005 debate captured in the Durango Telegraph, Parsons explains that Durango is facing a threat to its quality of life that will forever alter the landscape, the lifestyle and the community. While growth has brought certain benefits, the community is at a critical juncture (Wells 2005). According to Greg Hoch, Planning and Community Development Director for the City of Durango, "There are old-timers vs. newcomers, settled newcomers vs. new newcomers, and the inherent contradictions of keeping houses affordable, keeping regulations from becoming onerous and maintaining some sense of the community as it exists. But one of the underlying forces is city vs. county, or arguably, the attractive sprawl of low-density rural subdivisions vs. higher-density new urban development. As more people move in, and cities run out of room, the practice of allowing outlying areas to fill with rural-style, low-density subdivisions is becoming a flashpoint. (Hoch, 2004).

The city of Durango, which has experienced economic boom and bust periods over the past 55 years, was first incorporated in 1881. Since 1950, the city's greatest period of population expansion was from 1950 to 1960, when the population grew by 29 percent in ten years (Figure 2). Durango has seen only one ten year period since 1950 where the population actually declined, between 1960 and 1970. By the year 2000, the U.S. Census indicates that Durango had a total population of 13,922, a land area of 6.8 square miles and a population density of 2047 people per square mile. By 2003, the Colorado Department of Local Affairs (DOLA) estimates that Durango had a population of 15,324 with an annual growth rate of less than one percent between 2002 and

2003. Over the years Durango, like most Colorado towns, has experienced a fairly sporadic but generally increasing population. But, in the last couple years this population increase appears to have been slowing on a percentage basis which has been accompanied by a declining school enrollment.

According to the Colorado Preliminary Forecasts issued by DOLA in November 2004, "the growing number of tourist dollars as the baby-boomers reach middle-age, the desire of many small businesses to move to smaller areas, and the overall number of retirees, are expected to continue or increase" (DeGroen and Westkott 2004). In addition, Durango has seen a tremendous influx of people who want to recreate and have the lifestyle of spending as much time outdoors as they want. A lot of people are moving to Durango who have made a lot of money someplace else and are able to retire here. A lot of people are moving here who have sold homes somewhere else and can afford to pay more here. And so we have seen a tremendous increase in property values over the last few years.

The attraction of the surrounding open space on the local economy is having effects beyond that of inflated real estate prices and an increasing population, however. The new population has meant a declining primary and secondary student enrollment population as a result of these demographic shifts. The district had 107 fewer students in 2004 than it had in 2002, and it expected another dip in the 2005 school year. Enrollment in the district was hurt by high housing prices that made it difficult for families with children to afford living in Durango (Slothower 2005). In effect, land prices in the surrounding areas as well as the city center have increased tremendously due to development pressures brought on by new residents looking to have a front row seat to the open spaces surrounding Durango.

As residents search for housing they can afford, sprawling development is encouraged and decreased affordability has resulted in an increase in residents renting and a decline in home ownership. In 2000, 52% of the popula-

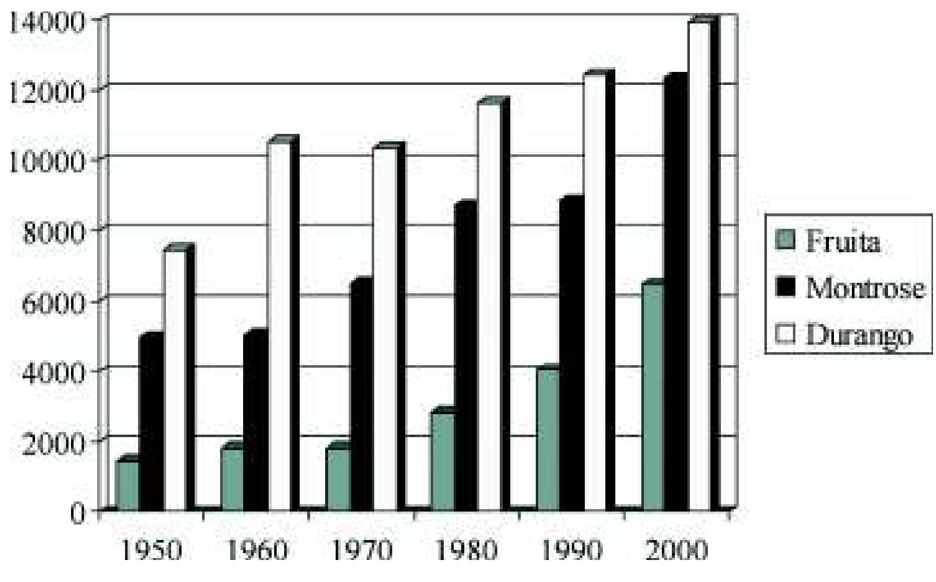

Figure 2. Population from 1950 to 2000 U.S. Census for Durango, Fruita, and Montrose, Colorado.

tion of Durango lived in a home that they owned, while 48% rented. And although housing prices in Durango are still lower then that of Boulder, the ratio of homeowners to renters are roughly 50/50 in both cities. Meanwhile, home ownership in Fruita and Montrose where housing is less expensive, are significantly higher (U.S. Census 2000). In reality, the decline in home ownership and declining school enrollment reflects a relocation of family units from the city of Durango to nearby cities and outlying sprawl where housing is more affordable. In November 2003, the median price of homes for sale in Bayfield, twenty-five miles east of Durango, was $207,000. Durango's median price was $410,000 (Hoch 2004).

Because Durango is surrounded by Bureau of Land Management (BLM), U.S. Forest Service and tribal land it is limited in its available annexable land. These abutting public lands are not only containing urban sprawl from moving out in every direction from the city center, they also force development to focus on the highway corridors and mix-matching affordable housing and very high-end residential development. In addition, as land prices increase from the heightened wealth accumulating in the City of Durango, pasture land, agriculture, and previously inexpensive home sites are being converted to high end residential subdivisions which are moving outward from the city center.

As these economic pressures combined with local land use regulations that restrict density in the inner city core are encouraging ever expanding sprawl, citizens are beginning to want growth controls. A responsible growth initiative just barely failed in 2004. The city is now built out so what they are looking at for the future is core infill (Parsons). Even though the Responsible Growth Initiative narrowly lost that would have required voter approval for new annexations to the city, an open space acquisition sales tax was passed and a proposed City / County Land Use Intergovernmental Agreement was started. The question now is how Durango will ultimately manage, and potentially contain, its outward growth in the future. It is predictable that such policy developments will lead the community toward its stated vision of a community living in harmony with its natural environment; where residents and visitors can enjoy a historic small town atmosphere, the Animas River, and easy access to exceptional cultural, educational and wilderness opportunities.

According to the Dawkins and Nelson Planning Advisory Service (PAS) report, Durango primarily fits into a category not previously mentioned and not analyzed as apart of their PAS report. Durango mainly fits into the category of 'Natural Containment', which limits cities like Honolulu, Hawaii, and Juneau, Alaska, as it is surrounded by state, federal and tribal lands. Even though Durango is limited by these physical land use constraints, growth pressures are coming to a head, and new development is starting to move out along the highway corridors and may actually create satellite communities (such as Grand View) if some other form of growth control is not instituted.

Fruita, Colorado

The community vision for Fruita is to preserve the rural, small town atmosphere of the Fruita Community, while providing quality community services for a growing population and striving for economic development and prosperity (City of Fruita 2000). Fruita is historically an agricultural community. Incorporated in 1894, Fruita was a town with hundreds of acres of apple orchards that actually won prizes for the fine quality of the apples that had grown there (Boeschenstein). Apple orchards were not destined to stay long term in Fruita, however. In the 1920s, according to Boeschenstein, Community Development Director for the City of Fruita, the Coddling moth wiped out the orchards. Today the agriculture that surrounds the town is primarily row crops and livestock and although agriculture is still big in Fruita, its population has grown significantly since the time when apple orchards ruled the local economy.

Like all the cities in this study, Fruita has gone through significant boom and bust cycles.

The town had a downturn in population between 1960 and 1970, but that is the only decade since 1950 in which Fruita has lost population (Figure 2). Between 1990 and 2000, the city saw the greatest increase in population, going from 4,045 to 6,478, almost a 38 percent increase. Among the cities included in this study, Fruita had the highest rate of population increase between 1950 and 2003 at 528%. Further, since 2000, Fruita has seen the strongest population increase of the cities in this study, growing at a rate of about six percent between 2002 and 2003. The cause of this increase is primarily its location: it sits next to the largest city on the Western Slope, Grand Junction, and is in the Interstate 70 corridor. In the mid-90s Grand Junction began an aggressive expansion push, threatening to turn Fruita into a bedroom community. The town suddenly found itself in the middle of an annexation war (Jenkins 2001).

According to Boeschenstein, “we had two choices, we could look like Orange County California with wall-to-wall subdivisions from the Book Cliffs to the Monument, or we could look like some other examples, which I really know upsets people, but Boulder is surrounded by open space … it did not sprawl and is one of the most attractive communities in the U.S.. It has some great corporate headquarters, it has some very high paying jobs, a strong intellectual base, it also is a caring community and they actually do have affordable housing. That would be another model.”

At roughly 8,000 people in 2003, Fruita is certainly at a different point in history than Boulder, which has a population of just fewer than 100,000 people. In light of this growth, public concern led to two years of meetings between the cities of Fruita and Grand Junction and a decision in 1996 to maintain an open-space buffer between them. Grand Junction and Fruita agreed that they would not annex and they would not extend sewer lines to properties in the buffer so that urbanization would be slowed in that strip (Jenkins 2001). The Town of Fruita then went a step further and in 2002 adopted a Community Plan that included a chapter on the Transfer of Development Rights. It took about three years of public meetings, futures workshops, and community surveys to sort out how much the citizens wanted the community to grow, how big they wanted the community to be, and what values were most important over the next 20 years. The idea was that it is important to preserve and protect open land and farm land around Fruita, including land that is adjacent to the Colorado National Monument, BLM lands, and the Colorado Canyon National Conservation Area (Boeschenstein).

What the Town of Fruita adopted is explained in the Fruita / Mesa County Transfer of Development Rights Users Manual. According to the manual, the purpose of the program is to encourage the retention of agricultural lands in Mesa County and to protect open lands between Fruita and Grand Junction (Fruita/Mesa County 2003). In addition, the manual explains that beyond a public policy foundation, the establishment of a Transfer of Development Rights / Credits (TDR/C) Program requires three fundamental components: (1) an intergovernmental agreement between Fruita and Mesa County providing a framework for coordinating the program; (2) updates to the City of Fruita Land Use Code and the Mesa County Development Code regulating the program’s implementation; and (3) a manual outlining the details on how to use the program (Fruita/Mesa County 2003).

The city and county government’s role in a TDR program is to set rules. The rules basically consist of two major components: a sending area and a receiving area. The program works on a free-market principle where it is simply necessary for the local governments to legally establish the market within the land use regulations. Once the program is established within the necessary codes and IGAs, a landowner in the Sending Area may voluntarily sell the development rights or credits to a landowner of a receiving site, at a market value established by the landowner and the buyer (Fruita/Mesa County 2003). What is bought and sold are development rights only, which means that the seller still owns their land and can keep doing what has historically been done on their property. However, like the sale of water rights, that land now has limited structural development potential. The purchaser of those rights can then place more units per acre on a development property in the designated receiving area.

The optimism that Boeschenstein has about this program is well founded as TDR programs have been used successfully by many jurisdictions throughout the country for many years (Cooper 1997). What makes Fruita unique is that it is not a particularly wealthy community yet it is still able to see the benefits in conserving open space as well as valuable farm and ranch land next to the city limits. "People here wanted the small town and they wanted the open space around them," Boeschenstein said. "It is hard, especially here on the Western Slope, because people want to do whatever they want with their land and do not think it should be regulated by government. But then again, the TDR and the conservation easement is not a government program, the government just has to enable it and if it happens it happens, if it doesn't it doesn't, but at least you are enabling it to happen. It is a big carrot incentive."

To this end, Fruita has been able to work with their neighboring jurisdictions to help achieve the vision for their community, with the impetus coming from the residents. Although the lack of precise control in a TDR program may scare many in government and planning offices, it places the fate of the city into residents' hands instead of elected officials and enables the free-market to provide payment to land owners, which is often not budgeted in government financial plans.

According to Dawkins and Nelson (2004), Fruita falls into the Strong-Accommodating category, in which Fruita is looking to balance open space with growth pressures and to shape metropolitan urban form. Based on the benefits that such protected open space will eventually provide Fruita economically and socially, I think it is clear that Fruita is doing what it can to make sure that its community vision is advanced while maintaining the small town atmosphere. Hence, I believe that Fruita's growth management measures can be considered effective.

Boulder, Colorado

Boulder has a long tradition of community planning. Most of the key policies and plans that have guided the development pattern in the Boulder Valley have not changed since the 1978 Boulder Valley Comprehensive Plan was first adopted, and many of them stem from long-standing community values (City of Boulder 2001). They represent a clear, articulate vision of the development pattern including:

- Respect for the community's unique identity and sense of place;
- Recognition of sustainability as a unifying goal to secure Boulder's future economic, ecological and social health;
- Commitment to open space preservation and the use of open space buffers to define the community;
- Use of urban growth boundaries to maintain a compact city (the boundaries of the service area have remained virtually unchanged since first developed in 1977);
- Growth management to regulate the rate and overall amount of residential development and redevelopment opposed to sprawl;
- Recognition of the importance of a central area (Downtown, University of Colorado, the Boulder Valley Regional Center) as a regional service center of the Boulder Valley; and
- Commitment to a diversity of housing types and price ranges to meet the needs of the Boulder Valley population.

The City of Boulder had a population of about 98,000 people in 2003; it is also the largest city and the city with the most significant population growth since 1950 in this study. Boulder began preserving open space in 1904 in order to protect watershed resources as insurance for a stable water supply, as well as to protect the mountain backdrop for recreational and viewshed purposes. Initially, the purchase of open space and growth controls were not linked. In the 1950s, Boulder's population grew from 25,000 to 37,000, and during the 1960s it grew by a whopping 29,000 to reach 66,000 (Figure 2). Some initial efforts to manage this growth included the Blue Line, a citizen-initiated amendment to Boulder's charter in 1959 that restricted the extension of city water service above an elevation of 1753 m (5,750 ft). What this Blue Line did was preserve the Flat Irons, the magnificent mountain backdrop of Boulder from being developed. In the proceeding years, Boulder extended the Blue Line concept to sewer service.

Another important growth management program began in 1967, when Boulder became the first city in the U.S. to pass a tax dedicated to preserve open space. This open space system forms the outer extent of the Boulder Valley, a joint planning area between the city and county (Pollock 1998). Since the passage of the first open space tax in 1967, the City of Boulder has established a 40,000-acre greenbelt around the city as a defense against sprawling development. Boulder County did not pass an open space tax until 1993. Since that time, Boulder County has purchased 75,000 acres of open space.

Too often we hear that communities cannot afford to 'grow smart' by conserving open space. But accumulating evidence indicates that open space conservation is not an expense but an investment that produces important economic benefits (Rogers 1999). Eric Bergman agrees, "Open space has so many values for a community. It can be a buffer between communities… and help preserve a sense of identity and boundary. Obviously, the viewsheds, habitat, agricultural ranch land and farm land viability and cultural value for a community make sure that it remains viable." In the process of preserving open space for almost forty years now, Boulder has become intimately familiar with the consequences. It makes it a great place to live, people move here because of the culture of the outdoors, and they move here instead of someplace else on the Front Range because of the availability and easy access to recreation (Billingsley).

The open space and urban containment programs in Boulder also come with critics. According to Billingsley, Boulder does not have growth management, Boulder has residential growth management where they have restricted residential growth to one percent a year while allowing commercial growth to occur at 7 percent a year. That is why Boulder has traffic issues. According to Stewart, Boulder has way too much land zoned for commercial and industrial and way too much potential for commercial and job growth in the city when at the same time they do not have much room for population growth. The city may grow by 10, 15, or 20 percent in population but has a potential of expanding 50, 60, or 70 percent in jobs. That equation should have been put in better balance. According to Dawkins and Nelson (2004):

> *It is one thing to limit urban development within boundaries but quite another to absorb the development that would have occurred in its absence. Montgomery County attempts to absorb its projected growth within urban areas contained by growth boundaries, as does metropolitan Portland. In contrast, cities such as Petaluma, California and Boulder, Colorado do not attempt to absorb large shares of the region's projected growth. Because of their sensitivity to meeting regional or sub regional housing needs, it may be no accident that housing prices rose less quickly in Portland and Montgomery County in the 1990s than in Petaluma, Boulder, or the counties of Ventura and Loudoun.*

The use of open space as a means of urban containment in Boulder, as well as a system for controlling the rate of population growth by limiting building permits, and a defined urban growth boundary managed in cooperation with Boulder County, has placed Boulder firmly in Dawkins and Nelson's category of Strong-Restrictive. As a result of these containment policies, housing demand appears to be displaced to Boulder County's other major city, Longmont, and into the rural areas around Longmont. Indeed, from 1988 through 1998, Boulder's share of Boulder County's new housing fell from 29 percent to 8 percent while

Longmont's share rose from 10 percent to 31 percent (Dawkins and Nelson 2004).

The Boulder Valley Comprehensive Plan has been successful in many areas. Its implementation has helped keep the community compact and limit sprawl. It has helped preserve open lands, intensify the core area and preserve important features of the local environment. It has also encouraged the development and use of alternative modes of transportation. Areas where additional efforts are still needed include the availability of affordable housing, the growing imbalance between jobs and housing, and reducing traffic congestion by providing safe and convenient alternatives to single occupant vehicles (City of Boulder 2001). According to Dawkins and Nelson (2004), as of 2000, the ratio of jobs to housing in the Boulder Valley was 92 to 1. To reduce this imbalance, the city adopted an inclusionary housing program in 1999 that requires 20 percent of all new residential development to be affordable to persons of low to moderate incomes. The 2001 comprehensive plan supplements this program with policies designed to promote housing development along transit corridors and within commercial centers. As a result, attaining the vision for Boulder has been mostly a success; however there are certain areas where improvement is needed and appropriate actions have been taken to enact those improvements. Boulder has maintained a central vision of a compact city with a clear identity in the midst of a rural area. The growth management techniques used in Boulder may vary from those used in other cities, and they may be changed from time to time to meet local conditions, but the vision has remained intact (Pollock 1998).

Montrose, Colorado

The community vision of the City of Montrose and its surrounding area of influence is that the citizens wish to achieve a balance between the protection of their natural environment and progressive economic development, maintain a sense of community character and quality of life, conserve their agricultural heritage and recreational resources, and accommodate diverse community needs for increased employment, education and business opportunities (BRW 1998).

The City of Montrose has experienced rapid growth for the past decade. In 2004, the city recorded almost one new single-family home built per day. In addition, Montrose has annexed more than 2,191 acres from 2000 to 2005 to bring the overall size of the city to over 15 square miles, only ten square miles less than Boulder. In addition, the city population grew at a rate of approximately 4% in 2003 and 2004. The Colorado Department of Local Affairs estimates that the city of Montrose had a population of 15,351 in 2004, up from 12,344 in 2000 and 4,964 in 1950. Since 1950 the city has grown in population by almost 310% (Figure 2). If the current rates of growth continue, Montrose will surpass Durango in population within the next few years, but population growth rates change very quickly in Colorado and Montrose is no exception. Unlike Fruita and Durango, Montrose has not had any decades since 1950 where the city has lost population and it has the lowest population density at 1,073 people per square mile. Overall concern for the growth of Montrose has been voiced frequently at public meetings as well as in the local newspaper. In an April 2005 article published in the *Montrose Daily Press*, then Montrose City Councilor Erica Lewis-Kennedy reinforced that one of the biggest issues facing the city is growth (Hildner 2005), and the Montrose community agrees: in a 2004 Household Survey conducted by the city, residents ranked traffic congestion, too much growth, and declining open space within the top five issues facing Montrose today. Meanwhile, the 1998 City of Montrose Comprehensive Plan sets its first goal to help ensure the continuation of Montrose's small town rural character and high quality of life.

Dennis Erickson related to me, "My fear is that the Western Slope is like the Denver metropolitan area and Front Range was 80 years ago — from Grand Junction to Delta to Montrose to Ridgeway is all going to become one metropolitan district." Further, according to Montrose Mayor Erica Lewis-Kennedy, growth is destroying the small town character. You cannot keep the rural nature of the community and have growth at the rates we are having them. Even with these concerns, Erickson explained that the Chamber looks at growth as being positive, because business is growing, and the area is growing and Montrose for so many years was limited with business opportunities.

Montrose is losing its vision for the future by a population temporarily blinded by the edification of monetary gains and a generally un-thoughtful search for the good life. Montrose is in transition, there are important elements of the community who want things to stay wide open, without government intervention, and this has made it difficult for staff and council to get to where other communities are in the state. Montrose has had a tremendous amount of growth and will likely continue to experience growth. It is important to have a good comprehensive plan and update that plan on a regular basis. Billingsley feels that simply having a decent comprehensive plan is not enough. One of the failings of a lot of communities that do a good comprehensive plan is that they do not really make people understand what is necessary to make it work. As long as it is a visionary document that does not have any teeth behind it, then everybody is supportive of it. So you really have to get those discussions going that say "if you really mean this, then these are the consequences of what you are saying." Montrose is leaning more toward the good visionary comprehensive plan without any teeth that everybody supports, but does not lead to any meaningful change.

In addition to having a good strong comprehensive plan that has teeth and which the community supports, if Montrose is going to be able to maintain its rural, small town character, it is imperative that there is agreement with the county. In late July 2005, the city and county of Montrose finally reaffirmed their commitment to a land use Intergovernmental Agreement (IGA). The IGA has several different roles, two important ones are that it sets the urban interface boundary and it allows the city to have first right of refusal to development that is happening inside this urban interface boundary.

The cost savings to pre-determining where growth will occur and attempting to define an infrastructure development plan is essential to providing the community with a reasonable level of service well into the future. "In the long-term, planning pays for itself. The problem is that most people do not really look that far into the future; they are kind of reactive. We represent all the taxpayers and as a result we have to look at what the future costs are going to be to the city and something that concerns me here is that someday there may not be the tax base to support this community" (John Schneiger).

It is clear that Montrose has made a small, yet important, first step to ensure the vision as stated in the 1998 Comprehensive Plan, with the recent signing of the land use IGA. However the city, as an organization, has made little effort to protect the natural environment and has taken a myopic view of economic development within the city. The principle purpose for doing things like defining the community and having some open space is to attract economics into the community and you want the ones that will bring variety. So that good and bad economic times create stability where the good times aren't as good and the bad times aren't as bad — so you want as much diversity as you can in a place (Billingsley). In addition, as is evidenced by ever increasing traffic, stagnant downtown sales tax receipts and strip commercial development along the state highways, Montrose's sense of small town character and corridors have arguably eroded away to be indistinguishable from almost anywhere else in the U.S. Furthermore, Montrose's land use codes, due to the lack of agricultural zoning or enabling preservation measures, arguably encourage subdivision sprawl and uncontrolled growth which has eaten away not only at the community's agricultural base (expressed in the vision statement as a important element to protect), but has also decreased the diversity of the local economy which, outside Russell Stover, government, the hospital and the school district, is primarily based on construction. According to Erica Lewis-Kennedy (July 2005, pers. comm.), "the new developments that have come to town with the new Hastings, Blockbuster, etc… are still not professional $30,000 or $40,000 a year jobs that people need to maintain houses. It is obvious that the value of jobs is not going up but the real estate market keeps increasing." To this end, although the IGA is an important first step toward the realization of the community vision, it would be erroneous to conclude that the city has truly worked toward the vision that the community set out in 1998. As Montrose does not have a growth-control program, it is clear that a lack of governmental action in this area will not lead the city toward its stated vision.

The large lot development is not farm ground. In addition, another recent American Farmland Trust (AFT) study found that Montrose County is among the top 25 counties in the seven-state Rocky Mountain West with 295,040 acres of prime ranchland at risk of conversion to low-density residential development. This land is equivalent to 21 percent of all land in Montrose County and 6 percent of all of Colorado's 'strategic' ranchland. Again, according to the study, nearly all of the 295,040 acres is along the Highway 50 corridor. The study also indicated that 11 percent of all prime ranchland in the Rocky Mountain West is threatened by conversion to residential development by 2020 (AFT 2000). By allowing for a TDR or even PDR (Purchase of Development Rights) and fee-simple purchase in the future in combination with collaborative regional planning efforts, local governments can help curtail this trend.

FINDINGS

Too many community leaders feel they must choose between economic growth and open space protection. But no such choice is necessary. Open space protection is good for a community's health, stability, beauty, and quality of life. It is also good for the bottom line (Rogers 1999). Urban containment and the preservation of open space are important attributes to creating efficient, sustainable, environmentally responsible, economically viable and livable cities. The need to control urban sprawl and preserve open space is particularly acute in the U.S., where the federal government and most states, including Colorado, have a hands-off approach to land use and development. As a result, it is up to local governments to construct places in a smart, forward-looking manner.

As the case studies for Durango, Fruita, Boulder, and Montrose demonstrate, each community is unique, but how do we compare them? Here are four possible elements of a definition for city greatness: (1) Allow everyone to live in well-planned communities and neighborhoods; (2) Save natural areas and open space and protect cultural and historic features; (3) Provide adequate infrastructure; and (4) Locate all intense, 'attraction' activities in well-planned, mixed-use areas — downtowns and cores (Engelen 2005). Although this study focuses on open space and urban containment, it is clear that each aforementioned element that contributes to a city's greatness affects the others in some way, shape or form. What makes a community, after all, is its inherent interconnectedness, not separateness.

Unfortunately, most U.S. and Colorado cities are growing in an ad-hoc, fiscally irresponsible manner. This is due to many considerations, not the least of which include: generally poor relationships between county and city government; little state or federal oversight requiring communication and planning between county and city governments; a limited tradition of regional planning; a long western tradition of strong private property rights; and a system that is fraught with politics that favor short-term economic gains for a few at the expense of the community. As a result, cities in the West generally grow in a politically motivated and shortsighted, manner instead of in a manner that is community oriented and future aware.

As a case in point, farmland and ranchland are the historical economic roots for Montrose and all communities in this study. However, of all these cities, only Montrose has no plan to protect those roots and that economic base. Durango has just passed an open space protection tax, Fruita has instituted a TDR program and Boulder uses many measures to protect rural places, farmland and ranchland. According to a recent study by the American Farmland Trust (AFT), the entire corridor along Highway 50 through Montrose County is considered among the highest quality farmland, yet it is facing a severe threat of development (AFT 2002). Dennis Erickson believes that if we surround Montrose with farm land and help the farmer farm his land, it will be a benefit to the community.

There is also a misconception that geographically confining a community inflates land and real estate prices. According to Dawkins and Nelson (2004):

> *Higher prices (especially for housing) could occur if planning fails to increase the supply of buildable land within the boundary" (which suggests that adequate planning to increase buildable land within the boundary could contain prices). Peiser (1989) observes that urban containment boundaries are "prudent land-use policies but only when accompanied by policies that increase urban density and intensity. Even if housing prices were to rise despite increasing densities, the increase itself might reflect savings and benefits [such as in transportation costs] realized by households because of urban containment.*

Instead of costing money, conserving open space as a smart growth strategy can save communities money. Far from being a drain on local taxes, farms and other types of open land actually subsidize local government by generating far more in property taxes than they demand in services (Rogers 1999). It is important to remember that ultimately, regardless of what improvements a developer may construct, public funds build and support sprawl's far-flung infrastructure: pavement, pipes, patrols, ambulances, and the other costs of unhealthy growth are paid for by taxing drivers and non-drivers alike, whether they are the inhabitants of sprawl or the citizens of more efficient environments, such as our core cities and older neighborhoods (Duany, et al. 2000). As was identified in the introduction, Montrose could literally save tens of millions of taxpayer dollars from going to developer subsidies by instituting some sort of growth control and urban definition measures. And to this end, the taxpayer burden is possibly larger with the current uncontrolled low-density urban sprawl than it would be with a tax for open space acquisition, a strong commitment to achieving the community vision, and high-quality planning.

If land use controls were done on a state or even federal level which encouraged or required cities, counties and regions to work together to control sprawl and work toward a stable, efficient community, cities like Boulder would not be unusual hotspots for investment. Further, many low-density suburban communities might suffer lower land values because of poor planning, increasing traffic, deteriorating housing stock, and loss of exclusivity; there is no greater risk to land values than unrestrained development (Rogers 1999).

It is clear that urban containment works less well when pursued only at the local or municipal level because of the spillover effect and the frequent creation of satellite communities (Martin et al. 2002). Boulder County has dealt with such spillover by creating a minimum lot size of 35 acres. Yet the true benefit to regional planning is that cities across the country would have the impetus to create communities that did not exude the geography of nowhere. Because Colorado cities are primarily funded through sales tax, even if you do a really good regional plan, the employment centers may not be where every city gets its fair share of employment to make it a good regional plan. So, if one town has more bedrooms then they do employment, and they do not get the revenue for making that sacrifice, then they are not going to go along with it (Billingsley).

Considering the foundation toward local governance and away from regional and state planning in Colorado, it is in the financial interest of municipalities to limit the residential growth potential, especially low-density residential growth within their communities and promote commercial, industrial and agricultural development leaving neighboring communities to take over the economic burden of residential growth. Further, even though conserving open space as a means to ensure urban containment will save city governments and tax payers money in the long run, it is ironic that finding the money to purchase fee-simple open space and development rights has difficulty gaining acceptance. In the end it is a fiscally conservative approach to physically define a community and the services that will be needed by that community in the future.

Yet, according Duany et al. (2000) because we have rebuilt our nation every fifty to sixty years, it is not too late. The choice is ours: either a society of homogeneous pieces, isolated from one another in often fortified enclaves, or a society of diverse and memorable neighborhoods, organized into mutually supportive towns, cities, and regions. In such a scenario, as suburbs and sprawl redevelop, there is always the opportunity to grow the city through higher density, create walkable neighborhoods, and correct past mistakes. Such redevelopment is already occurring in some eastern U.S. cities.

Although the Montrose community may not be as willing as some other communities to favor an open space as a means of urban containment program, the recent Household Survey and Parks Needs Assessment Survey suggests that there is more public support than is often given credit. The county needs to be working with the city as partners in this growth as the city is the largest municipality in the county (Belt). In addition, Belt believes that there is general sentiment in the county for rural preservation and agrees that the lack of a growth management plan has not been any kind of advantage. Yet, all of my interviewees agreed that such a plan would be an uphill battle for the Montrose community. “I think this is where strong leadership comes in from a strong council that can look well down the road and see where acquisitions like that may make a lot of sense” (Schneiger).

In addition, many of my interviewees had concerns that, in the words of Commissioner Allan Belt, “the squeaky wheels are often times the only ones that the elected officials hear. And when the rest of the folks come unglued and you have to ask where they were. John Schneiger, former Montrose City Manager had a similar perception:

> *The thing that always concerned me with Montrose was when we did our annual survey; it appeared as though there would be substantial support for planning and growth management. Just look at the numbers from the survey. But people did not come out to meetings. There are no groups on that side that come out. You get the NIMBYs, that is very strong. I was even surprised that the local environmental group did not come out, hardly at all, but when you have the real estate community and developers coming out, it did not take very many of them to really change the dynamics of an issue.*

According to Ron Stewart, former Boulder County Commissioner,

> *One of the things we did when I was commissioner was at least once a year do a public opinion survey. I think we have such a misconception in our society that when you hold a public hearing you have actually heard the public, you haven’t, you have heard a very thin slice of the public sentiment. And I have always believed in serving the broader public good and the broader public interest. I think that without knowing what the broader public thinks it is hard to do that. So, we used surveys to see what the public wanted us to do. And when the slings and arrows are coming your way, it is always comforting to know what the public really wants you to be up to.*

It is clear from the surveys that Montrose has conducted in the past year that the public is willing to listen to a community definition plan. Although the equations to determine the exact results of such a program are outside the realm of this study, the case studies indicate that the benefits are likely to outweigh the costs. At this point, Montrose is at a crossroads: the city can either continue on the same path as it has been on throughout its history and be willing to cope with ever-increasing traffic congestion, a void of local agriculture and a city with decreasing livability; or Montrose can learn from the growing pains of other municipalities in Colorado, incorporating what has worked and learning from what has not worked. One thing is for certain, the city of Montrose is not living up to the community vision with its current course of action. If the community decides to stay on the growth path it is on, it will be necessary to update the vision, leaving out any mention of agriculture, environmental protection or small town character. With this knowledge and looking into the future at a population that could easily be doubling within the next fifteen years, Montrose has much to gain by instituting growth control measures, which are reinforced by open space protection. There is no better time than now to start working toward the community vision. Not only will this step help stabilize and energize the local economy for the long run, it will also make Montrose, first and foremost, a fiscally responsible and increasingly livable community for future generations.

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HISTORIC TRANSPORTATION CORRIDORS IN THE SOUTHWEST, 1536 – PRESENT

Eric Vondy

After the Spanish conquered the Aztec empire they looked northward and saw a vast, inhospitable land that was sparsely populated by indigenous peoples. It was mountainous and arid. Water was scarce and often unreliable. Mountain ranges ran north to south making east-west travel difficult. Initial coastal surveys turned up little to spur rapid settlement of the region. Eventually, however, rumors of fabulous wealth drew explorers to the interior of this hostile land (Lorey 1999). Utilizing native guides, the explorers followed native trails to locations in the north, where they hoped they would find gold. Explorers like Coronado came expecting to find an Aztec-like empire filled with uncountable wealth but instead found dwellings made of mud and subsistence farming (Officer, 1987).

Soon silver was found in the interior spurring development in unplanned places. The existing trails were suitable for foot traffic, but were too rugged for horse or other animals. For the Spaniards to settle the north they needed to create a road network capable of horse and wagon travel. The Spaniards raced to turn the existing foot trails into wagon roads and built new roads to reach mine sites. Communities such as San Luis Potosi, Zacatecas, and Parral were founded because of silver. Towns were built along the trade routes to help protect the ore coming from the mines (Lorey 1999). What would become northern Sonora and Chihuahua, however, were still distant and unsettled.

As other European powers came close to the area, Spain planned to solidify its claim on what would become the border region (Lorey 1999). Mineral interests had not been found this far north and so missionaries were sent instead. The Jesuits and the Franciscans came to convert. They followed established native trails north and set up missions in or near existing population centers. In what would become Arizona, the routes they took followed the San Pedro, the Santa Cruz, and the Colorado Rivers.

In 1691, 150 years after the Spanish invaded the Aztec empire, Father Kino entered present day Arizona for the first time. Ten years later he had established the missions at Guevavi and Tubac. Spanish settlers were in Arizona by the end of the 1730s. Often European trade goods preceded the arrival of any Spanish as native peoples carried goods further and further north (Officer 1987). Traveling faster than the European goods was disease which devastated the native population. Spanish missionaries and farmers built settlements using the local population as a labor source. Native trade routes became conduits for this expansion. However, most roads were unsuitable for wagons due to the topography (Lorey 1999). This problem plagued all of New Spain. Many major cities in the interior lacked rivers to keep transportation costs low. Thus New Spain and later Mexico was burdened with high transportation costs due a lack of navigable rivers which in turn meant there was less money to be spent on building decent roads over the rugged terrain (Wasserman 2000). Native trails were given Spanish names. One example is the Camino Real. There are at least three roads called Camino Real that run from Mexico into the United States. One is the Camino Real which went from Mexico City to Santa Fe via silver mining areas and other centers (Gonzalez 1996; Moorhead 1998). One of the two other Royal Roads is of note. It linked Spanish missions from the southern tip of the Baja Peninsula up the California coast terminating north of present-day San Francisco. Today, it is almost a connect-the-dots of coastal Spanish missions.

Although the primary travel corridors of the Spanish were oriented north-south, there were exceptions. The Gila Trail runs along the Gila River through central Arizona. Juan Baptista de Anza, head of the garrison in Tubac, used the trail on his journey to California in the 1770s. In present day New Mexico and Texas, the Rio Grande was an east-west corridor, as was El Camino de los Tejas which leaves Mexico and crosses eastward through what would become Texas and Louisiana. In present day northern Sonora and southern Arizona there was also the Camino del Diablo, the infamous east-west route across the inhospitable desert (USFWS 2005). The first European to use it was Melchior Diaz during a side-trip with the Coronado expedition. Although it began in Caborca, the toughest part of the route did not start until leaving Sonoyta, Mexico, when it became a long, dry ride or walk across desert flats, leg-wrenching lava hills, and drifting sand. Much of the Camino del Diablo was not a road but rather a series of interwoven tracks following the lay of the land or following old shell trails coming from the Sea of Cortez. There was very little water along this trail which made it particularly deadly. It was used as a shortcut to circumvent the tribal raiding parties and bandits that often occupied the lands around the Gila River. It was heavily used by Mexican prospectors to reach the California gold fields during the 1840s and 50s. Though it was 150 miles shorter than the route through Tucson and via the Gila River, when choosing to take it, one was opting to risk dying of thirst rather than at the hands of Indians and bandits.

THE NINETEENTH CENTURY

Americans began creating east-west travel corridors when the Mountain Men explored the region hunting for fur in the early 1800s. Following the mountain men came settlers. In the years following its independence from Spain, Mexico had liberal immigration policies leading to easier settlement of its lightly populated northern lands by Americans (Martinez 1988). From Mexico's perspective there were several reasons for encouraging American immigration. First, they hoped to use the American settlers as a buffer against hostile Indians. Secondly, they hoped to stave off American expansionism by allowing them to immigrate freely. In reality, the distance was too great and the Mexican population too sparse for Mexican forces to secure the border, and there was no practical way to stop the Americans from coming. American prospectors came seeking mineral wealth, farmers and ranchers came seeking land, and merchants came to strengthen their economic holdings in Mexico. The U.S. became the region's primary trading partner rather than Mexico. It became abundantly clear that the country who settled the region fastest would ultimately rule the northern territory, and that depended on who built better roads.

The Spanish had no interest in trade with the U.S. and confiscated the goods of American merchants with whom they came in contact. It was only after Mexico's independence that trade with the Americans began. The Santa Fe Trail opened up the region to American expansion and Mexican trade. The Santa Fe Trail originated in Missouri and in Santa Fe met the Camino Real. Thus with the creation of the Sante Fe Trail it became possible for a traveler to leave Mexico City on the Camino Real, arrive in Santa Fe, and then travel on to Missouri on the Santa Fe Trail (Moorhead 1998).

By the 1830s Mexico had become concerned about the growing number of American settlers pouring into the frontier via American-built roads. Texas in particular was a threat as Americans were about to become the majority there. Only a little over a decade later, their fears came to fruition and not long after Texas fought to gain its independence, an all-out war broke out in 1846. During the Mexican-American War, a major east-west corridor was created by the Mormon Battalion which left Fort Leavenworth, Kansas, and traced a road across what was then Northern Mexico. This laid the foundation for a major east-west travel corridor in what was to become the southern portion of Arizona. The battalion did little road-building during its trip but rather focused on finding routes, leaving the retinue of over a dozen wagons to forge the road (Jackson 1952). When hostilities ceased in 1848, nearly half of Mexico was ceded to the U.S. (Martinez 1988).

The California Gold Rush caused untold thousands to pass through the border region. The population of California grew from 14,000 in 1848 to 225,000 in 1852. During the peak of the Gold Rush, San Francisco's population was growing by 4,000 people a month. Utilizing roads like the Camino del Diablo and the road laid out by the Mormon Battalion (both of which were built atop old Indian trails), the mass migration to the gold fields brought new prosperity to the borderlands. Agriculture and commercial development followed the prospectors on their migration. Many travelers abandoned their quest for California and settled along the route (Lorey 1999).

After the Mexican-American War and the Gadsden Purchase of 1853, there was a major migration of Mexicans from the U.S. across the newly formed border into Mexico. New settlements developed on both sides of the border. New roads were built in addition to the traditional routes to connect lines of communication (Figure 1). Mexico having seen that its scant population and lack of roads had led to the loss of half its land was anxious to populate and build an infrastructure in its new

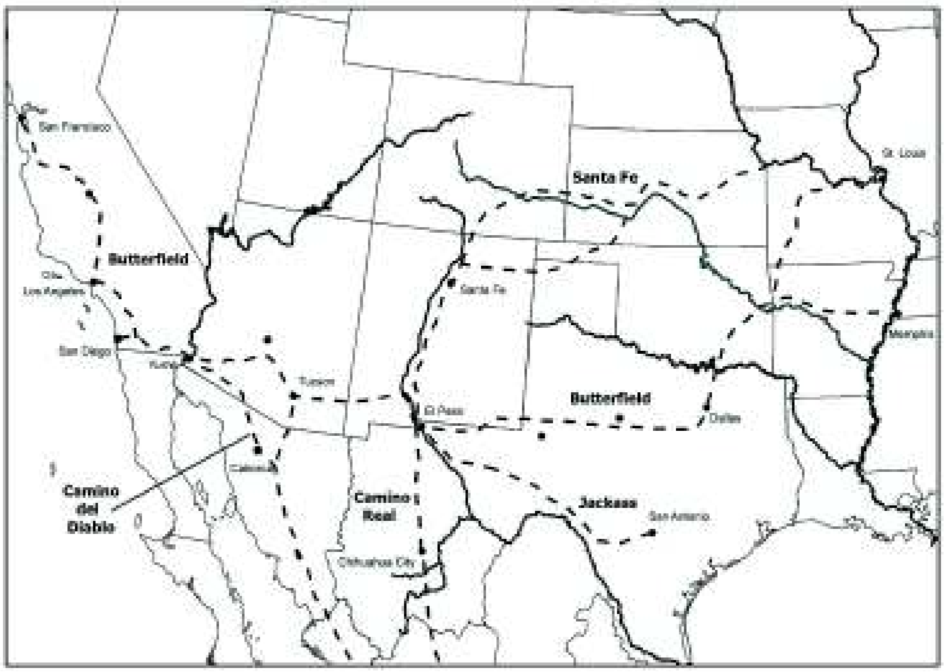

Figure 1. The commuting habits of the residents of the cities in the study as collected by the 2000 U.S. Census.

border region to protect against further expressions of American manifest destiny (Lorey 1999).

The growth of American east-west transportation corridors also grew after the war with the creation of stagecoach lines such as the short-lived Jackass Mail (Pearce 1969) and the Butterfield Overland Stage Coach. These companies followed the trail blazed by the Mormon Battalion, improving upon its route when more accessible passages were found. Stage stops and communities sprung up with the development. It was now as easy to travel east-west as it had been to travel north-south through the border region.

The boom period stimulated by the California Gold Rush came to an end with the beginning of the U.S. Civil War. Even though U.S. border areas had little actual combat (Arizona, for example, had only one small skirmish), troops were deployed back East and the war stopped most migration. With finances and energies being focused on the war in the East, stage coach routes fell into disuse and development of the railroad stopped even though routes had been chosen by the 1850s (Janus Associates 1989). Growth of the west and southwest picked up again after the war and a few years of financial recovery.

Profirio Diaz came to power in Mexico in 1876. His 34-year rule brought an unprecedented period of stability to the region but with dire consequences due to his 'pan or palo' — bread or club — method of governance. While the borderlands advanced in some ways, in others they remained unchanged. While attention was paid to enhancing the rail network, roads, which benefited the common man, were left largely unchanged. In all of Mexico there were only 400 miles of rail when Diaz took power. By the end of his reign there were over 15,000 miles (Wasserman 2000). This growth was brought about by Diaz encouraging foreign investment. By the twentieth century, 80% of the stock in Mexican railroads was owned by Americans.

The new rail lines dramatically lowered transportation costs — solving a problem that had plagued the country since Spain had conquered it 300 years earlier. By connecting the isolated borderlands with the Mexican interior, the railroads aided in eroding the autonomy of the region (Meyers and Beezley 2000). The railroad allowed the Mexican border region to rely more on the interior than it had previously been able to. Land values skyrocketed. Unique values, work ethics, and cultural practices were irrevocably changed by the connection to the Mexican interior. Alternately, connection to the U.S. also brought changes such as access to higher wages, exposure to labor unions, and new political ideas.

In 1877, on the American side of the border, Southern Pacific made a deal with Texas & Pacific to build a railroad that roughly followed the Butterfield Overland route. In March of 1881 the Santa Fe Railroad connected with the Southern Pacific rail line in Deming, New Mexico, thus creating the second transcontinental rail line in the United States. In December of that same year when Southern Pacific eventually linked with Texas & Pacific outside of El Paso, a third transcontinental link was created (Janus 1989).

As railroads stretched across the American Southwest and the Mexican Northern Frontier, linking them became a primary goal. This linkage represents the first major development in north-south transportation since the Santa Fe Trail linked to the Camino Real fifty years earlier. With the linking of the U.S. and Mexican railroad networks, growth along the border boomed. El Paso, for example became the biggest smelter site in the Southwest, processing ore from Texas, New Mexico, Arizona, and Chihuahua. The prosperity from the railroad in San Diego led to the founding of Tijuana in 1889. Both Nogaleses were founded in response to the railroad along the Santa Cruz River on an old native trail. After the turn of the century, Mexicali and Calexico were founded due to railroad development (Kearney & Knopp 1995). Many Mexican border towns strengthened economic ties to the U.S. to the point of being once again more dependent on the U.S. than on Mexico. With the coming of the railroads, commodities like silver, copper, coal, lumber, cotton, wool, cattle, and salt could reach distant markets for the first time.

The connection of Mexican railroads to American railroads allowed for the first time the mass migration of laborers from interior Mexico to the border region and on to the U.S. (Kearney and Knopp 1995). In the 1880s migrant labor forces were brought in by rail to pick cotton, work in mines and smelters, and on ranches.

The railroads often followed the old trails. In Arizona, the railroads built tracks which roughly followed the Butterfield Stage Line which had roughly followed the Mormon Battalion's route across Arizona which in turn had followed native trade routes. The railroad that crossed the border at Nogales was on a travel corridor along the Santa Cruz River that had been used for hundreds of years. There were exceptions. The Cienega Creek Corridor, for example, is an area in Arizona between Benson and Vail through which the Mormon Battalion, the Butterfield, and the Southern Pacific Railroad lines traveled yet the area has little evidence of being a Spanish or prehistoric travel corridor. Until American interests spurred the need for more east-west travel routes, there had been no need to traverse this region despite it having a steady water source.

Mining and agriculture spurred new transportation veins. Rail lines extended to meet the needs of the agriculture and mining industries. Mining companies were often involved with railroads. Phelps Dodge Company, for example, had controlling interest in the El Paso & Southwestern Railroad (Schwantes 2000).

TWENTIETH CENTURY

During the early decades of the 20th century the divergence in transportation development began between Mexico and the United States. In 1910, the Mexican Revolution began. During the Revolution, transportation was disrupted by fighting and bandits. The rail lines were targeted so that by the end of the revolution Mexico had lost half of its locomotives. Revolutionaries also raided crops to feed their soldiers. Ore shipments were seized and mines were destroyed. During the same period, the U.S. transportation infrastructure continued to grow from mining, federal efforts at reclamation, development of national parks, as well as the new oil industry in Texas and California. The population on the American side of the border grew as well as Mexicans fled the fighting in their country.

As the Mexican Revolution ended, World War I began. American copper was in much higher demand than Mexican silver. Mexico had also lost a valued trading partner in Germany throughout the war years. Mining efforts in Mexico were further hindered by embargos on certain explosives to Mexico. In part this was due to a telegram which was sent by the German Foreign Minister to the German minister in Mexico, suggesting a German-Mexican alliance to regain Arizona, New Mexico, and Texas should the U.S. enter the war (Degregorio 1984). Meanwhile American reclamation projects continued to open vast new areas of desert to be irrigated and turned into farmland.

By the second decade of the twentieth century, the race was on to create road systems. Most rural roads were still unfit for automobiles. Organizations sprung up about the U.S. promoting various automobile highways including several vying for the first ocean to ocean highway. Usually these routes proposed were very similar to each other due to the lack of roads on which automobiles could actually travel thus the Bankhead Highway, the Old Spanish Trail, the Coast to Coast Highway, the All Year Southern Route, and the Scenic Sunshine Route all encompassed big chunks of what would become US-80 (Finley 1997). Either San Diego or Los Angeles was usually the western terminus of these proposed southern routes. Savannah, Georgia was often proposed as the eastern terminus. Even after another highway was chosen as the first Ocean-to Ocean Highway, these organizations continued to promote their routes as being open all year since there was little winter weather with which to contend.

A major goal of those that promoted this southern route was to bridge all obstacles that could prevent it from being open all year. Bridges were built over rivers prone to flooding such as the Gillespie Dam Bridge on the Gila River and a plank road was built over the sand dunes in California (Bates, 1970; Keane and Bruder 2003).

Prohibition in the U.S. lasted from 1920 to 1933. Although Mexican border towns had begun marketing themselves as party destinations in the late teens, it was prohibition that made them boom. During prohibition the U.S. border towns became tourist destinations advertising the saloons and nightclubs just across the border in Mexico where alcohol was still legal. Many Mexican nightclubs were owned by American investors. The Mexican tourism industry exploded for the first time during this period. Conventions and conferences came to U.S. border towns for the access to Mexican nightlife. Once again, the Mexican border region strengthened its economic ties with the U.S. as the Americans enhanced their transportation systems to carry more and more people to the border so that they could do in Mexico what they couldn't do in the U.S. (Kearny and Knopp 1995).

The original design for the U.S. highway system came from a map created in 1922 by General Jack Pershing who selected roads that would be important to the Department of War. The original intention of the highway system was for defense. Pershing, having made military incursions into Mexico in pursuit of Pancho Villa during the revolution, made roads running along the Mexican border a high priority but made roads running along the Canadian border a lesser priority as he did not consider Canada a threat to the United States. Pershing's map contained over 78,000 miles of road deemed by the Department of War to be strategically important to the nation's defense or to aid with evacuations of large cities. Bureaucrats then cut down the plan to roughly half of what Pershing had recommended. This became the prototype for the Federal Highway System (Moon 1994) in which existing roads were included, highway names were replaced by a numbered system, and signage was standardized.

In one sense the transportation boom ended with the Great Depression of the 1930s. However, federal road building projects in the U.S. greatly enhanced the quality of vehicular transportation. Hundreds of millions of dollars was being poured into highway development. In Mexico reclamation projects, merchant associations, and free trade zones were utilized to offset the effects of the Depression. While transportation was also utilized it did not play as large a role as it did on the U.S. side of the border. Workers surged from the Mexican interior looking for work in the United States. Matamoras's population, for example, doubled during the course of the decade mainly due to people seeking work north of the border (Kearny and Knopp 1995).

World War II brought more federal aid to the Southwest states. The high-tech and defense industries as well as coastal ship building played important roles. Hundreds of thousands of soldiers came to the Southwest for training at Patton's Desert Training Center. New roads linking the U.S. to Mexico were built during the war including one utilizing the old shell trails that linked the U.S. to the Sea of Cortez which would be used as an emergency port if the Japanese blockaded the California coast. Mexican tourism boomed again as soldiers on leave and civilians visited Mexico's border towns to partake in its nightlife.

With the boom in manufacturing, the growth of agriculture, and the loss of workers who left to fight in the war, there was also great demand in the U.S. for fresh labor — the bracero program became the answer. Initially this program was to be short lived and used to transport Mexican laborers to agricultural areas and to help with the U.S. war effort. Each year, tens of thousands of Mexican men came to find seasonal work in the United States. The program proved so successful that it continued into the 1960s. In the off season many of the workers returned to the border region rather than their interior homes. Their families often joined them causing the border region to boom once again. With the bracero program the border could be opened and shut like a valve allowing cheap labor to pour into the U.S. as needed. During the Korean War and the Vietnam War, in addition to World War II, Mexican labor was in strong demand (Martinez 1988). When the program ended Mexicans continued coming.

In 1956 President Dwight Eisenhower authorized the Interstate Highway System. A possibly apocryphal story involved Eisenhower being so impressed with Hitler's Autobahn during the Second World War that it acted as the inspiration for the Interstate Highway System. While there may be some truth in this story, Eisenhower, in his early military career, had been a truck driver and understood the conditions of the American road network. He also used Pershing's map from 1922 for the new road system (Degregorio 1984).

The Interstate system serves the dual purpose of being designed for traffic flow and to aid in the evacuation of major cities in case of nuclear attack using a procedure called contraflow wherein in-bound lanes are reversed so that all lanes lead out of a city. The effectiveness of this second purpose was tested during 2005 with the evacuation of New Orleans due to Hurricane Katrina and the evacuation of Houston due to Hurricane Rita.

In Mexico, the 1950s also saw the development of major highway systems linking cities on the border to major interior cities. Smaller border towns like Nogales were also linked to major cities if they were located on major transportation routes. Deep in the interior, highways were created linking major cities to the growing beach resorts on the coast. In the latter half of the twentieth century, the reclaimed lands that had made the border regions an agricultural center were becoming suburbs of growing cities. The old Hohokam canal systems that were excavated when Phoenix was founded are now mostly covered by subdivisions. "It is striking that the growth of these cities has had little relationship to the earlier agricultural economy," Oscar Martinez said. Millions have now moved into the region that have no relationship to the natural environment or agricultural environment that made the region habitable (Martinez 1988).

SUMMARY

William Langewiesche (1993) said, "The border itself was no longer a distant desert, but rather a string of familiar cities closely linked to the rest of Mexico by improved roads and public transport." As north-south transportation needs grew, the highway system mimicked the rail lines which in turn were following the Spanish trails that had followed the tribal trails. The primary differences were elevation and water. Foot travel could reach places that horses could not. Automobiles and trains needed road and track on certain grades but could go longer without water than human and horse.

The U.S. Highway System followed old trails as well. Old wagon roads were replaced by primitive dirt roads. In turn, those dirt roads were replaced by narrow paved roads. The Mormon Battalion Road was used by the Butterfield Overland Stage Coach Route which was then used by the Great Southern Road which was then used for US-80 and later Interstate 10. You stand at certain places and see the layers of transportation history. You can stand on the San Pedro River where Coronado followed old native trails and see where the Mormon Battalion and the Butterfield trails met and you can see I-10 and the railroad and know that US-80 met these other systems only a couple of miles away. You can stand in Nogales and see the wall that splits the railroad and the road and then follow the Santa Cruz River and I-19 all the way to Tucson.

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