Anthropogenic Activities and Karst Landscapes:
A Case Study of the Deep, Thermal, Sulfuric Karst System
in Tamaulipas, Mexico

by

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Approved by

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Dedication

To my family, friends, and colleagues

Acknowledgments

There are a number of people who have provided integral input, guidance, and assistance to make the research of this thesis a success. My husband, Marcus Gary, introduced me to SCUBA diving and Sistema Zacatón. Marcus has played many roles—a surveyor, proof-reader, field team member and general support. Most importantly he provided the inspiration to seek answers based on scientific research and the encouragement to seek my master's degree. My parents, Anne and Rick Havens, taught me from an early age that nothing is impossible with hard work and persistence. They instilled in me a love for the outdoors that greatly influenced the research for this thesis.

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I extend my sincere gratitude to all the people that made this research possible.

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Global biodiversity is rapidly declining as a result of human induced environmental change. Environmental diversity has been proposed as a surrogate for biodiversity in an effort to identify areas for conservation in an effort to reduce biodiversity loss. Karst is a distinct landscape characterized by an underground drainage network that facilitates surface and sub-surface interaction. Karstification creates a heterogeneous matrix that allows for karst systems to support a diverse range of obligate cave flora and fauna. Landscape ecology offers an appropriate framework with which to investigate the impacts of human activities on karst landscapes. This thesis examines the effects of human impacts on a karst landscape using Sistema Zacatón in northeastern Mexico as a case study. A remote sensing analysis of agricultural land conversion, vegetation survey of an indicator species, and a cave and karst inventory provide data that suggest that the detectable signs of habitat degradation in Sistema Zacatón could be linked to human activity.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

Human activity has a profound effect on natural ecosystems (Giller *et al.* 2004). Global biodiversity is rapidly declining as a result of human induced environmental change (Sax and Gaines 2003; Loreau *et al.* 2001; Collinge 1996). Consequently, biodiversity conservation has become a global concern. In 2002 188 countries agreed to take steps to significantly reduce the rate of biodiversity loss by 2010 (IUCN Convention on Biological Diversity 2002). The lack of data on reference populations makes assessing the rate of loss of those species problematic (Scholes and Biggs 2005). Furthermore, fewer than two million—out of five to thirty million species expected to exist on Earth—have been documented (Mace 2005). One method to circumvent this deficiency of knowledge is to use environmental diversity as a surrogate for biodiversity (Faith *et al.* 2004). Given the well-established relationship between species and habitat, current literature posits that unique habitats often breed rare species; therefore, protecting unique or geographically limited habitats could ensure the persistence of rare or endemic species not yet discovered (Bonn and Gaston 2005; Culver *et al.* 2000).

Karst landscapes are highly heterogeneous and include a wide variety of habitats capable of supporting a diverse number of species (Gibert and Deharveng 2002). Karst landscapes are formed by the dissolution of soluble rock and are characterized by open conduits that facilitate surface and sub-surface interaction (White 2002). Carbonate rock formations, associated with karst landscapes, are widely distributed covering approximately 12 percent of the Earth's continental surface (Ford and Williams 1989). The characteristics of karst landscapes are highly variable and occur in a range of climates, altitudes, and strata (Klimchouk and Ford 2000). Karst systems provide a unique and often isolated environment that promotes endemism (Gillieson 1996). Differing flow rates, water chemistry, and void space size create a highly heterogeneous matrix (Bakalowicz 2005) that allows for karst systems to support a highly diverse range of obligate cave flora and fauna (Christman *et al.* 2005; Sket 1999). The World Commission on Protected Areas Working Group for Cave and Karst Protection states that karst areas are important hosts for special or endangered flora and fauna both at the surface and underground (Watson *et al.* 1997).

Sistema Zacatón, in northeastern México, is a highly specialized karst system that includes deep, thermal, phreatic sinkholes, known as cenotes, and an extensive, shallow dry cave network. The system formed at the interface of a thick, fractured bed of limestone and a geologically recent zone of volcanic activity (Gary *et al.* 2003). Four of the area's five cenotes contain thermal and slightly sulfuric water, consistent with the theory of hydrothermal karstification (Dublysky 2000); however, the extreme depth in conjunction with the elevated water temperature, make this system unique. The five sinkholes lie along an east-west transect within 1.5 km of each other (Figure 1.1). The cenotes, Zacatón, Caracol, Verde, La Pilita, and Azufrosa reach depths of 329 m, 85 m, 48 m, 112 m, and 4 m, respectively (Gary 2001). Zacatón, the system's deepest cenote, could be the deepest water-filled pit in the world (Gary 2002).

Additionally, the cenotes and the surrounding area represent a unique terrestrial ecosystem. The thermal waters provided refuge to tropical biota during glacial advances of the Tertiary period, 65-1.8 million years ago (Medrano 1998). Today, the vegetation surrounding the cenotes is classified as seasonally dry tropical forest (Medrano and Mejía 1998), which exhibit high diversity and endemism (Trejo and Dirzo 2002). Historically, seasonally dry tropical forest may have covered 14 percent of Mexico, however, by 1990 distribution was reduced to approximately 19 percent of the original coverage; today these forests are considered severely threatened (Trejo and Dirzo 2000). The diverse flora and ecological conditions in and around the pozas allows the system to continue to be a terrestrial biotic refuge in an area dominated by agriculture and ranching (Arriaga *et al*. 2000).

Though exploration and scientific investigation have addressed the cenotes' unique nature, no studies have looked at man's impact on Sistema Zacatón. A team of cave diving experts initialized exploration of the cenotes (Kristovich 1994; Gilliam 1995). Several researchers have examined the surface geology and the effect volcanism has had on the cenotes and surrounding areas

(Gary and Sharp *in press*; Fernández and Fernández 2004; Gary *et al.* 2003). Biologists and botanists have examined the flora and fauna of the system, finding rare and endangered species (Mejía and Medrano 2004; VanDuzer 2001; Medrano 1998; Medrano and Mejía 1998). Most recently, astrobiologists and microbiologists have begun research on colonies of sulfur-oxidizing bacteria, known as biomats (Gary *et al.* 2003), at depth in Zacatón (Stone *et al.* 2005). However, biological inventories offer only cursory lists of prominent species present within the system, instead of the complete knowledge of population size and status (Scholes and Biggs 2005; Brooks and Kennedy 2004). Agencies such as CONABIO, PRONATURA, and CESPEDES list Sistema Zacatón as a priority conservation area (Arriaga *et al*. 2002; Garcia-Segovia *et al.* 2002; Arriaga *et al*. 2000), yet no studies on the health of the system, the sensitivity of the system, or management options have yet been performed until research for this thesis began. This research provides a beginning point for documenting the sensitivity of Sistema Zacatón to contribute to local management as well as to the interface of karst, landscape ecology, and land use and land cover change literatures.

1.1 Problem Statement

Increased human activity and access can cause habitat degradation and fragmentation (Collinge 1996). Landscape ecology literature offers multi-scale theories for and analysis of ecosystems in order to understand the implications of the spatial patterns of a landscape, such as the size, shape, and configuration of habitat patches, on ecological processes (Turner *et al.* 2001; Forman 1995; Forman and Godron 1986). Habitat fragmentation, connectivity, and degradation are dominant themes within landscape ecology studies; however, few if any landscape ecology studies have related these themes to karst landscapes. This thesis investigates the effects of human activities on the ecological integrity of a karst landscape, using Sistema Zacatón as a case study.

Fragmentation associated with land conversion for human activities poses the most serious threat to global biological diversity (Wilcox and Murphy 1985). The four primary ecological consequences of habitat fragmentation are loss of native plant and animal species, invasion of exotic species, increased soil erosion, and decreased water quality (Collinge 1996). Karst areas are particularly susceptible to the consequences of habitat fragmentation (Hancock *et al.* 2005). These consequences would affect both aquatic and terrestrial life in Sistema Zacatón, home to several rare or threatened plant and animal species (Medrano and Mejía 1998). The loss of native species and the introduction of exotic species could further jeopardize already endangered populations. Karst areas are dramatically affected by soil erosion (Drew and Hötzl 1999). Increased soil erosion affects karst landscapes in two ways. First, erosion washes sediment directly into caves and conduits, which can block passages, divert streams, or smother cave life (Gillieson 1996). Second, decreasing the thickness or eliminating the soil layer reduces its filtering capacity and allows contaminants and sediment to rapidly infiltrate into the karst drainage system (White 1988), so there is little time for contaminants to break down or pathogens to die off (Mahler 2004). Decreased water quality can directly influence unique hypogenous flora and fauna by significantly altering the water chemistry (Sket 1999). Degradation to groundwater, cave, and terrestrial habitats in Sistema Zacatón would threaten several rare or endangered species. There is great potential for hydrologic change within karst landscapes due to tourism and the associated infrastructure and sewage disposal practices (Watson *et al.* 1997). The U.S. Environmental Protection Agency (EPA) declared septic system failure as a major source of karst groundwater contamination (Veni *et al.* 2001). As there is no sewage treatment facility within close proximity to Sistema Zacatón, careful regulation of waste disposal is necessary (Gillieson 1996). Increased farming, impervious surfaces, or waste disposal may alter recharge and water quality sufficiently to affect the unique aquatic biomats found on the walls of several of the pozas of Sistema Zacatón (Figure 1.2). Furthermore, visiting SCUBA divers can destroy biomats, because as divers' bubbles rise, they dislodge the delicate mats. Additionally, unregulated access to dry caves, typically low-energy environments, reportedly results in the introduction of energy sources from mud on clothes and food residues, cave vandalism, graffiti, enlargement of passage, and compaction of sediments which affect hydrology and fauna (Gillieson 1996). At least three species of bats, one of which has a substantial local wintering population, have been observed in the dry caves of Sistema Zacatón (personal observation). Cave-dwelling bats roosting in large aggregations during hibernation or reproduction are particularly vulnerable to disturbances which can reduce populations (McCracken 1989). Difficulty in counting and accurately investigating the presence of smaller metapopulations (Tuttle 2003; Carter *et al.* 2003) renders knowing the true number of species present in Sistema Zacatón difficult to discern. Given that bat populations are documented as declining, human disturbance in caves with hibernating bat populations should be minimized (McCracken 2003). Finally, terrestrial disturbances such as plant extraction and infrastructure expansion could result from an increase in human activity. Plant populations, such as the endemic ponytail palm, are known to be a target of human extraction; the plants are highly prized for commerce which causes severe declines in recruitment and seedling survival in areas where extraction occurs (Cardel *et al.* 1997).

1.2 Hypotheses and Thesis Scope

The goal of this research is to test how to assess the effects of anthropogenic activities on karst landscapes. Karst ecosystems are landscapes with highly connected surface and subterranean interaction (White 2002). Human impact on cave and karst systems is difficult to measure, because highly heterogeneous karst systems naturally demonstrate variable water chemistries, biotic diversity, and activity (Bakalowicz 2005). Landscape ecology principles provide well documented methods of analyzing human activities at multiple scales but seldom address karst landscapes (briefly discussed in Forman 1995, absent in: Turner *et al.* 2001). Are landscape ecology principles applicable when assessing the effects of human impacts in a karst landscape? This research posits that landscape ecology literature on the effects of fragmentation, isolation, and degradation of habitat can be utilized to investigate the biotic response to human induced changes in karst landscapes.

This research will examine the effects tourism and land use changes on the health of the karst system and its associated vegetation, using Sistema Zacatón as a case study. This thesis investigates historical and current ecological conditions of Sistema Zacatón and identifies the most vulnerable components of the system by examining the effects of anthropogenic activities. This study hypothesizes that in Sistema Zacatón surface vegetation patterns and population dynamics suggest that the area has been subject to substantial influence from human impact. Due to the effects of farming, ranching, and tourism, it is expected that floral populations will have a greater recruitment of seedlings and saplings in zones further removed from areas accessed by animals and humans. Furthermore, documenting the presence and extent of karst and cave features will illustrate the level of karstification in the area, which will suggest the level of surface-subsurface connectivity within the system (Veni 1999). It is further hypothesized that the system demonstrates a high level of karstification. Cave passages along well-traveled paths are anticipated to reflect heavy human use, as represented by large accumulation of trash, broken formations, graffiti, and remnants of guano extraction.

A remote sensing analysis of agricultural land conversion using a land use and land cover change detection will assess long-term change in the study area and surrounding regions. A vegetation survey of the endemic ponytail palm, *Beaucarnea inermis*, will explore the influence of anthropogenic activities, mainly tourism and ranching, on the study area. A karst and cave inventory will locate and quantify the extent of karstification in the study area. Baseline data for karst ecosystem health will be established by examining the fauna present in cave and karst features and by monitoring damaged formations and graffiti within the caves.

The lack of formal conservation and preservation guidelines coupled with current land use practices and local morphology has caused detectable signs of habitat degradation and has limited the reproduction of endangered species in Sistema Zacatón. This thesis will supply information for the development of a program to help educate local residents and visitors about Sistema Zacatón's unique karst system, increase awareness of the interconnectivity of land development and water quality in karst landscapes, and encourage conservation as a part of daily activity. This thesis will provide an inventory and study of baseline conditions of the most sensitive components of Sistema Zacatón and serve as a basis for educated management decisions. Effective conservation efforts at Sistema Zacatón could result in a substantial reduction of biodiversity loss in concordance with goals established by the IUCN Convention on Biological Diversity in 2002.

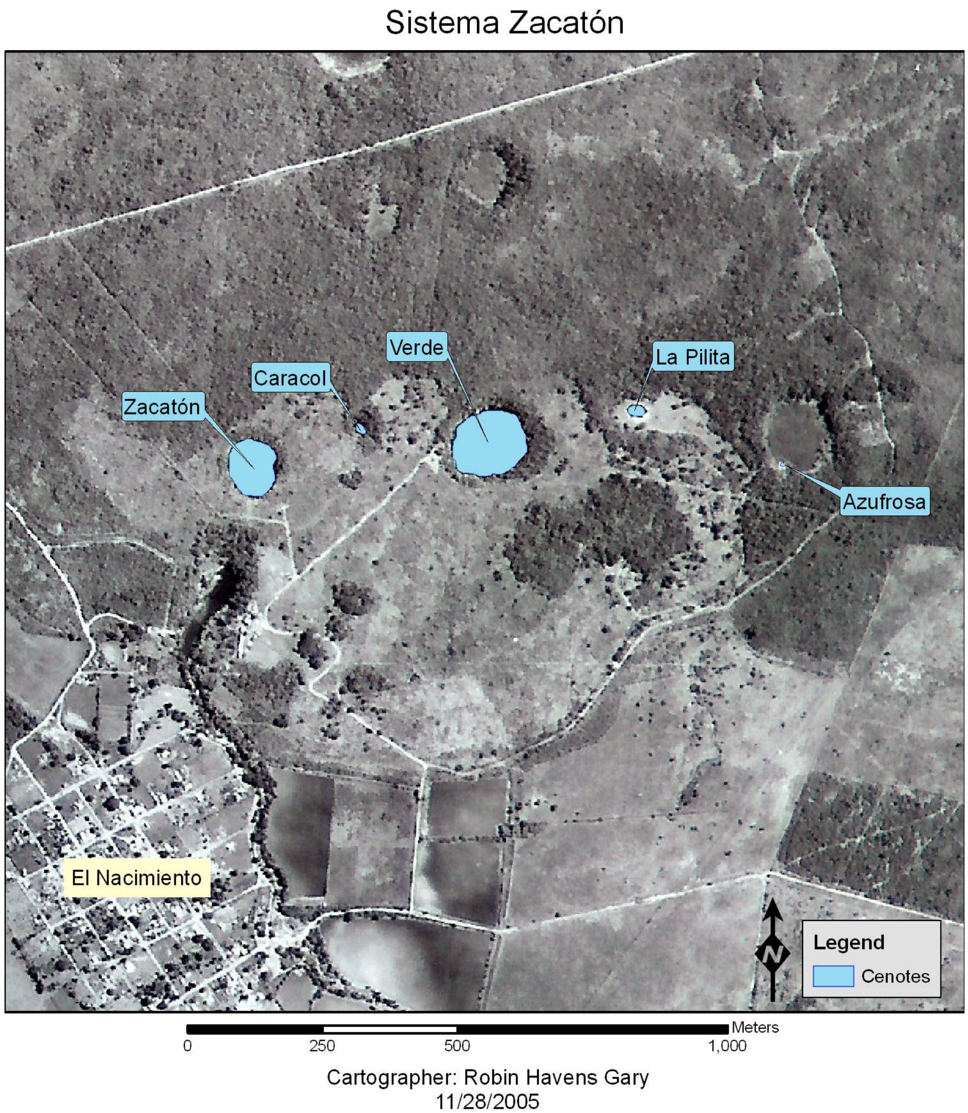


Figure 1.1 **Aerial photo of Sistema Zacatón.**
Shows the five major cenotes and the village of El Nacimiento.

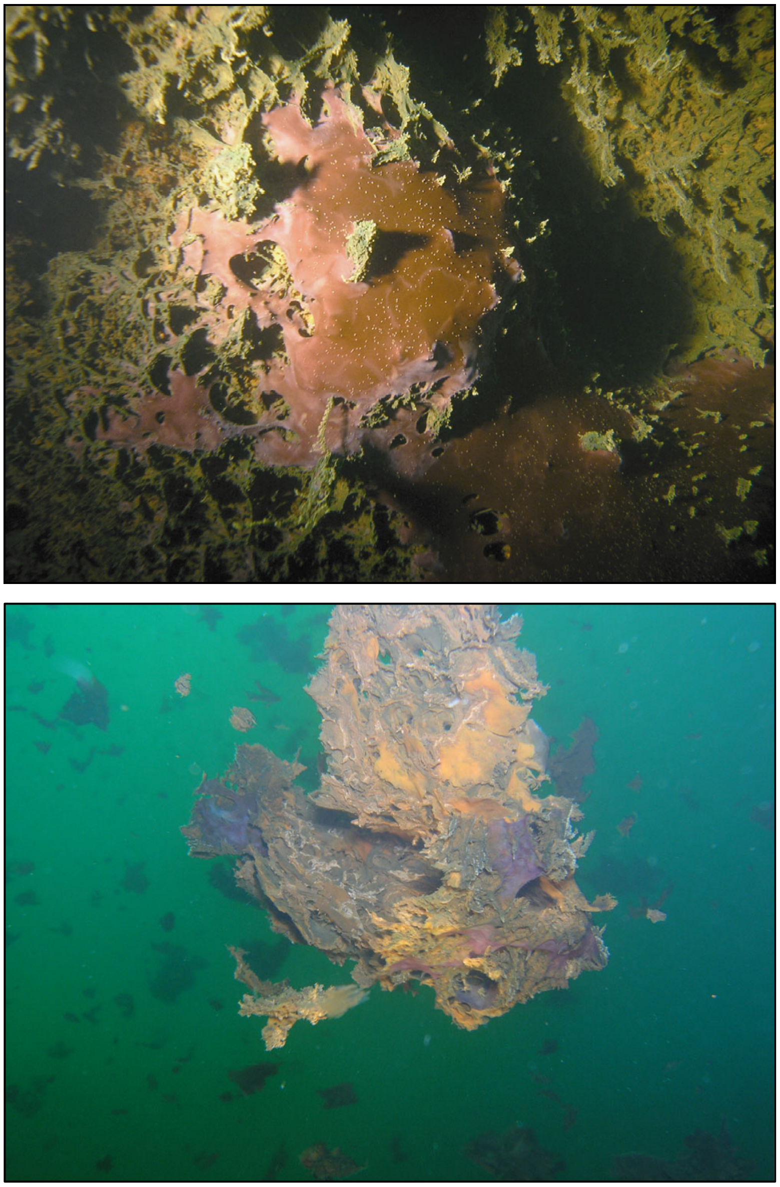


Figure 1.2 Biomats in La Pilita

The top photo shows an undisturbed biomat in La Pilita at approximately 7 m of depth. The lower photo was taken after divers' bubbles had dislodged the biomats on overhangs above them.

Chapter 2: Study Area

Sistema Zacatón serves as an appropriate case study to examine human activities in a karst landscape for a number of reasons. First, the system's numerous karst features were formed by a unique process of speleogenesis (Gary *et al.* 2003). Second, relatively little is known about the status of the system's rare and endangered species, necessitating further study. Furthermore, given that subterranean environments have been determined to harbor a rich diversity of species (Gibert and Deharveng 2002) and aquifers contain the highest proportion of rare taxa with restricted distributions (Hancock *et al.* 2005), the area presents a significant opportunity for biodiversity conservation. Finally, the area is under increasing pressure from ecotourism and land conversion.

This chapter discusses the geographic location of the study area and provides an in-depth review of the geological context of the system in order to demonstrate the ecological diversity of the area. Next, a review of climatic conditions, soil and vegetation types, and biological inventories associated with the system is provided. Finally, social concerns and pressures placed on the system through conservation efforts and ecotourism developments are reviewed.

2.1 Geographic Location and Extent

Sistema Zacatón is located in northeastern Mexico in the state of Tamaulipas, approximately 350 km from the southern tip of Texas (Figure 2.1). Villa Aldama, the closest city with over 10,000 inhabitants (INEGI 2000), lies roughly 12 km to the southeast. Sistema Zacatón is approximately 50 km from the Gulf of Mexico and 6 km from the southern tip of the Sierra de Tamaulipas. The system is located south of the Tropic of Cancer at latitude 22.99° N and longitude 98.16° W on the gulf coastal plain at an elevation of approximately 200 m above sea level (INEGI 1987).

Sistema Zacatón refers to the series of cenotes and karst features as defined by Gary *et al.* (2003) and Gary and Sharp (*in press*). This research focuses on the southern zone of the system comprised of five main water-filled sinkholes and associated surface features. These features are located within the bounds of Rancho La Azufrosa, and the study area follows the boundaries of the ranch (with consent from the landowner) covering an area of approximately 522 acres (Figure 2.2). The main cenotes are oriented along an east-west trending 1.5 km transect. The furthest west cenote, Zacatón, is the deepest at over 329 m and is easily identified by its round, floating grass islands (Figure 2.4).

2.2 Geology

Sistema Zacatón formed at the contact of Cretaceous limestone and Pliocene intrusive and Pleistocene extrusive volcanic rocks (Gary and Sharp *in press*; Fernández and Fernández 2004; Camacho 1993). The five main cenotes formed in a layer of thick Cretaceous carbonate rock that was uplifted and fractured during the mountain building events of the Laramide deformation (Camacho 1993). It has been hypothesized that precipitation enters the karstified limestone of the Sierra de Tamaulipas, less than 10 km to the northwest, and effectively recharges the system (Gary *et al*. 2003). As the groundwater travels down gradient, it contacts with a zone of volcanism at depth creating the environment necessary for hydrothermal karstification (Gary and Sharp *in press*; Palmer 2000).

Zacatón, the only cenote with spring outflow in the system, discharges through a sub-aqueous cave passage into the river, Nacimiento. This river passes the village of the same name and serves as the main water supply for the village and surrounding agriculture. Flow rates collected from the bridge range from 6.88 to 46.33 cfs (Table 2.1). Flow rates increase noticeably during the rainy season and in response to large storm events, suggesting the rapid recharge characteristic of heavily karstified limestone (White 2002). Hydrogen sulfide (H_2S) has been detected in Zacatón, Caracol, La Pilita, and La Azufrosa, further supporting the theory that hydrothermal karstification aided the speleogenesis of Sistema Zacatón (Gary *et al.* 2003).

2.3 Biology and Climate

The study area has a seasonally dry tropical climate with a summer rainy season; total annual precipitation varies from 800-1200 mm (31.5-47.2 inches) (Arriaga *et al.* 2002). Soils have been categorized as lithic leptosols reaching less than 10 cm of depth and eutric vertisols ranging between 20 and 50 cm of depth (Arriaga *et al.* 2000). A study by CONABIO reports that in 31 km^2 surrounding Sistema Zacatón, 72 percent is dominated by ranching, forestry, and agriculture and the remaining 28 percent is seasonally dry tropical forest (Arriaga *et al.* 2000).

Natural vegetation in the area is characterized by seasonally dry tropical forest and closely-related thorn forest (Medrano and Mejía 1998; Leopold 1950). Dominant families are Leguminosae, Euphorbiaceae, Burseraceae, Cactaceae, Malphigiaceae, and Anacardiaceae (Trejo and Dirzo 2000). The system hosts several rare and endangered floral species such as the Mathis spiderling (*Boerhaavia mathisiana*), Chestnut Dioon (*Dioon edule*), Walker's manihot (*Manihot walkerae*), and the Ponytail Palm (*Beaucarnea inermis*) (Mejía and Medrano 2004). Additionally, numerous endangered and endemic fauna have been reported in the area such as the: Tamaulipan blindcat (*Prietella lundbergi*), Yellow-headed Parrot (*Amazona oratrix*), Red-crowned Amazon Parrot (*A. viridigenalis*), and Green Parakeet (*Aratinga holochlora*) (Arriaga *et al.* 2002). Furthermore, several species of bats that have experienced a general drastic population decline (Harvey *et al.* 1999) have been discovered at Sistema Zacatón: the insectivorous Ghost-faced Bat (*Mormoops magalophylla*), the nectar-eating Nectar or Long-Nosed Bat (*Glossophaga soricina*), the Common Vampire Bat (*Desmodus rotundus*), and the Intermediate or Great Fruit-Eating Bat (*Artibeus intermedius* or *lituratus*). Bats were photographed and then identified by a biologist with Bat Conservation International (Figure 2.3).

The hydrothermal water and extreme depths of the cenotes of Sistema Zacatón suggest that this system is biologically unique on a global scale (Gary 2004; Culver *et al.* 2000). A recent NASA (National Aeronautics and Space Administration) grant has funded the investigation of life in extreme environments and is using Zacatón to test instruments that will search for life on one of Jupiter's moons, Europa (NASA 2003). The deep, phreatic shafts and unique water chemistry provide an environment similar to that believed to lie beneath the ice cap on the surface of Europa (Stone *et al.* 2005). The research will investigate and map the deep reaches of the sinkhole and search for signs of life (Fairfield *et al*. 2005). Thus far, humans have explored Zacatón to 281 m; however, due to physiological limitations, exploration was limited (Gilliam 1995).

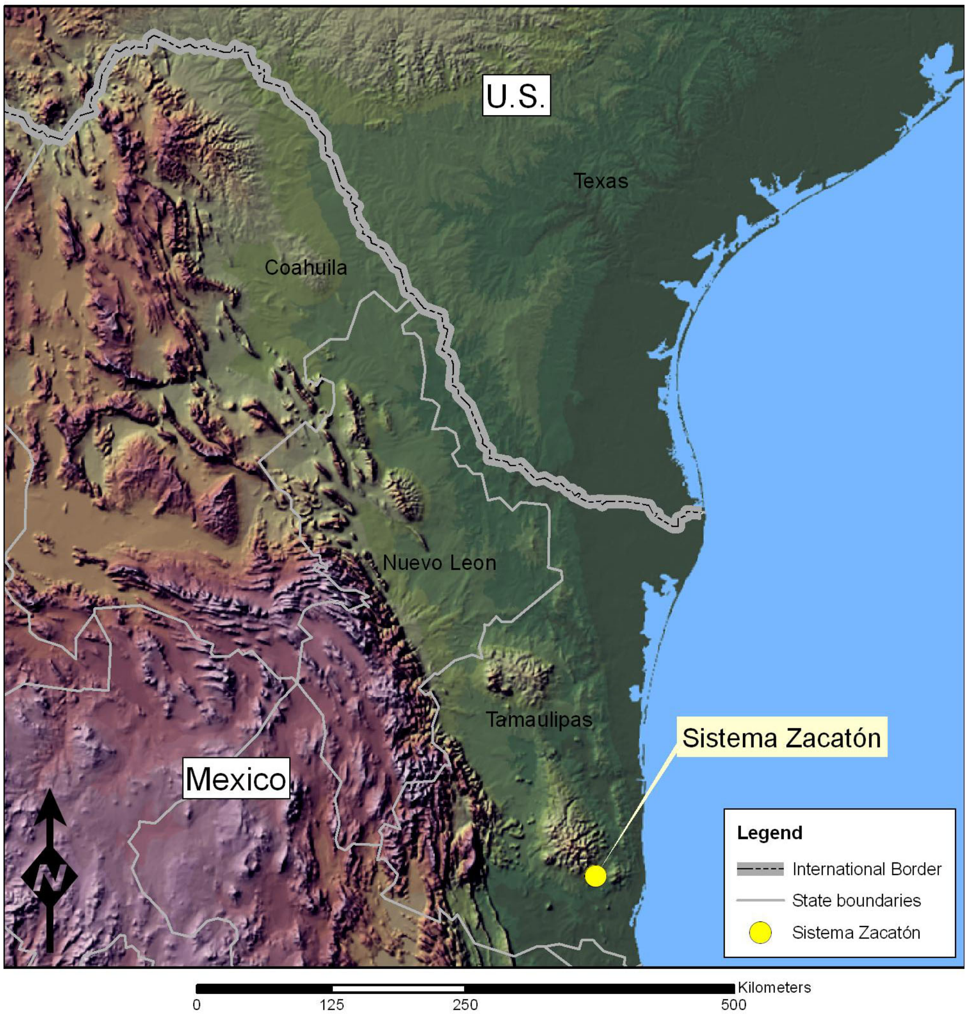
2.4 Conservation Efforts and Ecotourism

The sinkholes are known as both Sistema Zacatón and the Cenotes de Aldama. The term *Sistema Zacatón* refers to the area's karst system (Gary *et al.* 2003) and uses the deepest of the cenotes in the system, Zacatón, as a namesake (Figure 2.4). The name *Cenotes de Aldama* references the municipality, Aldama, and refers to the sinkholes using a modern version of the Mayan name *dzoonot* meaning "hole in the ground" (Mejía and Medrano 2004). The two names suggest two interpretations of the importance of the water-filled sinkholes. Sistema Zacatón implies a scientific view of the landscape as a whole that includes the sinkholes, dry caves, and surface features. Cenotes de Aldama suggests the cultural and economic importance of the water-filled sinkholes themselves by referring to similar water features found in the Yucatan peninsula that have become important tourist destinations.

CONABIO (the Mexican National Biodiversity Commission) identified the large water reserves and rich floral and faunal communities of the Cenotes de Aldama as ecologically important. CONABIO declared the system a viable resource to protect and designated it both a Priority Terrestrial Region and a Priority Hydrologic Region. The commission lists threats to the hydrology of the area as canalization, dewatering, modification of vegetation associated with agriculture, deterioration of soils, and contamination of waters by agrochemicals (Arriaga *et al.* 2002). Unregulated tourist activities, ranching, and selective wood cutting are considered the largest concerns to the quality of the terrestrial habitat, while increased sport SCUBA diving activities could jeopardize the aquatic habitats (Arriaga *et al.* 2000). Similarly, PRONATURA (the Mexican Association for the Conservation of Nature) and CESPEDES (the Private Sector Center of Studies for Sustainable Development) report the Cenotes de Aldama as a potential future Natural Protected Area (Garcia-Segovia *et al.* 2002).

There is abundant support for conservation of Sistema Zacatón at the national level; however, this support does not extend to local communities. Instead, the Cenotes de Aldama are identified as a tourist attraction. Despite being located on private property, several organizations advertise and promote tourism at the Cenotes de Aldama. The Aldama tourist department touts that because of the extreme depths and large size, the Cenotes de Aldama will become more famous than cenotes of the Yucatan Peninsula (Municipio de Aldama 2005). The tourism and international affairs department of the Tamaulipan state government cites the Cenotes de Aldama as a location for adventure tourism and SCUBA diving (2005). Each year there is an increase of visitors (personal observation). Individuals trespass onto the private ranch to see the sinkholes, bathe in their thermal waters, explore the extensive dry cave networks, and traverse the trails. Impact from visitors threatens to detrimentally affect the habitat in and around the sinkholes because no conservation or preservation plan exists (Arriaga *et al*. 2002; Arriaga, *et al*. 2000; Medrano and Mejía 1998). The thermal, sulfuric mega-sinkholes exist in only two known locations in the world, with only one in the western hemisphere (Gary 2002). Therefore, as Sistema Zacatón gains popularity care needs to be given to protect it from detrimental anthropogenic activities.

Sistema Zacatón Locator Map



Cartographer: Robin H. Gary
11/28/2005

Figure 2.1 Sistema Zacatón Locator Map
Sistema Zacatón is located in Northeastern Mexico in the coastal plane of the state of Tamaulipas. The shaded relief base map shows lower elevations in green and higher elevations in pink and brown.

Study Area Extent

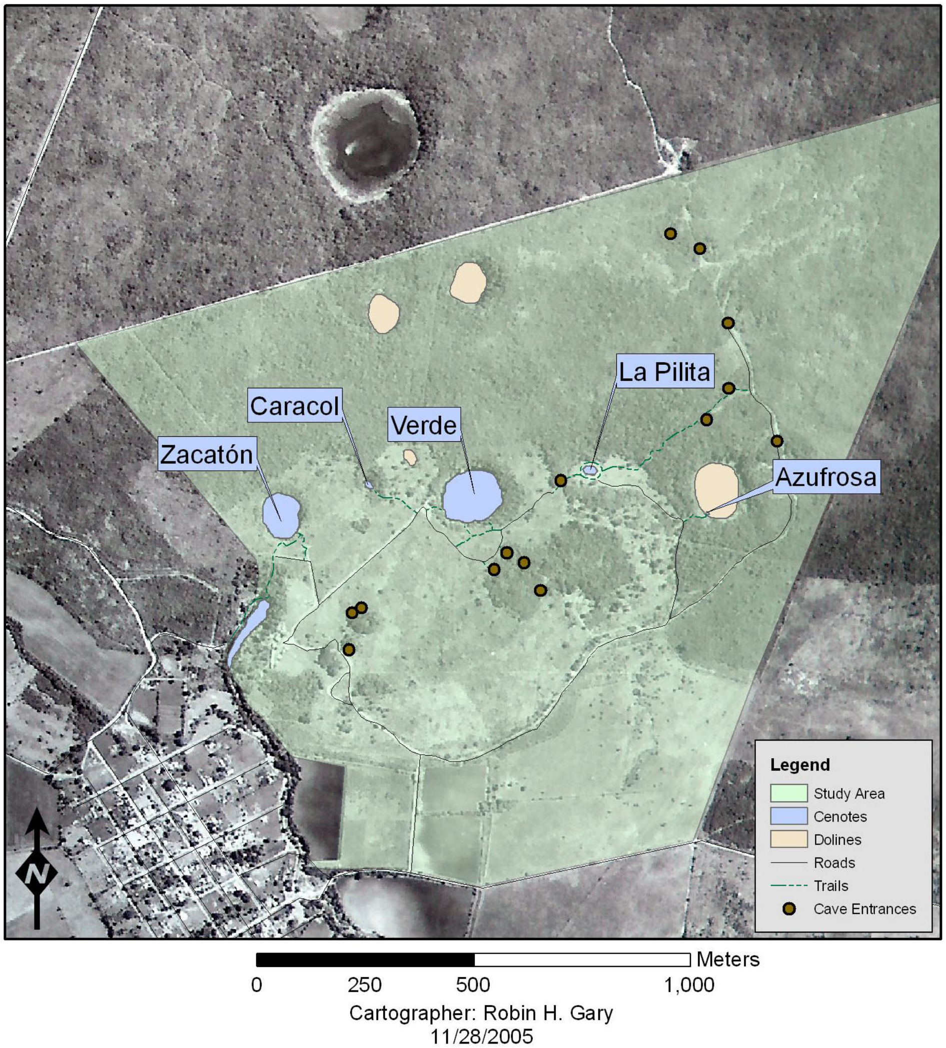


Figure 2.2 Study Area Extent
The study area boundary follows the boundary of the private ranch that encompasses Sistema Zacatón.

Table 2.1 Stage and Discharge Measurements Recorded at the Bridge at Nacimiento
Measurements were taken by Marcus Gary and the author using a Flow Tracker Flowmeter.

	Stage (feet)	Discharge (cfs)
8/20/2002	2.24	12.33
10/24/2004	2.36	26.43
12/27/2004	2.12	6.88
9/7/2005	2.56	46.33

Ghost-faced Bat
Mormoops megalophylla

Nectar or Long-Nosed Bat
Glossophaga soricina

Common Vampire Bat
Desmodus rotundus

Intermediate or Great Fruit-Eating Bat
Artibeus intermedius or lituratus

Figure 2.3 Bats of Sistema Zacatón
Photographs of the Ghost-faced and Fruit-Eating Bats were taken by Jean Krejca. The others were taken by the author.

Figure 2.4 Zacatón, Sistema Zacatón's Namesake
Zacatón is approximately 100 m in diameter and over 329 m deep. Floating grass islands, called zacate, make this cenote distinctive from the surface. Photo by Ann Kristovich.

Chapter 3: Literature Review

While human impact on a landscape is a common theme in landscape ecology, application of landscape ecology principles to karst landscapes is generally absent from the literature. This literature review first examines the principal themes within landscape ecology literature, followed by a review of literature on the characteristics and dynamics of karst systems. Finally, the applicability of a landscape ecology perspective in karst landscapes is explored.

3.1 Landscape Ecology

The term *landscape ecology* was originally introduced in 1939 by Carl Troll, a German geographer (Turner *et al.* 2001). Landscape ecology examines the effects of spatial pattern on ecological processes, linking pattern to process over a variety of scales and extents (Turner 1989). Research in landscape ecology has established that spatial heterogeneity in ecological systems at various scales often influences population structure, community composition, and ecosystem processes (Pickett and Cadenasso 1995). Causes of spatial variation have been attributed to biological (biotic), physical (abiotic), and societal (human) sources (Griffith 2002). The resulting landscape mosaic can thus be described as a combination of natural and human-managed patches that vary in size, shape, and arrangement (Turner 1989). Landscape ecology offers a framework capable of assessing the effects of human impacts on ecological processes at a variety of scales by examining habitat fragmentation, connectivity, and degradation (Pickett and Cadenasso 1995). Across many scales, landscapes can be described using several fundamental elements. Landscapes are viewed as a mosaic of patches and corridors of varying habitat types (Turner *et al.* 2001). Patches are nonlinear surface areas differing in appearance from their surroundings and consist of mostly interior, or an area of uninterrupted, homogenous land use (Forman 1995; Forman and Godron 1986). Corridors are all edge and have no interior (Forman and Godron 1986); they are relatively narrow and provide zones of transition and contact between areas of differing land uses (Turner *et al.* 2001).

Expansion of human activities has caused habitat fragmentation across the globe (Collinge 1996). Large, continuous complexes of natural habitat have been converted for agricultural, industrial, or urban land use, which has led to loss of original habitat and increased fragmentation of remnant patches (Jacquemyn *et al.* 2003). Land ownership, as a major determinant of land cover diversity and connectivity, was examined in an analysis of forest structure (Stanfield *et al.* 2002). The study established a positive correlation between landowner parcel size and forest cover patch (e.g., the larger the land tract, the larger the forest cover patch). In addition, the study determined that large numbers of landowners within a watershed increased the diversity of forest cover. And accordingly, watersheds under one landowner were found to be more homogenous and displayed higher connectivity. Whether in a rural, suburban, or urban environment, landownership directly influences patch quality, geometry, and connectivity.

Some patches conserve natural landscape remnants as others are developed and altered. As anthropogenic activities fragment the landscape, wildlife and wild plants become continually more isolated within remaining patches of suitable habitat (Stamps *et al.* 1987). Populations within large patches have less extinction risk given the possibility of stochastic disturbances because there is a larger resource base to compensate for the disruption of habitat (Hokit and Branch 2003). Critical thresholds and allee effects determine the fate of smaller populations (Groom 1998). Reproductive capability of species within a patch can be influenced by Allee effects, as depicted in Groom's study of an annual herb, *Clarkia concinna* (1998). The Allee effect describes the tendency of limited populations to drastically decrease reproductive productivity due to low density, small patch size, or patch isolation. Groom found *Clarkia concinna* to follow the Allee effect because species within the study area were often pollen limited; pollen receipt limited seed set, and therefore, limited the next year's population density. Such a downward cycle led to the extinction of 28 among 211 patches of *Clarkia concinna* over the course of six years.

Landscape connectivity, or the degree to which the landscape facilitates or impedes movement along corridors and among resource patches (Taylor *et al.* 1993), also plays a vital role in the health of metapopulations, or a population that is spatially subdivided yet migration from one local population to at least some other patches is possible (Turner *et al.* 2001; Pickett and Cadenasso 1995). Studies have shown that the loss of individuals within a metapopulation may be less dramatic if gene flow among survivors remains intensive (Jordán *et al.* 2003). Anderson and Danielson (1997) correlated patch connectivity and the quality, arrangement, and existence of corridors to the survival rates of a metapopulation. Anderson and Danielson's experiments determined that medium and high quality corridors aided dispersal and immigration while isolated patches resulted in lower populations. Additionally, patch area, or patch geometry, affects the dispersal rate (Stamps *et al.* 1987), and therefore, greatly affects the ability of a species to reproduce. Patch geometry would be negated entirely if the quality of the habitat within the patch were poor. Hokit and Branch's (2003) study of scrub lizards confirmed that survival and recruitment to patch areas can greatly influence the probability of extinction and determined that it is not only stochastic disturbance but connectivity that determines the success of a species. In a study of the endangered bush-cricket, Jordán *et al.* (2003) topologically and topographically explored the importance of habitat patches and corridors on metapopulation health. Their results concurred with Anderson and Danielson (1997) and Hokit and Branch (2003); well-connected populations were under less competition for resources and space and had a larger gene pool. Given the results of these studies, generalizations can be made that most species will benefit from well-connected habitat patches. Corridors and corridor quality, therefore, must be considered in conjunction with patch geometry and quality in conservation planning.

Bengtsson *et al.* (2003) examined the relationship of disturbance and resilience for various plant and animal species. They found that resilience depended on the ecological memory of the disturbed areas in conjunction with the matrix surrounding them. This finding raises major concerns in the case of *Beaucarnea gracilis*. A study by Cardel *et al.* (1997) showed *Beaucarnea gracilis*, endemic to the Tehuacán Valley in Mexico, to be threatened by goat grazing and human extraction. Due to its limited dispersal and rapid decline in individuals, it is theorized that *Beaucarnea gracilis* will soon reach a critical threshold. Its endemism severely limits its resilience; therefore, without a change in land use within its habitat, it will become extinct. The number of individuals within a population must be severely limited for this effect to influence population size, but it further reinforces the importance of healthy, well-connected patch habitats in conservation planning.

3.2 Karst Systems

Karst is a landscape formed by the dissolution of soluble rock including limestone, dolostone, or gypsum and is characterized by sinkholes, caves, and underground drainage systems (Gunn 2004). Mature karst drainage systems tout some of the largest water-producing wells and springs in the world (Veni *et al.* 2001). Ford and Williams (1989) estimate that 12 percent of the Earth's land surfaces are carbonate outcrops made up of limestone or dolostone up to several kilometers thick. In 1989 they reported approximately one quarter of the world's population, undoubtedly more today, obtained their domestic water supplies from these rocks. Given that close to 99 percent of all freshwater is located in underground aquifers and more than three-fourths of that underground water is non-renewable (Jackson *et al.* 2001), water availability and quality in karst aquifers becomes a global concern. Additionally, thousands of obligate subterranean animals have been described, and this number continues to grow with approximately 20 new species discovered each year (Culver *et al.* 2004). Researchers hypothesize that only 20 percent of the actual species have been identified suggesting that underground habitats are areas of high biodiversity (Sket 1999). These species' tolerance to ecological changes is largely unknown (Sket 1999), which raises concerns because subterranean flora and fauna have limited distributional ranges and may be highly specialized and diversified (Veni *et al.* 2001).

Karst rocks are widespread, occurring on almost every continent, while Europe has the largest percentage of carbonate rock outcrop relative to its area (Drew and Hötzl 1999). In general, carbonates are more abundant in the Northern Hemisphere (Ford and Williams 1989); however, record deep and long caves have been reported in Europe, North America, Central America, and Asia (Gillieson 1996). The degree of karstification depends more on the solubility and development of secondary porosity of the host rock than the geographic location (Drew and Hötzl 1999).

Primary and secondary porosity, joints, faults, and fractures play a significant role in determining the intensity of karstification of a landscape. In general, karstification relies on two types of porosity: primary and secondary. Primary porosity refers to a rock's ability to transmit water between grains, while secondary porosity refers to the ability of water to pass through fissures and conduits in the host rock (Ford and Williams 1989). Both types of porosity can play an integral part in water transport within the karst system (Gillieson 1996). Additionally joints, faults, and fractures influence the water flow paths. Joints are simple fractures that lack significant vertical or lateral displacement and can occur across several bedding planes (Ford and Williams 1989). Most joints are penetrable and offer a pathway for water to enter the karst system. Faults and fractures with substantial displacement up, down, and/or laterally can offer a wide opening and are often particularly important in karst drainage networks for their ability to host interconnected solution conduits (Ford and Williams 1989).

Cave passages can be of two general types: vadose or phreatic. Passages of vadose origin form above the water table and follow the steepest available openings (Palmer 1991). These passages typically have well-defined channels etched into the cave floor. Phreatic passages form under the water table in saturated conditions and follow the path of greatest hydraulic efficiency (Palmer 1991). Cross-sections of phreatic passages commonly resemble ovals, because acidic water is in contact with the walls, floor, and ceiling at the same time causing dissolution at generally the same rate. Solutional caves can form through epigenic or hypogenic processes. Epigenic caves are formed by movement of water rich in carbon dioxide from the recharge area on the surface, through the karst drainage network, then to valleys and springs; this process is the most common form of speleogenesis (Hill 2000). Carbon dioxide, present in the atmosphere and in decaying matter in soil, mixes with hydrogen molecules in water and creates weak carbonic acid, the most abundant epigenic acid (Palmer 1991). The weak acid flows down from the surface through natural fractures and fissures, enlarging the pathway by dissolving calcite (Gillieson 1996). This process allows progressively larger volumes of water into the drainage network, which exponentially—though only on a geologic timescale—accelerates karst development (Gunn 2004). Rainwater travels from the surface through the underground flow network until it reaches the water table where the karstified limestone acts as an aquifer storing large quantities of water. Hypogenic caves are formed by water in which the aggressiveness has been established at depth by sulfuric acid, cooling of ascending water, or acids produced by the maturation of hydrocarbons (Palmer 2000). Contrary to epigenic speleogenesis, hypogenic processes start at depth. Common characteristics of hypogene caves can be large passage size, ramiform-spongework pattern, horizontal passages connected by deep pits and fissures, and native sulfur deposits (Hill 2000). It is feasible for a karst system to be influenced by both vadose and phreatic passage development and have both epigenic and hypogeneic processes.

Karst landscapes are complex, three-dimensional, integrated, natural systems that include rock, water, soil, vegetation, and atmosphere elements. Most of the karst solution process is moderated by factors operating on the surface and upper skin of the rock (Gillieson 1996). Vegetation and soil regulate the quality and quantity of the inputs into the karst system (Drew and Hötzl 1999). Nearly all surface karst features, such as dolines, sinkholes, and cave entrances, are formed by internal drainage, subsidence, and collapse triggered by the development of underlying caves (Palmer 1991). Dissolution associated with karst development creates a complex, heterogeneous underground flow network with a range of permeability that spans many orders of magnitude (White 2003).

Karst formation creates unique and highly specialized ecosystems adapted to low-energy and lightless environments (Veni *et al.* 2001). There are three basic levels of adaptation to life in caves. Trogloxenes are terrestrial species that take shelter in the warmth and high humidity in cave entrances but leave the cave to forage for food. Bats are a good example of this group. Troglophiles are terrestrial species that dwell in the twilight zone of the cave and are capable of surviving on the surface in similar environments, such as under logs or rocks. Cave crickets, spiders, and millipedes are adapted to the low light environment found in caves but have also been found living outside caves. Troglobionts and stygobionts are terrestrial and aquatic (respectively) obligate cave dwellers; their adaptations limit them to cave areas. Blind catfish, salamaders and cave beetles exhibit significant eye and pigment reduction typical of obligate cave dwellers and could not survive on the surface. Trogloxenes and troglophiles are less sensitive to changes in habitat than troglobionts and stygobionts (Gillieson 1996). Isolation of species in caves promotes evolutionary changes that cause endemism (Christman *et al.* 2005; Culver *et al.* 2000; Sket 1999). Troglobionts and stygobionts have small ranges and high-endemism (Christman *et al.* 2005). Typically, even with unimpacted conditions, the primary producers in the cave food web (bacteria and fungi) have limited productivity restricting population numbers of cave biota (Gillieson 1996). They are highly specialized which makes them especially sensitive to ecosystem changes caused by pollution or increased sedimentation (Gillieson 1996). Troglobites and stygobites make up more than 50 percent of the imperiled U.S. animal species (Culver *et al.* 2000). Due to sampling and inventory inadequacies in extreme environments the literature posits that the extent of obligate cave fauna is incompletely known (Culver *et al.* 2004). Furthermore, research suggests that the 24 species with federal endangered species status do not adequately represent underground endemic and threatened species (Christman *et al.* 2005; Culver *et al.* 2004; Culver *et al.* 2000).

Karst remains one of the most difficult landscapes to understand and model because it varies widely in scale and expression (White 2003; White 2002; Veni 1999). First, karst is difficult to identify, and the physical characteristics that typify the karst landscape are largely subterranean (Gunn 2004). Furthermore, investigating the presence of endemic and rare species is often complicated by a strenuous journey to remote sampling locations (Culver *et al.* 2004). Finally, assessments of water quality and quantity in karst aquifers are difficult because karst aquifers are highly heterogeneous; water quality and quantity change substantially within small distances (Dogwiler and Wicks 2005; Ford and Williams 1989).

Three methods for identifying and characterizing karstic terrains are dye tracing, geophysical analysis, and geomorphological analysis (Veni 1999). The first method relies on tracking a known amount of traceable dye injected in karst surface features through conduits within a karst aquifer by repeatedly testing wells and springs along the probable route (Ford and Williams 1989). Dye tracing is a commonly used method that provides unequivocal evidence for groundwater flow paths; however, this method can be time consuming on a large scale (Smart and Worthington 2004). The second method, geophysical analysis, probes for cavities within the subsurface by analyzing the contrasts in physical properties (density, electrical resistivity, magnetic susceptibility, or seismic velocity) between subsurface structures (Stierman 2004). Downfalls of this technique are the expense and the limited penetration of the analysis (Stierman 2004). The third method, geomorphological analysis, provides the most cost effective and thorough terrain analysis (Veni 1999). Identifying the subtlies of epikarst, or surface karst features, and investigating the depths and sizes of fractures, sinkholes, and caves can characterize the degree of karstification (Veni 1999). A similar landscape assessment approach employs geomorphological analysis techniques in conjunction with Geographical Information Systems (GIS) analysis. Using this method, the prevalence of epikarst, presence of protective cover (soil), infiltration conditions, and degree of karst drainage define an area's sensitivity (Doerfliger *et al.* 1999). This method provides a large-scale analysis tool that policy makers and land managers can easily reference.

Furthermore, estimating and predicting water availability in karst landscapes is a way to better allocate water supplies. Accurate measurements of aquifer recharge leads to efficient and effective use of water, balancing quantities to maintain ecosystem function and provide water for human use (Jackson *et al.* 2001). Research suggests that groundwater protection zones in karst environments are typically not founded on solid hydrogeologic principles; they are often inadequate and as a result they may be ineffective (Doerfliger *et al.* 1999). Due to the effects of hydrologic connectivity within a karst landscape, catchment basin scale attention is needed (Pringle 2001). As the hydrologic cycle links habitats by transporting water—and pollution, sediment, and organics with it—water quality in all portions of a watershed be taken into account; however, studies have shown that conservation efforts in the upper portions of watersheds are more successful due to less contamination from anthropogenic activities (Pringle 2001).

Adaptive management and ecological restoration techniques are common in the United States but less so in Mexico (Drew and Hötzl 1999). Mexico is home to significant karst terrain (Gillieson 1996) and an examination of several natural protected areas reveals the need for management reform. Merely setting aside land will no longer be sufficient to restoring ecosystem function in degraded areas (Whisenant 1999).

The Yucatán peninsula in southern Mexico is arguably one of the world's most karstified landscapes. The landscape is so heavily karstified that there are no naturally occurring rivers in the peninsula and the freshwater lens extends down from 10 to 23 m of depth (Gerrard 2000). Mérida, the largest city in the

Yucatán peninsula with 600,000 inhabitants, relies solely on karst groundwater for its water supply (Escolero *et al.* 2000). Four strategically located, protected well fields provide drinking water for residents. Agriculture and hog raising activities add chemicals and nutrients to surface runoff which flows down gradient towards the protected well fields and threatens to influence water quality. Catchment-level management and regulation of human activities would preserve water quality and, therefore, water availability. Currently, a hydrogeological reserve has been proposed, but it has gained little governmental or popular support.

Cuatro Ciénegas valley in the northern state of Coahuila received Natural Protected Area status in 1994 (Calegari 1997); as of 2003 the only visible changes have been the construction of a visitors center and the installation of a few signs instructing visitors to stay on established roads and not to leave trash (personal observation). Scientists have discovered at least 23 endemic plants and 28 aquatic species; it is one of two desert systems with such high rates of endemism (Calegari 1997). The other, Ash Meadows, Nevada, is considered a critically endangered habitat in which human activities are strictly regulated. Attempts to educate Cuatro Ciénegas valley residents and visitors about the ecological importance and vulnerability of karst landscape have managed to change attitudes about the valley, but have done little to minimize human impact. Tourist numbers increase each year and there is little increase in park infrastructure and management.

3.3 Karst Landscapes in a Landscape Ecology Framework

The process of karstification connects a subterranean ecosystem to an existing terrestrial landscape through open conduits which serve as low-resistance pathways for water flow (White 2002). The landscape ecology analysis of karst terrains can utilize the traditional landscape elements such as matrix, patch, and corridor to examine effects of change on the three-dimensional landscape. In a karst landscape, the surface matrix includes and distinguishes surface karst features from traditional land covers. Connectivity with the subterranean component of the landscape is established through the surface karst features (Ford and Williams 1989). Conduits (fractures, fissures, and passageways—depending on size) can be considered corridors, because they are relatively narrow and differ from the adjacent areas (Turner *et al.* 2001). Corridors vary from wide to narrow, high to low connectivity, and from meandering to straight (Forman 1995); this definition is particularly true of conduits in karst landscapes (Klimchouk 2004). Additionally, a patch defined as “a relatively homogenous nonlinear area that differs from its surroundings” (Forman 1995) in the subterranean portion of a karst landscape can range in size from caverns to drip pools.

Patch connectivity and quality within the subterranean component of the karst landscape is greatly influenced by land use changes on the surface. Because subterranean flora and fauna have limited ranges and high-endemism (Christman *et al.* 2005; Culver *et al.* 2004; Culver *et al.* 2000), allee effects can be used to describe metapopulation dynamics. Allee effects occur in response to low density, small patch size, or patch isolation; populations in these situations face low reproductive rates, increasing the likelihood of extinction (Groom 1998). Populations with severely restricted ranges, typical of subterranean flora and fauna (Christman *et al.* 2005), face a higher probability of stochastic extinction due to demographic, environmental, and genetic factors (Morgan 1999; Amarasekare 1998). Populations under the Allee effect can be devastated by further limiting connectivity or patch quality (Stephens and Sutherland 1999).

Land conversion for human activities is a leading cause of habitat fragmentation, isolation, and degradation (Stamps *et al.* 1987). As karst areas are characterized by high permeability, the effects of urban and tourist, agricultural, and industrial development pose serious threats to the karst ecosystem (Drew and Hötzl 1999). Pollution (point source and non-point source), extraction, and disturbance associated with these human activities can severely limit ecosystem functions by influencing patch quality and connectivity (Drew and Hötzl 1999).

Overall, land conversion affects the subterranean component of the karst landscape in two ways: deteriorating patch quality and decreasing patch connectivity. Air pollution, discharge of wastewater and fuels, storage and deposition of solid waste, and excavations in connection with construction are four of the main impacts on karst caused by urbanization and tourism (Drew and Hötzl 1999). Patch quality is affected by multiple factors. Emissions from automobiles and industry contribute a significant amount of carbon dioxide to the atmosphere; the carbon dioxide mixes with hydrogen producing acidic rainwater; the more acidic rain mobilizes pollutants and increases subterranean dissolution which can lead to collapse or water quality deterioration (Drew and Hötzl 1999), both of which could lead to habitat destruction for troglobites and stygobites. Furthermore, the residence time of poor quality water caused by contaminants from wastewater and fuel spills depends on the nature of the contaminant (whether it floats, sinks, or dissolves) and the karst structure (Drew and Hötzl 1999). Spill remediation is complicated when the contaminant sinks into fissures and cavities deep within the aquifer or floats at the water table coating the ceiling and walls as the water level fluctuates; it is nearly impossible to determine the exact location of the contaminant (Drew and Hötzl 1999). Additionally, leachate from solid waste deposits such as landfills and domestic trash piles directly affect karst waters as rainwater passes through solid waste deposits and mobilizes organics, metals, and toxic chemicals flushing them into the karst drainage system (Veni *et al.* 2001). Though dwell times for dissolved materials are typically rapid (Ford and Williams 1989), solid waste deposits contribute such contaminants over long time periods (Drew and Hötzl 1999). Furthermore, human activities on the surface can decrease patch connectivity. Excavation for foundations and roadways expose cracks and fissures that lead to the underground drainage network, and with a lack of surface vegetation to slow runoff, surface water carries sediment and pollutants directly into the karst aquifer (Danielopol *et al.* 2003). Sediments and contaminants flushed into in karst drainage systems can decrease permeability, and therefore connectivity (Mahler *et al.* 1999) causing patch isolation.

Similarly, agricultural activities affect subterranean patch quality and connectivity. Runoff from agricultural fields can severely alter groundwater conditions. Karst areas typically have a shallow soil layer, so both point source (e.g., localized animal effluent) and non-point source (e.g., fertilizer, pesticides) pollutants bypass the natural filtration provided by thick soils and directly enter the karst drainage system (Drew and Hötzl 1999). Common problems in agricultural areas include nitrate contamination, micro-organism blooms, gully erosion and the salinization of soils and water (Danielopol *et al.* 2003). The introduction of large amounts of nitrate and micro-organisms into the karst ecosystem significantly alters the conditions for troglobites. Additionally, erosion of topsoil causes sedimentation of cave passages, which can lead to local extinctions. Salinization of soils and water through irrigation with saline water intensifies the rate of karstification of rocks, which can lead to structural collapse.

Landscape-level management can alleviate environmental stressors in karst landscapes through effective management of surficial land use and land cover. A process-oriented approach to restoration, repairing the natural regulatory processes, is well suited for improving conditions in karst terrains (Whisenant 1999; Drew and Hötzl 1999). The quantity and quality of water passing underground is regulated by the surface elements of karst system: vegetation, soil, regolith and closed depressions (Gillieson 1996). Degradation or removal of any of these elements results in the reduction of quality or quantity of recharge. Contrarily, the restoration of vegetative cover reduces erosion and slows runoff (Dobson *et al.* 1997). Plant roots both stabilize soils and break up the surface, which allows more infiltration. Additionally, plants can immobilize phosphorous and nitrate, reducing levels that flush into the karst drainage network. Substantial soil layers provide an essential buffering zone that guard against aquifer contamination (Drew and Hötzl 1999). Soils trap pollutants before they wash into the karst drainage. The use of mulch on top of existing soils and straw bale filters aided efforts to slow and clean runoff entering sinkholes (Gillieson 1996). Such temporary solutions lead to soil stabilization and return of vegetation. Terminal land covers such as concrete and asphalt associated with urbanization seriously compound runoff and pollution concerns (Mahler *et al.* 1999). Roads, parking lots, and buildings concentrate pollutants and increase runoff rates; limiting impervious cover in karst areas to no more than 15 percent of the total land area, allowing enough infiltration area to counterbalance collection on impervious surfaces (Veni 1999). In addition to soil and vegetation recovery, Gillieson (1998) names development of sewage treatment facilities in order to prevent raw effluent from accessing the aquifer directly as a priority. Likewise, reducing use of fertilizers and pesticides in karst areas would increase the quality of recharge entering the aquifer.

In order to improve management and regulation of human activities in karst landscapes, a few fundamental changes are required. First, karst must be recognized as a resource and maintain the same protection as forests and wetlands. Day (1996) notes the correlation of karst landscapes to conservation areas; typically protected karst areas coincide with endangered forest or marine ecosystems covered by federal or state regulations. Drew and Hötzl (1999) reveal that cave or karst protected areas are justified more by natural history than biodiversity or water source protection. Recognizing karst as a unique landscape with a distinctive ecosystem could aid development of management and protection techniques specific to karst. Expanding ecosystem types to include subterranean, solutionally formed environments would help educate policy makers, managers and the public about the vulnerability of karst areas. Plagnes and Bakalowicz (2001, 2002) suggest the most powerful reform for the heavily populated Larzac karst plateau in southern France is the education of the residents. Additionally, Veni *et al.* (2001) suggest creating Best Management

Practices with standards high enough to be appropriate for management in fragile karst areas.

Karst provides an essential source of water for more than one quarter of the world's population (Ford and Williams 1989). Additionally, karst systems increase the biodiversity of an area by adding an extreme environment to the known terrestrial environment. Lack of careful management and protection of karst landscapes will undoubtedly result in loss of biodiversity and reduction in water quality and availability (Urich *et al.* 2001; Vermeulen and Whitten 1999; Watson *et al.* 1997). It is imperative to consider the connectivity of surficial ecosystems and the impact of land management regimes to the subterranean system present in karst landscapes (Danielopol *et al.* 2003; Drew and Hötzl 1999).

Chapter 4: Methods

Several different methods will be used to quantify the extent of human influence on Sistema Zacatón. A range of scales and extents will be employed to examine the effects of anthropogenic activities on the system. First, in order to investigate land conversion for agricultural use in and around the study area, a land use and land cover change detection will be performed. Second, on a smaller scale to establish localized impacts within the study area, a vegetation survey will compare populations of the ponytail palm, *Beaucarnea inermis*, in three zones subject to different land use practices. Third, a survey and investigation of karst and cave features in the study area will be completed to establish the degree of interconnectivity between the surface and underground components of the landscape.

4.1 Remote Sensing Analysis of Agricultural Land Conversion

Remotely sensed images enable land use and land cover change detection over time (Jensen 2000). Land use and land cover change detection is limited by the spatial and temporal resolution of imagery (Lillesand *et al.* 2004). This research will utilize an MSS triplicate developed for The North American Landscape Characterization (NALC) program, due to the availability, low cost, and representative time span. A recent study shows that NALC MSS triplicates provide the best available, continuous, public source of medium-resolution images for land use and land cover change detection in Mexico over the 1972-1992 time period (Lunetta *et al.* 2002). The change detection will be performed to investigate trends in land conversion for agricultural use over time in and around Sistema Zacatón. The land cover change analysis will employ an expanded extent in order to establish regional land use trends. Additionally, as vegetation around the cenotes is more similar to vegetation located at higher elevations in the Sierra de Tamaulipas (Medrano and Mejía 1998), the extent will include a representation of seasonally dry tropical forest for training data purposes.

Analysis will be performed using ERDAS Imagine 8.7 and ESRI's ArcGIS 9.0. Images will be selected as close to the same calendar date is feasible to minimize sun angle and seasonal differences (Lillesand *et al.* 2004). Climate data including monthly temperature and precipitation averages will be collected for the area. This research will attempt to use imagery sensed after a period of substantial rainfall to minimize complications associated with remote sensing of arid environments such as high reflectance values of sparsely vegetated ground and atmospheric dust (Tueller 1987).

ERDAS Imagine's periodic noise removal algorithm will be used to compensate for banding present in any of the scenes. Several iterations will be run to select the minimum affected frequency to be removed to minimize distortion. Atmospheric interference, such as scatter or absorption, presents challenges in remotely sensed land use and land cover change detections (Lillesand *et al.* 2004). Pixels affected by clouds or their shadows will be removed from all three images before performing a change detection. To remove the effects of clouds, the images will be classified into seventy-five classes through an unsupervised classification process. The clouds and shadows will be identified and then masked out of the MSS image. A model will be created to expand the classes identified as clouds or shadows into fifty classes, and those classes will be investigated more closely. After identifying the clouds and shadows, the fifty classes will be recoded to create a mask that can be used to remove pixels affected by clouds or shadows from the analysis.

Each of the three processed images will be classified using a seventy-five class unsupervised classification with forty iterations and a convergence threshold of .99 using the ISODATA (Iterative Self-Organizing Data Analysis) cluster technique in Imagine. This clustering algorithm assigns pixels that illustrate similar spectral signatures to the same class (Lillesand *et al.* 2004). The seventy-five spectral classes will be reduced to thirty by evaluating spectral signatures and manually selecting the most distinctive. Then using the thirty selected spectral classes as training data for a supervised classification, each image will be reclassified. The resulting spectral classes will be attributed to a land use and land cover classification scheme developed by the author.

The classification scheme will follow the Level I categories developed by Anderson *et al.* (1976) with a few modifications. Due to the location of the remote sensing study extent several of the classes will be eliminated from the scheme. The remote sensing study area is in an arid area with no wetland, snow or ice fields, or tundra. Additionally, due to the rural nature of the extent, the low population density, the tendency of residents to use natural building materials, and the lack of asphalt and concrete, there will be not be an urban or built-up class as in Anderson's Level I classification scheme. The modified class descriptions are detailed below:

Bare or built-up: Areas with little or no above-ground vegetation including compacted soil, gravel or dirt roads, or barren fields. Or areas with high-density primitive structures that use mud or dry palm fronds as roofing materials. This category is characterized by areas with high reflectance.

Agriculture: Agricultural land including grassland/pasture, cropland, fallow fields, or areas used for ranching.

Forest: Seasonally dry tropical forest and Tamaulipan Thorn Forest.

Water: Water features including rivers, cenotes, and lakes.

No data: Pixels found to contain either clouds or shadows of clouds.

This minimal land use and land cover classification scheme was created because it meets the goal of this study. First, the extent that will be included in the land use and land cover change detection has a limited elevation range (160-

300 m) (INEGI 1987), and since the extent encompasses a relatively small area, it is assumed that the entire extent is subject to the same climatic conditions. The simplified classification scheme attempts to minimize misclassifications by lessening ambiguity between the classes. As the goal of the change detection will be to determine the amount of land converted to agriculture, with special emphasis on Forest to Agriculture conversion; therefore, the simplified classification scheme is sufficient.

Excluding the pixels affected by atmospheric interference, the land use and land cover change detection will quantify the square meters for each class in each classified image. Three change detections will be performed to examine change between the images selected images in the NALC MSS triplicate. A model will be created to spatially represent the areas that changed from Forest to Agriculture and from any other category to Agriculture.

4.2 Vegetation Survey

Many applications of landscape ecology address the relationship between the landscape mosaic and how it changes over time and a particular environmental variable of interest (Turner *et al.* 2001). In this thesis, the application of a remote sensing analysis of agricultural land conversion will examine trends in the overall landscape mosaic, and a vegetation survey will address an indicator species' response to those changes over time. The identification of an indicator species is a typical tool for characterizing landscapes used in biogeography and ecology (Dufrêne and Legendre 1997). The selection of management indicator species reflecting the effects of a disturbance regime is an accepted method of examining the effects of abiotic conditions and/or changes in ecological processes (Lindenmayer 2000). It is hypothesized that unregulated tourism, agriculture, and ranching pose serious threats to the sinkholes and the surrounding karst landscape. The ponytail palm is affected by land use changes, extraction, and grazing (Osorio-Rosales and Mata-Rosas 2005). The ponytail palm, *Beaucarnea inermis*, was selected as the management indicator species due to its proven sensitivity to human extraction, habitat destruction, and ranching practices (Figure 4.1).

The ponytail palm species present at Sistema Zacatón, *Beaucarnea inermis* (Medrano and Mejía 1998), has been listed as a threatened species by numerous sources (INE 2002; Reserva Especial de la Biósfera Sierra del Abra-Tanchipa 2005). In many locations throughout Mexico, *Beaucarnea* populations have been found to be in a critical state due to very low recruitment rates and the destruction of habitat by agriculture, goat raising, and human extraction (Cardel *et al.* 1997). A study of seedling emergence and establishment in arid environments found that seedling survival rates were dramatically reduced by predation (Flores *et al.* 2004; Mandujano *et al.* 1998). Therefore, the status of the *Beaucarnea inermis* population in Sistema Zacatón serves to indicate the level of impact of anthropogenic activities such as tourism and ranching. Investigating the status of the ponytail palm population within Sistema Zacatón may indicate that the landscape has undergone major changes due to human impact.

Prior to the vegetation survey, the study area was divided into three zones according to land use: agriculture, trail, and forest through aerial photo interpretation and ground reconnaissance and random starting points and bearings were generated (Figure 4.2). Differences between the remote sensing land use and land cover classification and the vegetation survey land use zones can be attributed to the differing spatial resolution of imagery used to classify land use and land cover. MSS imagery has a significantly more course resolution (60 m by 60 m) than a DOQQ (2-4 m resolution). The agriculture zone (185.21 acres) included areas that were currently under production or illustrated secondary growth resulting from regeneration after intensive clearing. The trail zone (67.38 acres) was calculated by including the area easily accessible from the trail, estimated as 50 m from known, existing trails. The forest zone (263.55 acres) was interpreted from aerial photos and defined by dense canopy. Three starting points in each zone were determined using a random point generation tool in ArcMap to select three points within each zone polygon. A random bearing was calculated using the random number generator in MS Excel (Table 4.1).

The vegetation survey of the ponytail palm, *Beaucarnea inermis*, will be performed using the wandering quarter method, adapted from the plant-centered quarter method or point quarter method, as described by Catana (1963) and

Brower *et al.* (1998). The random starting points will be located using a hand-held global positioning system (GPS) receiver. The random compass bearing for each survey will be measured using a standard mapping compass. Distances from the starting point, between individuals, and circumferences at breast height will be measured using a 50-meter survey tape. Each survey will be performed with two or more people; one individual will stand at the reference point (either at the starting point or at the last ponytail palm surveyed) and monitor whether the other surveyor(s) is/are within the 45-degree search radius off the compass bearing. Location, distance, and circumference at breast height will be recorded for each individual ponytail palm within the survey.

4.3 Cave and Karst Inventory

The ability to represent and characterize karst landscapes, including the interactions of all components, has not been fully achieved (White 2002). The high heterogeneity associated with karst landscapes creates challenges in developing a comprehensive understanding of karst systems (Bakalowicz 2005). A geomorphological strategy for landscape characterization offers a framework for karst landscape assessment (Veni 1999). The karst landscape of Sistema Zacatón consists of a variety of karst features. Features vary from horizontal, dry cave passage to deep, phreatic shafts; surface features include dolines, cave entrances, springs, and sinking streams.

In order to examine the extent of karstification and establish baseline conditions of caves and karst features and the associated biota within Sistema Zacatón, a comprehensive survey will be performed. Geographic Information Systems have proven to be an effective tool for representing and analyzing karst features (Florea 2005; Kerski 2004). Traditional cave survey techniques will be combined with GPS and GIS to construct a geospatial inventory of the caves, karst features, roads and trails of Sistema Zacatón. Three survey techniques will be employed to investigate the karst landscape of Sistema Zacatón. Surface karst features will be located and recorded using a GPS. Shallow cave passages (dry and water-filled) will be mapped using standard cave survey techniques (Dasher 1994). The cenotes will be surveyed using temperature variation as a tool to examine water source and interconnectivity (Ford and Williams 1989).

A georeferenced and rectified digital orthophoto quarter quadrangle (DOQQ), obtained from the Ciudad Victoria INEGI office, will provide a base map for cataloged features. Primary data will be gathered using a Garmin Summit GPS with an accuracy of 15 m (Garmin 2005) and will be cross-checked with the georeferenced DOQQ. Roads and trails will be recorded by the tracking feature on a Garmin Summit GPS. Any dolines or cave entrances will be marked as a waypoint and attributes will be recorded in a field book. All tracks and waypoints will be downloaded as a comma delimited text file using the freeware program, Waypoint+ (Hildebrand 2001), imported into MS Excel, attributed, and exported as a DBF4 file. Tracks and waypoints will then be loaded into an ArcMap project. The roads and trail systems will be digitized by tracing tracks and waypoints overlaid on the rectified DOQQ. The karst features will be extracted from the waypoints file and exported to a karst features feature dataset. The extents of the cenotes will be digitized from the rectified DOQQ, and the feature class will be attributed with surface area and name.

The author will organize and participate in survey trips and utilize already existing raw survey notes to create a caves feature dataset. All survey teams will follow traditional cave survey methods as reported by Dasher (1994). Teams will be made up of no less than two people. Survey stations will be designated with flagging tape and assigned a unique identifier. Distances between stations will be measured using a 50-meter measuring tape. Azimuths from station to target will be measured using a survey-grade sighting compass. Inclinations from station to target will be measured using a 1-degree inclinometer. Cave sketches will be produced as the survey proceeds and will document information such as: the location of formations, types of floor materials, presence of bats, station location, etc. Station names and distances, azimuths, and inclinations along with sketches will be recorded in field books. Survey information will be compiled in Excel and imported into the survey program Walls (Mckenzie 2005). Coordinates for the initial surface survey station will be fixed into the survey by using coordinates taken by a GPS at the time of the survey or estimated from the georeferenced

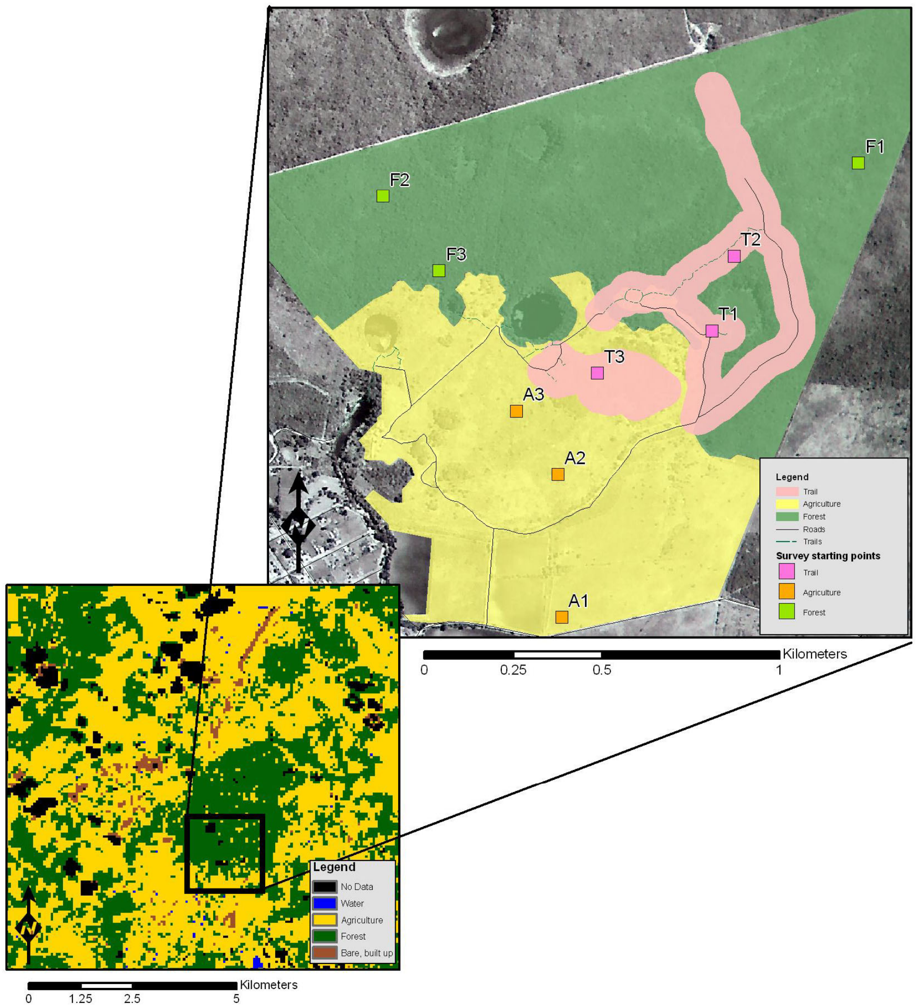
DOQQ, and a georeferenced cave line plot will exported as a shapefile. The shapefile will then be incorporated into the geodatabase. Furthermore, the cave line plot will be overlaid with survey sketches in Adobe Illustrator, and a digital map of the cave walls and features will be created. During each field campaign at Sistema Zacatón, observations concerning ecological health and human impact will be tied to locations on the maps. Locations and amounts of trash, graffiti, and broken formations will be recorded. General observations on number of bats and other cave-dwelling species will be made.

The cenotes are deep, water-filled caves do not lend themselves to direct exploration, and therefore, they will be surveyed using a separate method. In karst aquifers, temperature variations can indicate discrete groundwater bodies, which can be associated to water movement from different source areas (Ford and Williams 1989). Depths for each cenote were determined through SCUBA exploration efforts and plumb line surveys (Kristovich 1994). Interconnectivity will be examined through continuous water temperature variation surveys. StowAway Tidbit underwater optical temperature loggers will be deployed at several locations in the cenotes. The proposed deployment period is August 2002 to September 2005. The temperature loggers will be programmed to log at regular intervals, several times each hour.

Figure 4.1 The Ponytail Palm, *Beaucarnea inermis*

The top photo shows a mature ponytail palm. The bottom photo shows the effect of land alterations for ranching purposes on a ponytail palm.

Vegetation Survey Land Use Zones In Relation to the
Land Use and Land Cover Classification of 1990 MSS Image



Cartographer: Robin H. Gary
12/01/2005

Figure 4.2 Distribution of Random Starting Points and Land Use Zones in Relation to the Land Use and Land Cover Classification of the 1990 MSS Image
These zones were used in selecting the random starting points for the wandering quarter surveys. Specific locations and bearings are provided in Table 4.1. The image in the lower left displays the land use and land cover classification for the 1990 MSS image established for the land use and land cover change detection.

Table 4.1 Locations and Coordinates for Random Sampling Points

Coordinates are listed in UTM Zone 14, WGS84 and Bearings are in degrees. Figure 4.3 illustrates locations and zone delineation.

Point	Bearing	X	Y
T1	247	586441.36	2543022.59
T2	11	586503.47	2543233.59
T3	150	586118.77	2542903.15
F1	270	586853.53	2543496.65
F2	83	585513.94	2543402.48
F3	30	585672.39	2543191.91
A1	142	586017.79	2542213.36
A2	266	586007.09	2542617.44
A3	255	585890.31	2542796.41

Chapter 5: Results and Discussion

5.1 Remote Sensing Analysis of Agricultural Land Conversion

The images selected from the NALC MSS triplicate for path 26, row 44 were sensed on November 9, 1972, October 30, 1985, and October 20, 1990. The sun elevations for these images are comparable at 42°, 44°, 46° above the horizon for the 1972, 1985, and 1990 images, respectively. The acquisition dates fall at the end of the rainy season when monthly average temperatures are beginning to decline (Figure 5.1). A change detection extent of approximately ninety km^2 was used to subset the 1972, 1985 and 1990 MSS scenes in Imagine to isolate the same area of interest for each scene.

Due to banding, the 1972 image was run through the periodic noise removal algorithm in ERDAS Imagine. The banding was successfully minimized, but in so doing, the image was generalized (Figure 5.2) (Lillesand *et al.* 2004). Compared to the original image, the corrected image appeared more washed out and the edges of features were less distinct (Figure 5.3). The corrected image, however, did appear to smooth out the effects of banding on the reflectance values within each band.

The 1990 image was minimally affected by clouds. In order to remove the clouds and the shadows from the 1990 image, they were first identified. A seventy-five class unsupervised classification with 40 iterations and a convergence threshold of .99 was executed, and the classes that potentially contained clouds or shadows were identified. It was evident that the classes containing clouds and shadows also included areas of similar reflectance that should be classified as water, agricultural, or bare land. All classes that contained portions of clouds or shadows were expanded into fifty additional classes. In 27 iterations ERDAS reached a convergence of .991. The expanded classes were then examined and attributed accordingly. The pixels affected by clouds or shadows were then masked out of the 1990 image (Figure 5.4).

Next, a seventy-five class unsupervised classification with 40 iterations and a convergence threshold of 0.99 were run for the already processed 1972 and 1990 subsets and the original 1985 subset. The seventy-five spectral signatures for each of the unsupervised classes were then reduced to the most unique thirty classes by examining the separability of the spectral signatures. The best average separability for each images' resulting thirty classes using the distance measurement transformed divergence were 1976.93 for the 1972 scene, 1984.51 for the 1985 scene, and 1979.77 for the 1990 scene. The thirty remaining signatures formed the training data for a supervised classification that was then attributed according to the modified classification scheme (Figure 5.5).

Forest is the most dominant class in the classified 1972 image. The largest forest patch lies in the northwest portion of the remote sensing study area. It is largely intact with scattered agricultural and water patches in the interior. A central forest patch appears to be consistently interrupted by agricultural activity, but it maintains connectivity with the northwestern forest patch. Small forest patches are also evident in the southeast, northeast, and southwest corners. These patches are fragmented by agriculture and bare, built-up patches.

The most striking aspect of the classified 1972 image is the prominence of small-scale agricultural activity. Furthermore, it is interesting to note the section of small, isolated agricultural patches to the west of the central, triangular forest patch. Much of the land in the western section of the remote sensing study area is part of a land cooperative, or *ejido.* The small, independent agricultural patches probably represent areas worked by one or two families. The largest area of agricultural activity is evident in the northern section of the remote sensing study area. Today, this area corresponds to a large horse and cattle farm. It is probable that this agricultural activity corresponds to the early establishment of pasture and hay fields. Bare, built-up patches could correspond to residences, barns, and infrastructure development.

Overall, the classified 1985 image is dominated by large patches of continuous forest and smaller well-defined agricultural patches. Thorn forest still dominates the 1985 land use and land cover classification. The large forest patch continues to occupy the northwest section of the remote sensing study area and is interrupted minimally by miniscule patches of agriculture and water, though it does show a reduction in size. The second largest patch in the center of the remote sensing study area is connected to the northwestern forest patch by a corridor. This central, triangular forest patch appears to have regained continuity. Small-scale agricultural activities have ceased to interrupt the forest patch. It is at the southern section of this patch that the vegetation survey will seek to explore population status of the selected indicator species. This patch is nearly triangular in shape and is interrupted mainly by small water bodies. The lower two patches of water correlate with the cenotes, Zacatón and Verde. Another section of uninterrupted forest is observed in the east central section. This patch is connected with the central, triangular forest patch; however, there is a large number agricultural patches at the connection.

Agriculture is the next largest class within the classified 1985 image. Significant agricultural activity is evident in the northern section of the remote sensing study area. The near-linear edges on the southeast and western edges correlate to fence lines that define the boundary of the well-established horse and cattle ranch. The agricultural patch is dotted with water patches that represent man-made and natural water features on the ranch. The bare, built-up patches represent ranch infrastructure. Of particular interest is the growth of a medium-sized, continuous agricultural patch just west of the continuous, triangular forest patch. This new, continuous agricultural area illustrates the growth of the town of Nacimiento. To the south and slightly west of the central forest patch, the beginnings of the present town of Nacimiento are evident. A mixture of agriculture and bare, built-up patches extend northward from a significant water patch. This larger patch of water is expected to correlate with the river of Nacimiento that flows from Zacatón.

Despite interference from clouds, it is clearly evident that large agricultural tracts dominate the classified 1990 image. Forest patches are considerably smaller than years previous. The forest patch in the northwest quadrant is reduced in size and more fragmented. Forest patches within the horse and cattle ranch have been further isolated and are surrounded by agriculture. The central, triangular forest patch shows a reduction in area and is more interrupted by agriculture. Unlike areas to the north and immediately adjacent to the west, this triangular forest patch contains a large number of dolines and cave entrances. The prominence of surface karst features in this area may have contributed to the minimal amount of agriculture in the interior of the patch; shallow soils and rocky, uneven terrain make it unsuitable for agricultural activity.

The agricultural patch to the north encompassing the horse and cattle ranch has expanded past the boundaries observed in the classified 1985 image, and there are fewer forest patches in that area. This could be attributed to the growth of a new, large-scale cattle ranch to the southwest. Additionally, agricultural activity has expanded and further fragmented the forest patches in sections east and south of the triangular forest patch. Perhaps most noticeable is the agricultural expansion to the west of the central forest patch. Agricultural patches now dominate the area that was previously forest. Bare, built-up patches have expanded northeast representing further growth of the town of Nacimiento. A clearly defined corridor of bare, built-up shows the expansion of the road leading to the horse and cattle ranch.

In order to spatially analyze the conversion of thorny forest to agriculture, the images needed to be normalized. Since data were removed from the 1990 image, the same data also needed to be extracted from the other images to allow for an unbiased comparison. The model created to extract clouds and shadows from the 1990 image was then applied to the 1972 and 1985 images to make sure that each image has the same total number of pixels. Each image contains a total of 25,754 pixels and 1,329 of those contain no data. As the spatial resolution of a pixel in MSS scenes is 60 m by 60 m, each pixel covers an area of 0.0036 km^2. The area for each class in each image was calculated by multiplying the number of pixels by 0.0036 km^2 (Table 5.1).

Examining the land use and land cover classifications, it is evident that land used for agricultural purposes increases through time. Areas calculated from the land use and land cover classification indicate an 80.30 percent increase in agriculture and a 39.67 percent decrease in forest from 1972 to 1990 (Table 6.1). Additionally, analysis of the percent change from 1972 to 1985 and the percent change from 1985 to 1990 suggests that the greatest land conversion happened from 1985 to 1990. The results of the land use and land cover change detection imply that agricultural land use in the area has increased and areas of forest have decreased since 1972.

Land use and land cover change detections between the 1972 and 1985, 1985 and 1990, and 1972 and 1990 images were performed (Figures 5.6 and 5.7). The change detection spatially investigated the increase in land used for agricultural purposes with special attention on the transition from thorny forest to agricultural land use. Total area for pixels that exhibited no change, a change from any class other than forest to agriculture, and a change from forest to agriculture were calculated by multiplying the number of pixels in each class by the area represented by a pixel (Table 5.2). Consistent with the calculated areas, the spatial trend analysis showed an increase in agriculture, and a decrease in forest.

The change detection performed on the 1972 and 1985 classified images reveals that the majority of loss of thorn forest in this timeframe is concentrated in the northern section of the remote sensing study area. A considerable amount of forest area was lost in the boundaries of the horse and cattle ranch. The boundaries of the ranch are evident when examining the change from forest to agriculture. Sections of forest were lost in the western region of the remote sensing study area, but these sections tend to be small and isolated. However, the southern section displays larger clusters of forest converted to agriculture. The area south of what will become the town of Nacimiento shows a concentrated loss, and a large, somewhat more fragmented area of change is evident in the southeastern portion of the remote sensing study area. There are two major areas that do not display a change of any kind in the 1972 to 1985 spatial trend analysis. The northwestern forest patch remains largely in tact with the exception of the northeastern section within the horse and cattle ranch. Additionally, the triangular forest patch in the center of the remote sensing study area displays little loss of forest for agricultural land use.

The 1985 to 1990 land conversion analysis displays a much greater area of forest converted for agricultural use. The largest area of conversion is evident in the western portion of the remote sensing study area. Substantial clumps of the northwest forest patch were converted to agriculture. This conversion isolates and fragments the remaining forest patch. Furthermore, forest to agriculture conversion in the eastern section effectively eliminates the eastern forest patch. Conversion to the west and east isolates the central, triangular forest patch. Agricultural expansion in the southern section of the central, triangular forest patch reduces forest patch size. There is continued conversion of forest to agriculture in the northern section within the bounds of the horse and cattle ranch.

The overall analysis of agricultural land conversion displays the most significant amount of change within the western and northern portions of the remote sensing study area. Small-scale, yet prolific conversion is present in the eastern section. And medium-sized patches were converted in the south and southwestern areas. The central, triangular forest patch shows less overall change than the surrounding matrix. Similarly, the northwestern forest patch retains a small area of unchanged forest.

Image processing steps such as the noise reduction algorithm and the cloud removal process in the 1972 and 1990 images increased the potential error within the postclassification comparison (Lillesand *et al.* 2004). It is well established that the accuracy of the individual land use and land cover classifications limits the accuracy of the change detection (Lillesand *et al.* 2004; Yuan and Elvidge 1998; Anderson *et al.* 1976). The algorithm used to minimize the effects of banding in the 1972 image changed digital numbers associated with the pixels. Banding had already introduced considerable error into the 1972 image, and the correction added a negligible amount of additional error given that a postclassification change detection was being employed (Lillesand *et al.* 2004). Additionally, the clouds and shadows in the 1990 image proved to be a limiting factor; however, assuming the clouds and shadows were correctly identified, the areas of no data within the 1990 image could be transferred to the other two images. The clouds and shadows made it impossible to compare those areas affected in 1990 to any other year (Yuan and Elvidge 1998). The band correction modified the data for the 1972 image, but the modified land use and land cover classification scheme minimized classification error. The exclusion of pixels in all images that were affected by clouds or shadows in the 1990 image preserved the integrity of the land use and land cover change detection between data sets.

After considering the modifications made for differences in data quality, climate conditions for the date of acquisition should be analyzed. The eastern portion of Tamaulipas undergoes its wettest period during May, June, July, August and September with 4.2, 4.5, 2.4, 3.1, and 5 inch monthly averages for Ciudad Victoria (Weatherbase 2005). Since the three images were sensed in September 30th, October 10th, and October 20th, it was determined that there was sufficient temporal continuity to minimize spectral differences associated with vegetation conditions (Lunetta *et al.* 2002); and therefore, a comparison of vegetation change was viable. Additionally, utilizing imagery post-rainy season has several benefits. Remote sensing analysis in arid climates can be challenging. During extremely hot and dry periods, imagery can be heavily influenced by dust, high reflectance values of bare ground, and exceedingly hot temperatures (Tueller 1987). Additionally, the postclassification method for land use and land cover change detection was selected as the most appropriate method to evaluate change in land cover at Sistema Zacatón (Yuan and Elvidge 1998). Postclassification change detection bypasses the difficulties associated with using images with varying atmospheric conditions, sun angles, and times of acquisition (Lillesand *et al.* 2004; Yuan and Elvidge 1998). Due to nature of the selection and elimination process of spectral classes and the difference in spectral qualities between the images, it is likely that the resulting thirty classes were not exactly the same for each image. The postclassification change detection alleviated the complications due different spectral ranges by requiring that each image be processed individually and then subjected to a common classification scheme (Yuan and Elvidge 1998). Given the date of the imagery and the historic precipitation and temperature data for the area and the postclassification change detection method, it was assumed that no atmospheric correction for the imagery was necessary.

The change detection for the study site located in eastern Tamaulipas was challenged by the quality of images gathered in 1972 and 1990. However, the basic nature of the classification scheme was effective in identifying the rudimentary land use and land cover trends despite the alterations caused by the fourier transformation used in the debanding process. The patterns illustrated in the individual image land use and land cover classification show that areas of forest are becoming more isolated (Figure 5.5).

5.2 Vegetation Survey

The vegetation surveys were performed over the course of three field campaigns in 2004: August 15-18, October 22-26, and December 22-28. Waypoints taken near each individual measured were downloaded from the Garmin Summit GPS using Waypoint+. The resulting text file was imported into Excel and attributed with data gathered during the survey. Starting locations, distances, and base and breast-height circumferences were transcribed from field notebooks. For the purpose of this study, only survey number, location, description, breast-height circumference, and distance were needed. Diameter at breast height was calculated and added to the vegetation survey data table (Table 5.4). The Excel file was exported as a DBF4 file and brought into ArcMap as an event. The events were exported into the soyate_survey feature dataset within the rancho_la_azufrosa geodatabase. The locations of the individuals surveyed in the wandering quarter vegetation survey are illustrated in Figure 5.8.

Total densities for the forest and trail zones were calculated using the distance between individuals within each survey (Brower *et al.* 1998). The density data for both zones were compared using a t test (Table 5.5) to determine whether the densities were significantly different. All surveys in each zone were included in the calculations. The calculated value of t was found to be 1.3945, which is lower than the critical value of t at a degree of freedom of 4 and a significance level of 5 percent. Second, the DBH measurements for all individuals were grouped according to their sampling zones: forest or trail. A t test was then performed comparing the DBHs for the 22 forest ponytail palms with the 20 trail ponytail palms (Table 5.6). The calculated value of t was 3.0534, which was higher than the critical value of t at a significance level of 5 percent and a degree of freedom of 40.

Given that the DBHs for the two groups were found to be statistically different, a goodness of fit analysis was performed using size classes within the zone divisions (Figure 5.9). Three groups allowed for the maximum number of values in each class (Brower *et al.* 1998). The goodness of fit was examined using the chi-square test using the formula:

$$X^2 = \sum \frac{(O-E)^2}{E}$$

where O are observed values and E are expected values. The value of chi-square calculated for this population was 6.466 (Table 5.7). Critical values of chi-square for a degree of freedom of 2 are reported as 5.991 (Brower *et al.*, 1998).

The land use zones established for the wandering quarter vegetation survey were selected according to the level of human impact on the landscape. Several assumptions are made of the land use zones: the agricultural areas are or were once subject to intense clearing and alteration; the trail zone experiences a high-level of human and livestock traffic, though it has still maintained primary growth forest; and the forest zone has very limited access points and maintains mostly intact primary growth forest. These assumptions allow comparison between the vegetation in each unique zone.

The null hypothesis for this survey is that *Beaucarnea inermis* populations within each land use zone illustrate the same characteristics—both total density and mean DBH—regardless of location. On the contrary, the working hypothesis is that the characteristics of the *Beaucarnea inermis* populations differ according to areas subjected to differing land use regimes. It was hypothesized that total density of populations would be greatest in the forest zone, next greatest in the trail zone, and least dense in the agriculture zone. Additionally, it was initially expected that the diameters at breast height (DBH) for populations within the forest zone would show the lowest average, and the average DBH for populations in the trail zone and agricultural zones would be significantly higher.

The study found no individuals in the agricultural zone; therefore, the agricultural population is considered statistically different from those in both the forest and trail zones. Accordingly, both initial working hypotheses hold true. The total densities for the forest and trail zones, however, are not statistically different; therefore, the null hypothesis is valid when comparing total density between these two zones. This could be attributed to a shortcoming in the wandering quarter sampling method in measuring densities of species with clumped distribution patterns. In the three wandering quarter surveys performed in the forest and trail zones, 22 and 20 individuals, respectively, were recorded. One forest survey included no individuals; and similarly, one trail survey included only three individuals. The scarcity or lack of ponytail palms could be attributed to a clustered dispersal pattern. Alternatively, the lack of difference in total densities could be attributed to the small number of surveys within each zone. The accuracy of the total density calculations within each zone could be greatly improved by increasing the number of surveys. However, this was not feasible during this study. Surveys took anywhere from one to six hours to perform, and funding and field personnel for this project allowed three surveys per zone.

The results of the *t* test indicate that the DBHs of individuals found in the forest zone are statistically different than those of the individuals in the trail zone. The lowest DBH recorded for the forest zone (0.13 m) is smaller than the lowest DBH recorded in the trail zone (0.19 m). Additionally, the mean DBH for individuals in the forest zone was calculated as 0.57 m, while the mean DBH for individuals in the trail zone was substantially higher at 0.93 m. Given that both zones share similar geology, soil types, and topography, these data suggest that the population in the forest zone has more recently recruited seedlings and saplings successfully. Assuming that the forest zone has limited accessibility and human impact, it can be concluded that the forest population responds better than that of an area with increased human activity.

Testing the goodness of fit of three size classes by using the chi-square test examined the correlation of spatial distribution and size. Three classes were established by dividing the DBHs into young, medium, and old groups by directly relating DBH with age. The chi-square test determined that the null hypothesis—size classes are evenly distributed throughout the zones—is invalid. Because the calculated chi-square value was higher than the critical value of chi-square for a degree of freedom of 2, the populations were determined to be statistically different. The difference in frequency distribution shown in Figure 5.9 supports this conclusion. The results of the chi-square test suggest that the working hypothesis—size classes vary according to the land use zones—holds true. The forest zone had a significantly different and larger number of ponytail palms with small DBHs, which suggests that human impact influences reproduction.

It must be recognized that the number of survey iterations within each zone is a limitation of this vegetation survey. Due to the difficulty of traversing both the trail and forest zones, each survey took a significant amount of time and energy. Additionally, heat, humidity, ticks, and chiggers added to the effort required to complete each survey. A low number of surveys could potentially influence the accuracy of the density data, the comparison of the DBHs, and the goodness of fit test. Additional surveys with a larger field staff might resolve this issue. This vegetation survey does successfully initiate the study of the ponytail population of Sistema Zacatón.

The data suggest that human impact has had a major effect on the reproduction of ponytail palms. Agricultural areas showed the largest influence as no ponytail palms were observed in the three surveys in that zone. Almost an equal number of ponytail palms were measured in the forest and trail zones, but mean DBHs suggest that the ponytail palm population in the forest zone has more recently had the opportunity to reproduce. Given that the smallest DBH recorded in all surveys was 0.13 m, it can be concluded that the ponytail palm population as a whole within the study area is under stress and not adequately reproducing.

5.3 Cave and Karst Inventory

The initial step in the cave and karst inventory was to identify and map roads, trails, and surface karst features. A total of 4.6 km of roads and 1.6 km of trails were mapped. There were four dolines identified that cover a combined surface area of approximately 5.5 acres. The cenotes, including the river, Nacimiento, cover approximately 6.1 acres. The smallest cenote is Azufrosa with 0.01 acres (43.9 m^2), and the largest is Verde with 3.3 acres. The author located 14 cave entrances with substantial air flow.

The underground survey required a large number of volunteers and was accomplished over the course of 2001-2004, with the exception of Pasaje de la Tortuga Muerta which was surveyed by Jim Bowden and Ann Kristovich during initial SCUBA exploration of the system in 1990. Bowden and Kristovich provided the original survey notes, and they were incorporated with primary data gathered from surveys organized by the author. The three dry caves extended the length of surveyed passage in the study area to a length of 3.023 km. The longest cave was Caverna los Cuarteles with a total length of 1680.2 m; the Confusion Tubes, Pasaje de la Tortuga Muerta, and Cueva de la Casa total 521.8 m, 507.5 m, 313.8 m, respectively. Survey data were entered into Walls and coordinates were associated with each initial survey station. Survey data were compiled for each of the four caves, and a shapefile was exported from Walls. The shapefiles were imported into the cave_lineplots feature dataset within the rancho_la_azufrosa geodatabase. These four passages and surface karst features are illustrated in Figure 5.10. Furthermore, detailed sketches were developed for the two dry caves determined to house bats: Caverna los Cuarteles and Cueva de la Casa. Locations of bat sightings and graffiti and broken formations were recorded during the cave survey (Figure 5.11). Cave sketches were scanned and overlaid on the line plots generated in Walls. Features were transcribed onto a digital map created in Adobe Illustrator (Figures 5.12 and 5.13, respectively).

Caves and karst features are common throughout the study area. Numerous dolines and cave entrances demonstrate that the study area has been heavily karstified. Dry caves exhibit ramiform and spongework solutional patterns. Ramiform passages, such as those observed in northern and middle sections of Caverna los Cuarteles, have highly variable cross sections that fluctuate noticeably in shape and size. Ramiform passage patterns indicate that these caves may have once served as outlets for ground water (Palmer 1991). Spongework solutional patterns, observed in the Confusion Tubes and the southern section of Caverna los Cuarteles, suggest that these caves formed in mixing zones where aggressive water mixes with flowing, oxygenated water

(Palmer 2000). These patterns are consistent with hypogenic cave formation by deep-seated H_2S and CO_2 of volcanic origin (Gary and Sharp *in press*).

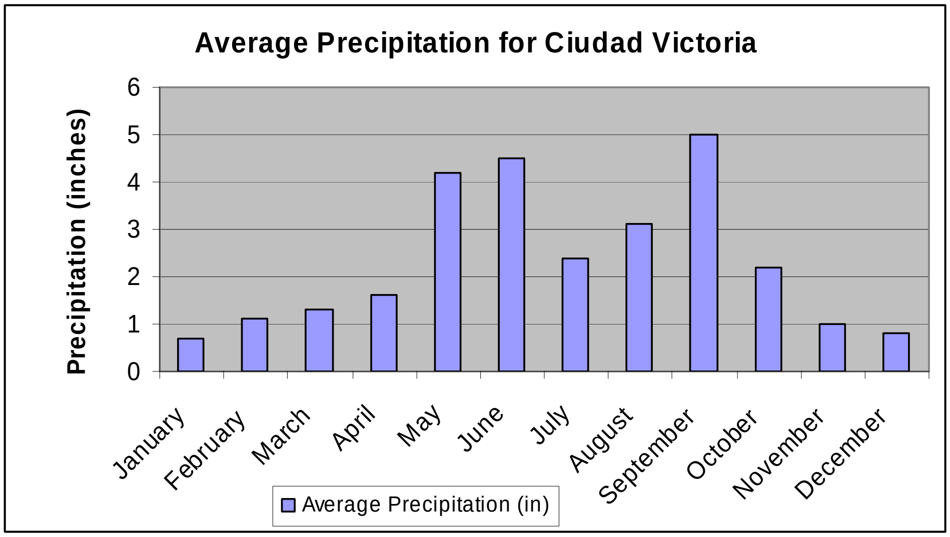
For the cenote survey, the continuous temperature loggers were periodically downloaded in text file format. Due to the adaptive sampling method, not all data for each station are continuous (Table 5.8); however, averages and variation patterns of all measurements made at each site provide a useful indicator of temperature variability in the system. The text files were individually imported into an MS Access database and integrated into a common table. A deployID field was established to track the number of files per site. Station IDs, depth, and location were associated with the date, time, and temperature recorded by the loggers. The files were examined and anomalies associated with the installation and retrieval processes and instrument malfunction were extracted. Additionally, depths were associated to sites by creating a tbl_SiteID table with a one-to-many relationship to the tbl_All_temp table that stores all data gathered by the Tidbits. Calculations were performed using Access queries. Average daily temperature and the standard deviation by site were calculated. Historical temperature data gathered at the nearest weather station, in this case Ciudad Victoria, was also averaged and the standard deviation was calculated from monthly averages recorded over a period of three years (Weatherbase 2005). Average air and water temperatures were compared (Figure 5.14). The largest standard deviations were observed with data from the Verde 5 m and thermal vent sites, the Azufrosa site, and the Ciudad Victoria air temperature data. Measurements recorded at all deep sites (Zacaton-120 m, Caracol-65 m, and La Pilita-90 m) illustrated notably lower standard deviations with the exception of the Verde-40 m data, which is within the range of the shallower sites.

Though the temperature datasets gathered in the cenotes are periodically interrupted, the data are an effective tool in investigating hydrologic connectivity within the system. The average temperatures indicate that all sites are influenced by a thermal source to some degree (Dublyansky 2000). All averages were above the average air temperature. It is theorized that the cenotes can be further separated into three groups according to their connectivity and water sources. An analysis of average temperatures illustrates this grouping; standard deviation calculations and trends in temperature fluctuation support the theory. Temperature data suggest that Nacimiento, Zacatón, and Caracol are connected; Verde is primarily isolated, though not entirely; and La Pilita and Azufrosa are connected to some degree.

Nacimiento, Zacatón, and Caracol demonstrate similar average temperatures. The physical connection between Nacimiento and Zacatón, established by cave divers, confirms that water passes from Zacatón through a water-filled cave to Nacimiento. Therefore, it is not surprising that both sites have similar average temperatures. On the contrary, no physical connection between Zacatón and Caracol has been discovered (Gilliam 1995; Kristovich 1994). However, average temperatures at the shallow sites (2 and 15 m) are only 0.34° different, and average temperatures at depth (120 and 60 m) are 0.05° different. Temperatures may have been more closely linked if measurements were taken at exactly the same depths. Verde, on the other hand, has a significantly cooler average temperature at depth. During the temperature monitoring phase, a thermal vent in the northwest wall of the cenote was discovered. Temperature loggers located in the vent (Verde, vent-6 m) and just outside (Verde, 5 m) illustrated an average temperature slightly cooler than that calculated for the other cenotes. While the thermal influence was observed in and near the vent, the quantity of thermal water flowing from the vent was not sufficient to raise the water temperature at depth. Therefore, it can be concluded that the majority of the water in Verde has a different source than the other cenotes; and it is minimally connected to the system, though the thermal water source cannot be determined from the temperature data. Average temperatures recorded at La Pilita and Azufrosa indicate that there is substantial influence from a thermal heat source. The average temperatures for both these cenotes are notably higher than the others.

Furthermore, an examination of the standard deviations for each cenote indicates that some cenotes are more subject to seasonal air temperature fluctuations than others (Figure 5.15). There are several factors that can influence water temperature change such as: depth, volume of the water body, surface area, circulation, and contributing water sources. Water at depth is less likely to be influenced by seasonal air temperature fluctuations. This theory is observed in the three lowest standard deviations, which correspond to the three deepest sampling sites (65, 120, and 90 m). The next four lowest standard deviations, however, are shallow sites, ranging from 5-15 m of depth. It is possible that the corresponding cenotes are regulated more by a thermal heat source than by air temperature. The Verde 40 m site illustrates the next lowest standard deviation and is somewhat anomalous. Because shallower sites in other cenotes have demonstrated less fluctuation than the Verde 40 m site, it can be inferred that there is less regulation from a thermal heat source at Verde than in the other cenotes. This is supported by the standard deviations calculated from the shallow site (5 m) within Verde. Next to air temperature, water temperature in Verde fluctuates the most dramatically.

Temperature fluctuations in response to seasonal air temperature trends further supports the theory that Nacimiento, Zacatón, Caracol, La Pilita, and Azufrosa are heavily influenced by a heat source and that Verde is more isolated from the thermal source. The sample site at Nacimiento measured the temperature of water discharging from Zacatón. Both the average temperature and the temperature fluctuation pattern suggest that water at both Zacatón and Nacimiento share sources (Figure 5.16). Caracol and La Pilita exhibit fairly constant temperatures which appear to fluctuate only minimally in response to air temperature changes (Figure 5.17). Temperature patterns recorded at La Pilita are similar to those recorded at Caracol with the exception that temperatures are more elevated. This more elevated temperature, combined with the minimal seasonal influence suggests that La Pilita could be closer to the heat source. Azufrosa and Verde both illustrate temperature patterns that suggest that air temperature regulates the water temperatures (Figure 5.18). Data gathered at the shallow thermal and non-thermal sites also show changes that could be attributed to seasonal air temperature fluctuation; however, data gaps from instrument malfunction or loss limit conjecture at these sites. Additionally, though patterns observed at Azufrosa indicate a strong seasonal air temperature influence, temperatures are consistently warmer than air temperature. The shallow depth and low water volume at this cenote could attribute to the seasonal patterns, but the elevated temperatures suggest that there is substantial contact with the hydrothermal source.



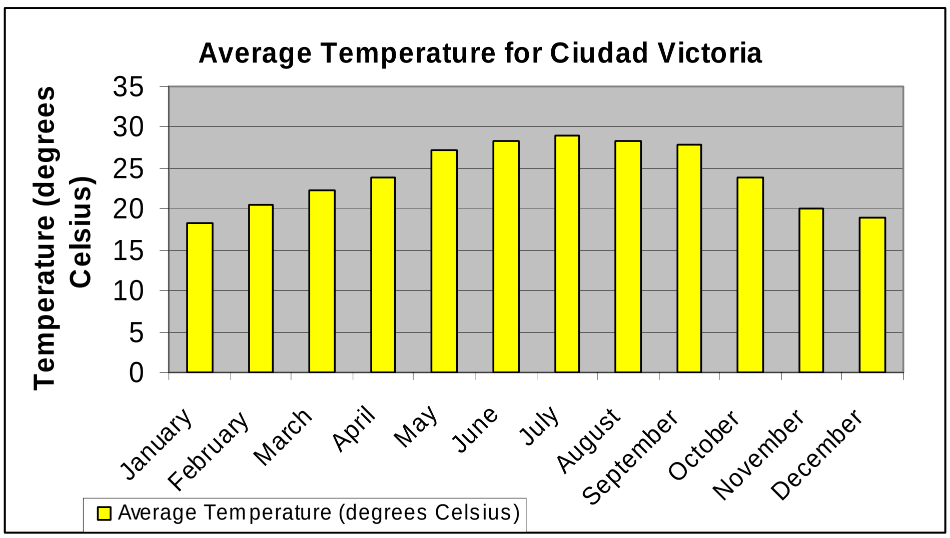


Figure 5.1 Average Precipitation and Temperature for Ciudad Victoria
Ciudad Victoria is the closest location with a weather station with long-term precipitation and temperature data. Data shown represent seven years of monthly precipitation averages and three years of temperature averages (Weatherbase 2005).

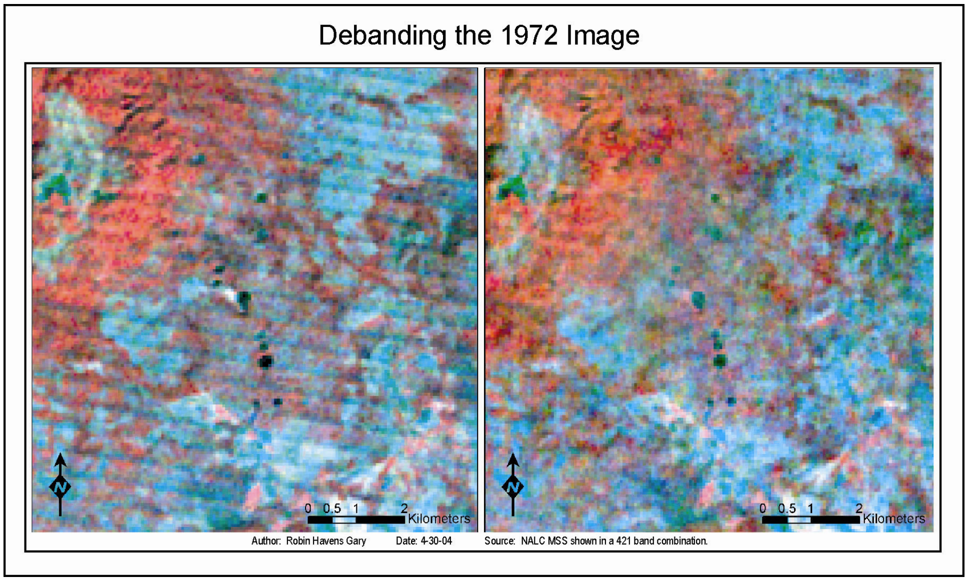


Figure 5.2 Effects of the Debanding Process on the 1972 Image
Shows the original 1972 MSS image subset and the corrected image in a 421 band combination. Notice the more generalized features and reduced contrast in the corrected image.

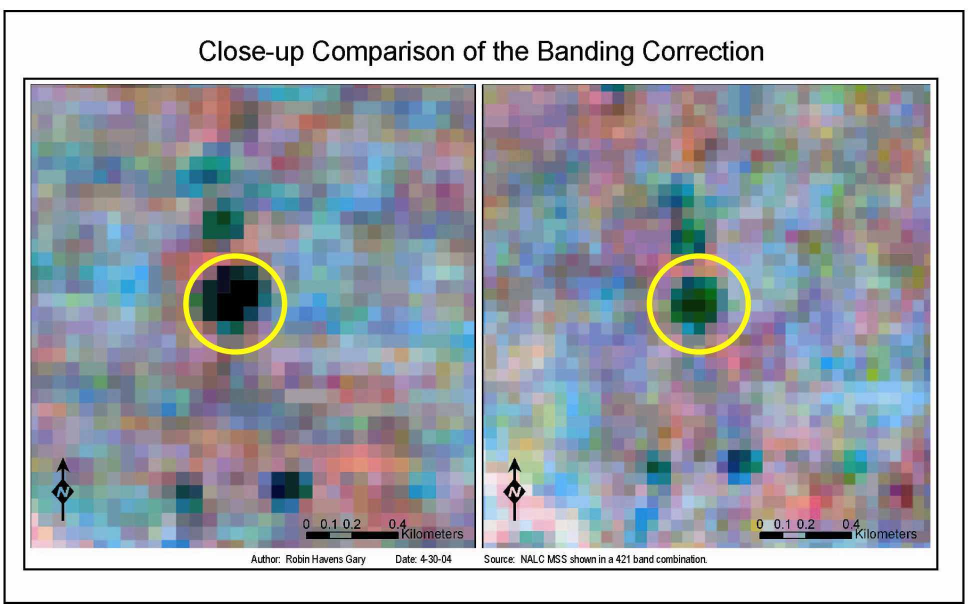


Figure 5.3 The Effects of the Periodic Noise Removal
Well defined cenotes, or water-filled sinkholes, as seen on the left appear more washed out after the correction (right). This generalization is particularly noticeable when examining the feature circled in each image

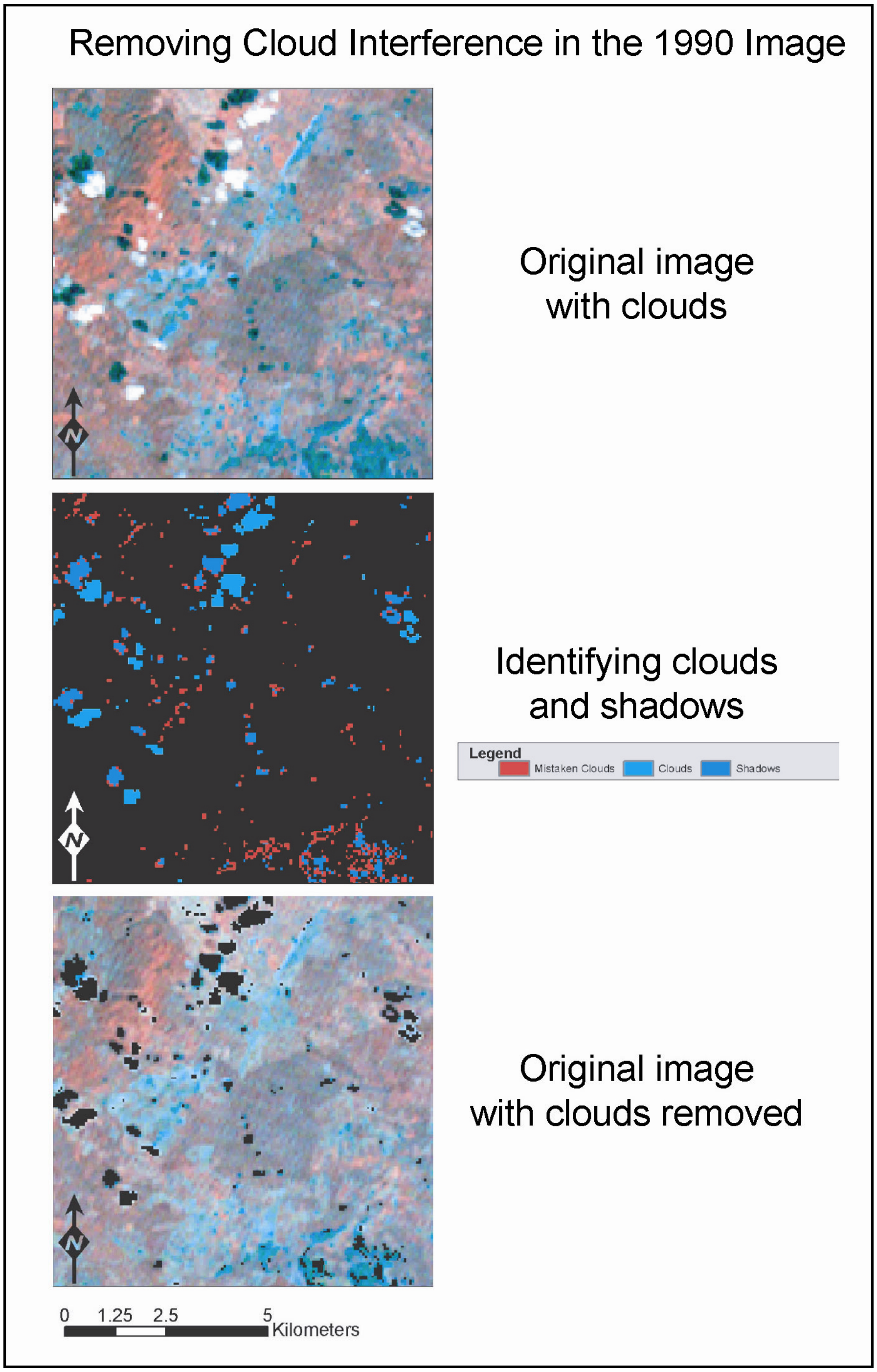


Figure 5.4 Removing Cloud Interference in the 1990 Image
Illustrates the steps taken to remove clouds and their shadows from the 1990 MSS image.

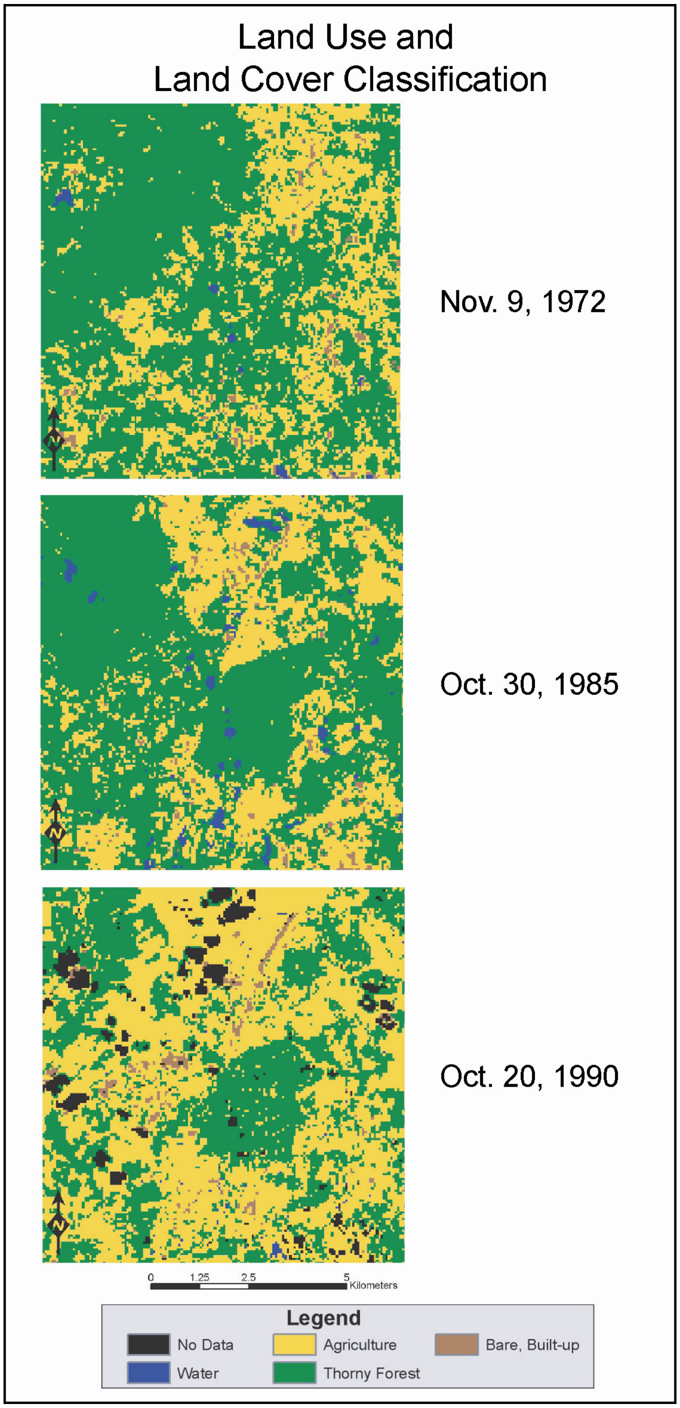


Figure 5.5 Land Use and Land Cover Classification
The three images were classified according to the same general four class land use and land cover classification scheme.

Table 5.1 Areas Represented by Class for the 1972, 1985, and 1990 Land Use and Land Cover Classification

These calculations were made from the class pixel totals counted after clouds were extracted from all three images.

	Area (km^2)		
	1972	1985	1990
Water	0.23	1.21	0.28
Agriculture	28.25	28.05	50.93
Forest	58.14	57.30	35.08
Bare, built up	1.31	1.37	1.64
total:	87.93	87.93	87.93

Table 5.2 Percent Change Observed in Land Use and Land Cover Classifications

Percent increases are shown as positive numbers, and percent decrease are shown as negative numbers. Percentages were calculated from area totals reported in Table 5.1.

	Percent change		
	1972 to 1985	1985 to 1990	Overall
Water	416.92%	-76.49%	21.54%
Agriculture	-0.70%	81.57%	80.30%
Forest	-1.44%	-38.78%	-39.67%
Bare, built up	4.67%	19.69%	25.27%

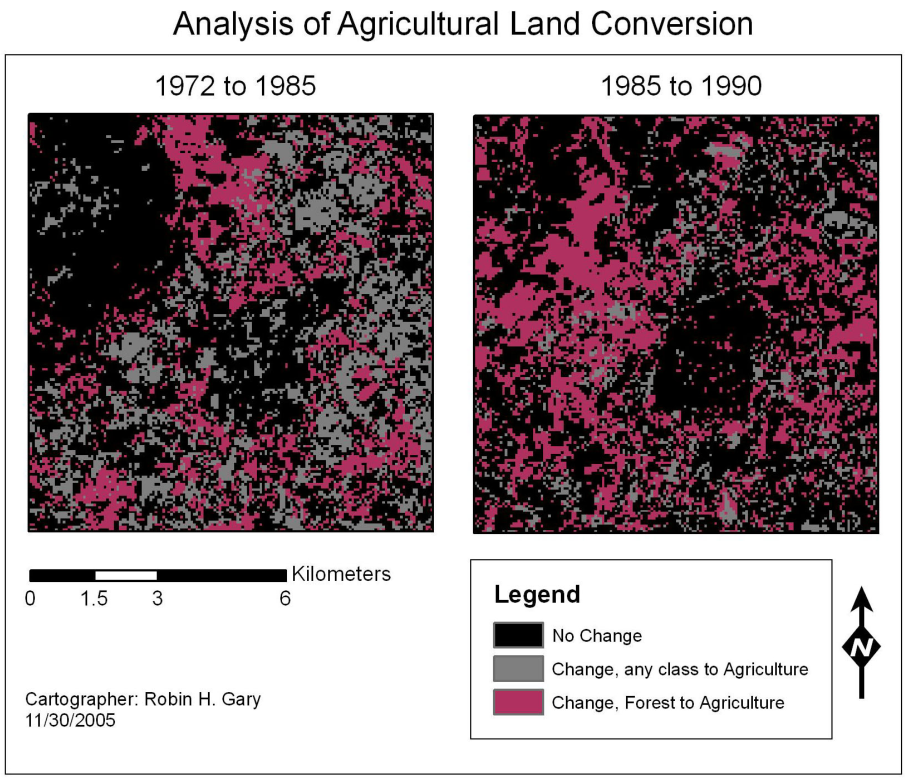


Figure 5.6 Analysis of Agricultural Land Conversion
Pixels that originally had no data are included in the No Change category.

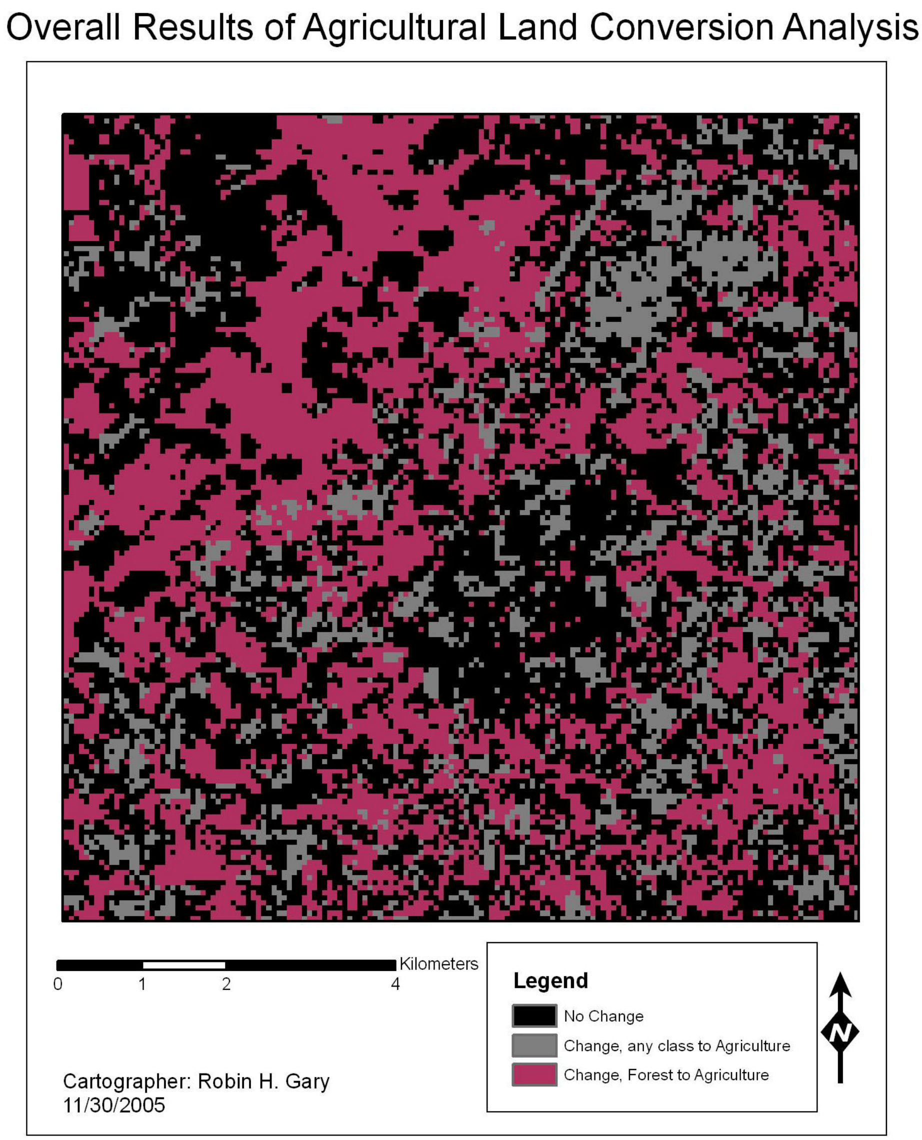


Figure 5.7 Overall Results of Agricultural Land Conversion Analysis
This image shows the results of a land use and land cover change detection between 1972 and 1990. Pixels that originally had no data are included in the No Change category.

Table 5.3 Summary of Land Use and Land Cover Change Detection Results

This table displays area calculations for the three spatial analyses performed in the land use and land cover change detection. These areas correlate to data displayed in Figures 5.6 and 5.7.

	Area (km^2)		
	1972 to 1985	1985 to 1990	Overall
No Change	54.61	57.15	45.54
Change, any class to Agriculture	20.94	8.88	14.10
Change, Forest to Agriculture	17.16	26.68	33.07

Table 5.4 Data gathered in the wandering quarter vegetation survey. X, Y data are given in WGS 84, UTM 14N. No ponytail palms were found in the A1, A2, A3, and F1 surveys.

Survey Results						
Survey	**X**	**Y**	**Description**	**Circum (m)**	**DBH (m)**	**Distance (m)**
T1	586445.8932	2543022.2390	Start			
T1	586445.5344	2543023.3780	1	1.89	0.602	0.364
T1	586437.0889	2543056.3010	2	3.66	1.164	6.096
T1	586439.4062	2543073.1380	3	0.61	0.194	11.582
T1	586443.6932	2543080.6140	4	1.52	0.485	3.353
T1	586447.9623	2543089.7050	5	1.22	0.388	9.449
T1	586448.1407	2543094.5410	6	1.83	0.582	7.315
T1	586440.7218	2543105.8100	7	1.83	0.582	10.973
T1	586447.9364	2543113.6280	8	0.91	0.291	3.353
T1	586460.3278	2543142.9960	9	2.29	0.728	9.716
T1	586460.3278	2543144.9960	10	2.29	0.728	1.829
T2	586512.6296	2543226.8240	Start			
T2	586470.7651	2543198.4280	1	4.11	1.310	15.419
T2	586464.0871	2543188.4320	2	3.96	1.261	4.267
T2	586464.3800	2543186.8010	3	4.27	1.358	13.716
T2	586435.3964	2543189.2600	4	2.74	0.873	13.106
T2	586419.7865	2543199.6840	5	3.35	1.067	12.192
T2	586415.2877	2543148.3600	6	4.88	1.552	16.764
T2	586408.4724	2543160.7560	7	4.57	1.455	5.182
T3	586123.9270	2542911.2890	Start			
T3	586139.9094	2542906.3510	1	2.44	0.776	5.099
T3	586143.0728	2542865.5570	2	1.98	0.631	12.471
T3	586147.2237	2542868.3360	3	4.51	1.436	1.523
F3	585669.4314	2543188.2900	Start			
F3	585701.7044	2543199.5260	1	1.90	0.605	6.600
F3	585682.8337	2543203.3440	2	1.20	0.382	4.500
F3	585680.5905	2543200.4910	3	0.42	0.134	8.600
F3	585685.7081	2543213.0200	4	3.20	1.019	19.600
F3	585697.5404	2543229.1880	5	0.20	0.064	12.600
F3	585691.7210	2543231.2710	6	1.20	0.382	2.600
F3	585694.6515	2543243.1660	7	1.70	0.541	7.200
F3	585694.0504	2543246.1220	8	3.20	1.019	8.700
F3	585694.9299	2543256.1030	9	1.15	0.366	1.900
F3	585697.1476	2543255.8930	10	1.00	0.318	4.300
F3	585698.2337	2543262.8030	11	2.20	0.700	6.500
F2	585512.4290	2543408.6150	Start			
F2	585515.0729	2543424.0810	1	0.90	0.286	11.000
F2	585545.0982	2543424.1310	2	2.80	0.891	28.500
F2	585550.1370	2543412.7830	3	1.00	0.318	6.000
F2	585601.8756	2543397.0790	4	1.00	0.318	30.000
F2	585588.9408	2543413.1060	5	1.40	0.446	12.900
F2	585587.7843	2543407.9960	6	1.70	0.541	1.800
F2	585591.3853	2543406.2530	7	3.85	1.225	7.400
F2	585605.2849	2543413.9140	8	3.80	1.210	8.700
F2	585611.8441	2543422.2100	9	2.60	0.828	6.000
F2	585630.1260	2543444.7990	10	1.20	0.382	15.000
F2	586851.9318	2543496.8450	11	2.10	0.668	2.000

Vegetation Survey Results

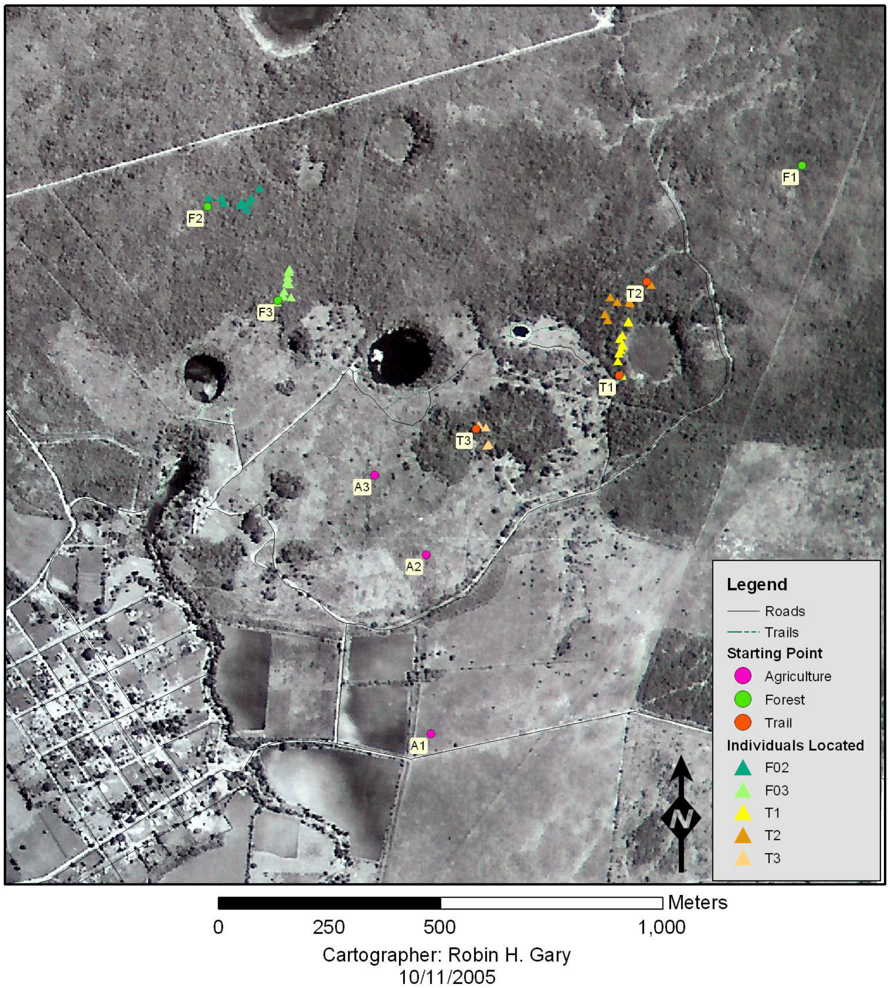


Figure 5.8 Vegetation Survey Results
Shows the distribution of random starting points and individuals located during the wandering quarter surveys.

Table 5.5 Total Density *T* Test Calculations

This calculation compares the total densities of forest and trail ponytail palm surveys. Critical values of *t* used were reported by Brower et al. (1998)

	Forest: Total Density	**Trail: Total Density**
Mean	82.532ha^{-1}	188.719ha^{-1}
Number	3	3
Sum of x^2	35940.1329	126130.3028
((sum of x)^2)/n	20434.3974	106844.1542
SS=Sum(x^2)-((sum of x)^2)/n	15505.7355	19268.1486
DF=n-1	2	2
s^2=SS/DF	7752.8677	9643.0743
s=sqrt(s^2)	88.0504	98.1992
Difference of the means		106.187
SS_1+SS_2		34791.88
DF_1+DF_2		4
$s^2_p=(SS_1+SS_2)/(DF_1+DF_2)$		8697.9710
sqrt((s^2_p/n_1)+(s^2_p/n_2))		76.1488
t		**1.3945**
critical value of *t* at 5% significance level for DF of 4		2.78

Table 5.6 DBH *T* Test Calculations

This calculation compares the DBH of forest and trail ponytail palms. Critical values of *t* used were reported by Brower et al. (1998)

	Forest: DBH	**Trail: DBH**
Mean	0.57m	0.93m
Number	22	20
Sum of x^2	9.5862	18.6047
((sum of x)^2)/n	7.2660	15.2492
SS=Sum(x^2)-((sum of x)^2)/n		2.3201
DF=n-1	21	19
s^2=SS/DF	0.1105	0.1766
s=sqrt(s^2)	0.3324	0.4202
Difference of the means		0.36m
SS_1+SS_2		5.6757
DF_1+DF_2		40
$s^2_p=(SS_1+SS_2)/(DF_1+DF_2)$		0.1419
sqrt((s^2_p/n_1)+(s^2_p/n_2))		0.1164
t		**3.0534**
critical value of *t* at 5% significance level for DF of 40		2.02

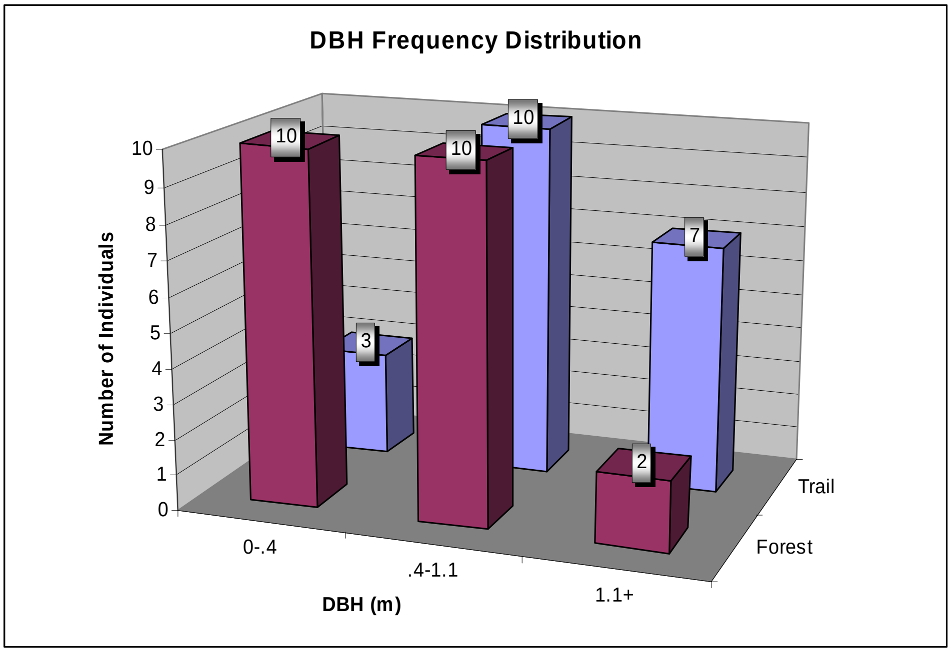


Figure 5.9 DBH Frequency Distribution
Shows the frequency distribution across three size classes for ponytail palm DBH in the two zones.

Table 5.7 DBH Chi-Square Calculations

Shows Observed DBH frequency distribution, the calculated expected distribution, and the chi-square calculations. Critical values of t used were reported by Brower et al. (1998).

Observed

	0-.4	.4-1.1	1.1+	total
Trail	3	10	7	20
Forest	10	10	2	22
total	13	20	9	42

Expected

	0-.4	.4-1.1	1.1+	total
Trail	6.1905	9.5238	4.2857	20
Forest	6.8095	10.4762	4.7143	22
Total	13	20	9	42

Chi-Square Calculations

	0-.4	.4-1.1	1.1+	
Trail	1.6443	0.0238	1.7190	
Forest	1.4948	0.0217	1.5628	
				6.4664

Critical value of chi-square at 5% for DF of 2 = 5.991

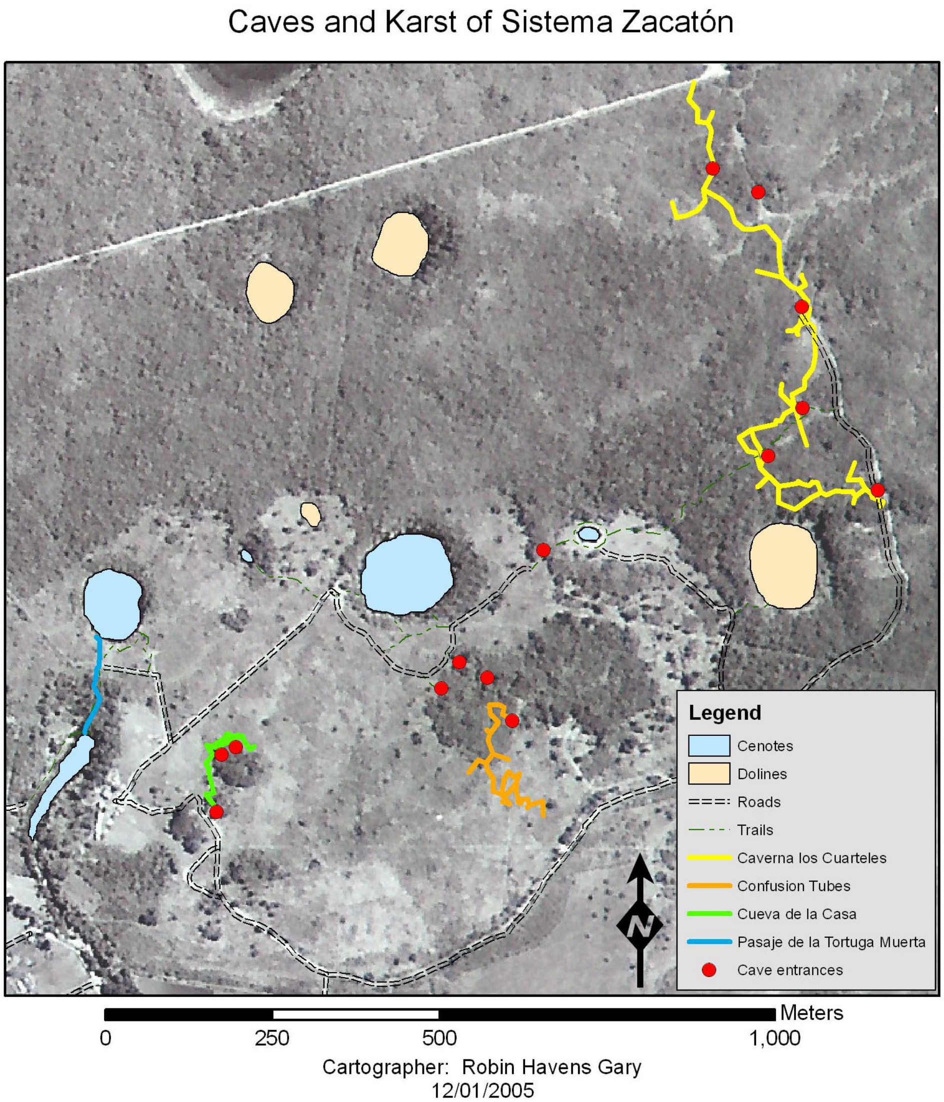


Figure 5.10 Caves and Karst Features of Sistema Zacatón

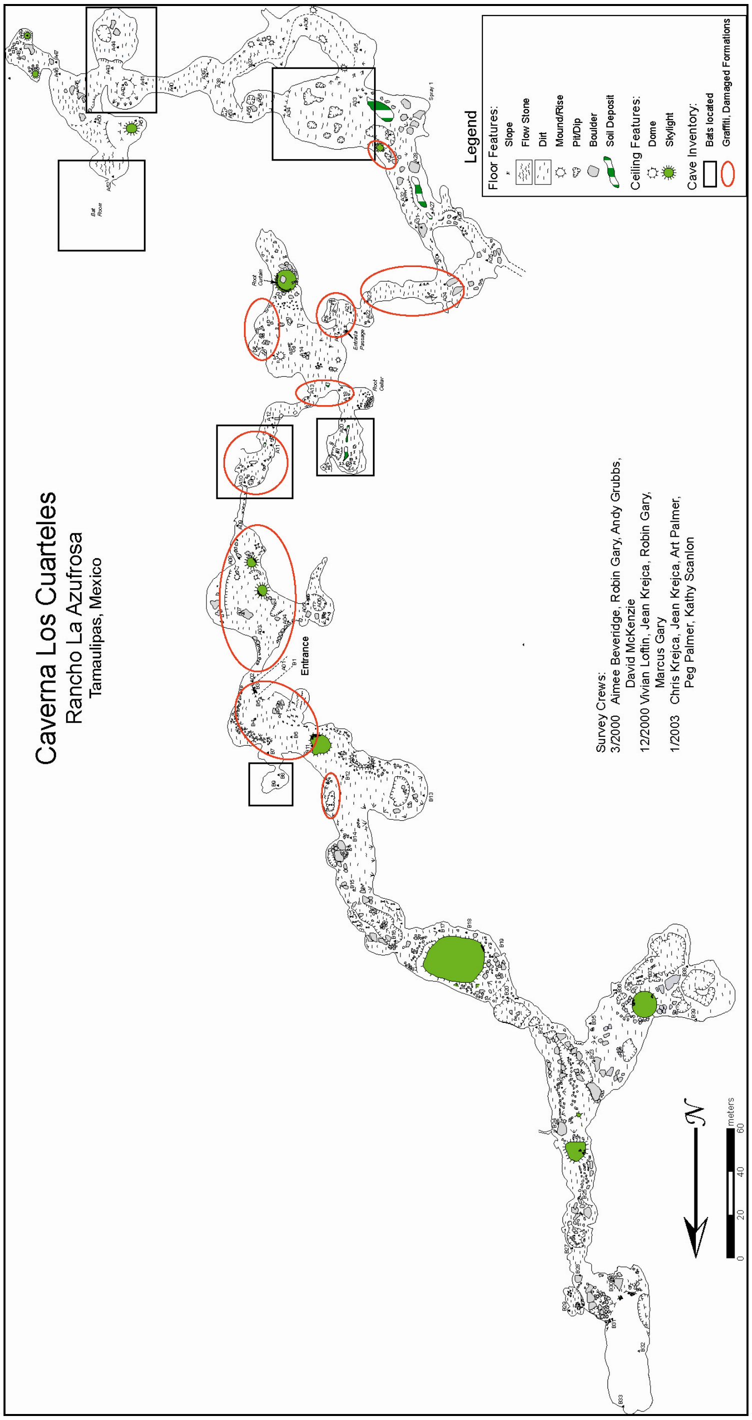


Figure 5.11 Caverna Los Cuarteles Map

The plan view map of Caverna Los Cuarteles showing the locations of bats, graffiti, damaged formations, etc.

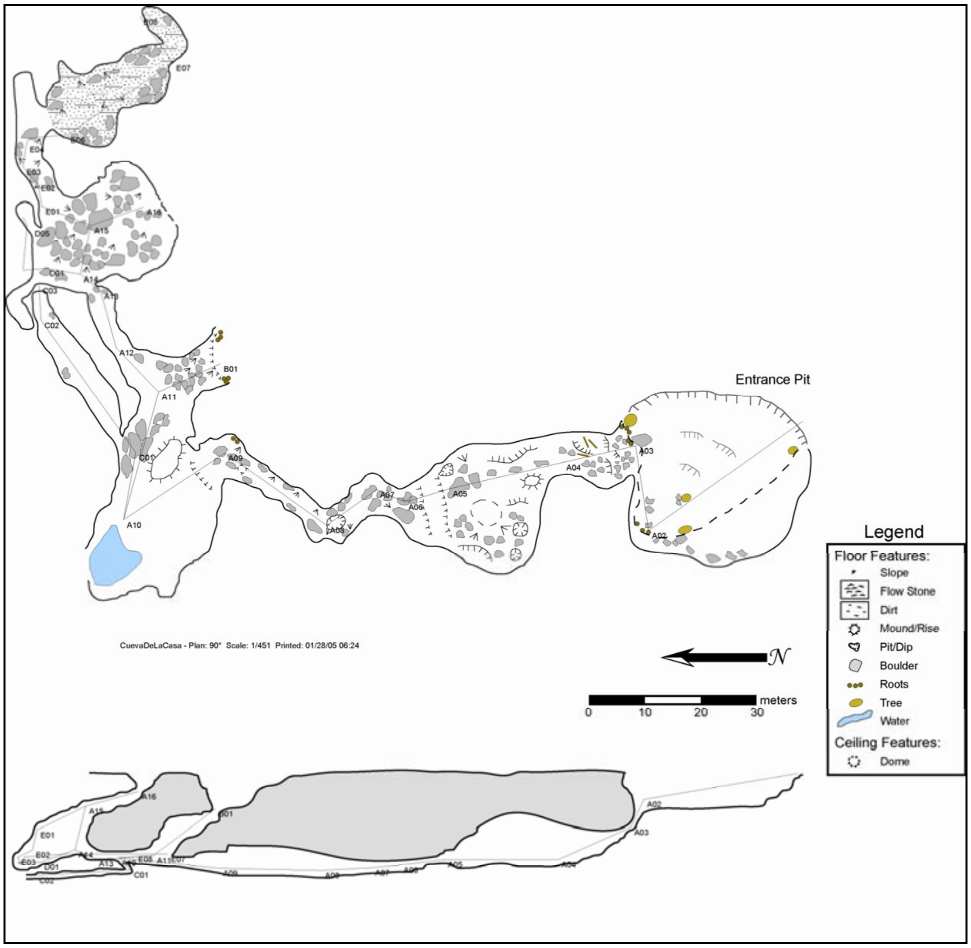


Figure 5.12 Cueva De La Casa Map
Plan and profile views of the cave

Figure 5.13 Damaged Formations and Graffiti in Caverna los Cuarteles
The upper photo shows a curtain formation where the tips have been broken. The lower photo shows graffiti and ash marks left where someone has tried to break off a portion of a formation.

Table 5.8 Locations and Deployment Periods for Continuous Temperature Loggers

Cenote	Depth (m)	Deployment	Start Date	End Date
Nacimiento	8	1	1/8/2003	8/22/2003
Nacimiento	8	2	9/7/2003	1/6/2004
Nacimiento	8	3	1/6/2004	5/27/2004
Nacimiento	8	4	5/27/2004	8/19/2004
Nacimiento	8	5	8/19/2004	12/26/2004
Zacaton	2	1	1/9/2003	8/23/2003
Zacaton	2	2	9/7/2003	1/6/2004
Zacaton	2	3	1/6/2004	5/27/2004
Zacaton	2	4	5/27/2004	10/24/2004
Zacaton	2	5	10/25/2004	12/29/2004
Zacaton	2	6	12/28/2004	9/6/2005
Zacaton	120	1	8/13/2002	8/20/2002
Caracol	15	1	9/7/2003	1/6/2004
Caracol	15	2	1/6/2004	5/27/2004
Caracol	15	3	5/27/2004	12/28/2004
Caracol	65	1	8/12/2002	8/19/2002
Verde	5	1	8/10/2002	8/21/2002
Verde	5	2	9/7/2003	1/6/2004
Verde	5	3	5/26/2004	8/17/2004
Verde	5	4	12/28/2004	9/7/2005
Verde vent	6	1	9/7/2003	1/6/2004
Verde vent	6	2	1/6/2004	3/6/2004
Verde vent	6	3	5/26/2004	8/17/2004
Verde vent	6	4	12/28/2004	3/8/2005
Verde	40	1	8/10/2002	8/21/2002
Verde	40	2	1/5/2003	8/19/2003
Verde	40	3	9/7/2003	5/26/2004
Verde	40	4	5/26/2004	8/17/2004
Verde	40	5	8/17/2004	12/28/2004
Verde	40	6	12/28/2004	9/7/2005
La Pilita	5	1	8/10/2002	8/19/2002
La Pilita	5	2	1/4/2003	8/18/2003
La Pilita	5	3	9/7/2003	1/6/2004
La Pilita	5	4	5/27/2004	8/19/2004
La Pilita	5	5	8/19/2004	12/26/2004
La Pilita	90	1	8/10/2002	8/19/2002
La Pilita	90	2	1/4/2003	8/18/2003
Azufrosa	1	1	8/10/2002	8/19/2002
Azufrosa	1	2	9/7/2003	1/6/2004
Azufrosa	1	3	1/6/2004	5/27/2004
Azufrosa	1	4	5/27/2004	12/26/2004
Azufrosa	1	5	12/28/2004	9/7/2005

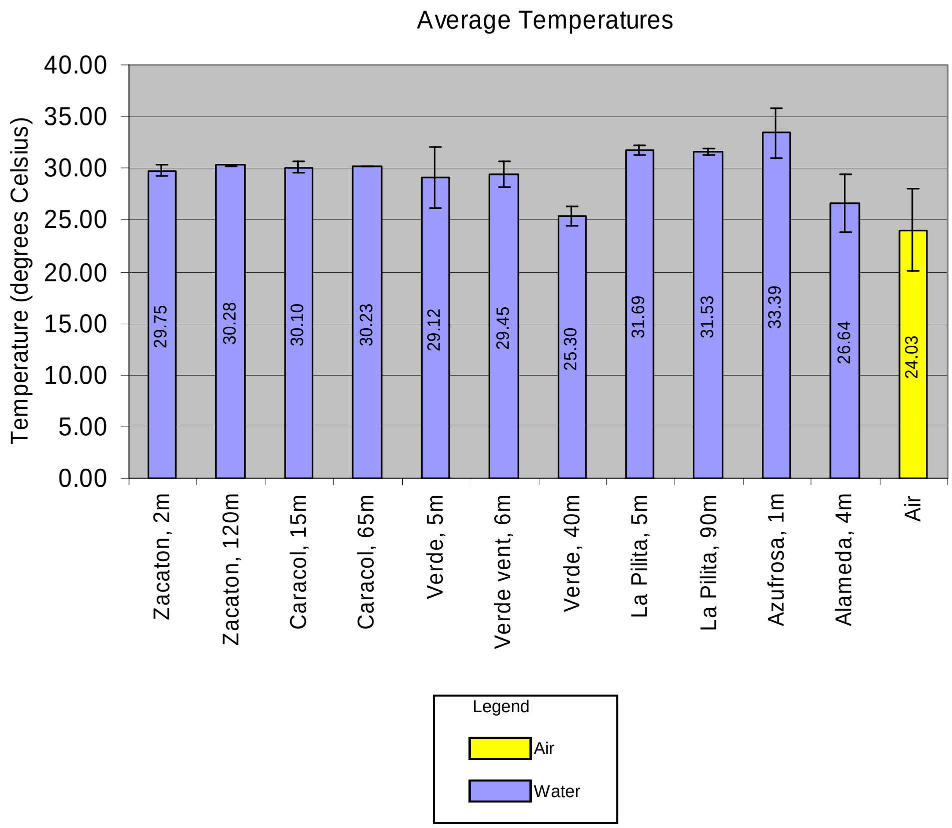


Figure 5.14 Average Temperatures

Available water temperature data for each sample site were averaged and standard deviations were calculated. The error bars represent one standard deviation. Air temperature average was calculated from weather data reported at the nearest historical weather station in Ciudad Victoria.

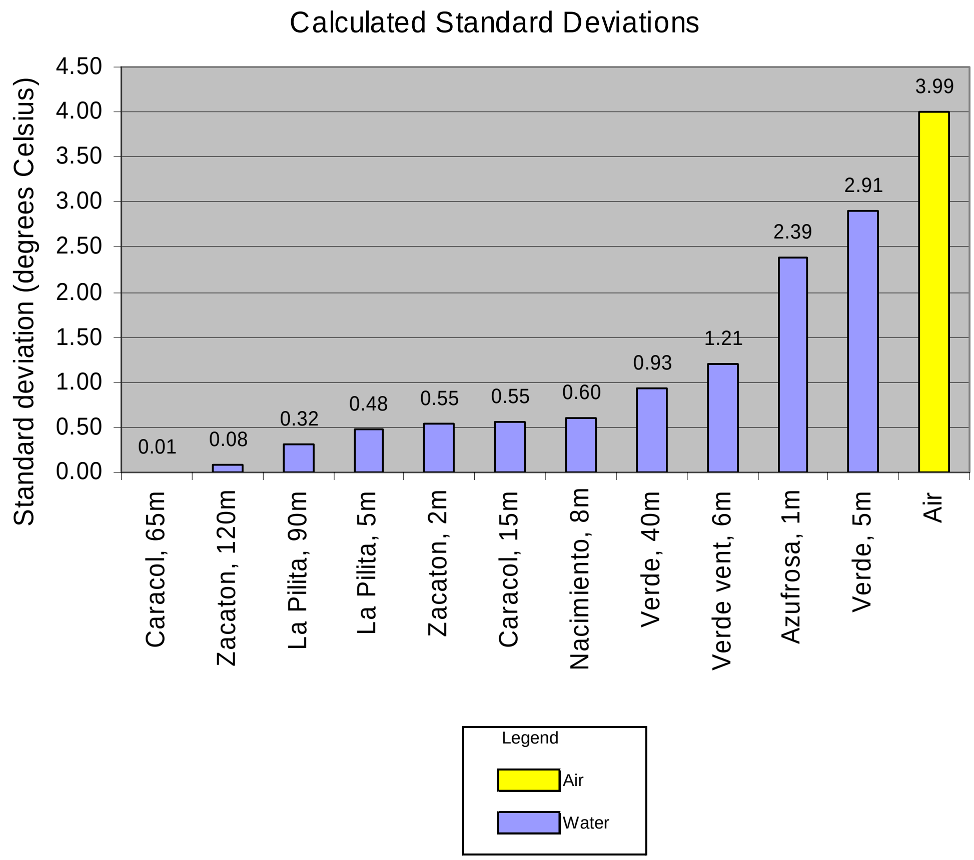
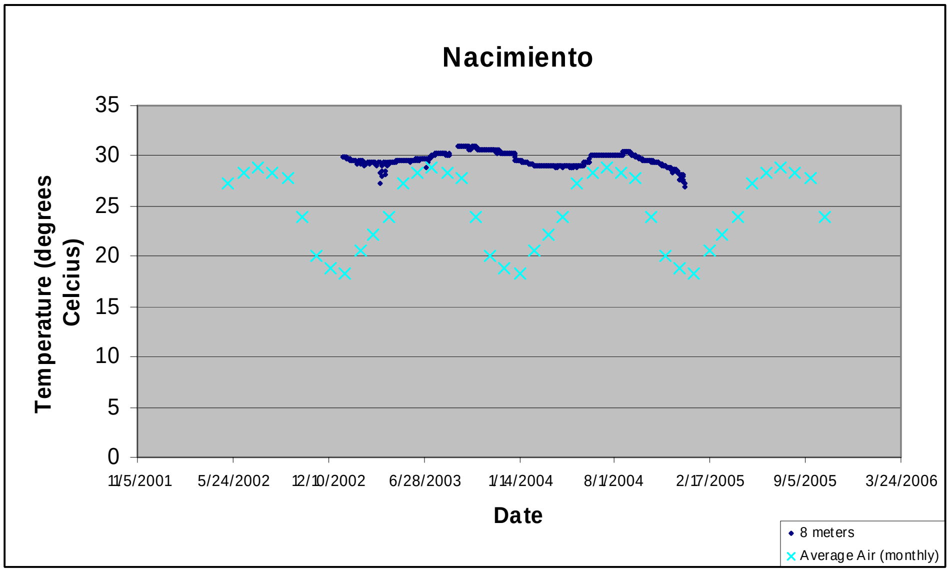


Figure 5.15 Calculated Standard Deviations for Temperature Data



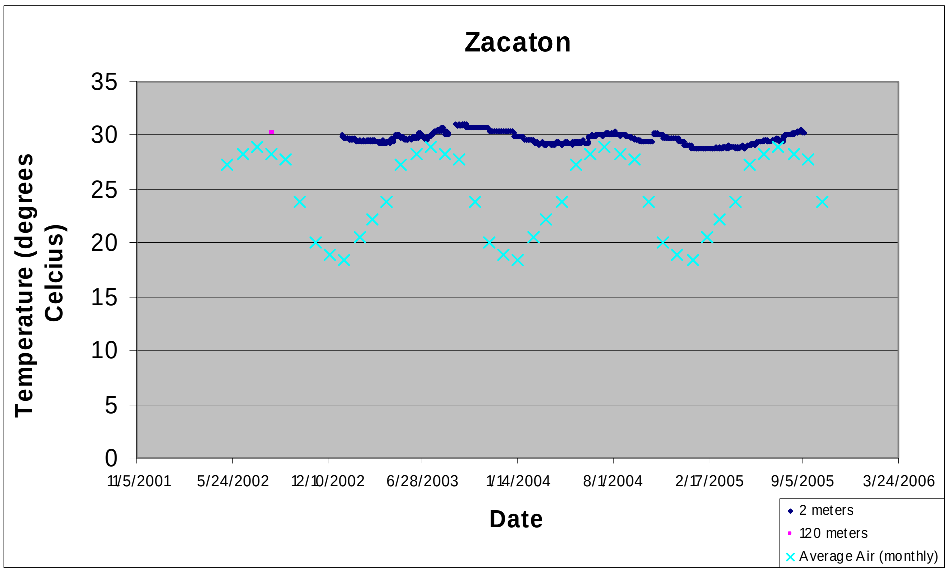


Figure 5.16 Daily Temperature Averages: Nacimiento and Zacatón
Nacimiento and Zacatón illustrate similar temperature fluctuations when compared to monthly air temperature averages for Ciudad Victoria.

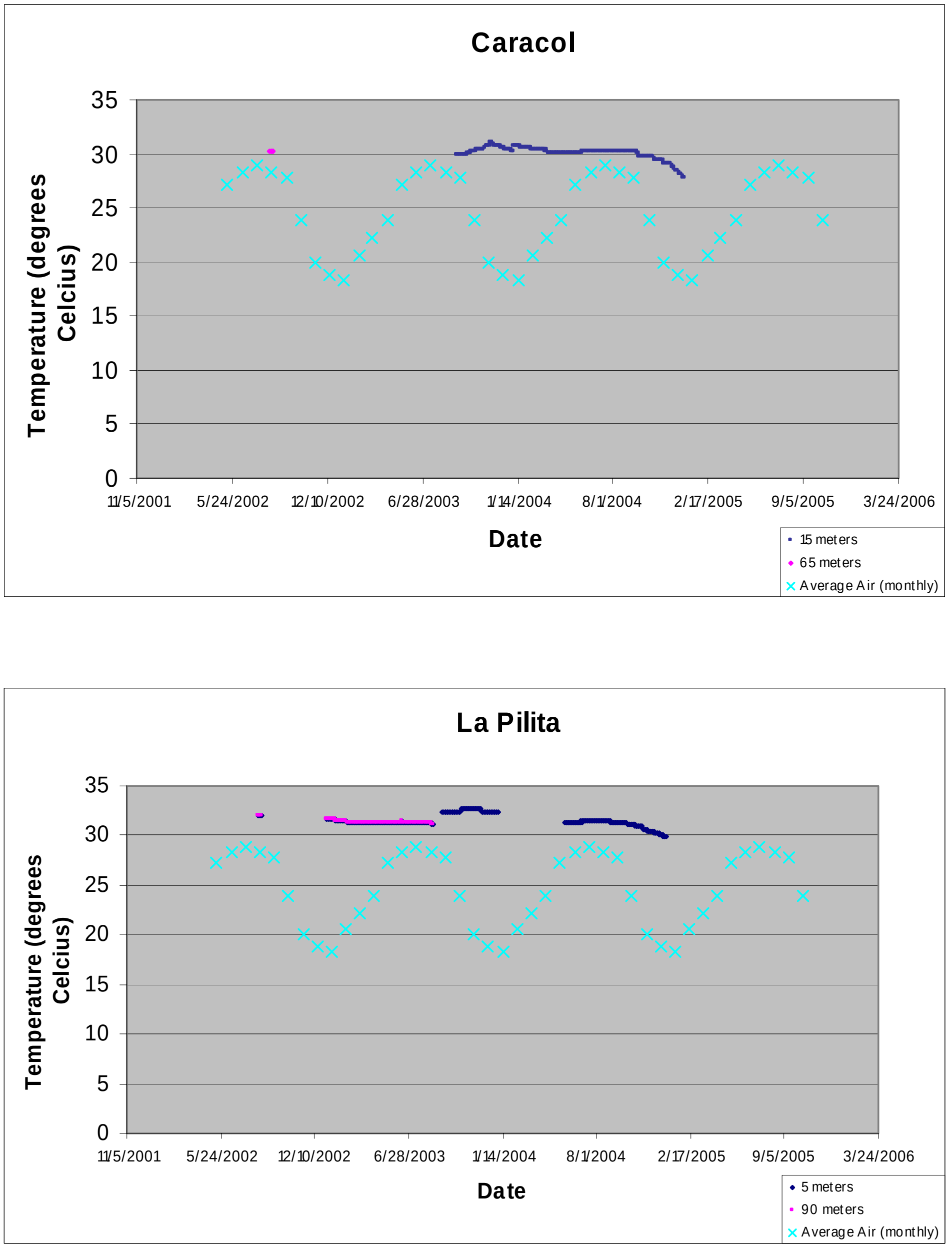
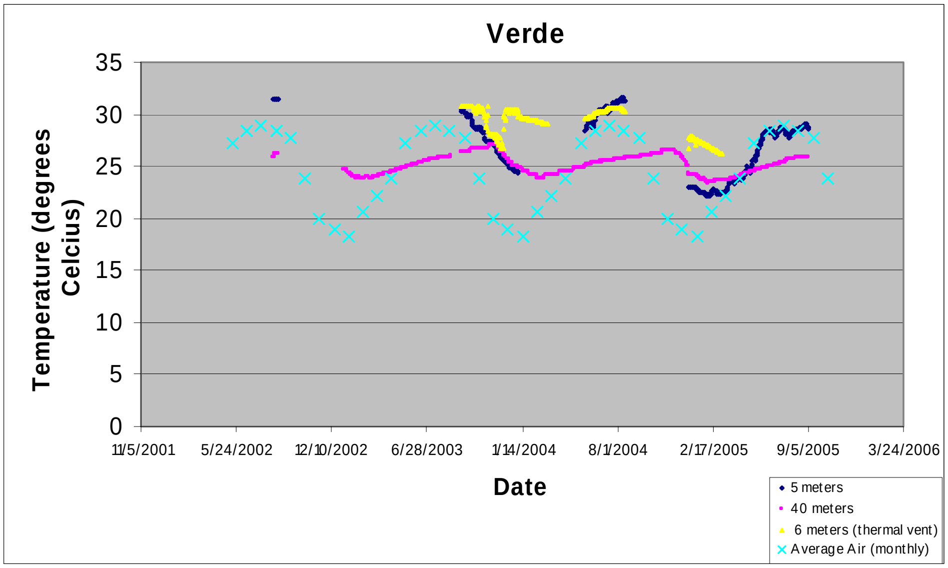


Figure 5.17 Daily Temperature Averages: Caracol and La Pilita
Temperature fluctuations at Caracol and La Pilita indicate that seasonal air temperatures have minimal influence on water temperatures in the cenote. Note that temperatures at La Pilita are consistently higher than those observed at Caracol.



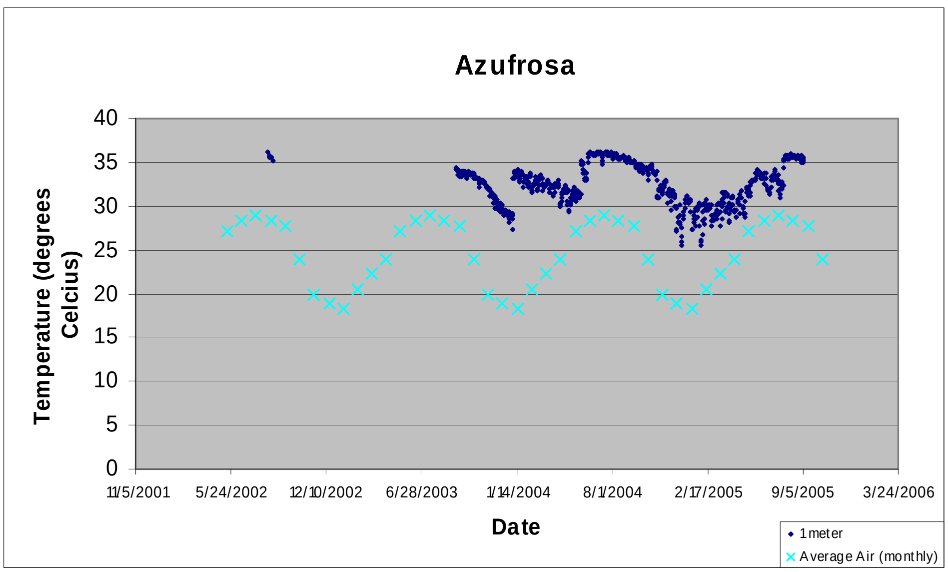


Figure 5.18 Daily Temperature Averages: Verde and Azufrosa

Both Verde and Azufrosa appear to be highly affected by seasonal air temperature fluctuations.

Chapter 6: Conclusions and Implications

This chapter synthesizes the results from each of the research methods. It compares results found through this research to other appropriate published studies. Then it discusses the applicability of the methodology used in this thesis for future research in karst landscapes. Finally, it discusses the importance of multi-scale analysis in karst regions for biodiversity conservation.

6.1 Conclusions

Remote sensing analysis of agricultural land conversion suggests that the forest areas in and around Sistema Zacatón are becoming smaller and more fragmented. Large forest patches observed in the 1972 imagery were substantially reduced in size in the classified 1990 image. Furthermore, forest patches in the earliest image displayed good connectivity with other forest patches; however, stepping through the classified images reveals that connectivity diminishes with time. Analysis of class area for each classified image shows a drop in forest area from 1972 to 1985 and an even more substantial reduction in area between 1985 and 1990.

Agricultural areas experience the opposite effects when compared to forest areas. Small-scale agricultural activity dominates the 1972 classified image. Progressing through the years the size of agriculture patches increase.

Additionally, the earliest classification shows a considerable number of small, isolated patches, and the later images reveal that connectivity between agricultural areas increases with time. Comparisons of class area for each classified image demonstrates that agricultural activity increases more from 1985 to 1990 than it did from 1972 to 1985.

The change detection performed with the classified images shows the location and quantity of agricultural conversion. In the first change detection, from 1972 to 1985, the majority of the forest to agricultural conversion was within the northern section of the remote sensing study area; a large intact forest area was converted to agriculture. The southern section of the remote sensing study area showed that smaller, less continuous areas of forest were converted to agriculture. The northwestern and the central forest patches remained largely intact. In the second change detection, from 1985 to 1990, the western portion of the remote sensing study area displayed the most concentrated conversion to agriculture; however, substantial agricultural activity also increased the eastern area. This second change detection shows a drastic reduction of size of the northwestern forest patch and only a minor area decrease in the central forest patch.

The third change detection, from 1972 to 1990, provides an overview of the agricultural land conversion trend. It summarizes all land use and land cover change within the study area. The central forest patch retains a large area original forest, despite agricultural land conversion. Similarly, a continuous, intact forest patch in the northwest preserves original forest area. Overall, approximately one-third of the remote sensing study area changed from forest to agriculture over the period between 1972 and 1990.

The results from the remote sensing analysis of agricultural land conversion suggest that there is a very limited amount of original forest remaining in the remote sensing study area as of 1990. The existing forest patches are reduced in size and isolated from other forest patches by agricultural areas. This loss of area and connectivity suggests that forest obligate species are under more stress and may experience a population loss (Stephens and Sutherland 2005; Hokit and Branch 2003; Stamps *et al.* 1987).

The vegetation survey of the ponytail palm provided a method to examine the effects of land conversion on a metapopulation level. The wandering quarter vegetation survey found no ponytail palms within the agricultural zone. The survey recorded nearly the same number of individuals in the forest and trail zones. Analysis of the densities for the two zones with individuals suggests that total density does not vary substantially between the groups. However, a *t* test proved that the DBHs for individuals in the forest zone are statistically different from the DBHs recorded in the trail zone. An examination of a size-class frequency distribution for each zone with individuals demonstrated that the forest zone has a significantly higher number of smaller ponytail palms.

These data suggest that human activities have substantially influenced the population dynamics for the ponytail palms within Sistema Zacatón. Agricultural activities presented the largest impact as no ponytail palms were observed in the three surveys in that zone. Tourist and ranching activities potentially created a disruption in the reproductive capabilities for the individuals within the trail zone, because there was a significantly reduced number of individuals with low DBHs in the trail zone when compared to the forest zone. It is possible that the number of smaller individuals in the forest zone is greater because the ponytail palm population in the forest zone has more recently had the opportunity to reproduce. However, given that the smallest DBH recorded in all surveys was still fairly large, it can be concluded that the ponytail palm population as a whole within the study area is under stress and not adequately reproducing.

The cave and karst inventory explores the study area's surface-subsurface connectivity and investigates the speleogenesis in the area. The surface karst feature inventory recorded dolines, cenotes, and cave entrances in all sections of the study area. Survey of the shallow cave passages reveals that there is an extensive network of passage that directly connects the surface to the underground components of the karst landscape. The four species of bats recorded at Sistema Zacatón indicate that the dry caves are essential habitat for important the conservation of species with declining numbers. The amount of graffiti and broken formations and proximity to areas recorded as bat roosts within the dry cave system raise concerns about the fate of the bat populations given the sensitivity of hibernating and maternity colonies (Tuttle and Moreno 2005) and the observed negative impacts humans have had in the caves.

Furthermore, the analysis of water temperature data from the cenotes suggests that four of the five cenotes contact a heat source at extreme depths. Water temperatures recorded at depth in Zacatón, Caracol, and La Pilita differ only slightly with temperatures recorded in shallow locations. The lack of difference suggests that temperatures in these three cenotes are controlled by a heat source at depth. Temperature and fluctuation pattern similarities indicate that Caracol may share a connection with La Pilita and verify that water coming out of the spring at Nacimiento is most likely directly related to water in Zacatón.

Dublyansky cites four characteristics—all present in Sistema Zacatón—as evidence of hydrothermal karstification (Dublyansky 2000). They are elevated water temperatures, large discharge volume, oxidation of hydrogen sulfide and mixing waters of contrasting chemistry. Average water temperatures collected by the continuous data loggers from 2002-2005 in the five cenotes support this theory. Results show that Zacatón, Caracol, La Pilita, and La Azufrosa display mean water temperatures significantly higher than the mean yearly air temperature. Groundwater is considered to be hydrothermal when it reflects 4-5°C above the mean yearly air temperatures (Dublyansky 2000); thus it is likely that water recharging the pozos comes in contact with a subterranean heat source.

The three research methods used in this thesis provide an integrated multi-scale analysis of human activities and the karst landscape in and around Sistema Zacatón. The remote sensing analysis informs the local-level fieldwork by assessing land use trends both regionally and within the study area. The agricultural land conversion study established that the study area for the vegetation survey and the cave and karst inventory contained a patch of relatively intact, original forest. This research strengthens conclusions made in the vegetation survey, because the land use and land cover classification and change detection identified that the forest zone had not been cleared for agricultural activities. Furthermore, the remote sensing agricultural land conversion analysis informed the cave and karst inventory by providing the tool to examine historical land use in the study area.

There are several advantages to using remote sensing to inform local-level field work. Remote sensing analysis provides access to historical conditions over large geographic extents (Jensen 2000). The frequent passes of satellites facilitate the study of rapid landscape change over large areas (Forman 1995). Multi-spectral imagery allows for identification of vegetation, soils, water, etc. by using data gathered beyond the limits of the human eye (Lillesand *et al.* 2004). Furthermore, trends across large areas and timeframes can be quickly analyzed enabling the extrapolation of conditions to other times or locations (Turner *et al.* 2001).

Remote sensing analysis does have qualitative and quantitative limits. Perhaps the most evident is that remotely sensed imagery, by virtue of being remote, can be subject to different interpretations by different analysts (Robbins 2001). Furthermore, the quality of sensed data can be influenced by atmospheric interference, sensor failure, sensor calibration problems; while technology exists to minimize the effects of atmospheric interference and mechanical failure, it invariably affects the integrity of the analysis. Temporal and spatial resolution can also limit the effectiveness of remotely sensed imagery to inform field work (Lunetta *et al.* 2002). Satellite flight paths and acquisition dates may not correspond to field campaigns. Spatial resolution of imagery may limit the recognition of specific features or items of interest. Additionally, the cost of high-resolution imagery can be restrictive; traditionally, imagery can either be of high spatial or temporal resolution, not both concurrently (Lillesand *et al.* 2004).

Combining remote sensing analysis with surveys performed at a local level alleviates some of the limitations experienced with remote sensing analysis alone and allows local level results to be applied region-wide (Griffith 2002; Trejo and Dirzo 2000; Yuan and Elvidge 1998). The spatial resolution of the MSS data used in this thesis proved limiting at the local level. Ground recognizance combined with aerial photo interpretation defined land use boundaries for the vegetation survey (Kepner *et al.* 2000). Results from the vegetation survey can be extrapolated to similar land use and land cover categories for discussion of trends at a regional level (Trejo and Dirzo 2000). Furthermore, results from the karst and cave inventory establish ground conditions and the level of interconnectivity of the surface and subsurface in the area. These results can be used to interpret the effects of human activities on the subsurface environment in and around the study area.

6.2 Implications

First, at a small scale, the remote sensing analysis of agricultural land conversion shows that forested areas in and around Sistema Zacatón are being fragmented and converted for agricultural and ranching purposes. These results are consistent with studies done across Mexico. Conversion of dry tropical forest to agricultural land is a very common practice and has made intact forest patches scarce (Burgos and Maass 2004). A study reports a thirty percent decrease in dry tropical forests across Mexico due to conversion to agricultural and ranch lands from approximately 1970 to 1990 (Trejo and Dirzo 2000). This finding is nine percentage points lower than the percent calculated for this research (Table 5.2). The high floristic diversity, high levels of endemism, and current threats to their survival make seasonally dry tropical forests an issue of local and global concern for biodiversity conservation (Trejo and Dirzo 2002).

The endemic and endangered ponytail palm, *Beaucarnea inermis*, is found in seasonally dry tropical forests (Reserva Especial de la Biósfera Sierra del Abra-

Tanchipa 2005; Flores *et al.* 2004). One of the only recorded systematic inventories of *Beaucarnea* species identified 10 species in Mexico, nine of which are threatened or endangered (Cardel *et al.* 1997). The study found that *Beaucarnea gracilis* reproduction was severely impacted and the concluded that most *Beaucarnea* species are in a critical state due to two human activities: extraction and goat-raising (Cardel *et al.* 1997). *Beaucarnea* species appear to be an appropriate indicator of the cumulative effects human impact, mainly harvesting and agriculture, has had on the landscape. The results of the vegetation survey performed as a portion of this thesis suggest that agricultural land conversion has had an adverse affect on native plant communities within Sistema Zacatón. By correlating population status with land use zones established through the remote sensing analysis of agricultural land conversion and primary investigation of the study area, the vegetation survey indicates that tourism, ranching, and agriculture have severely impacted the landscape.

Tourism, ranching, and agriculture can also have severe consequences on caves and karst features (Calaforra *et al.* 2003; Veni *et al.* 2001; Drew and Hötzl 1999). The geomorphological cave and karst inventory of Sistema Zacatón indicates that this system is both intensely karstified and potentially globally unique as a result of speleogenesis associated with the area. Sistema Zacatón could be unique on a global scale because it displays evidence of hydrothermal karstification, and it has one of the deepest, water-filled caves in the world.

The data collected as a part of this thesis provides a baseline for future studies in the area. Analyses performed on water quality and quantity established reference conditions that can be used in the further investigation of surface and sub-surface interaction within the system. Vegetation surveys on the condition of the ponytail palm created documentation on the status of the metapopulation that can be used to quantify changes due to changes in land use. More immediately, the data and analyses recorded in this thesis provides the science data for educated management decisions. The land owner and governmental agencies involved with biodiversity conservation have a baseline assessment of the effects of human activities on Sistema Zacatón.

Complex landscapes necessitate multi-scale analysis in order to assess habitat quality and population dynamics (Hall *et al.* 2004; Turner *et al.* 2001; Turner 1989). The methodology established in this thesis offers an approach to analyze the effects of human activities on complex karst landscapes. Remote sensing analysis established regional land use trends (Lillesand *et al.* 2001; Trejo and Dirzo 2000). The vegetation survey provided a linkage to the effects of specific land uses on the landscape by examining the response of an indicator species sensitive to human activities (Osario-Rosales and Mata-Rosas 2005; Lindenmayer *et al.*1999). The cave and karst inventory investigated the degree and qualities of habitat provided by the system to establish the sensitivity of the karst landscape (Veni 1999).

Furthermore, the use of landscape ecology principles to interpret multi-scale results provides an appropriate framework with which to extrapolate the impact of human activities to a karst system. Fragmentation and habitat degradation both on the surface and underground threatens rare and endangered species (Hancock *et al.* 2005; Gibert and Deharveng 2002; Collinge 1996; Schemske *et al.* 1994; Stamps *et al.* 1987). Describing the karst landscape through terms established and defined by landscape ecology literature allows for analysts to investigate the linkages of surface conditions with the remote underground habitats that make up an important portion of the karst landscape.

Recent concerns for biological diversity conservation make the methodologies established in this thesis for analysis of human activities and karst landscapes particularly timely. Given that environmental diversity is a viable surrogate for biodiversity (Bonn and Gaston 2005) and karst landscapes offer high proportions of rare and endemic taxa (Hancock *et al.* 2005) conservation practices in karst landscapes offer an opportunity to reduce biodiversity loss substantially. Within the literature there has been substantial debate on procedures for conservation area selection and monitoring (Scholes and Biggs 2005; Mace 2005; Brooks and Kennedy 2004). In response to the call for conservation area selection procedures, this thesis offers a method for identifying areas with a high concentration of biodiversity and provides the tools for assessing and monitoring environmental health in relation to human activities on the surface within karst landscapes.

Appendix A: List of Acronyms

CESPEDES: Centro de Estudios del Sector Privado para el Desarrollo Sustentable or The Private Sector Center of Studies for Sustainable Development

cfs: cubic feet per second

CO_2: Carbon dioxide

CONABIO: Comisión Nacional para el Conocimiento y uso de la Biodiversidad, México, or Mexican National Biodiversity Commission

DOQQ: digital orthophoto quarter quadrangle

DBH: diameter at breast-height

GIS: Geographic Information Systems

GPS: Global Positioning System

H_2S: hydrogen sulfide

ILICE: Instituto Latinoamericano de la Comunicación Educativa

INEGI: Instituto Nacional de Estadistica, Geografía e Informatica, or the National Institute of Statistics, Geography and Information

ISODATA: Iterative self-organizing data

IUCN: The World Conservation Union

m: meter(s)

NASA: National Aeronautics and Space Administration

PRONATURA: Asociación Mexicana Pro Conservación de la Naturaleza, or the Mexican Association for the Conservation of Nature

SCUBA: Self Contained Breathing Apparatus

SEDUE: Secretaría de Desarrollo Urbano y Ecología

SEMARNAT: Secretaría del Medio Ambiente y Recursos Naturales, or Secretary of the Environment and Natural Resources

SEP: Secretaria de Educación Pública

USGS: United States Geological Survey

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