APPLICATIONS OF GIS AND REMOTE SENSING FOR THE CHARACTERIZATION OF HABITAT FOR THREATENED AND ENDANGERED SPECIES

DISSERTATION

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By

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Geographic Information Systems (GIS) and remote sensing technologies were used to identify and describe potential habitat for three species endemic to the Southwestern United States; the Golden-cheeked Warbler (*Dendroica chrysoparia*), the Black-capped Vireo (*Vireo atricapillus*) and the Texas kangaroo rat (*Dipodomys elator*). For each species, the computerized classification of digital satellite imagery was integrated with ancillary spatial information (e.g. soils, geology and landuse) to construct a data base to be used for ecological evaluation as well as habitat protection and management measures.

For the Golden-cheeked Warbler, 80 meter resolution Landsat Multi-spectral Scanner (MSS) data were classified to identify potential nesting habitat across the breeding range of the species. Additionally, several indices were developed to describe the spatial characteristics of and between patches of identified habitat.

Potential nesting habitat for the Black-capped Vireo was identified on Camp Bullis, Texas. This was accomplished

with a combination of classification of Landsat Thematic Mapper data (30 meter resolution) coupled with information about the major geologic formations underlying the study area.

For the Texas kangaroo rat, a map of potential habitat was developed for a portion of their range. The variables employed for the model were; landuse (from Landsat MSS data), major geologic formation and soil association. The model was developed and tested with locations of collection sites for Texas kangaroo rats.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Improvements in computer and remote sensing technologies have created opportunities for their combined application to ecological research, particularly for habitat description. The studies described here have addressed the integrated analyses of digital remote sensing data with Geographic Information System(s) (GIS) for habitat identification and characterization. Techniques were developed and assessed to identify and describe potential habitat for three endangered or threatened species endemic to the southwestern United States; the Golden-cheeked Warbler (*Dendroica chrysoparia*), the Black-capped Vireo (*Vireo atricapillus*) and the Texas kangaroo rat (*Dipodomys elator*).

In 1973, the United States Congress passed the Endangered Species Act (ESA) to provide for the conservation of animal and plant species currently in danger of extinction ("endangered"), and those that may become so in the foreseeable future ("threatened"). Section 7 of the Act mandates responsible actions by all federal agencies to ensure protection of endangered and threatened species and their critical habitat (USFWS 1987a).

The identification and appraisal of such habitat is imperative. For many species, classification of remotely sensed data offers a means to achieve this goal. Through remote sensing, important habitat elements such as vegetative cover (composition, density and interspersion) may be interpreted. Additionally, remote sensing analyses offers a means of monitoring temporal changes by tracking the physical properties of communities or ecosystems.

Subsequent to interpretation of remotely sensed data, its integration into a GIS affords the potential for multi-dimensional analyses with ancillary data bases. GIS were developed as a means to assemble and analyze diverse data pertaining to specific geographical areas (Estes 1986). A GIS was used to analyze data with more variables and for larger areas than would be possible with traditional methods. Given the inherent complexity of ecological systems, use of these tools offer a means for systematic research into spatial habitat characterization.

The success of an integrated approach for studying a given species or community depends on considerations such as the spectral characteristics of the selected features, the resolution of the data and the physical complexity of the region. Additionally, sufficient knowledge of natural history, ecology and behavior is needed for submitting pertinent and germane questions.

The research presented here entails the integrated application of remote sensing and GIS for the identification and ecological evaluation of potential habitat for the Golden-cheeked Warbler, Black-capped Vireo and the Texas kangaroo rat. Due to the distinctive habitat requirements of each species, individual strategies were developed. The emphasis of the research was the development of techniques for identifying and quantifying potential habitat, rather than the issue of defining habitat quality for these species.

For the Golden-cheeked Warbler and Black-capped Vireo studies, satellite imagery was used to identify their respective nesting habitats. A GIS was then used to integrate the classified satellite data with additional factors to further characterize these habitats. The Texas kangaroo rat, a species whose habitat appears to be primarily dictated by edaphic features, was approached primarily as a GIS study. For this species, the interpretation of remotely sensed data to describe general landcover was supplemental to the other factors considered.

Each of these studies, although primarily computer-based, was supplemented with field work for collection of data pertaining to verification of the image classification, descriptions of vegetation and information concerning the utilization of each habitat by the appropriate species.

The objectives for this research were:

A. The computerized classification of digital imagery, used in conjunction with ancillary spatial data, to identify vegetational communities representing potential nesting habitat for the Golden-cheeked Warbler and the Black-capped Vireo.

B. The combination of GIS and remote sensing techniques to model suitable habitat for the Texas kangaroo rat.

C. The establishment of data bases useful in monitoring habitat changes for these species.

E. The development of a generalized approach to serve as a model for additional GIS and remote sensing studies addressing habitat studies for threatened or endangered species.

CHAPTER II

LITERATURE REVIEW

This chapter presents a review of pertinent literature. The chapter begins with a description of the natural history and current status of each of the three species. Following this is a review of previous applications of remote sensing and GIS to habitat description studies. Explanation of the basic remote sensing and GIS principles utilized are also included.

Golden-cheeked Warbler

Distribution

Golden-cheeked Warblers nest exclusively in Central Texas from Palo Pinto and Bosque Counties, south through the Eastern and South-Central portions of the Edwards Plateau (Fig. 1). The species has been observed in 41 Texas counties, of which 31 were considered by Pulich (1976a) to be within the current nesting range. This breeding range coincides with the range of Ashe juniper (*Juniperus ashei*), which the species depends upon for nesting material. Wintering range of the Golden-cheeked Warbler is not known, but evidence suggests it may be in the mountainous areas of Central-Eastern Guatemala through Honduras to Nicaragua

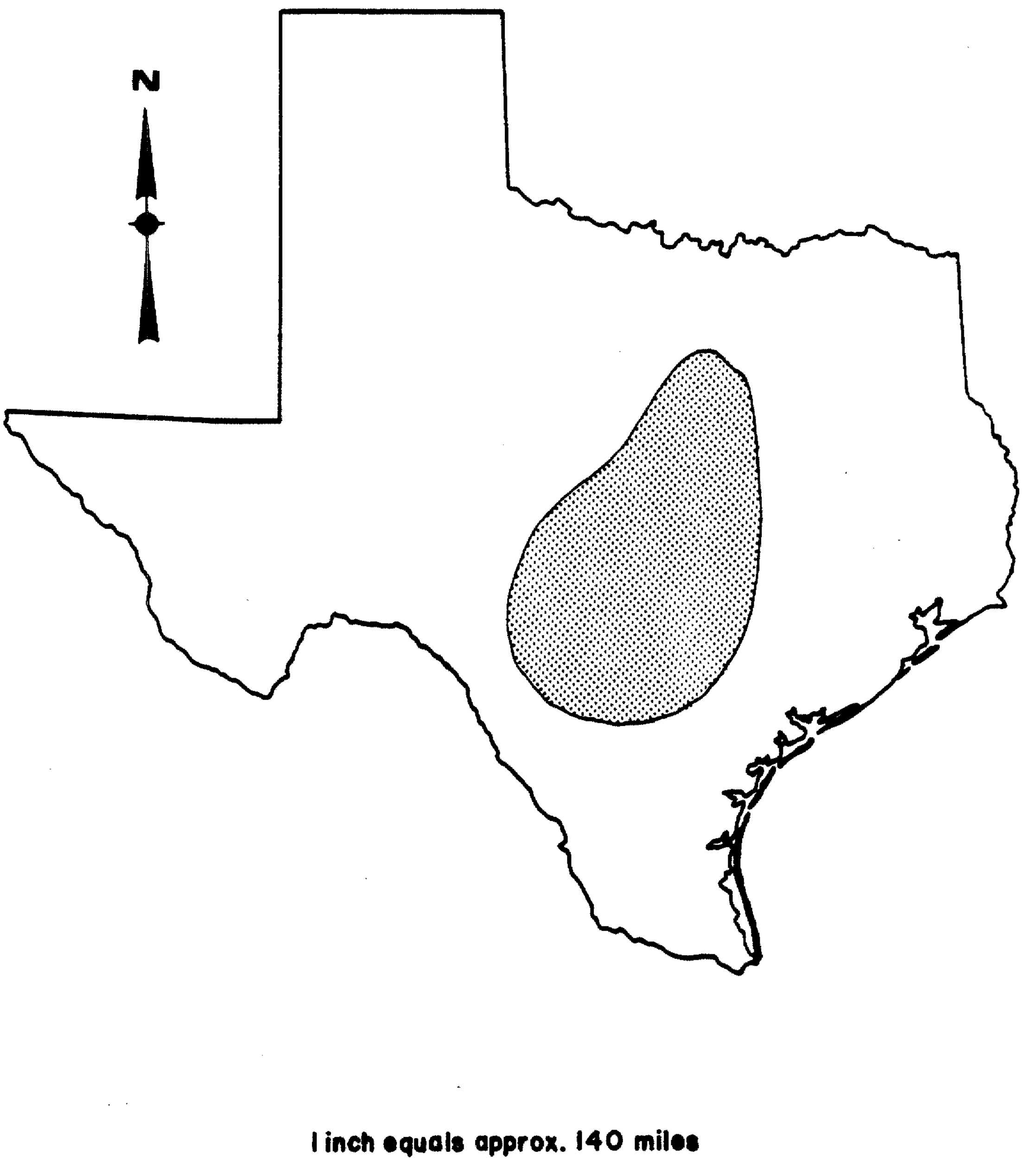


FIGURE 1. Breeding distribution of the Golden-cheeked Warbler (from TOS 1984).

(Pulich 1976a).

Morphology

The Golden-cheeked Warbler is a small, insectivorous, parulid warbler species, measuring approximately 11.25 cm in length, with a wingspan of 19 cm. In breeding plumage, the male has yellow cheeks, outlined in black. His throat, neck, upper breast and streaking along the flanks are black. Wings are black with two distinct white bars and a blackish tail. Immature males have backs that are streaked with green. Females are duller than the male with less black on the throat and underparts (upperparts are olive-green). Cheeks of the female are not as bright as those of adult males (Pulich 1976a).

Habitat

Ashe juniper is the dominant tree species wherever Golden-cheeked Warblers occur. According to Kroll (1980), Ashe juniper must be at least 20 years old to be of use to the warbler. Ladd (1985) described several plant associations favored as nesting habitat by the warbler, all include Ashe juniper and species of oak which provide essential foraging substrate.

The breeding range of the Golden-cheeked warbler lies within the Edwards Plateau, Cross Timbers and Prairies, and Blackland Prairies ecological areas of Texas. Avian species found nesting in association with the Golden-cheeked Warbler are: Carolina Chickadee (*Parus carolinensis*), Bewick's Wren (*Thryomanes bewickii*), Carolina Wren (*Thryothorus ludovicianus*), White-eyed Vireo (*Vireo griseus*), Brown-headed Cowbird (*Molothrus ater*), Painted Bunting (*Passerina ciris*) and Lark Sparrow (*Chondestes grammacus*). With respect to other parulid warblers, the Golden-cheeked Warbler occupies such a restricted ecological niche that it has little competition. Several species of parulid warblers are found within the range, such as the Black-and-White Warbler (*Mniotilta varia*), the Northern Parula Warbler (*Parula americana*) and the Yellow-throated Warbler (*Dendroica dominica*), but none appear to be in direct competition with the Golden-cheeked Warbler (Pulich 1976a).

Breeding Biology

The Golden-cheeked Warbler arrives in Texas in early March. The female builds the nest and incubates the eggs. Nests are built in forks of vertical limbs at heights of about 5 m. A typical clutch is three or four eggs. The incubation period is twelve days, with fledging at eight or nine days. Males cease to sing after eggs are hatched and take an active role in feeding and care of the young. Banding studies have shown these warblers return to the same area each year (Pulich 1976a).

Average territory size was determined by Pulich (1976a) to be from 1.3 to 2.5 ha. Within this area, males sing and defend territories against conspecific males. A census of densities by the Travis Audubon Society in the 1950s estimated 16 pairs of birds per 40.5 ha, about 2.5 ha per pair of birds (Pulich 1976a).

Status

Pulich (1976a) estimated the total population of Golden-cheeked Warblers to be 1,950 birds. The USFWS (1985) currently lists the species as Category 2 (taxa for which listing may be appropriate, but for which conclusive data on biological vulnerability are not currently available to support listing). The Texas Parks and Wildlife Department lists the species as threatened.

The primary concern for the future of the species is from loss of suitable nesting habitat. Oberholser (1974) suggested three causes for decline in habitat: clearing for agricultural use, real estate development and reservoir construction. Pulich (1976a) added that social parasitism by Brown-headed Cowbirds may be a major contributor to the decline of this species.

To ensure the preservation of the species, Pulich (1976a) suggested that mature juniper breaks ranging from several hundred to a thousand acres or more be preserved. He reported that juniper acreage in Texas had been reduced by 50% since the 1950s and speculated that if habitat destruction continues unchecked, mature Ashe juniper, which fulfill the warbler's nesting requirements, could be eliminated by the turn of the century.

Black-capped Vireo

Distribution

The present breeding range of the Black-capped Vireo is from Blain County, Oklahoma, south into Texas, through Dallas County, the Edwards Plateau, Concho Valley, Big Bend National Park, and south to the Sierra Madera (Central Coahuila, Mexico) (Fig. 2). The majority of known nesting populations are located in central Texas. The Black-capped Vireo winters along the Pacific coast of the Central Highlands of Mexico (Graber 1961). The former known breeding range of the Black-capped Vireo was from Kansas through Oklahoma and Texas to Central Coahuila, Mexico (AOU 1983). Today, the species is no longer found in Kansas (Tordoff 1956), nor does it nest in several portions of Oklahoma and the Edwards Plateau.

Morphology

The Black-capped Vireo is a small, migratory insectivorous species. The following description is from Bunker (1910):

> "The adult male is olive green in the upper surface, white beneath with flanks faintly yellowish green. The crown and upper half of the head is black and sharply demarcated. This pattern

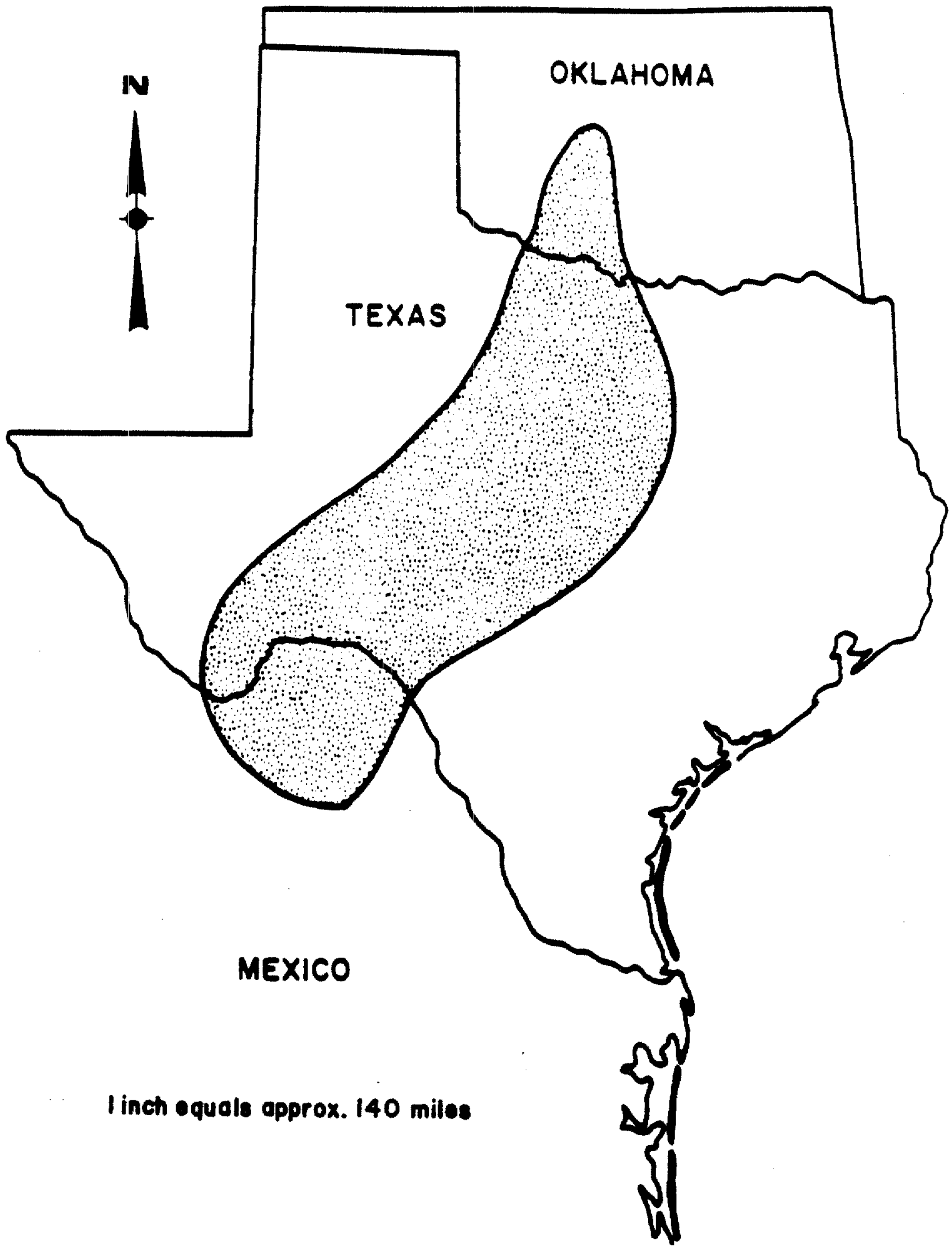


FIGURE 2. Current breeding distribution of the Black-capped Vireo.

is unique in the family Vereonidae. There is a large angular white patch along the side of the head which included the lores and an interrupted eye-ring. This white area is entirely surrounded by black. The white patches from the two sides converge and become pointed anteriorly above the bill where they are separated by only a speck of black. The iris is browning red, the bill black, the feet plumbeous. Wing and tail feathers are dark olive, becoming blackish on the tertials and secondary coverts. All are conspicuously rimmed with cream or lemon yellow. The adult female is colored the same way except that the crown is slate gray instead of black and the underparts are a greening yellow."

Habitat

The Black-capped Vireo occupies primarily transitional shrub or scrub brush vegetation found between grassland and woodland ecotones. Vegetation consists of short trees scattered among patches of brush (Marshall et al. 1984). Habitat often contains scrubby oak growth of heterogeneous heights, with spaces between clumps and vegetation cover to ground level. Suitable habitat is found in a diversity of plant communities, the primary requisite appears to be availability of suitable nesting substrate (i.e. broadleaved deciduous trees, dense foliage from ground level to approximately 1.5 m and stems with adequate horizontal limbs to facilitate construction of the pensile nests) (Grzbowski 1985).

In Central Texas, the Black-capped Vireo is found in association with the following hardwood species; live oak (Q. virginia), spanish oak (Q. Texana) and Ashe juniper (J. ashei). In the southwestern part of its range, the Black-capped Vireo is found in various scrub oaks (Q. undulata, texana, mohriana, grisea, intricata), yuccas (Yucca sp.) and cornaceous shrub (Garrya sp.) (Grzbowski 1985).

Throughout their range, the vegetative communities in which they are found are usually transitory, eventually crowded out by juniper, oak or other deciduous species which grow into a closed woodland canopy. Perennial habitat of this type is found only on steep, rocky slopes where erosion and interspersion of boulders preclude growth of a closed canopy (Marshall et al. 1984).

Oberholser (1974) described a relationship between the "erosional region of limestone exposures" and the "dry limestone hilltops, ridges slopes, and gulches of the Edwards Plateau" with the distribution of good vireo habitat. Sexton (1988) further suggested that the distribution of breeding populations of the Black-capped Vireo is highly correlated with a few narrow strata of limestones, especially the lower Cretaceous Fredericksburg

Group. He suggests the correlation may explain the patchiness of the vireo distribution and may be used to focus future searches for vireo habitat.

The Black-capped Vireo is an important ecologic component in the particular habitat of its limited range. It is an indicator for the vegetational configuration that it occupies and as Marshall, et al. (1984) suggested, the vireo is an even more competent habitat indicator than the dominant plants, inasmuch as these drop out and are replaced by ecologic equivalent species in an irregular sequence from west to east and north to south.

Breeding Biology

Males arrive at the nesting area in late March or early April, a week or two in advance of females. Males select territories and defend them aggressively from potential predators, as well as other male vireos. All nesting activities through fledgling are confined to this territory. Males often return to the same site, each year, and mating is usually for the entire season (Graber 1961).

Nest construction is completed a day or two prior to laying of the first egg. The typical nest site is 0.76 to 1.02 m above ground, suspended from the crotch of a horizontal forked branch, about 45 cm above ground. The clutch is typically four white unmarked eggs.

Incubation ranges from 14 to 17 days. Hatching chicks weigh about 1 gm, they are blind and completely without feathers. They grow at a rate of about 1 gm per day and fledge at approximately eleven or twelve days (Graber 1961).

Status

An estimate of the 1985 Black-capped Vireo population ranged from 248 to 510 adult breeding pairs (Marshall et al. 1984). Steed (1987) pointed out that, "even if these estimates are 100% off, the Black-capped Vireo is one of the rarest of American songbirds". Grzybowski (1985) suggested Black-capped Vireo populations may be in decline, particularly along the western edge of their Texas range.

The exact cause of the species' decline is not known, however, Marshall (1984) identified four major threats to the species; real estate development, grazing by goats, sheep and exotic herbivores, growth of junipers into a closed canopy and nest parasitism by the Brown-headed cowbird. According to Marshall et al. (1984) parasitism may be so severe that no young Black-capped Vireo young are fledged in particular colony.

In November 1987, the Black-capped Vireo was listed as endangered by the USFWS (USFWS 1987b). This affords the species full protection under the Endangered Species Act. Possible recommendations for the preservation of the species include management of transitory habitat and active efforts at cowbird control. Steed (1987) suggested that the availability of large tracts of suitable habitat was essential to survival of the species. This follows Grabers' (1961) estimation that a minimum of approximately 2 ha is required for a breeding pair, and a minimum of 4.2 ha is required for the species to be established in an area.

Texas Kangaroo Rat

Distribution

The current known range of the Texas kangaroo rat (Dipodomys elator) extends across nine counties in North-Central Texas (Fig. 3). Several old records exist from outside the range. From Oklahoma, the species is documented by three specimens, two from Chattanooga County, collected in 1904 and 1905, and one from Cotton County collected in 1969. There have been no records from Clay County, Texas since early in this century (Martin and Matocha 1972), although there are specimens from Montague County, immediately east of Clay County (Cokendolpher et al. 1979). Martin and Matocha (1972) suggested the lack of recent records of Texas kangaroo rats from previously reported areas indicates some former habitat is no longer suitable. An additional record of the species exists from Coryell County, Texas (Blair 1949) but, according to several authors (Dalquest and Collier 1964; Martin and Matocha 1972), it is

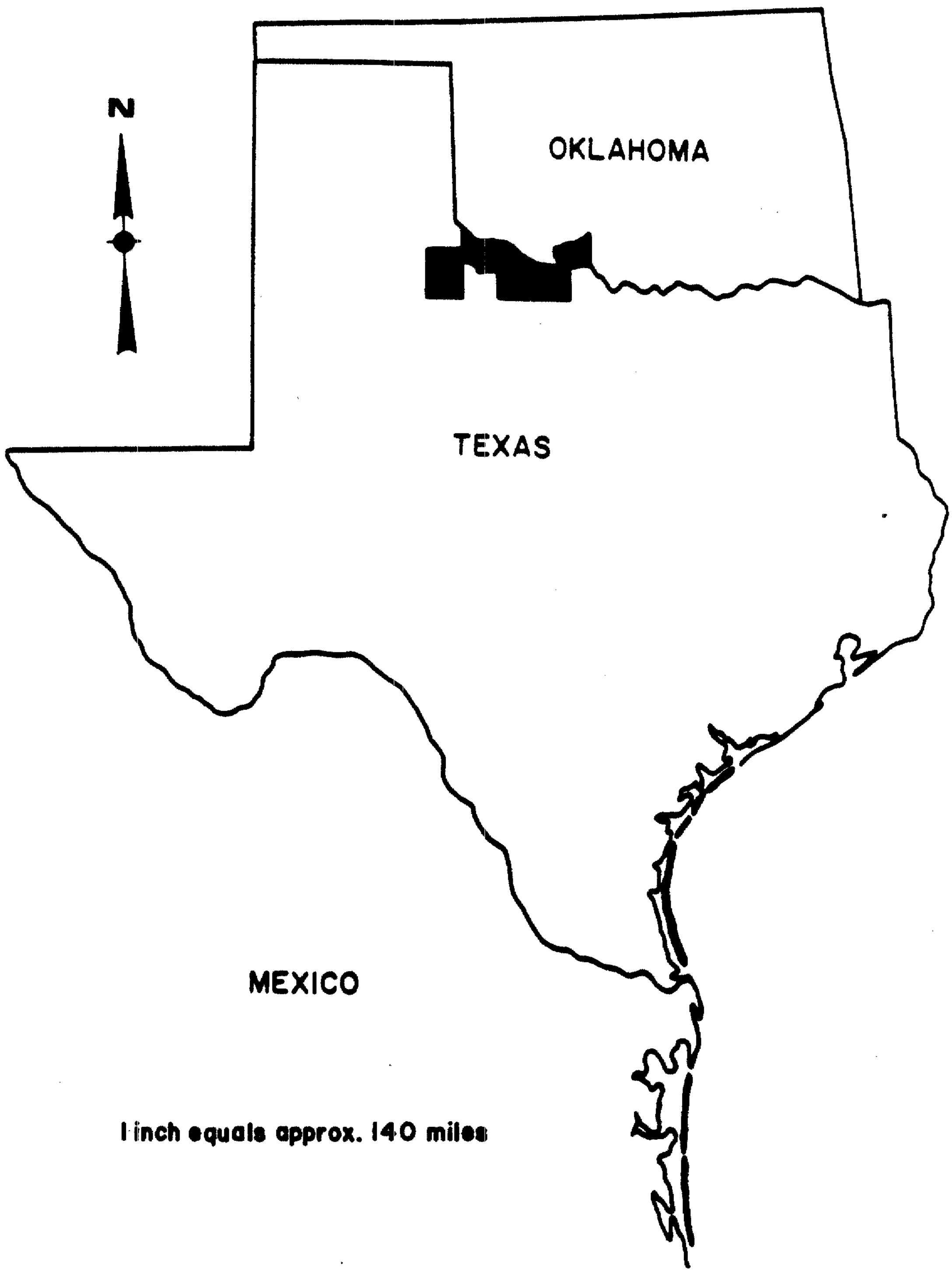


FIGURE 3. Current range of the Texas kangaroo rat.

subject to question.

Morphology

The Texas kangaroo rat was described by Merriam (1894), on the basis of specimens collected from Clay County, Texas. The Texas kangaroo rat is a monotypic species for which there is some disagreement as to its exact taxonomic relationships. Davis (1942) believed that the Texas kangaroo rat belongs in a species taxa of its own, while others contend it is closely related to either the Merriam kangaroo rat (D. merriami) or the southern banner-tailed kangaroo rat (D. phillipsii) (Jones and Bogan 1986). The species is described by Davis (1942) as:

> "A rather large four-toed kangaroo rat with conspicuous white "banner" on tip of tail; tail long, relatively thick, and about 162 percent of length of head and body; body large (about 121 mm in length); upperparts buffy, washed with blackish; underparts white....external measurements average: total length 317 mm; tail 196 mm; hind foot, 46 mm".

The Texas kangaroo rat is largely granivorous. Chapman (1972) found cultivated oats (Avena sativa) and Johnson grass (Sorghum halepense) were the most common food items in cheek pouches. Additional food items included leaves and immature fruits of stork's bill (*Erodium circutarium*) and goathead (*Tribulus terrestris*). Perennial shrubs were infrequently utilized. Few seeds of prickly-pear cactus (*Opuntia* sp.) and mesquite were found in pouch samples, despite their abundance throughout the range of the Texas kangaroo rat.

Habitat

The historical range of the Texas kangaroo rat extends over portions of two major physiographic provinces, the Rolling Plains (eastern portion) and the Cross Timbers (western portion). Within the Rolling Plains, the native vegetation includes prairie grasses, such as little bluestem (*Schizachyrium scoparium*), big bluestem (*Andropogon gerrardii*), sideoats gramma (*Bouteloua curtipendula*), Indian grass (*Sorghastrum nutans*), and dropseed (*Sporobolus* sp.). Invading plant species, typical of overgrazed or disturb landscapes, include mesquite (*Prosopis glandulosa*), western ragweed (*Ambrosia psilostachya*), tumble grass (*Schedonnardus paniculatus*) and sandburrs (*Cenchrus incertus*).

The native vegetation of the Cross Timbers in north-central Texas includes grasses such as little bluestem, big bluestem, Canada wildrye (*Elymus canadensis*), tall dropseed (*Sporobolus asper*) and Texas wintergrass (*Stipa leucotricha*). Also characteristic are clusters of post oak (*Quercus stellata*) and blackjack oak (*Q. marlandica*).

Status

The Texas kangaroo rat is currently listed as threatened by the Texas Organization for Endangered Species and as protected by the Texas Department of Parks and Wildlife (Roberts and Mills 1983). It is listed as rare by the International Union for Conservation of Nature and Natural Resources (ICUN 1986). Habitat alteration, such as clear cutting and brush control for agricultural development, has reduced available habitat for the species (Hamilton et al. 1987). Martin and Matocha (1972) suggested the extensive modification of mesquite pastures or conversion of pastures to monoculture may adversely affect the kangaroo rat.

Remote Sensing

Remote sensing is the science of obtaining information on the properties of an object or phenomenon, through analysis of data acquired by a sensor not in physical contact with the object or phenomenon. The most important medium for environmental remote sensing is electromagnetic radiation (EMR), and involves measuring (sampling) EMR within the electromagnetic spectrum. All objects exhibit distinct "spectral signatures" characterized by the pattern of spectral emittance across the electromagnetic spectrum. Such signatures are often presented as spectral reflectance or spectral emittance curves. Figure 4 displays such spectral signatures for typical green vegetation, dry loam soil and clear water. Relative spectral differences between these materials are the basis for interpretation of satellite imagery.

Sensors

In 1967, the National Aeronautics and Space Administration (NASA) initiated the Earth Resource Technology Satellite (ERTS) program. Through this program five satellites, carrying a variety of remote sensing systems have been deployed. Their primary intention is to acquire earth resource information.

The most recent satellite in the program, Landsat 5, was launched in March 1984 and carries a 4-band multispectral scanner (MSS) and a 7-band thematic mapper (TM) scanner. It orbits the earth at an altitude of 705 km in a sun synchronous near polar orbit. Its repeat coverage is 16 days (Slater 1985).

MSS systems are so named because they simultaneously record energy from several portions of the electromagnetic spectrum. The MSS scans with a rapidly oscillating mirror, which directs reflected radiation through an optical system thereby separating the radiation by wavelength bands. Each band is then focused on individual detectors with specific spectral sensitivities which convert the EMR to electrical energy (Estes 1985). These four bands of EMR sensitivity

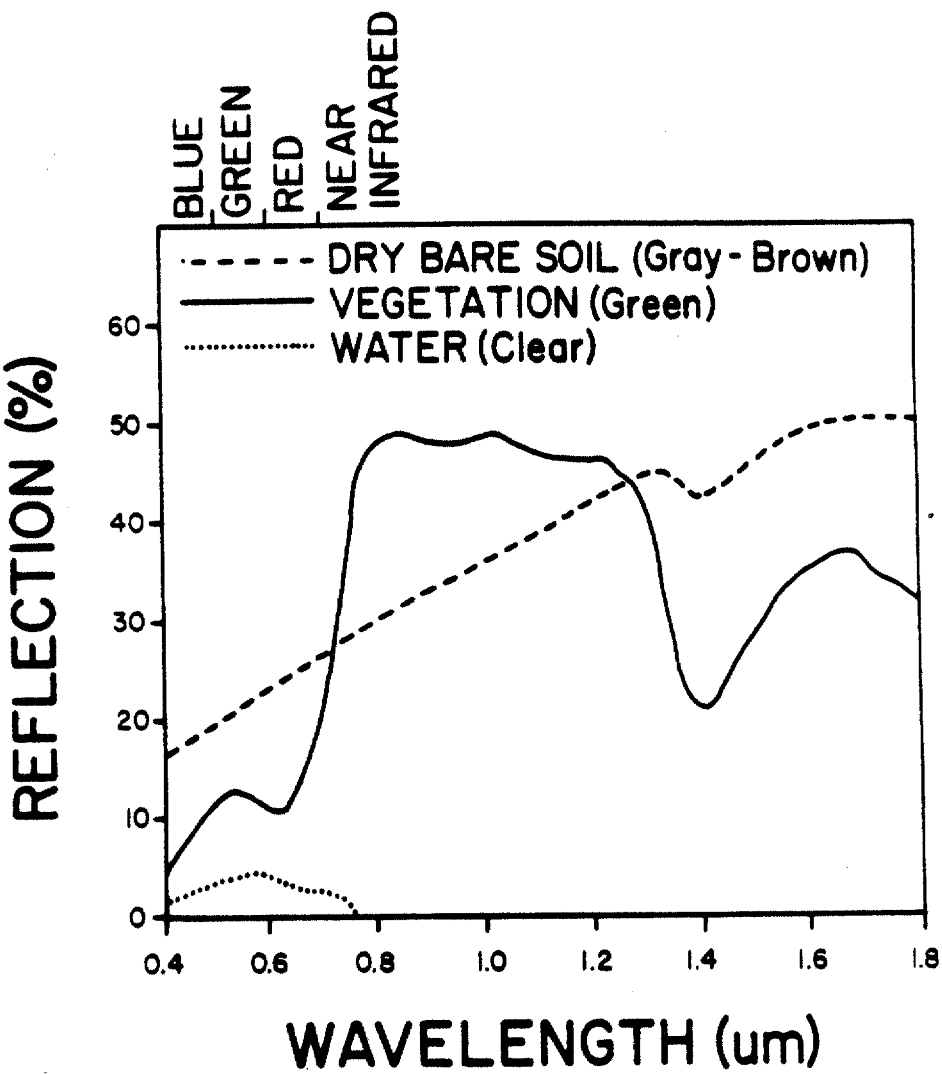


FIGURE 4. Typical spectral reflectance curves (from Swain and Davis, 1978).

are 0.5 to 0.6 μm (green), 0.6 to 0.7 μm (red), 0.7 to 0.8 μm (reflective infrared) and 0.8 to 1.1 μm (reflective infrared).

As with any optical system, the MSS is limited in its ability to distinguish surface features. The limit defines its spatial resolution. The area of spatial resolution for the MSS is square and covers an area of approximately 79 x 79 m. This area is termed a pixel (abbreviation for "picture element"). The reflective energy levels of individual pixels are recorded as digital values. Within one MSS image, data from all four spectral bands are a set of more than 30 million data values.

The MSS has been carried aboard all five Landsat satellites and has provided consistent data, uninterrupted since 1972. Such data collected on multiple dates for the same area allow users to not only inventory but also to monitor. The TM scanner has been aboard only Landsats 4 and 5. TM discriminates reflected and emitted energy in seven bands; three in the visible, one in the near-infrared, two in the middle infrared and one in thermal-infrared region of the electromagnetic spectrum. The TM scanner has higher spatial (30 m x 30 m), spectral (7 bands) and radiometric resolution than the MSS. Because of these improvements, Solomonson (1984) suggested that the TM scanner is twice as effective in providing information as the MSS.

Data from Landsat satellites are relayed to earth either directly or through a relay satellite to one of several acquisition centers around the world. Data are then sent to the NASA Image Processing Facility (IPF), part of the Landsat Ground Data Handling Systems at Goddard Space Flight Center. At the IPF, high density digital tapes are produced and sent to Sioux Falls South Dakota where computer compatible tapes (CCTs) and film products are produced and distributed to users (Short 1982).

Related Applications

The potential of remote sensing for ecologically related applications was recognized as early as 1937, when Dalke (1937) reported the use of aerial photography for habitat mapping. More recently, satellite imagery has been utilized as an important component of many wildlife and resource management studies. This section focuses on the most relevant of these studies.

Much of the pioneer work for such applications has focused on the use of imagery for wetland applications (Work et al. 1973; Cowardin and Myers 1974; Work and Gilmer 1976), especially with respect to the application and evaluation of habitat for waterfowl. With remote sensing, researchers have been able to map and assess the number of ponds in a given area. From this they can make evaluations about the quality of breeding habitat based on presence, abundance and spatial relationship of various land cover classes.

Specifically, satellite imagery and meteorological satellite data were used by Kerbes and Moore (1975) to monitor snow clearance from nesting colonies of Lesser Snow Geese (Chen canagica) in the Canadian Arctic. Based on rate of snow melt, they found they could predict nesting success. In another study, Klaas et al. (1978) used Landsat imagery to monitor food availability for Snow Geese (Anser caerulescens) on the DeSoto National Wildlife Refuge in Iowa and Nebraska. Food availability was estimated as a function of the acreage left unplowed following harvest.

Digital classification has also been used to monitor and map habitat for reindeer (Rangifer tarandus) and moose (Alces alces). LaPerriere, et al. (1980) prepared vegetative maps for 13 million hectares in east-central Alaska which correlated vegetation type with moose habitat. (George and Scorup 1981; Laperriere et al. 1980). Their preliminary verification results found an overall accuracy of 77% in comparison to a reference data set collected independently (George and Scorup 1981).

In Australia, kangaroo habitat has been identified with the use of Landsat data. Hill and Kelly (1987) found that standard cover habitat for gray kangaroos (Macropus giganteus) could be identified. MSS imagery was used to map habitat categories, which were then integrated with aerial census work and used to estimate population levels of the kangaroos. Also in Australia, Landsat MSS imagery has been used to map the distribution of the hairy-nosed wombat (Lasiorhinus latifrons). This was possible due to the wombat's propensity for building large and extensive mounds which can be detected on imagery. Hairy-nosed wombats are agricultural pests, thus the ability to monitor their spread is a valuable management tool (Loffler and Margules 1980).

Geographic Information Systems

The processed product of Landsat imagery is often contained in some type of thematic map. This in itself may be adequate, but such information may just be one of a series of data sources to be integrated, compared and synergistically manipulated to arrive at a result or interpretation (Short 1982). These analyses can be accomplished with GIS.

GIS are computer-based systems designed to facilitate the manipulation and analysis of spatial data. They were developed to assemble and analyze diverse data pertaining to specific geographic areas. Prior to their development, the most common medium for storing and analyzing such information was the basic analog map. The technology involved in the creation and display of such analog devices has reached a considerable level of sophistication but has never overcome some important obstacles. Even with the use of measurement tools such as scales and planimeters, analyzing large amounts of data from large numbers of maps is a difficult and slow process (Marble et al. 1983).

Garrison et al. (1965) first described the potential for integrating remotely sensed data with other nominal or attribute data (e.g. soil type, rainfall, species distribution). Since then, GIS technology has continued to develop and there are now many such systems. Tomlinson (1984) reported more than 1,000 GIS and automatic cartography systems were in operation in North America. They generally contain the following four major capabilities: data encoding, data management, data manipulation and data output.

Data encoding or input is the component in a GIS which collects spatial data derived from existing maps, sensors, etc. These data can be encoded with either manual (digitizing or keyboard) or automatic (scanning or digital data bases) techniques at a variety of scales. The second component of a GIS is data storage and retrieval. This subsystem organizes and stores data in a way to permit quick retrieval and rapid update. Each variable (termed layer) is stored digitally as a geographically referenced layer. When digital layers are geographically registered to one another, they form a data set of theoretically unlimited number of layers. These can then be queried according to user specifications.

The third component of a GIS, data manipulation, is the process used to extract information from data bases and perform a variety of tasks. These include estimations of perimeters, areal calculations, search radius, distance calculations and comparisons and evaluations of multiple data layers. The data output component of a GIS is the subsystem capable of displaying all or part of the original data, as well as manipulated data and output in tabular or map forms. Output may be a hard-copy map or a listing of statistics scaled to any user-defined map dimensions (Jensen 1986).

Since the development of GIS, potential for ecological research in a spatial context has improved tremendously. GIS offers cost-effective techniques for addressing ecological planning, modeling, evaluation and research efforts. For example, a GIS approach has been used for the development of a program to model human intrusion into grizzly bear (Ursus arctos) habitat in Glacier National Park, Montana. This study successfully integrated locational data of human access areas, feeding preferences of the bears (which influence distribution of the bears), digital terrain information and bear sightings (Martinka and Kendall 1985).

In another GIS study, Ornsby and Lunetta (1987) identified food availability for whitetail deer (Odocoileus virginianus) in California, using TM data and a GIS. The GIS was used to delineate areas of escape cover and food values on the classified TM image, habitat suitability was then assessed from these variables. GIS has also been used to link vegetative cover information with point coverage of radiotelemetry locations to assess the preference for old growth vegetation by Spotted Owls (Strix occidentalis) in Washington (Young et al. 1988).

CHAPTER III

TECHNIQUES USED FOR IMAGE CLASSIFICATION

A detailed description of the digital image classification techniques employed to identify and describe habitat for the Golden-cheeked Warbler, Black-capped Vireo and Texas kangaroo rat are presented in this chapter. The specific GIS approaches developed for each of these species are described in the following chapters. The image processing analyses for these projects were conducted with the Earth Resources Data Analysis System (ERDAS) and ARC/INFO systems. ERDAS is raster based software which includes a range of digital image processing programs for image enhancement and classification, as well as basic geographic information systems operations (ERDAS 1986). The ERDAS programs referenced in the text are described in Appendix A. ERDAS software (versions 7.1 and 7.2) was run on an IBM Personal Computer (PC) system with the following hardware:

- IBM AT Personal Computer (80 megabyte hard disk)
- Monochrome monitor
- Number Nine image processing board
- RGB Color Monitor (12 inch)
- Panasonic KPX-1524 dot matrix printer

- Tektronix 4695 color printer
- Calcomp 9100 digitizing tablet
- Cipher 9-1/2" magnetic tape drive

A schematic illustration of the ERDAS personal computer work station is provided in Figure 5. ERDAS analyses were also conducted on the University of North Texas VAX 11/785 Cluster mainframe computer (ERDAS version 7.0 and 7.1).

All the digital satellite data acquired for this research were from Landsat satellites. Data were obtained in computer compatible format on magnetic tapes. Portions of seven separate images were utilized (Table 1). Digital image analyses of these data involved the extraction of significantly different classes of data, termed clusters. These clusters were isolated on the basis of statistical differences in spectral reflectances. For each of the images acquired, the basic image analysis procedures were the same (Fig. 6). The basic steps were: image rectification, data transformation, unsupervised cluster analysis, signature extraction, image classification and accuracy assessment.

Image Rectification

Image rectification was performed on each image to provide spatial reference (all images were referenced to the Universal Transverse Mercator [UTM] coordinate system), and to correct for error produced by changes in

FIGURE 5. Schematic illustration of the ERDAS PC workstation at the University of North Texas.

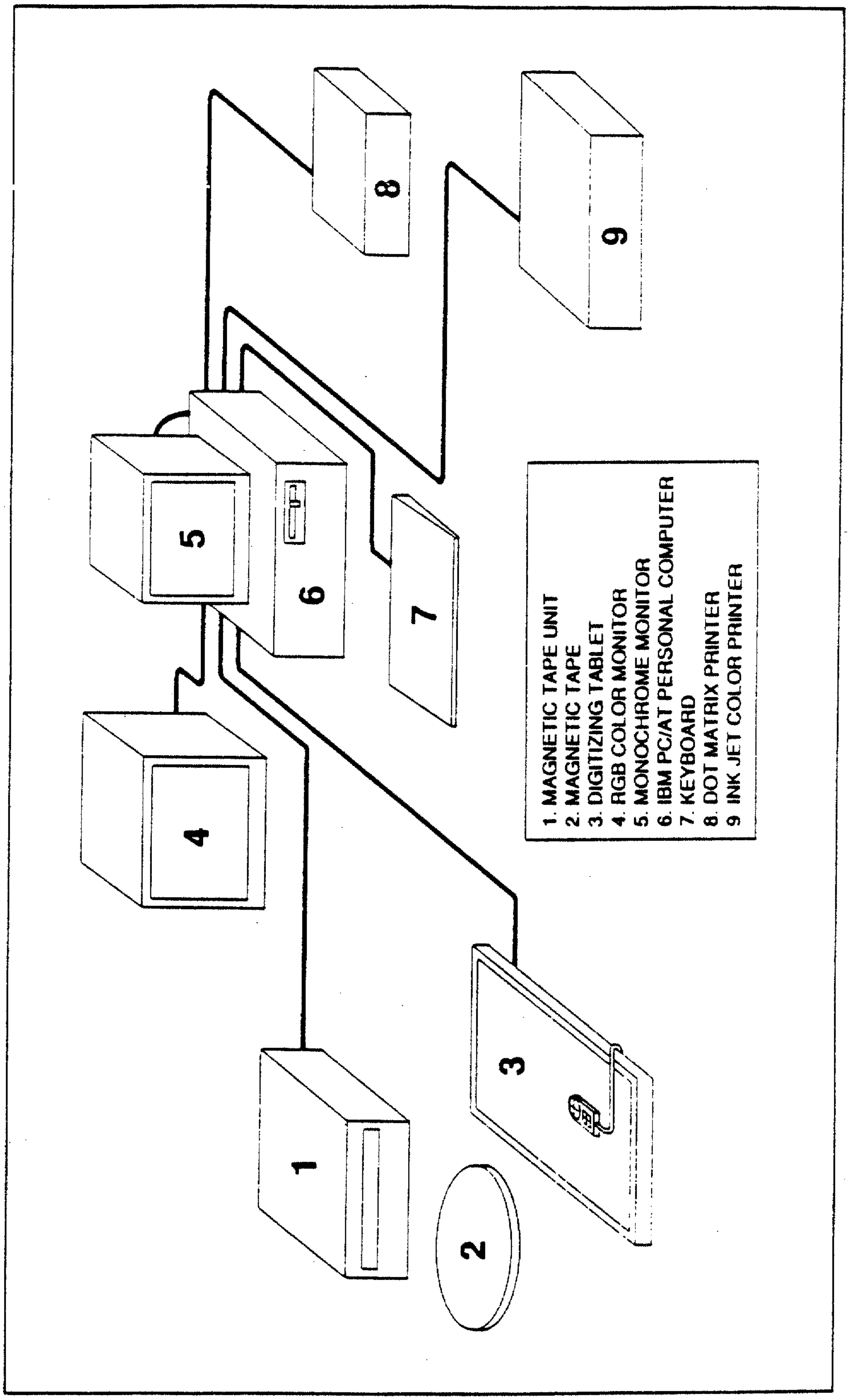

1
2
3
4
5
6
7
8
9
1. MAGNETIC TAPE UNIT
2. MAGNETIC TAPE
3. DIGITIZING TABLET
4. RGB COLOR MONITOR
5. MONOCHROME MONITOR
6. IBM PC/AT PERSONAL COMPUTER
7. KEYBOARD
8. DOT MATRIX PRINTER
9. INK JET COLOR PRINTER

TABLE 1. Landsat images acquired.

LANDSAT IMAGES ACQUIRED

TYPE [1]	DOA [2]	ID NUMBER	PATH/ROW [3]	LOCATION
MSS	04 MAR 79	30364-16254	29/39	AUSTIN
MSS	07 JAN 81	22177-16232	29/38	WACO
MSS	30 MAR 74	10615-16315	29/40	SAN ANT.
MSS	10 NOV 81	22484-16315	30/39	KERRVILLE
MSS	18 JUL 86	85086916364	29/36	QUANNAH
TM	20 APR 88	Y5151116330X0	27/39	AUSTIN

[1] MSS - Multispectral scanner; TM - Thematic mapper

[2] DOA - Date of acquisition

[3] PATH/ROW - Image location code (NOAA 1982)

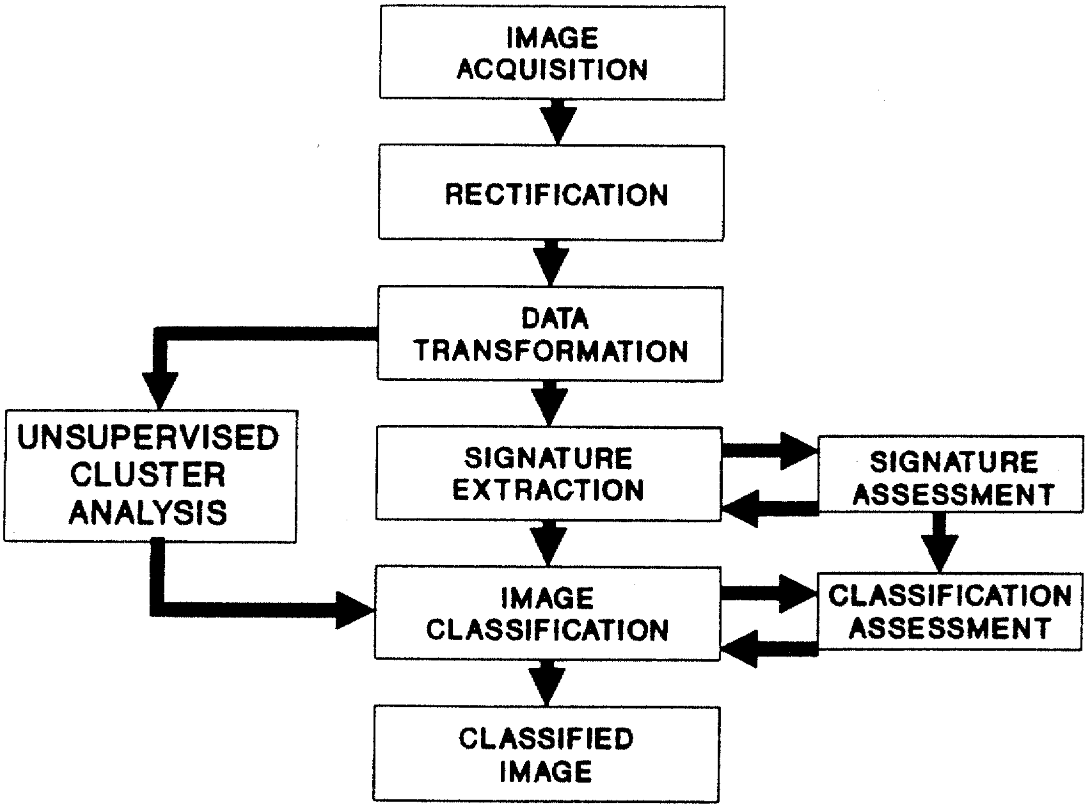


FIGURE 6. Basic steps for Landsat image analyses.

satellite attitude (roll, pitch and yaw) and altitude. Rectification was a multi-step procedure which generated a georectified image from a raw imagery (Fig. 7). To achieve this, recognizable features on each image were matched with specific locations on maps (USGS 1:24,000 and 1:250,000) from which precise coordinates (e.g. meters in northing and easting) were determined with a digitizing tablet. These points were referred to as 'ground control points' (GCPs). Examples of sites useful as GCPs are road and stream intersections, dams, airports and bridges. A minimum of 25 GCPs were identified for each image.

The second step of image rectification, spatial interpolation, required the determination of a coefficient matrix which described the geometric relationship between image pixel locations (row and column within the data base) and associated map coordinates of the GCPs. To achieve this, total root mean square (RMS) of the spatial error between the GCPs and the image locations, and the RMS attributable to each GCP were calculated using the equation:

$$RMS_{error} = \sum_{i,m=1}^{n} \left[(x_i - x_m)^2 + (y_i - y_m)^2\right]^{1/2}$$

where: x_i and y_i = digital image location
x_m and y_m = map location

A RMS error of 1.0 pixel (79 m^2 for MSS, 30 m^2 for TM) was tolerated for each image. GCP coordinate pairs contributing the greatest error were sequentially removed

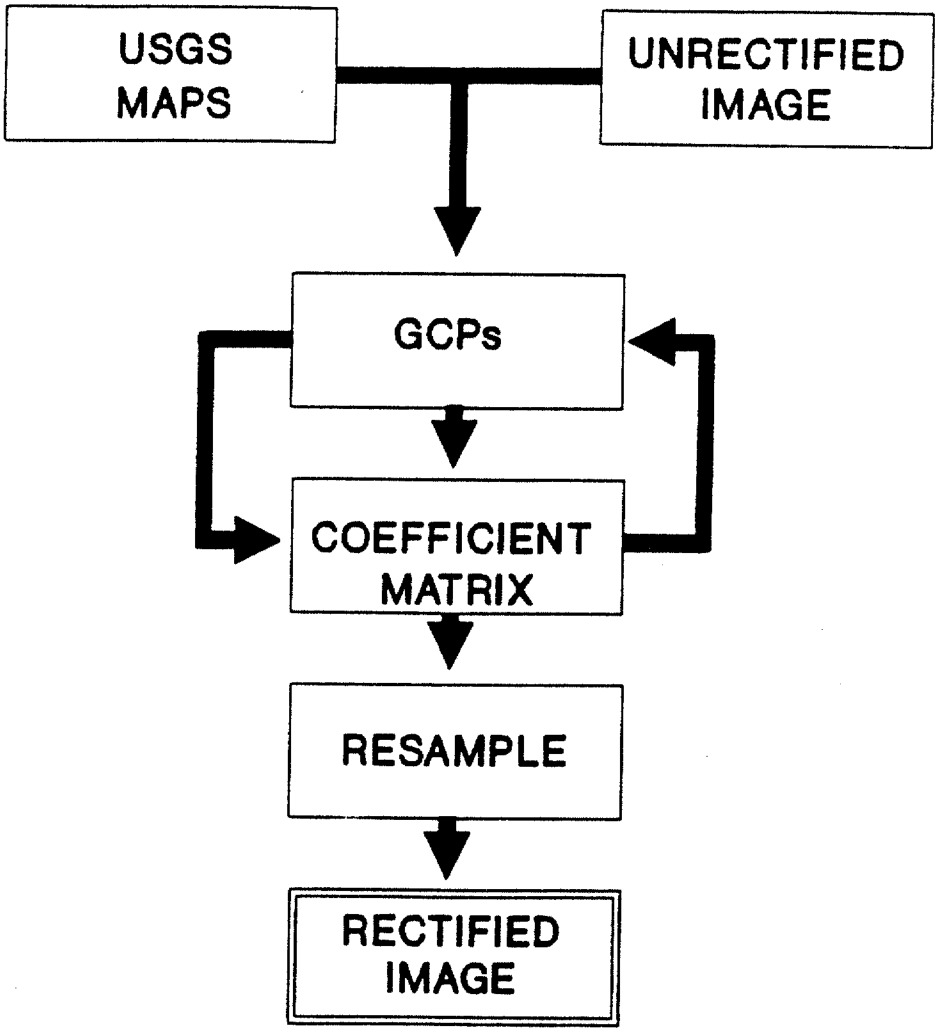


FIGURE 7. Basic steps for digital Landsat image rectification.

until the total RMS was less than or equal to 1.0. The points remaining were used to calculate the final set of coefficients that model the geometric distortion of the image. This was achieved with the ERDAS program, COORD2.

The output of COORD2 was six coefficients that contained all of the information necessary to rectify an image. They modeled six types of data distortion; translation in X and Y, scale changes in X and Y, skew and rotation (Billingsly 1983). These coordinate transformation coefficients were applied to every pixel in the input image in order to relocate it to its proper position in the rectified output image.

The final phase of rectification resampling involved the extraction of an individual pixel's value from its original location and placement of that value at the appropriate new coordinate location. Resampling was accomplished with the ERDAS program, RECTIFY. The Nearest Neighbor interpolation algorithm was used for all image resampling. After rectification, resulting image pixels were referenced not only by row and column but also with respect to the UTM map projection system.

Principal Component Analysis

Interpretation of remote sensing data requires analyses of information contained in data bases which are composed of multiple bands of data. These data sets, consisting of four or seven bands, are difficult to work with both conceptually and with respect to computer space and time. In order to reduce the dimensionality and thus the volume of data, the application of Principal Component Analysis (PCA) to digital image analysis has become an accepted procedure (Kauth and Thomas 1976; Wheeler and Misra 1976).

Through the use of PCA, the spectral information in a four channel MSS or seven channel TM scene can be well represented by only two or three dimensional data rather than four or seven. This is possible due to the high degree of interband correlation among the spectral bands of MSS and TM images. The intrinsic dimensionality, or true volume of information in an image is contained in less space than that required by the original number of bands (Ready and Wintz 1973). For these reasons, PCA was performed on each image (with the exception of the MSS scene used for identifying landcover for the Texas kangaroo rat). PCA was accomplished with the ERDAS program PRINCE.

PRINCE is a two step program which involved the computation of a covariance matrix computed from a user specified sample of the image. The matrix provided a measure of the correlation among bands. In the second step, actual principal components (PCs) are calculated. The first PC is taken as a vector along the greatest variation of pixel brightness values in all bands of the original image. The variation allows calculation of the largest eigenvalue and its associated eigenvector, and are taken as the first axis of the transformed coordinate system. The next eigenvector, orthogonal to the first, represents the direction of the next widest variance of brightness values, the second PC. The extraction of eigenvectors at orthogonal angles is repeated in N dimensions corresponding to the number of input bands. The result is a new set of band values which are projections of old values along a new set of axes (Swain and Davis 1978).

For the MSS images on which PCA was applied, the first three transformed bands were utilized. These new bands incorporated at least 98% of the variation of the original data set (Fig. 8). For the TM image, only six of the seven bands of data were input for PCA. Due to the properties of the thermal band (six) and its subsequent effective resolution of 120 m (as opposed to 30 m for the remaining bands), it was not included for analysis. From the remaining six bands, as many PCA bands as required to represent at least 97% of the variation of the original data were used (Fig. 9).

Image Classification

Classification of digital imagery is a means of spectral pattern recognition. The objective is to create an output image with a finite number of classes. Each of these classes represents a category of interest. There are

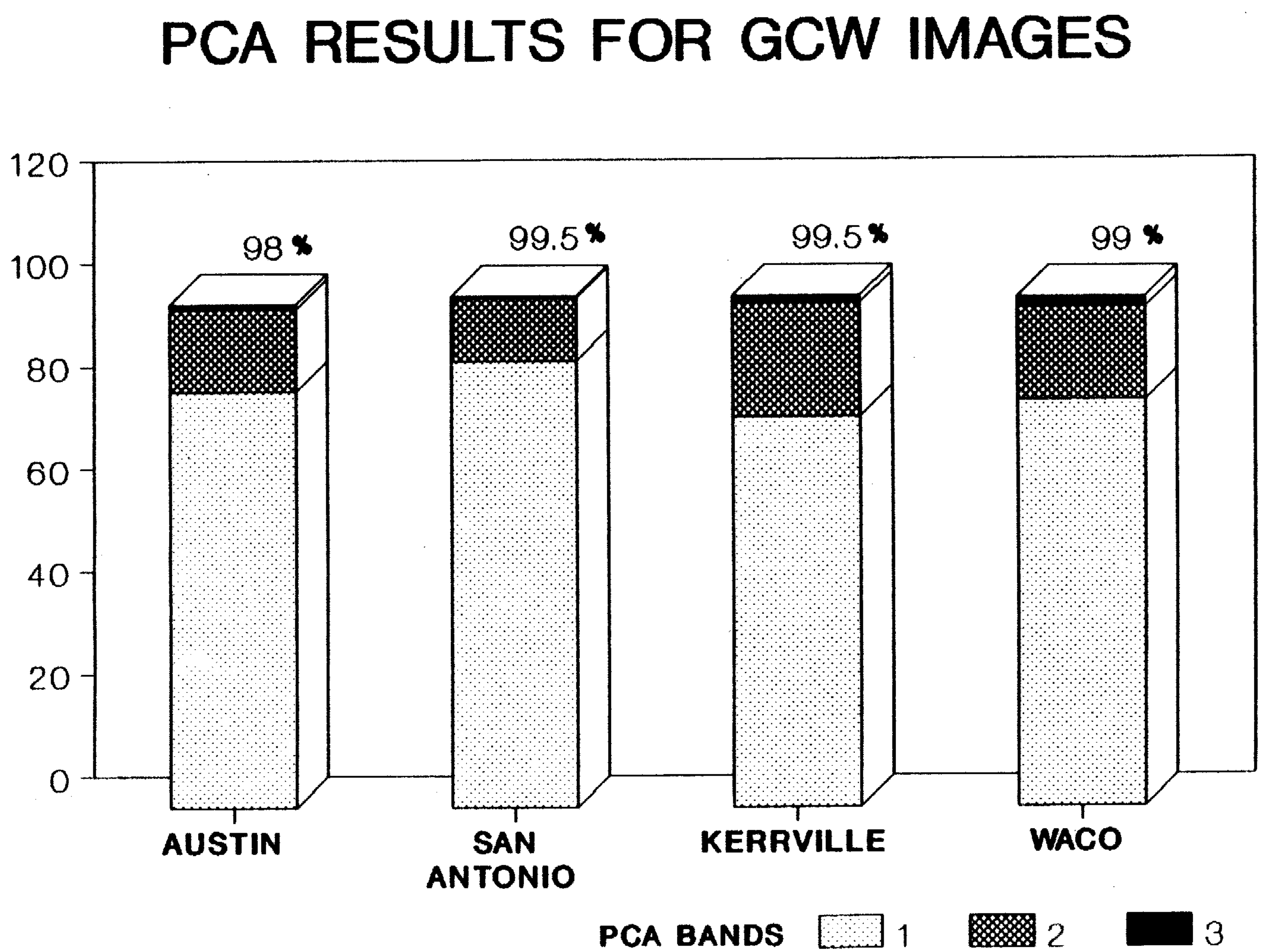


FIGURE 8. Percent variation accounted for by the first three Principal Component Analysis (PCA) bands for Multi-spectral Scanner (MSS) images.

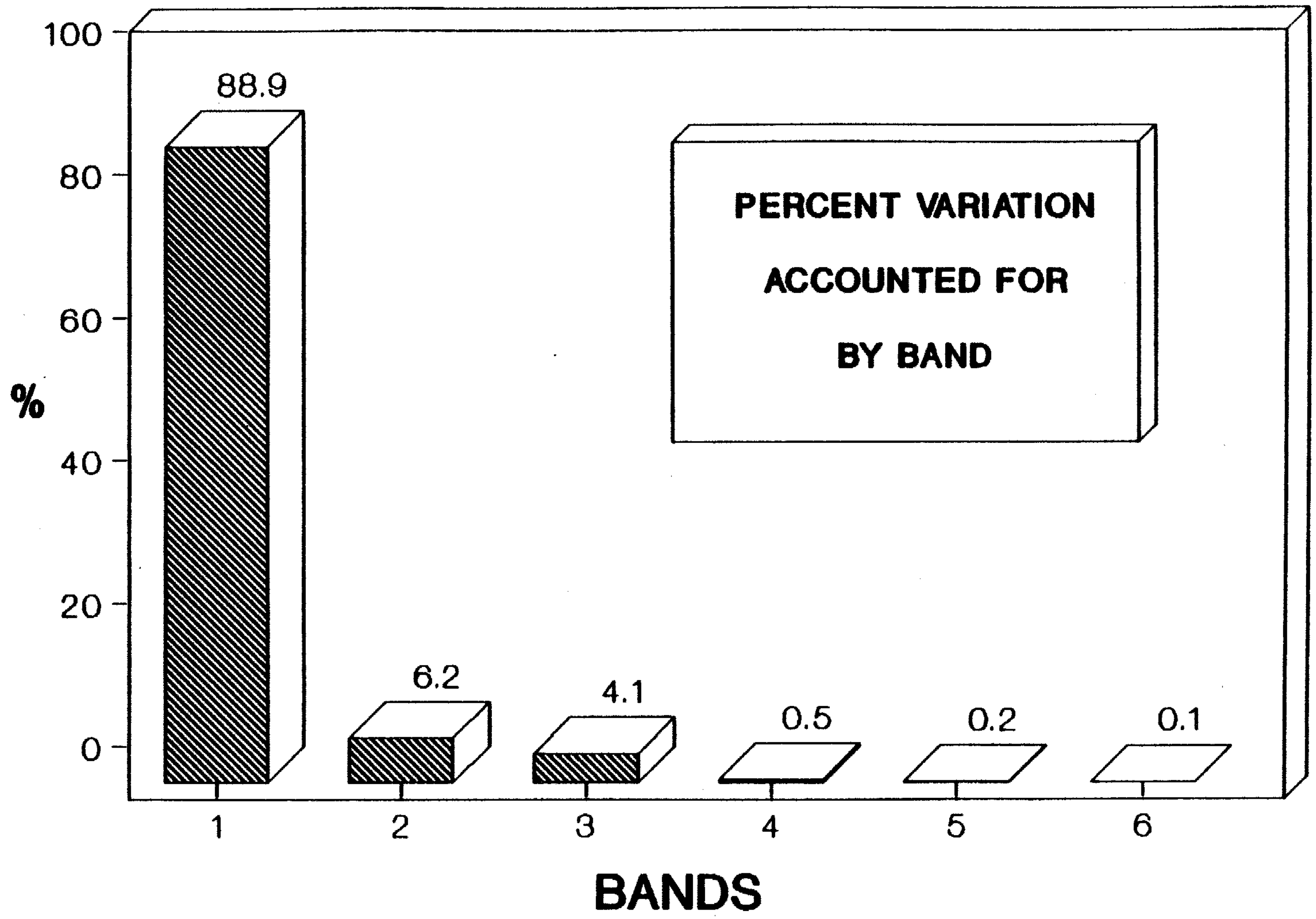


FIGURE 9. Percent of data variation per band after Principal Component Analysis on the Thematic Mapper images.

two major types of classification, supervised and unsupervised. In supervised classification, training fields, regions of pixels of the same cover type, are selected in the raw image. It is from these areas that signatures are derived. Statistics on the electromagnetic radiation reflected from these training fields (mean brightness value, standard deviation, and covariance matrix) are determined. Each pixel in the input image is then compared to a "catalog" of training field signatures and is then assigned to the most appropriate statistical class. Conversely, unsupervised classification does not require interpretive operator input with respect to spectral identification of different cover types. It utilizes a clustering algorithm that groups pixels into clusters of similar spectral response.

Classification of each image for this research wasaccomplished with a combination of supervised and unsupervised classification techniques (Fig. 10). This method provided the advantage of the autonomy of unsupervised classification but allowed for the inclusion of signatures from training fields that were important. This provided a degree of control over the output image not obtained by unsupervised classification alone.

The first step of the classification process was the initiation of an ERDAS unsupervised classification program (CLUSTR). The program extracted signature statistics from

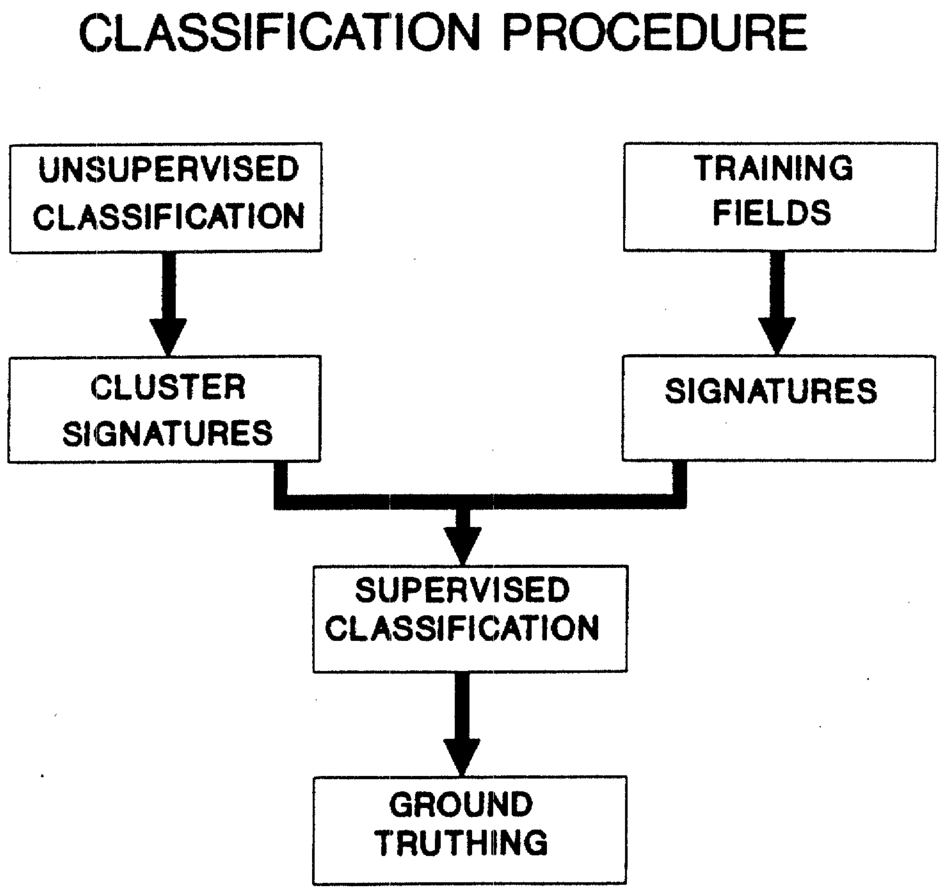


FIGURE 10. Procedure used for classification of digital Landsat data.

the input image based on spectral response variations within and among bands. The second step was the collection of a set of field signatures from the input image. Field signatures were extracted (with the ERDAS program FIELD) from areas on the image that were identified from air photos and with ground truthing to be particular land cover types. Signatures created from the unsupervised method and from the training samples were merged. The entire set of signatures was then evaluated by overlaying a probability curve for the signatures (ellipse) on to a scatter plot of all pixel values for all possible band combinations with the ERDAS program ELLIPSE. Evaluation of each signature was based upon size and shape of these ellipses. Ellipse overlap as well as the portion of pixels in the scatter plot not included in ellipses was considered. If, based on these criteria, signatures were judged unacceptable, they were discarded and new signatures were generated from a different set of training fields.

The final step of the classification procedure was the application of a supervised classification algorithm known as maximum likelihood (ERDAS program MAXCLAS). With this algorithm the original input image was analyzed with respect to the collection of signatures. The program begins by evaluating every pixel independent of neighboring pixels, and comparing it with all signatures. Each pixel is then assigned to the class to which it has highest probability of belonging, based on statistical similarity. An output image is then generated in which every pixel from the input image has been assigned to a particular class (ERDAS 1986).

Accuracy Assessment

The determination of the reliability of an image classification is an integral part of a remote sensing study. For this research, each classified image was sampled from points selected on 1:24,000 scale USGS maps. These sites were selected based on consideration of adequate representation of classes as well as ease of accessibility for ground truthing. The sampling objective was to identify the position and attributes of random sites and compare their characteristics to these same points on processed data. The number of sites correctly assigned to each class and those assigned to other classes was assessed with a contingency table. This table was a summation of omissions, commissions and overall classification accuracy. Errors of omission occurred when a pixel area appeared to be suitable habitat was not identified by the classification process. Errors of commission occurred when other landuses were identified as habitat. For the proposed research, with respect to the Golden-cheeked Warbler and the Black-Capped Vireo, the only concern of mapping accuracy was with respect to the identification of suitable vegetative communities. For the Texas kangaroo rat, concern was for all cover types in the study area. Therefore, a matrix was created that compared classification accuracies for all covertypes. When each of the images was classified within acceptable accuracy levels, they were included into the GIS for further analyses.

CHAPTER IV

HABITAT IDENTIFICATION AND DESCRIPTION FOR THE GOLDEN-CHEEKED WARBLER

Introduction

The Golden-cheeked Warbler (Dendroica chrysoparia) is a small insectivorous warbler that nests exclusively in the eastern and south-central portions of the Edwards Plateau (TOS 1984) (Fig. 1). Suitable nesting habitat for the species consists of woodlands containing mature Ashe juniper (Juniperus ashei), upon which the Golden-cheeked Warbler relies for nesting material.

Concern for the future of the Golden-cheeked Warbler is linked to the decline of potential nesting habitat. The loss is attributed to urban expansion as well as to agricultural and range management practices which clear this particular habitat type (Oberholser 1974). In 1987, the USFWS initiated a status survey for this species. The research described here was part of that effort. Two major objectives were identified: (1) assessment of the utility for Landsat Multi-Spectral Scanner (MSS) data to identify and quantify potential nesting habitat for the Golden-cheeked Warbler and (2) employment of remote sensing and GIS technologies to describe spatial characteristics of areas identified to be potential nesting habitat for the species.

Study Area

The Edwards Plateau of Texas is a southern extension of the Great Plains Physiographic Province of North America (Hunt 1974). On the basis of abiotic factors such as climate, soils and geology, four distinct subregions are recognized. The first, the Balcones Canyonland forms the eastern and southeastern portions of the Plateau. It is bordered by the Balcones Fault zone to the east. This is the most dissected subregion, with high gradient streams and steep-sided canyons. A second subregion, the Lampasas Cut Plain, north of the Colorado River forms the northeastern margin of the Edwards Plateau. This region is relatively flat and consists largely of broad valleys and steep, scarp-bounded benches. The area is a transition between the flatter Rolling Plains region to the north and the Edwards Plateau proper. A third subregion, the Llano Uplift, in the northcentral portion of the Plateau is underlain predominately by granitic and metamorphic bedrock and on this basis is clearly distinguished from the Cretaceous limestone of the rest of the Plateau. The fourth subregion, the central and western portion of the Plateau, is an area moderately dissected area with extensive flat to gently sloping stream divides and rounded hills (Sellards et al.

1932).

Climate

The climate of the Edwards Plateau is increasingly arid to the west and cooler to the north. The eastern and central portions of are sub-tropical to subhumid, while the western one-fourth is sub-tropical to semiarid (Larkin and Bomar 1983). Mean annual precipitation ranges from about 85 cm/yr on the eastern edge to 35 cm/yr on the western edge of the plateau (Bomar 1983) (Table 2). The general decrease in moisture content of Gulf air as it flows northwestward across the plateau is the controlling factor responsible for the difference in moisture regime across the region.

Geologic Formation and Soils

Most of the Edwards Plateau is formed on Cretaceous limestone. The central and western portions are composed of Edwards Group limestones. In the southern and eastern portions of the plateau, Edwards Limestone has largely been eroded, exposing older cretaceous rocks, primarily of the Glen Rose and Georgetown Formations. The Llano Uplift is an area of Precambrian granitic metamorphic rocks overlain by early Paleozoic sedimentary rocks including limestone, dolomite, sandstone and shale (Sellards et al. 1932). The area is quite different from the rest of the Plateau.

The variation in geologic substrate and the hilly

TABLE 2. Precipitation means from 1951-1980 for stations across an east to west transect across the Central Edwards Plateau. (From Riskind and Diamond 1986).

STATION	PRECIPITATION (cm) ANNUAL	PRECIPITATION (cm) GROWING SEASON
AUSTIN	80.0	54.5
FREDRICKSBURG	72.8	54.6
SAN ANTONIO	70.0	56.8
JUNCTION	57.2	41.5
OZONA	46.3	37.2

terrain of the Edwards Plateau have contributed to the development of varied soils. Over much of the plateau,soils are primarily shallow and rocky on slopes and deeper in the broad valleys and on the flats. Surface texture of the soil varies from loamy to clayey depending on substrate and profile development.

Vegetation

The interaction of climate, topography and edaphic factors results in major changes in vegetative patterns across the Plateau. The Balcones Canyonland, the most mesic region, supports woodland vegetation on slopes and canyons. The Lampasas Cut Plain is also mesic but flatter and with more grasslands. The Central and Western Plateau regions are xeric, generally dominated by grasslands. The Llano Uplift, also somewhat xeric, supports a variety of woodlands and grasslands consisting of a species composition that is similar to the remainder of the Plateau. A summary list of the dominant species for each region is found in Table 3.

Across the plateau, vegetation generally varies with slope, aspect and moisture availability. This is most pronounced in the steeper canyon areas. North and east-facing slopes are generally wetter than south-facing exposures and support a more diverse community structure. South and west-facing slopes, as well as the scarp edges contain the most xeric habitats. These vegetative

TABLE 3. (a) Dominant trees and shrubs of floodplain forest and slope woodland of the Balcones Canyonland and the Lampasas Cut Plain; generalized transect from wet (left) to dry (right) environments. (b) Dominant species of major grassland-types of the Edwards Plateau; generalized transect from east (left) to west (right) (From Riskind and Diamond 1988).

A.

Floodplain Forest	Deciduous Woodland	Evergreen Forest
box elder*	ash (var)	agarita
pecan	Arizona walnut	Texas persimmon
sugarberry	Ashe juniper	Ashe juniper
oak (var)	black cherry	plateau live oak
black willow	Lacey oak	scalybark oak
bald cypress	scalybark oak	Texas oak
American elm	Texas oak	sumac (var)
cedar elm	cedar elm	mountain laurel

B.

Tall Grassland	Mixed Grassland	Short Grassland
big bluestem	threeawn (var)	threeawn (var)
sideoats grama	bluestem (var)	sideoats grama
silver grama	sideoats grama	blue grama
Texas cupgrass	grama (var)	Texas grama
Ashe juniper	buffalo grass	grama (var)
seep muhly	Texas cupgrass	buffalo grass
plateau live oak	curlymesquite	hairy tridens
scalybark oak	muhly (var)	curlymesquite
little bluestem	mesquite	tobosa
indian grass	oak (var)	muhly (var)
Texas wintergrass	little bluestem	mesquite
tall dropseed	Texas wintergrass	sand dropseed

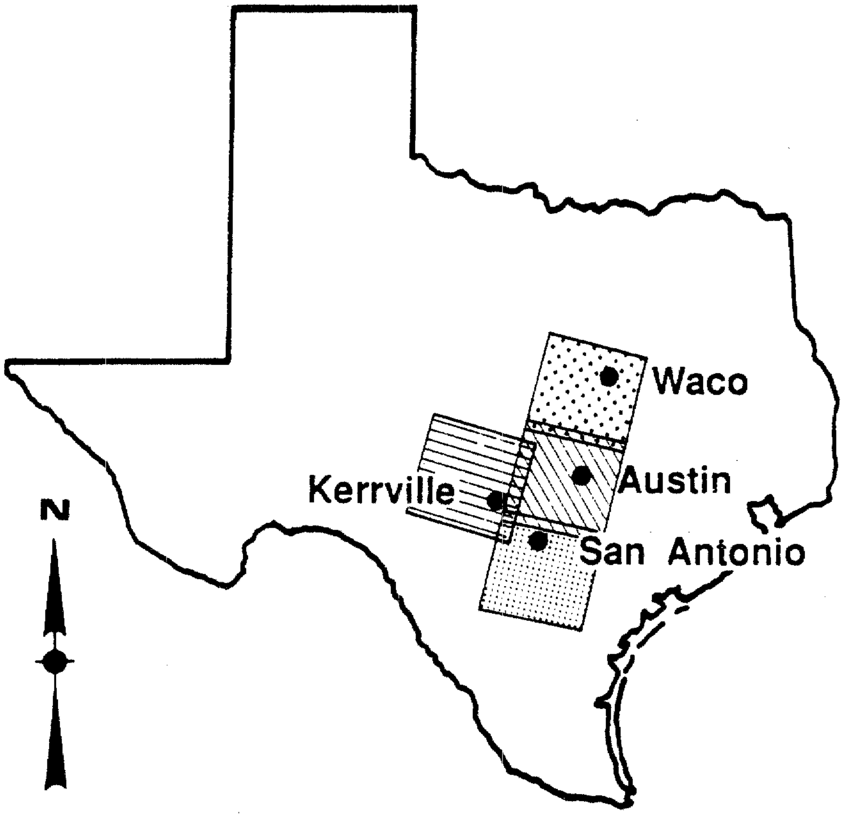
* scientific names are provided in Appendix B.

communities are often open canyon woodlands of short trees and shrubs. Ashe juniper, scalybark oak, plateau live oak and Texas persimmon are common species here. In the xeric woodlands all species, especially Ashe juniper, are autosuccessional, although periodic fires shift the species dominance away from the Ashe junipers towards oaks. Ashe Junipers cannot withstand fire unless they grow in the protection of oaks, especially oak clumps (motts) whose sprouting was induced by fire. Today, with fire at a minimum, Ashe juniper has rapidly invaded (aided by nurse trees) open woodlands and grasslands where, historically the species had grown only in comparatively fire-free oak motts and rocky areas (Amos and Gelbach 1988). Year-round grazing by domestic livestock has also lead to widespread increases in the woody species and subsequent decreases in grassland across the Plateau (Bray 1904, Smeins 1980).

Methodology

Habitat Identification

Potential nesting habitat for the Golden-cheeked Warbler was identified throughout the breeding range of the species. Portions of four Landsat Multi-spectral Scanner (MSS) scenes were classified and combined to cover the breeding range (Fig. 11). Winter and early spring scenes were chosen, as they were determined to be best for identification of the particular habitat type. Because of



SCENE	PATH/ROW	DATE
Waco	29/38	07 January '81
Austin	29/39	04 March '79
San Antonio	29/40	30 March '74
Kerrville	30/39	10 November '81

FIGURE 11. Landsat MSS scenes obtained for Golden-cheeked Warbler habitat identification.

cost limitations, the scenes that were obtained were not current nor of the same year (1974-1981). Scene classification and analyses were accomplished with Earth Resources Data Analysis System (ERDAS) software. Each of the MSS scenes were rectified to the Universal Transverse-Mercator (UTM) coordinate system based on a 79 x 79 m pixel size. Nearest-neighbor algorithms were employed for the geometric correction. Principal component analysis (PCA) was run on each of the MSS scenes in order to reduce their dimensionality and volume. The result of the PCA for each scene yielded four new uncorrelated bands in which the first three transformed bands accounted for at least 97% of the spectral variation within each scene (Fig. 8). These first three bands were included for classification.

Classification of each of the four scenes was achieved with a combination of supervised and unsupervised classification techniques. For each scene, an unsupervised classification algorithm was utilized to generate cluster signature statistics from the PCA data. The second step was the interactive extraction of signatures for Golden-cheeked Warbler habitat from the PCA data. Areas of known quality nesting habitat for the Golden-cheeked Warbler were delineated on USGS 1:24,000 maps by Texas Parks and Wildlife Department, Natural Heritage Division (Table 4). The signatures extracted from these areas were merged with the signatures derived from the unsupervised classification

Table 4. Sites used for Golden-cheeked Warbler habitat training fields.

LOCATION	USGS 1:24,000 MAP
MERIDIAN STATE PARK	MERIDIAN, TEXAS
FORT HOOD	SHELL MOUNTAIN, TEXAS
FORT HOOD	BLAND, TEXAS
TRAVIS COUNTY AUDUBON SANCTUARY	JOLLYVILLE, TEXAS
LAKE AUSTIN CITY PARK	AUSTIN WEST, TEXAS
LOST MAPLES STATE PARK	SABINAL CANYON, TEXAS
GARNER STATE PARK	MAGERS CROSSING, TEXAS
GUADALUPE RIVER STATE PARK	ANHALT, TEXAS

technique. A supervised classification (maximum likelihood algorithm) was then performed, utilizing the newly merged signature catalogue. Classification was run on the PCA data.

After classification, all landuses other than potential habitat were combined, resulting in two final categories, potential habitat and non habitat for the Golden-cheeked Warbler. As the emphasis for the study was a specific vegetative community, minimal attention was devoted to classification results for the other categories. Estimates of potential habitat were reported by county. The boundaries of the 43 Texas counties falling within the study area were manually digitized to a GIS file from 1:250,000 USGS maps. A sample portion of the data layer is provided in Figure 12. The GIS layer was overlain on the combined classified scenes. Using the ERDAS program SUMMARY, the number of hectares of classified habitat that fell within each county was estimated. For accuracy assessment of the classification, sections corresponding to United States Geological Survey (USGS) 1:24,000 scale maps were extracted from the classified scene. Map overlays (1:24,000 scale) were generated for use in ground truthing the classification. Each of the overlay maps were re-rectified. This was done to improve the mapping accuracy. Potential habitat for the Golden-cheeked Warbler was plotted out on mylar overlays. A total of 34 overlay maps were produced

FIGURE 12. Sample portion of the county boundary GIS layer.


HAYS
GUADALUP
BLANCO
COMAL
GILLESPIE
KENDALL
BEXAR
KERR
BAND.

for ground truthing (Table 5). The number of maps produced for each scene was determined by the area of the scene the picture included in the study area. The maps that were printed were randomly selected from the entire study area.

A stratified random site selection identified points to be ground-truthed from the maps generated. Interpretation of classification accuracy for each of the points was verified by field assessment from light aircraft, by car survey and on foot. A matrix comparing the classification at the 1:24,000 scale and the correct landcover was constructed for potential and nonpotential habitat. The number of correct points as compared with the total number of points were compared and stated as percent of accuracy using the technique described by Fitzpatrick-Lins (1978).

Habitat Fragmentation

Quantification of habitat for a given area is not sufficient information with which to estimate usage or population size. Although vegetative composition may be appropriate, it is likely that other constraints affect suitability. These are likely to include habitat patch size, distance between patches and the configuration of the patches.

To assess these conditions, a series of spatial analyses was conducted on the potential habitat identified in four counties within the study area, Llano, Travis,

TABLE 5. USGS 1:24,000 Map overlays generated to ground truth the classification of Golden-cheeked Warbler habitat.

SAN ANTONIO MSS IMAGE	AUSTIN MSS IMAGE
Pipecreek	Hammetts Crossing
Medina Lake	Austin West
San Geronimo	Wimberley
Heliotes	Marble Falls
Castle Hill	Lake Buchannan
Van Raub	Devil's Backbone
	Johnson City
	Perdenales Falls
	Oak Hill
	Jollyville
KERRVILLE MSS IMAGE	**WACO MSS IMAGE**
Bee Caves Creek	Fort Hood
Garven Store	Gholson
Waring	China Springs
Mudge Draw	Whitney
Cherry Mountain	Meridian
Cypress Creek	Allen Bend
Stark Creek	Glen Rose
Boneyard Draw	Mosheim
Big Draw	Eagle Springs

Bosque and Kerr (Fig. 13). In consideration of the patch size factor, all patches of contiguous pixels (minimum connectivity radius of 1.5) (Fig. 14) of habitat were identified within an area of 355,000 ha for each of the counties. The area comprises at least 75% of the area in each county. The patches were sorted and totaled with respect to size classes.

A second spatial analysis technique was used to describe the spatial interaction between patches. A modification of a gravity model was implemented. The gravity model, so called because of its similarity with Newton's law of gravitation, postulates that the potential attraction between two bodies increases with the product of their masses and decreases with distance between them. For this particular application, mass alludes to the area of the patches and distance separating their centroids. The gravity value increases as patch size increases, and decreases as the intervening distance increases (Hartshorn 1980).

The theory was expressed with the following equation:

$$G = \frac{(A_1)\ (A_2)}{D}$$

where: G = interaction
A_1 = area of one patch
A_2 = area of the neighbor patch
D = centroid to centroid distance

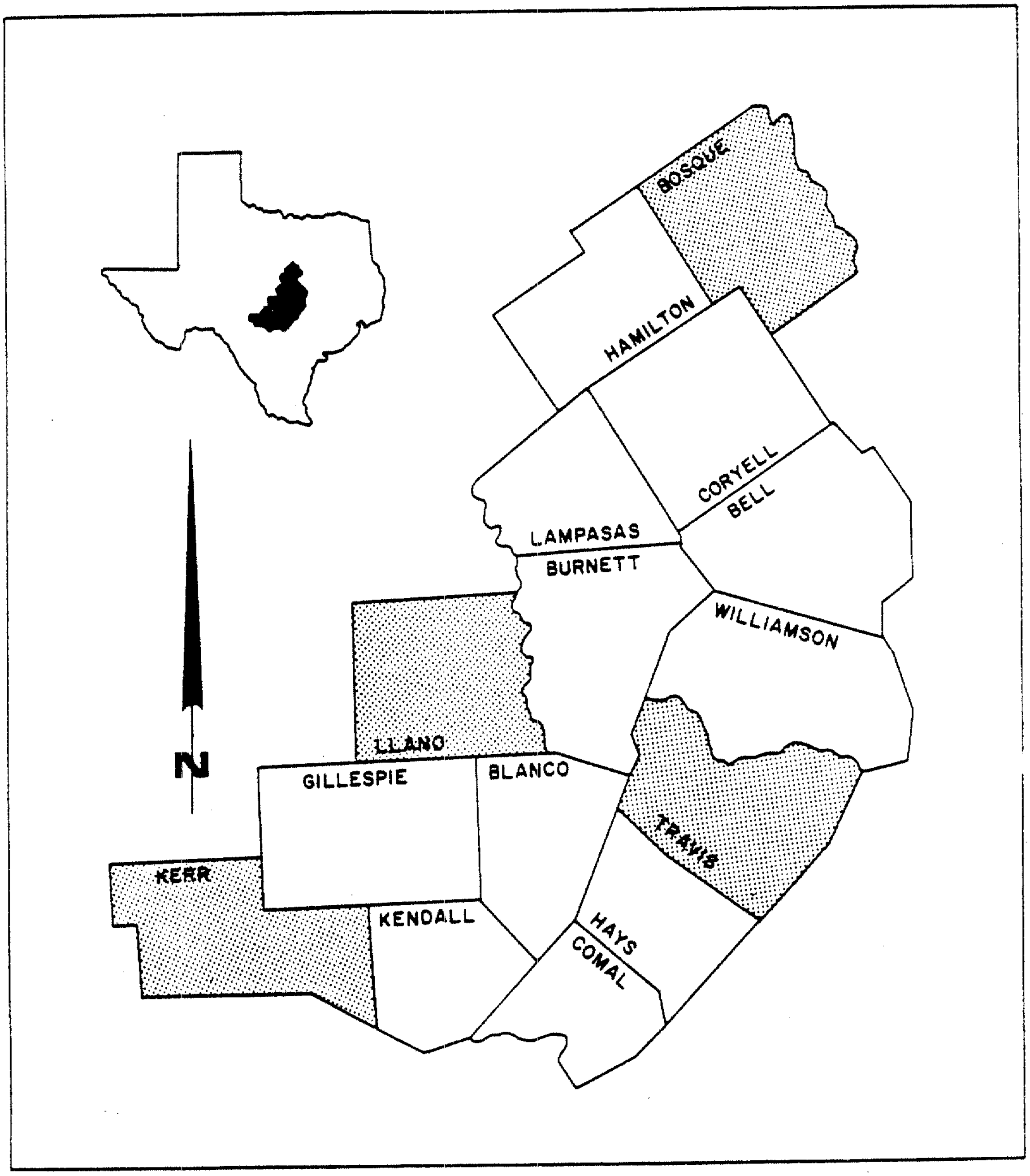


FIGURE 13. Locations of Llano, Travis, Bosque and Kerr counties.

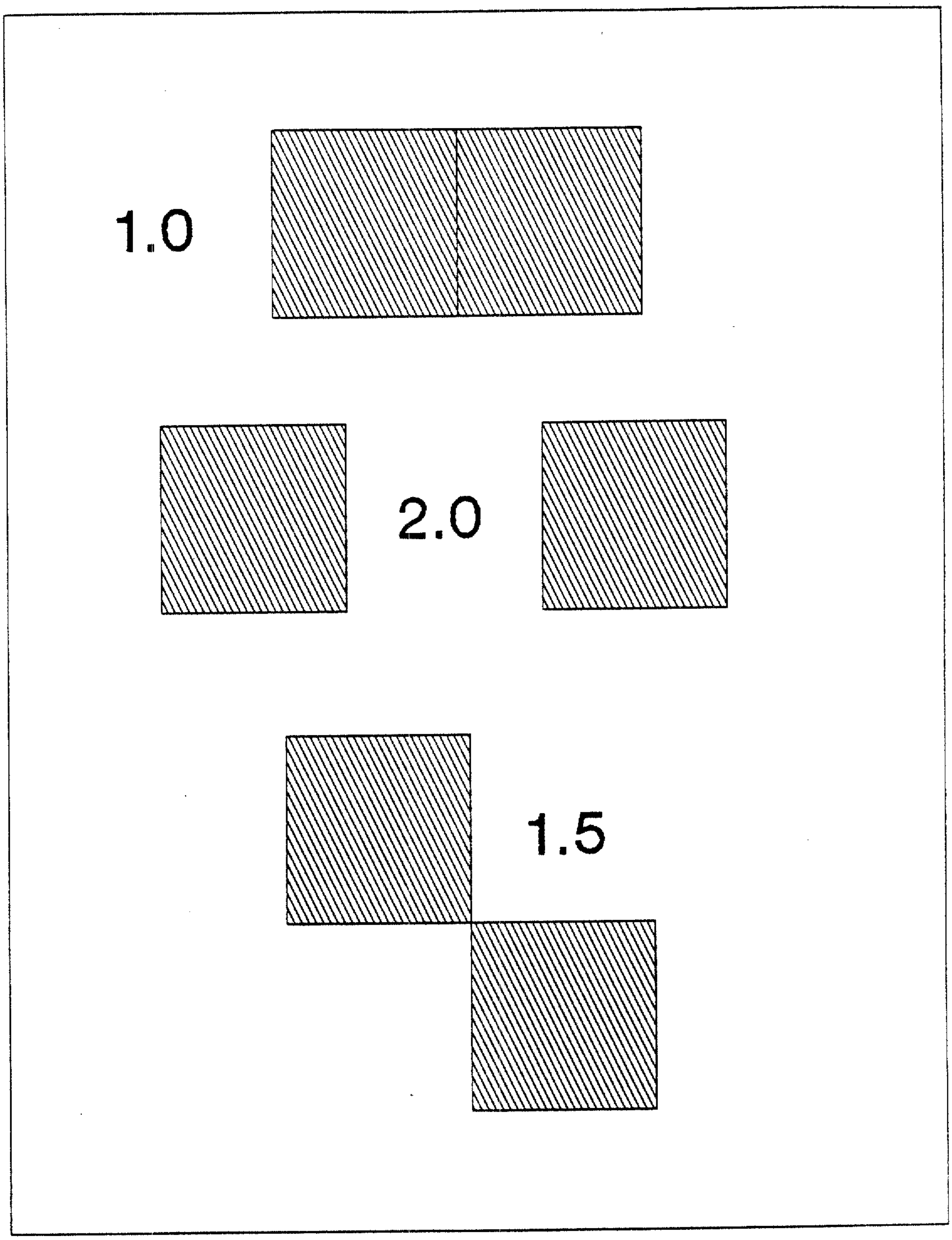


FIGURE 14. Illustration of connectivity radius.

Using this formula, an average gravity value was determined for each county. To do this, 50 habitat patches were randomly selected within each county. For each patch, its nearest neighbor patch was identified. The area of both patches as well as the distance between their centroids were determined. A mean and standard deviation for the 50 gravity values for each county were calculated. An illustration of the gravity model for a variety of areas and distances is provided in Figure 15.

Next, a Configuration Index (CI) was generated to characterize the shape of habitat patches. The index was developed to compare the perimeter of a given patch with the circumference of a circle of corresponding area, it provides an estimation of the extent that the shape of a given patch deviates from a circle. The CI can be used if the area and perimeter of a given patch are known. The CI represents the extent to which the circumference (perimeter) of a patch deviates from the circumference of a circle of the same area (Equations). An illustration of its application is provided in Figure 16.

EQUATIONS :

$$A = \pi R^2$$

$A = A_p$, if A_p were a circle

hence $R = (A_p/\pi)^{1/2}$

$$C = 2\pi R$$

$$C = 2\pi \ (A_p/\pi)^{1/2}$$

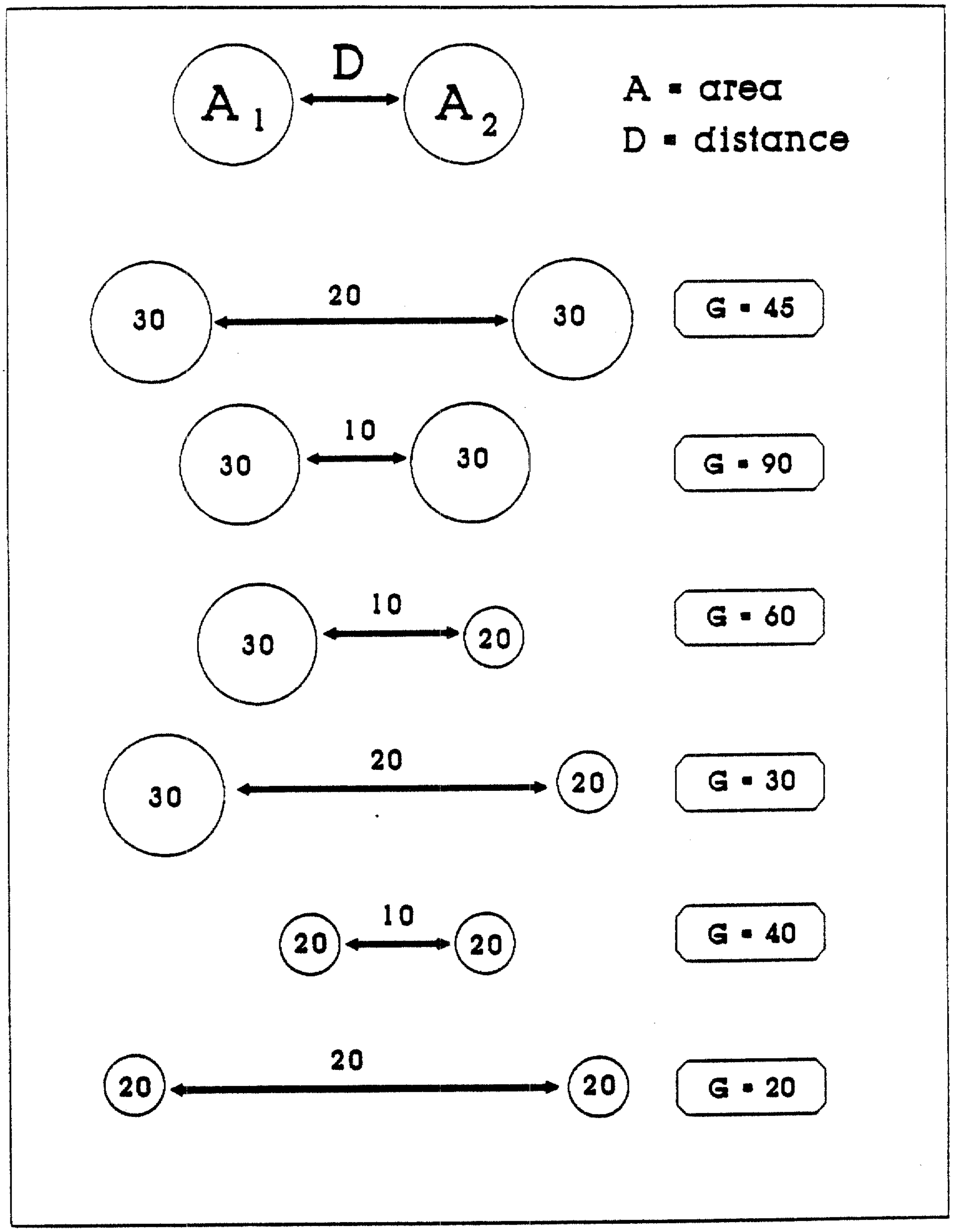


FIGURE 15. Potential cases of the gravity model.

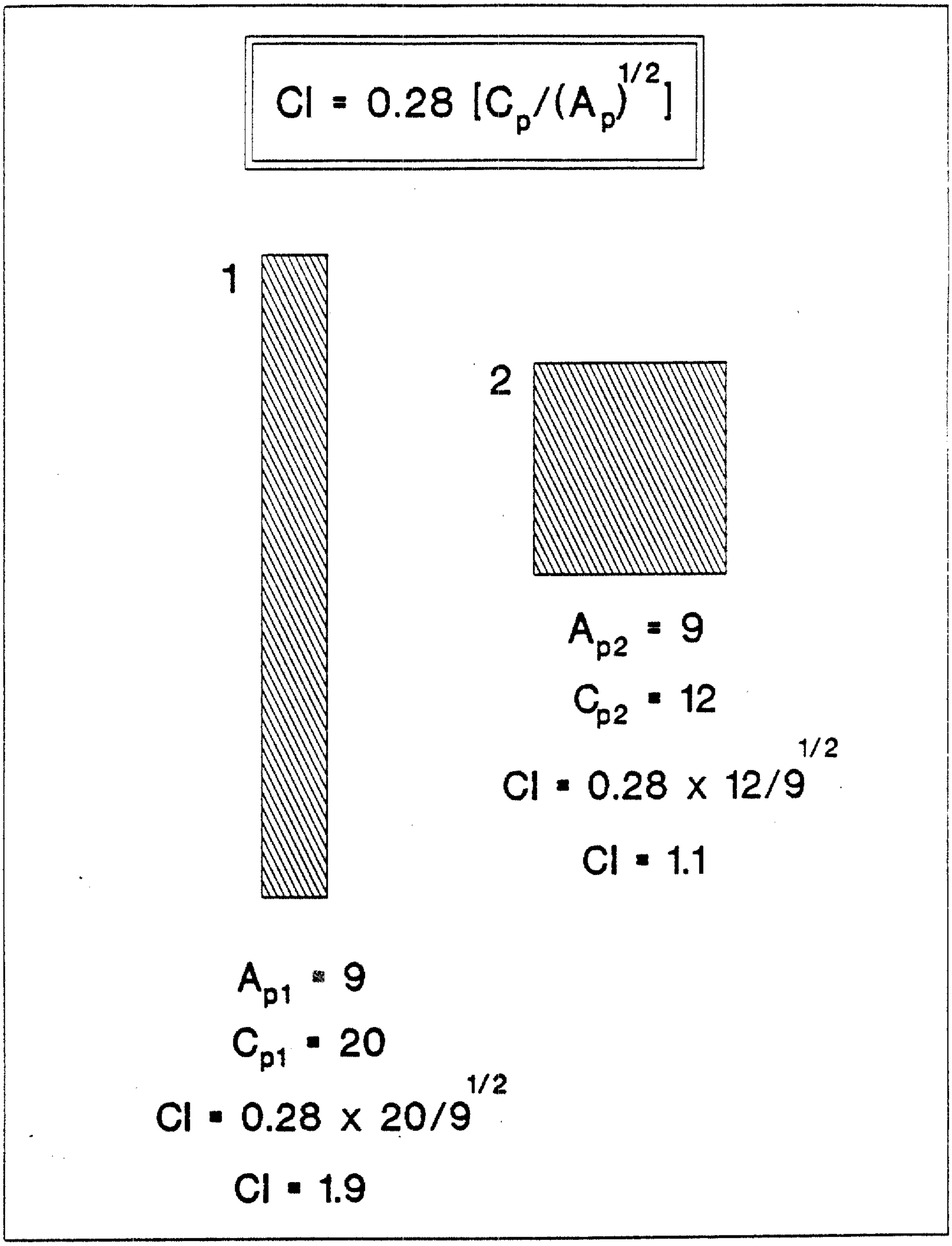


FIGURE 16. Potential cases of the Configuration Index.

$$C = 2(p)^{½} (A_p)^{½}$$

$$\text{let } CI = C_p/C = [C/(A_p)^{½}]/2(p)^{½}$$

$$\text{hence } CI = 0.28\ [C/(A_p)^{½}]$$

where:

A_p = area of any patch
R = radius of circular patch of area A_p
C = circumference of circular patch of area A_p
C_p = perimeter of patch A_p
CI = configuration index

For each of the four counties, 50 patches of potential habitat were randomly selected and their area and perimeter calculated. For each patch, CI was determined. For each of the four counties, a mean and standard deviation was determined from all of the CI values.

Topography

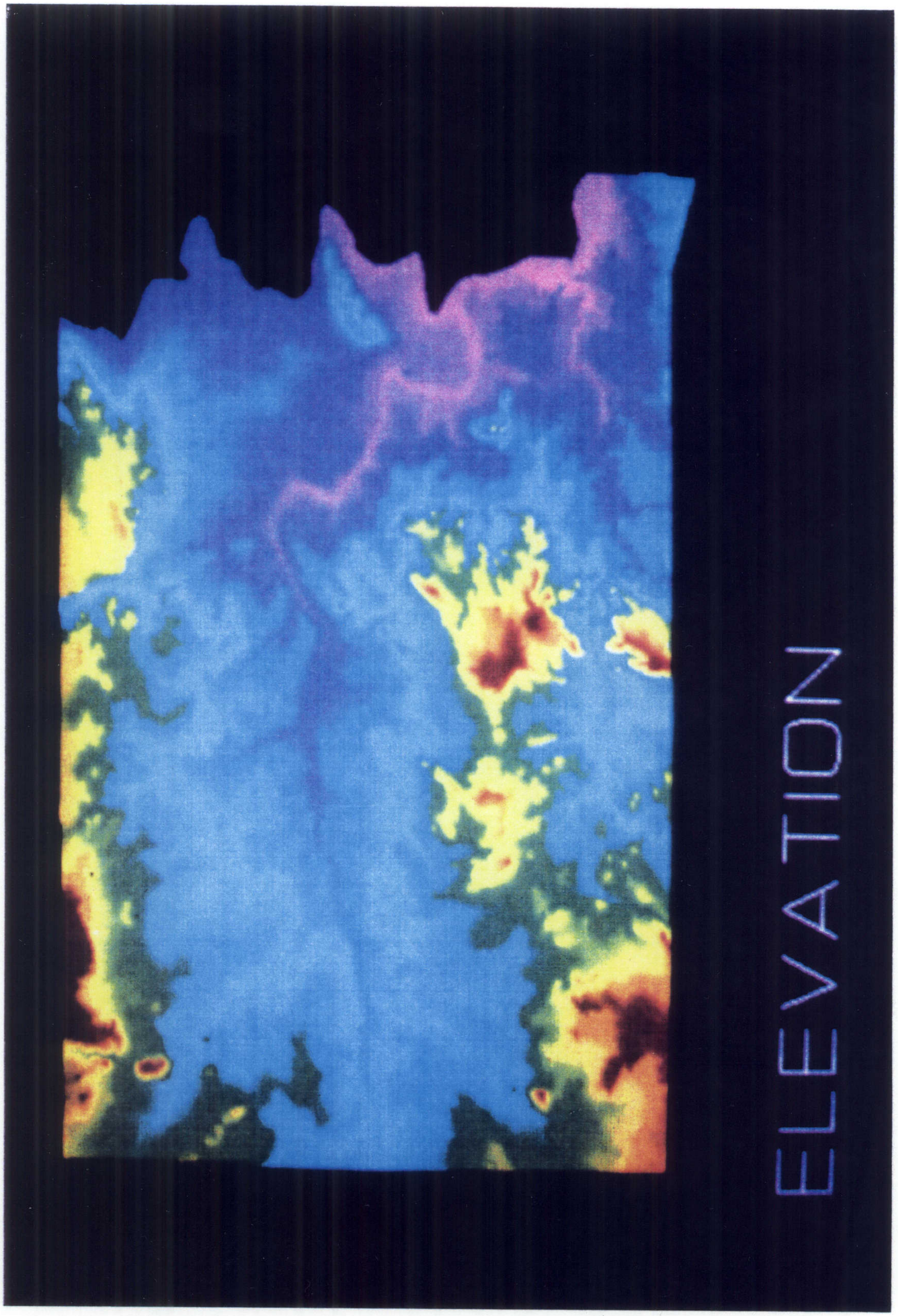
It has been suggested that a correlation can be found between the quality and occurrence of Golden-cheeked Warbler habitat with slope (Wahl 1988). To investigate this, a small portion of the study area was selected, topographic data for Llano county was integrated with habitat data. Digital elevation model (DEM) data were obtained from the USGS National Cartographic and Information Center (NCIC). These terrain data were produced by the U.S. Defense Mapping Agency (DMA) from the digitization of 1:250,000 scale topographic maps with contour intervals of 61 m. Resulting pixels have a ground resolution of 79 m (USGS 1982). An illustration of these data for Llano county is provided in Figure 17. The colors in the figure represent the range of elevations in the county. The yellows and oranges are areas of high elevation, the blues and purples are areas of low elevation.

The 1:250,000 scale source data were produced by interpolating elevations at intervals of three arc-seconds from contour lines on USGS 1:250,000 scale topographic maps. Three seconds of arc represents approximately 90 m north south and a variable amount in the east-west direction (Elassal and Caruso 1983). With the ERDAS program SLOPE, slope data were generated in increments of 4%. This was used to characterize the topography of the potential previously identified in Llano county.

Vegetation and Golden-cheeked Warbler Sampling

Vegetation sampling was conducted by personnel of the Texas Parks and Wildlife Department on 14 sampling sites throughout the study area. These sites were chosen based on known or reported occurrences of Golden-cheeked Warbler. Sampling sites were distributed across the entire range of the warbler (Fig. 18). Vegetative characteristics for each of the sites were measured by point-quarter method for trees (vegetation greater than 3 m in height) (Cottam and Curtis 1956) and quadrat method (4 x 5 m) for shrubs (vegetation less than 3 m) (Hays et al. 1981). Twenty sample points

FIGURE 17. Illustration of DEM data for Llano County, Texas.


ELEVATION

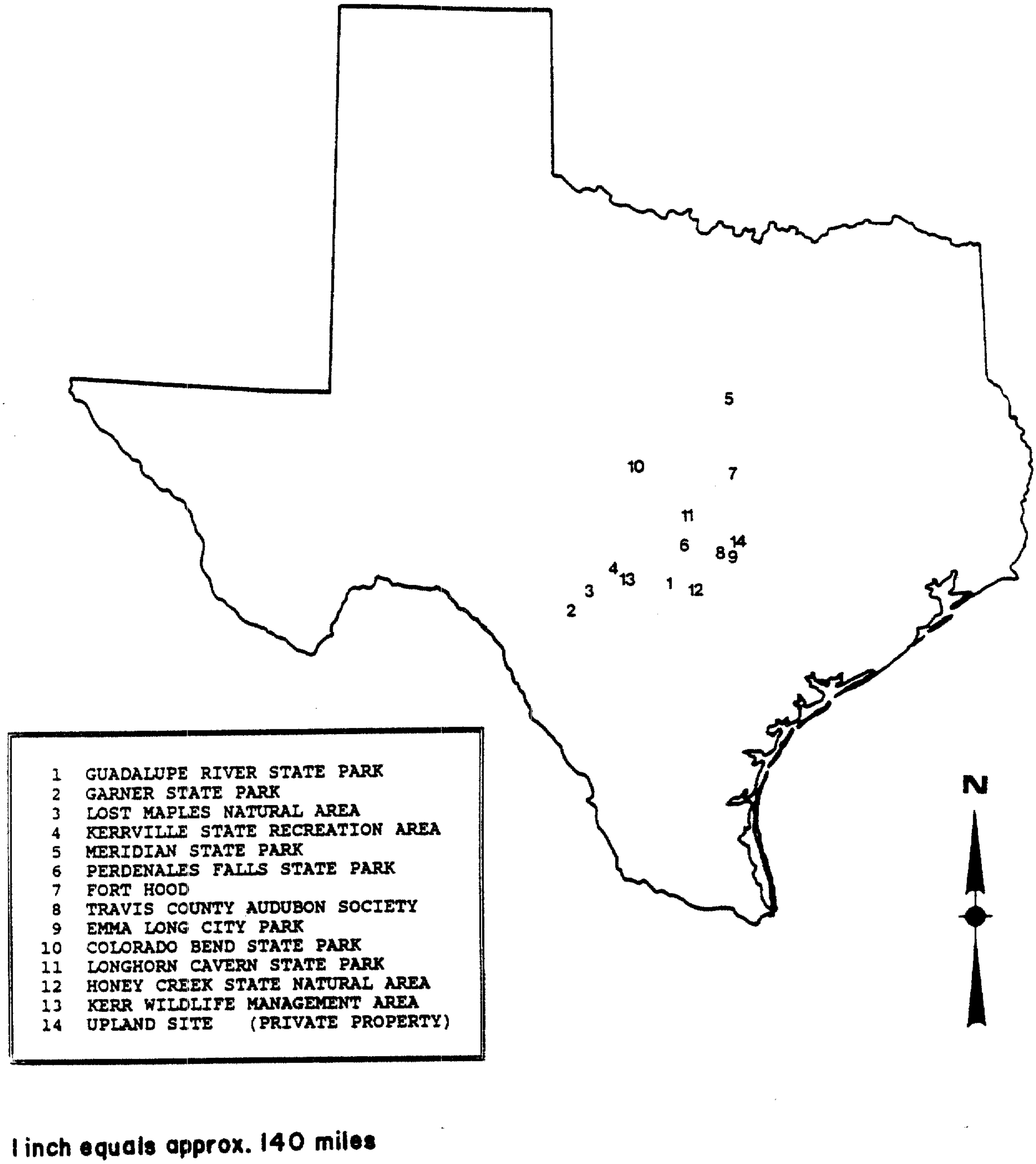


FIGURE 18. Transect locations used for vegetation sampling and estimation of Golden-cheeked Warbler densities.

were randomly selected along 1.6 km transect. The variables measured at each point included height, density, frequency and canopy cover at 3 m, 5 m, and maximum (above 5.5 m). Golden-cheeked Warbler densities were estimated at the same sites that were used for vegetation sampling (Fig. 18). Census work was also conducted by the Texas Parks and Wildlife Department. Bird densities were approximated using a modification of the Emlen strip census method (Emlen 1971). A census line was placed in suitable habitat such that 1.6 km of habitat was traversed. Each transect was walked on two consecutive days during the breeding season. Warblers heard and seen were noted and their distances perpendicular to the census lines estimated. The census began within one half hour of local sunrise and finished within two hours.

For each transect, the distance was determined in which, theoretically, all birds are detected (Emlen 1971). For most of the transects, distance was estimated at 40 m. All observations within 40 m of the transect were counted, therefore the effective area surveyed (EAS) for these transects was 12.8 ha. This was calculated as the area of the survey width (2 x 40 m) multiplied by the length of transect (1.6 km). A density estimate of birds for each site was determined as the average number of birds counted within 40 m of the transect line, divided by the EAS. The results of the survey were compared with historical data citing previous estimates of Golden-cheeked Warbler breeding densities.

Results

Habitat Identification

Based on the classification of the four digital MSS images, a total of 330,824 ha of potential habitat for the Golden-cheeked Warbler were identified. This represents approximately 4.7% of the entire study area (7.3 million ha). This estimation does not include any patches of habitat less than 1.8 ha (three pixels; connectivity radius of 1.5). It should be pointed out again, that data used for these estimates were as much as 10 years old; for some areas in the study area there have been considerable changes in landuse since this time.

To accommodate the change, a correction factor was estimated. The factor was based on data collected during ground truthing. As individual points were assessed for accuracy, it was noted if a site classified as habitat had undergone a recent landuse change (i.e. new roads or housing developments). These changes were tabulated per scene, and a Landuse Change Factor (LCF) for each of the four scenes was calculated as a percent of these points. The estimations of landuse change varied from 30% for the Austin image to 3% for the Kerrville image. These estimates were based upon changes that have occurred only in areas identified to be the Ashe juniper/deciduous hardwood vegetative community. Incorporating this correction factor, a revised estimate of 272,098 ha of habitat was made. The estimate was based on the LCD and number of hectares of habitat identified for each scene (Table 6). Table 7 presents the data specifically for Llano, Travis, Bosque and Kerr counties.

A 3-dimensional representation of the distribution of the habitat illustrates that the majority of potential habitat for the Golden-cheeked Warbler was located in the Southeastern portion of the study area (Fig. 19). The magnitude (Z direction) was calculated as the percent of habitat per county (Appendix C). The estimate was based on the original habitat estimates (prior to adjustment for landuse change). Classification accuracy varied with scene from 87.7% (Kerrville) to 90.7% (Austin). The accuracy assessment for each scene was taken as the ratio of the correctly classified points to the total number of points sampled. Points on the ground were judged to be potential habitat if the vegetative composition was correct (a mature Ashe juniper/deciduous woodland). The number of correctly classified points varied for each image, but for the entire study area, 382 of 425 points sampled were correct (Fig. 20). This was based only on the categories of habitat and nonhabitat. Any points which were determined to have clearly changed in landuse since the scene was imaged were

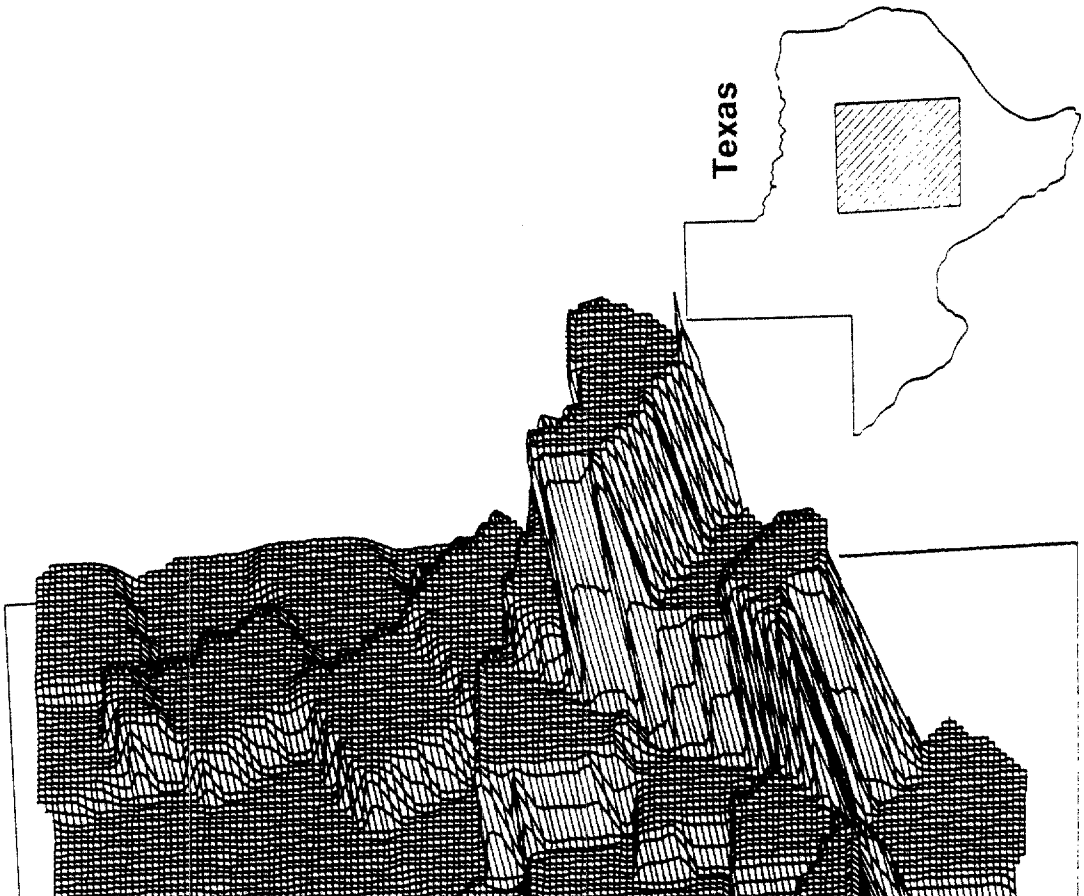
Table 6. Original habitat estimates per scene, their respective landuse change factors (LCF) and the revised estimate of potential habitat for the Golden-cheeked Warbler.

Scene	Original Estimate (ha)	LCF	Revised Estimate (ha)
AUSTIN	164815	30	115371
KERRVILLE	125453	3	121690
SAN ANTONIO	8071	8	7425
WACO	32485	15	27613
TOTAL	330824		272099

Table 7. Estimates of potential Golden-cheeked Warbler habitat for Llano, Travis, Bosque and Kerr Counties, Texas.

	LLANO	TRAVIS	BOSQUE	KERR
Size (ha)	249368	265010	257093	276869
% County in study	100	72	100	100
Habitat (ha)	7430	43098	6389	18163
% County with habitat	3.0	16.0	2.5	6.6
Scene year	1979	1979	1981	1981
% Change	30	30	15	3
Revised habitat estimate (ha)	5201	30169	5431	17618

FIGURE 19. 3-Dimensional representation of the distribution of potential Golden-cheeked Warbler habitat as identified from Landsat MSS images.


Texas
0
25
50
75
Miles
N

* (cl) / (ob)

	HAB	NON
HAB	46	5
NON	7	70

AUSTIN N=128
90.6%

	HAB	NON
HAB	23	0
NON	6	30

SAN ANTONIO N=59
89.8%

	HAB	NON
HAB	46	0
NON	13	81

WACO N=140
90.7%

	HAB	NON
HAB	30	3
NON	9	56

KERRVILLE N=98
87.7%

* CL = CLASSIFIED OB = OBSERVED

FIGURE 20. Matricies of habitat classification as compared with field assessment.

not included.

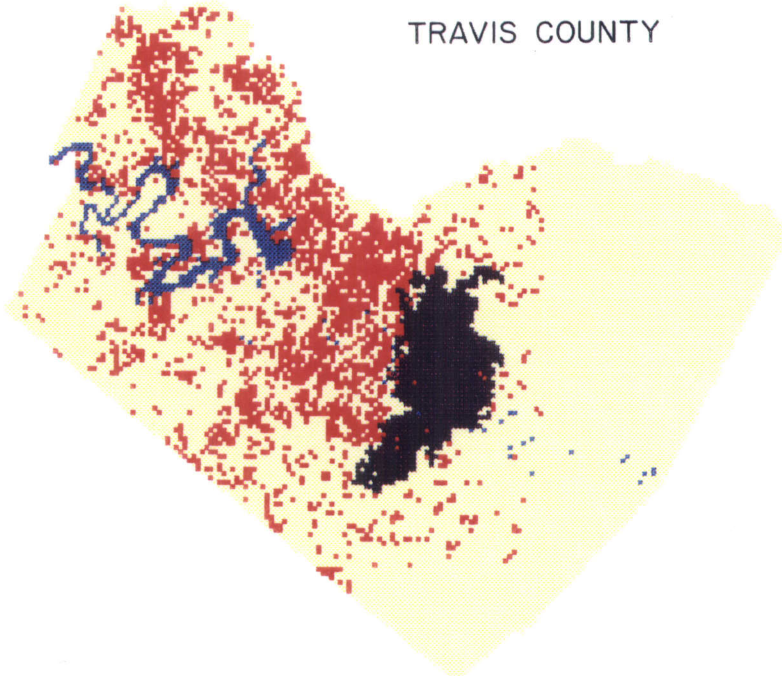
Habitat Fragmentation

Several aspects of spatial distribution of potential habitat were described for Llano, Travis, Bosque and Kerr counties. Figures 21 and 22 illustrate the variability of habitat distribution within these counties. To estimate the patch size distribution for each county, the number of habitat patches within an area of 335,000 ha were assessed. Patch size data were collected for seven size categories, from 6.2 to 279+ ha (connectivity radius of 1.5) (Table 8). Kerr county had the largest total number of patches, 4,118; 87% of which were between 1.8 and 6.2 ha in size. Bosqûe county had the fewest patches of habitat, 661; 66% of these were between 1.8 and 6.2 ha in size. Travis county had 3,262 patches in total; 79% of these were between 1.8 and 6.2 ha. Travis County had the greatest number of patches greater than 279 ha; 21. The only other county with patches greater than 279 ha was Kerr, with two (Fig. 23).

The gravity model provided a measure of "attraction" between patches. This measure was based on both patch size and distance between patches. Travis county had the highest mean gravity value, 301.2; considerably higher than the other three counties. For the remaining counties, the mean values were similar; Llano (89), Bosque (46) and Kerr counties (57). Standard deviations ranged between 76 (Kerr) and 854 (Travis), these standard deviations indicate high

FIGURE 21. Golden-cheeked Warbler habitat distribution in Travis and Llano Counties.

TRAVIS COUNTY



LLANO COUNTY

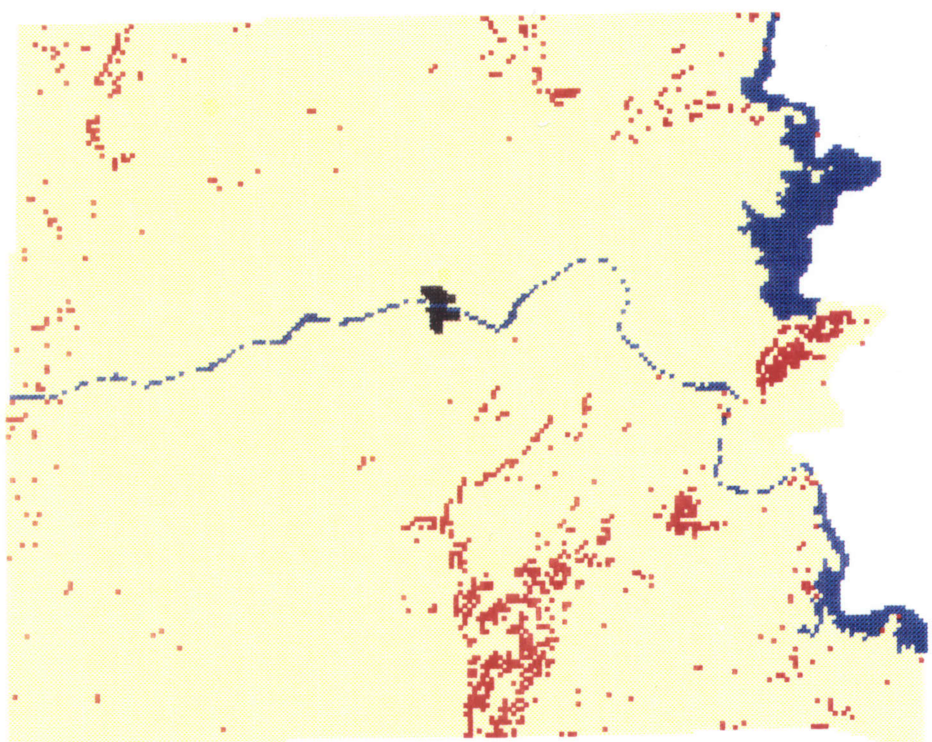
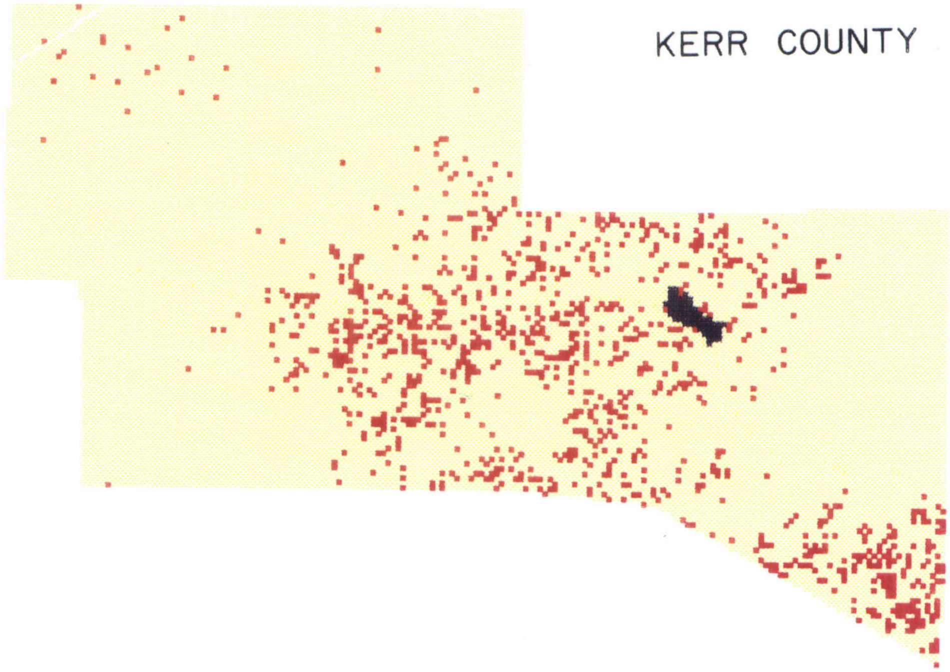


FIGURE 22. Golden-cheeked Warbler habitat distribution in Kerr and Bosque counties.

KERR COUNTY



BOSQUE COUNTY

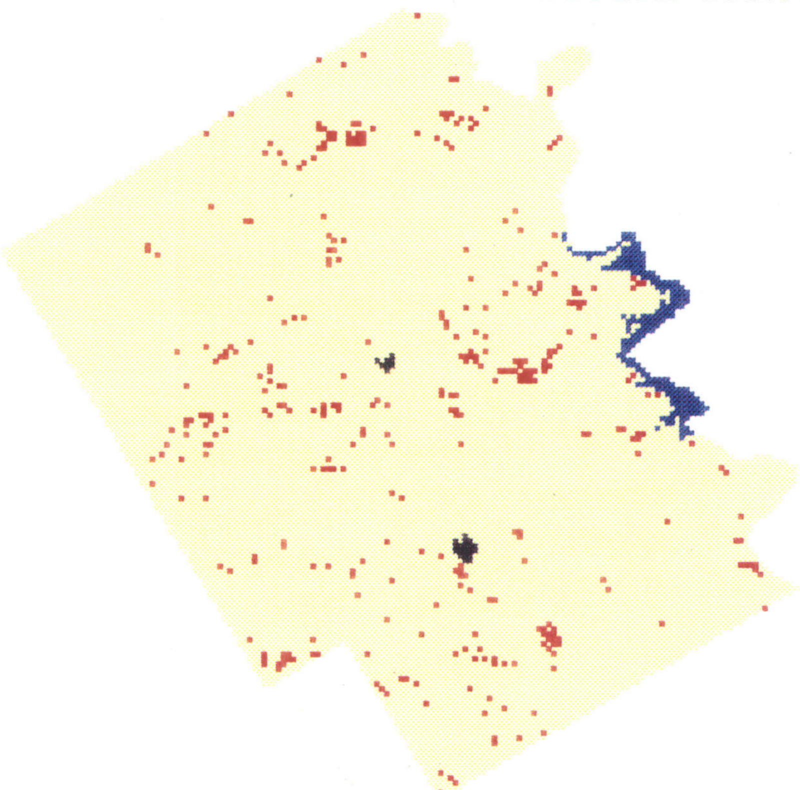


TABLE 8. Patch size distribution of potential habitat for the Golden-cheeked Warbler in seven categories for Llano, Bosque, Kerr and Travis Counties.

	A	B	C	D	E	F	G	TOTAL
LLANO	694 (86)*	99 (11)	4	3	5	0	0	805
BOSQUE	434 (66)	217 (33)	4	4	0	2	0	661
KERR	3572 (87)	525 (12)	14	3	1	1	2	4118
TRAVIS	2569 (79)	600 (18)	43	18	6	5	21	3262

* percent

A	1.8 to 6.1*
B	6.2 to 61
C	62 to 123
D	124 to 185
E	186 to 247
F	248 to 309
G	310 +

* hectares

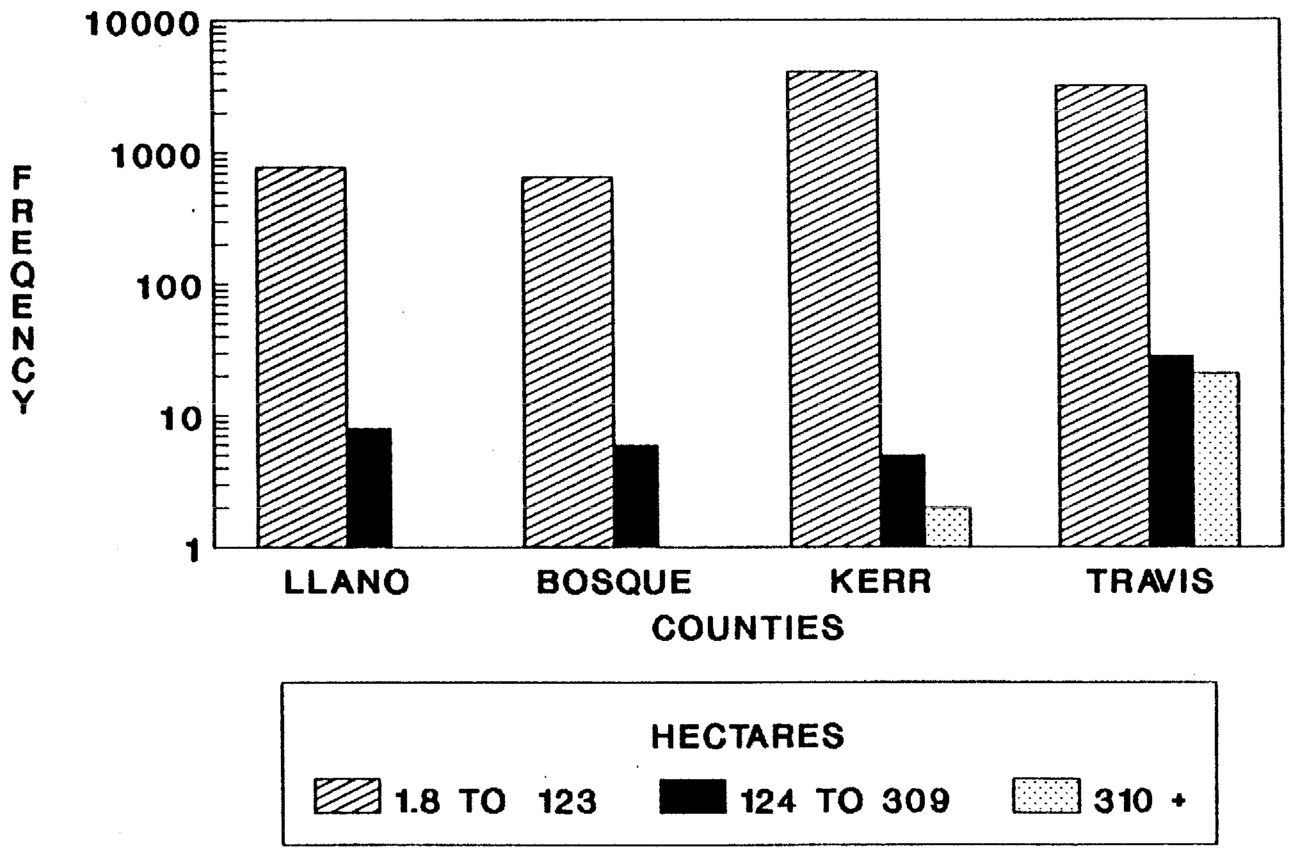


FIGURE 23. Distribution of habitat patch sizes for Llano, Bosque, Kerr and Travis counties.

variability with respect to the patch measurements of sizeand distance (Fig. 24).

The Configuration Index was used to describe the shape of the patches as they deviate from a circle of the same area. The lower the CI value, the closer the configuration of the patches approach that of a circle. The mean CI values for the counties varied from 5.4, for Bosque to 8.5 for Travis. Travis County again, had a the highest standard deviation, 4. This indicates that among the patches in Travis county, there is considerable variation in their configuration (Fig. 25). The remaining three counties had similar mean CI values. Of these Bosque county had the highest (6.3).

Topography

Areas identified as potential nesting habitat for the Golden-cheeked Warbler in Llano County were merged with slope information derived from DEM data. The analysis in Llano county provided a description of the slope on which habitat was located. A total of 7,429 ha of potential habitat were identified in Llano county. Fifty-seven percent of the habitat was located on slopes between 0 - 3 %; 20% of all habitat was on slopes of 4 - 6%; 10% was on slopes of 7 - 9%; and 13% of all habitat was located on slopes of greater than 10% (Fig. 26). Slope may be an important indicator for Golden-cheeked Warbler habitat.

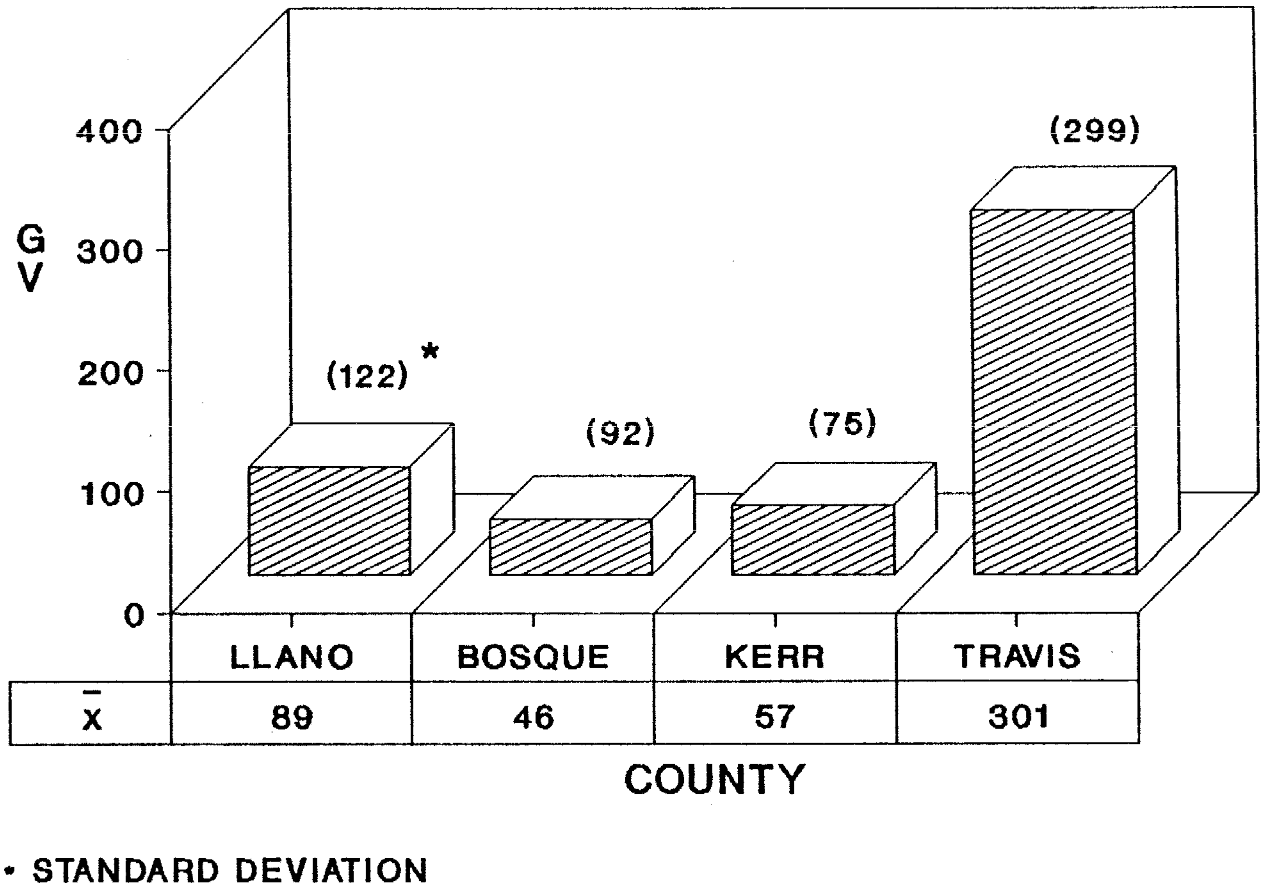


FIGURE 24. Gravity calculations for habitat patches in Llano, Bosque, Kerr and Travis counties.

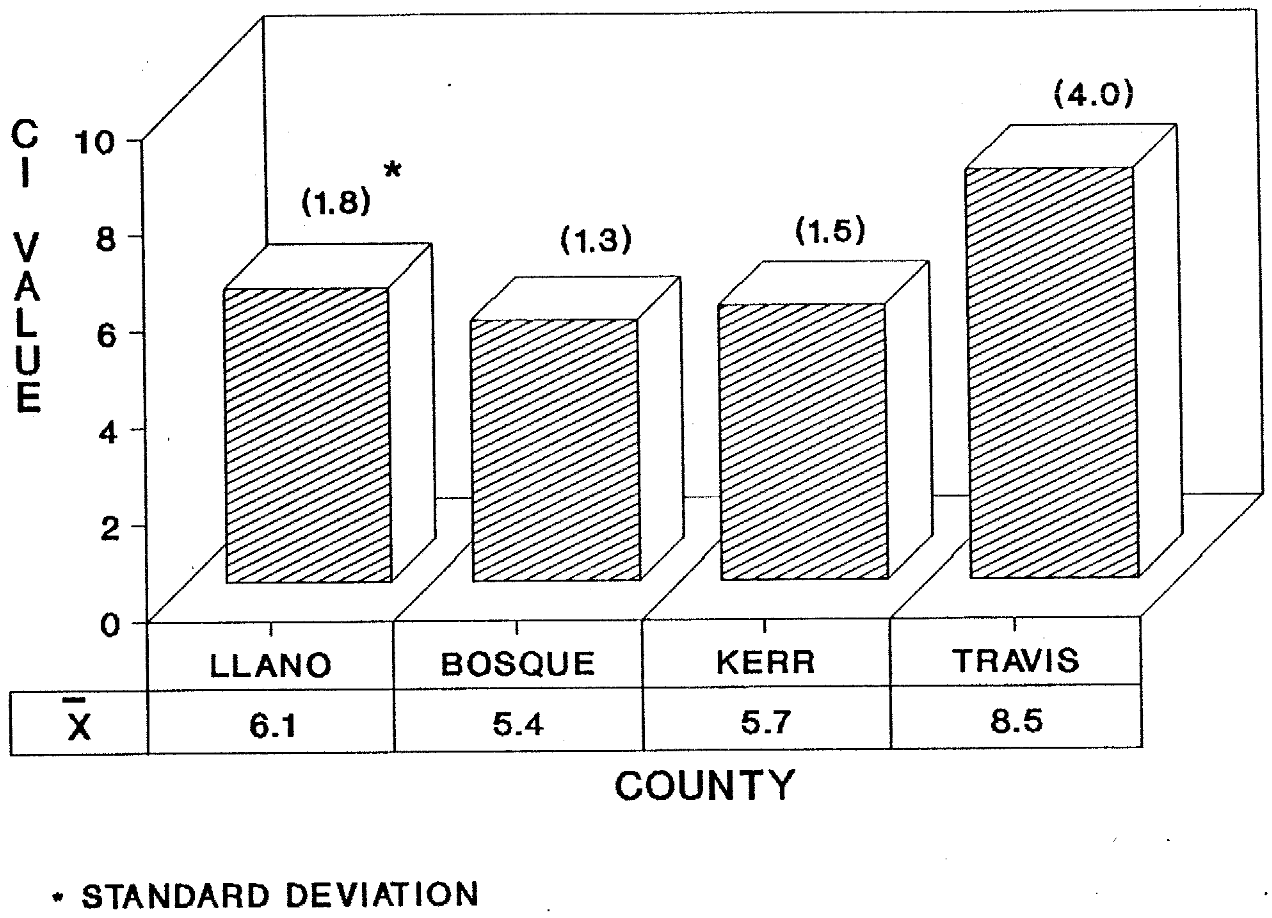


FIGURE 25. Configuration Index (CI) values for habitat patches in Llano, Bosque, Kerr and Travis counties.

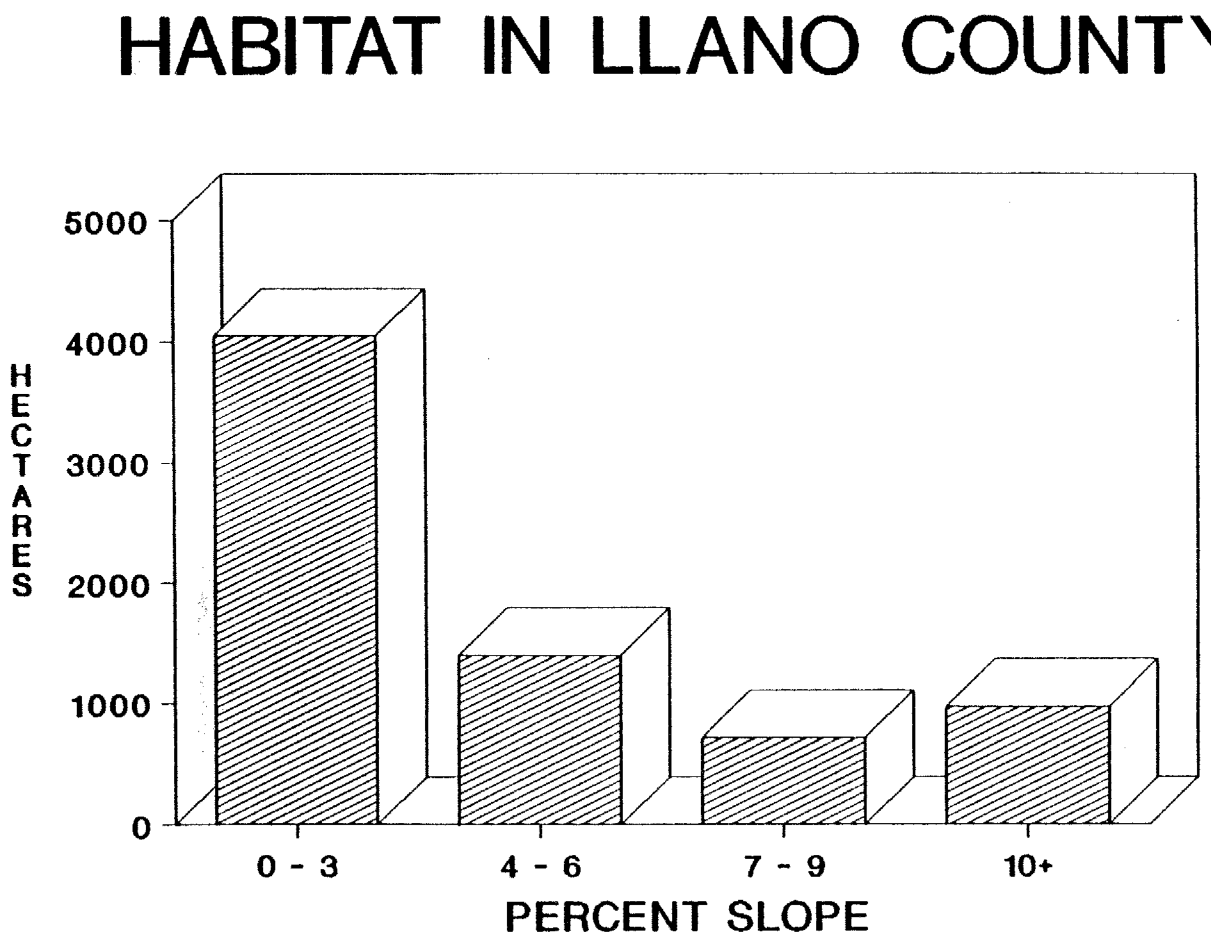


FIGURE 26. Slope description for potential Golden-cheeked Warbler habitat in Llano county.

Several authors have suggested that preferred warbler habitat is usually found on steep slopes and canyons. This may be attributed to the solar regime or to the edaphic factors which influence the vegetation. An additional consideration is that, steep slopes and rocky canyons are less frequently cleared for agricultural and development.

Vegetation and Golden-cheeked Warbler Sampling

A series of vegetation variables were measured relative to the estimated warbler densities. Vegetative data from ten of the sampling sites were used in a multiple stepwise regression of descriptive variables. The top two significant, explanatory variables were canopy species diversity at 5 m ($r^2 = 0.46$, $P = 0.03$) and deciduous foliage dominance at 5 m. (r^2 added 0.29, $P = 0.02$) (Total $R^2 = 0.75$, $P<0.001$). Both of these had positive effects and no other parameters were significant (at $P< 0.05$) (Table 9). The vegetative data collected for at the sites are provided in Appendix D.

Survey data for the Golden-cheeked Warblers were collected for 13 of the 14 sampling sites (Fig. 18). They were conducted during the 1987 and 1988 breeding seasons. The EAS was 12.8 ha for 12 of the sites and 8.0 ha for Guadalupe River State Park and the Uplands Site (Table 10). The estimated number of males per hectare varied from 0 (Kerrville City Park) to 0.63 at Guadalupe River State

TABLE 9. Relationship of Golden-cheeked Warbler breeding density to significant vegetative structural determinants for 10 sites (data arranged from highest to lowest warbler density).

Site	Warbler Density[2]	Canopy Diversity[3]	Foliage Dominance[4]
Guadalupe River S.P.	0.63	2.48	2915
Friedrich Park	0.52	2.17	2519
Travis Co. Audubon	0.36	2.37	2918
Lost Maples S.P.	0.31	2.93	8301
Emma Long Park	0.31	2.39	6816
Clifton Site	0.25	1.55	868
Meridian S.P.	0.23	0.76	509
Ft. Hood	0.15	0.34	679
Garner S.P.	0.11	1.30	5599
Kerrville S.P.	0	1.03	2907

[1] In a multiple stepwise regression of leading explanatory variables r^2=0.46 (P=0.03) for canopy diversity, and r^2 added 0.29 (P=0.02) for deciduous foliage dominance (R^2=0.75, P<0.001).

[2] Estimated as males/ha

[3] Canopy species diversity based on crown cover at 5m ($H'\log_2$)

[4] Deciduous foliage dominance (m^2/ha) at 5m; canopy diversity and deciduous foliage are correlated (r=0.65, P<0.05) hence they are additive rather than compensatory.

TABLE 10. Density estimates of Golden-cheeked Warblers. Observers indicated in parentheses (RW = Rex Wahl, RM = Robert Murphy, CS = Chuck Sexton, DG = Don Giller).

STUDY SITE (observer)	Av. # males (range)	EAS (ha.)	Males/ha	Date
Colorado Bend (RW,DD)	2	12.8	0.15	16-17 May
Emma Long Park (CS)	4 (2-6)	12.8	0.31	1-3 May
Fort Hood (RW)	1 (2-0)	12.8	0.15	17,20 May
Garner S.P. (RW)	1.5	12.8	0.11	7-8 May
Guadalupe River (RM)	5 (3-7)	8.0	0.62	9-10 Apr
Honey Creek (RW)	1.5	12.8	0.08	4-5 May
Kerrville (RW)	0	12.8	0.0	4-5 May
Longhorn Cavern (RW)	.5 (0-1)	12.8	0.08	28-29 May
Lost Maples (RW)	4 (3-5)	12.8	0.31	9-10 May
Meridian (RW)	3 (1-3)	12.8	0.23	20-21 May
Pedernales Falls (RW)	1.5 (1-2)	12.8	0.15	9-10 May
Travis Co. Audubon (DG)	4.7 (3-7)	12.8	0.36	14-16 May
Uplands Site (RW)	.5 (0-1)	8.0	0.12	24-25 May

Park. For all sites which had males, the average was 0.20 males/ha, comparable with results from previous studies which ranged from 0.11 to 0.93 males/ha for several counties in Texas (Table 11)

Summary of Results

The classification of digital satellite MSS imagery for the breeding range of the Golden-cheeked Warbler identified 330,824 ha of potential habitat. The most abundant and contiguous habitat was located on the eastern and southeastern edges of the Edwards Plateau, this portion of the plateau is characterized by deeply incised canyons that support deciduous woodlands (Riskind and Diamond 1988).

Distinguishing this habitat community with digital satellite imagery on the basis of spectral reflectance at 80 m resolution appears to be feasible (ground truthing showed 89.7% overall accuracy). For the classification, signatures from Golden-cheeked Warbler nesting habitat throughout its range were utilized. This was necessary because of the variability in vegetative species composition which was utilized as habitat across the study area. The errors in classification occurred as omissions (points which were habitat but were classified as nonhabitat) and commissions (points incorrectly classified as habitat). Two percent of the points were commissions and 8% were omissions. The large majority were correctly classified. Due to the age of

TABLE 11. Reported estimations of Golden-cheeked Warbler densities (from Ladd 1985).

County	Males/ha*	Researcher
BOSQUE	0.22-0.11	KROLL 1980
TRAVIS	0 43	JOHNSTON et al. 1952
TRAVIS	0.37	WEBSTER et al. 1954
TRAVIS	0.43	McDONALD 1972
TRAVIS	0.53	CHOBAN 1974
TRAVIS	0 50	McKINNEY 1975
KENDALL	0 50	PULICH 1976
KERR	0.93	COOKE 1923
KERR	0.50	LADD 1985

* Originally reported as Ha/pair; the assumption was made that there was one male per pair.

the original data and the ensuing landuse changes which have occurred, a correction factor (LCF) was introduced. The LCF was calculated as an estimation of the loss of habitat within each scene that was clearly since the image was taken. Based on the LCF, a revised estimation of potential habitat 272,098 ha was made. The estimation of habitat does not account for any permutations of habitat suitability dictated by patch size, configuration or separation. No attempt was made to estimate the amount of area which may have successed into suitable habitat in the ensuing years.

For four counties in the study area, Llano, Bosque, Kerr and Travis, indices were developed to describe the spatial characteristics of habitat. Consideration was given to patch size distribution, the distance between adjacent patches and the configuration of the patches. For each of the indices, a random set of patches were sampled. A comparison of these indices for all four counties is provided in Table 12.

For Bosque county, in the northern portion of the study area, the distribution suggests considerable habitat fragmentation. Only 2.5% of the county was estimated to have potential habitat. This is probably due to extensive clearing for agricultural purposes on the flatter Lampasas Cut Plain. The remnant patches of habitat are found on the rocky and steep sides of the tablelands and are widely separated from other patches. Bosque had the lowest gravity

TABLE 12. Comparison of spatial Golden-cheeked Warbler habitat parametes for Llano, Travis, Bosque and Kerr counties.

	Llano	Travis	Bosque	Kerr
Percent habitat	3.0	16.0	2.5	6.6
# patches > 62 ha.	12	93	10	21
GV (sd)*	89 (122)	301 (299)	46 (92)	57 (75)
CI (sd)	6.1 (1.8)	8.5 (4.0)	5.4 (1.3)	5.7 (1.5)

*Standard deviation.

value of the four counties, which suggests that the patches were smaller and further apart than in the other counties. Bosque had the second highest CI value next to Travis county, supporting the speculation that the remaining habitat in this portion of the range is confined to mesa valleys and canyons.

Travis county was at the other extreme. Sixteen percent of the county was covered by habitat (from 1979 data). Further, Travis county had the largest number of large patches and the highest gravity and CI values. This indicates that the potential habitat is contiguous and in larger patches that are more circular than for the other counties, possibly a function of the underlying lithology and its influence on vegetation. Indices in Llano and Kerr counties were intermediate between Bosque and Travis Counties.

Fourteen sampling locations were established in the study area. These were used to measure vegetational parameters as well as the breeding density of Golden-cheeked Warblers. These sampling sites were not random but areas known to have had nesting Golden-cheeked Warblers. When the vegetation measurements were regressed against relative density of warblers, the most significant factors were canopy diversity (based on crown cover at 5 m) and foliage dominance (also at 5 m).

Gelbach (1988) has proposed that deciduous trees in

Golden-cheeked Warbler nesting habitat are important for foraging. The higher the diversity of deciduous trees, the greater the variety of insect species (especially caterpillars). Subsequently, the larger the deciduous canopy, the more caterpillars. He suggested that as long as there is a critical minimum of Ashe juniper for nesting material, the abundance of deciduous trees determines warbler nesting density.

Discussion

Although satellite multispectral data have previously been used to map wildlife habitat over large areas (Colwell et al. 1978, LaPerriere et al. 1980, Hill and Kelly 1987), to date, this is the largest study to map habitat for a single species. This is also the first remote sensing research to address the identification of potential habitat for the entire breeding range of a species. Results indicate that it is possible to map from Landsat MSS data, with acceptable accuracy (89% overall), the vegetative community utilized as nesting habitat by the Golden-cheeked Warbler. This research habitat is characterized as a mixed evergreen-deciduous forest, where the dominant evergreen is mature Ashe juniper. As observed during the vegetative survey, the variety of deciduous species and their relative proportions to Ashe juniper was highly variable. The vegetative survey found 18 deciduous species in association with Ashe juniper; their relative abundance and densities varied considerably across the study area. With respect to the presence of deciduous species, other authors have reported similar conclusions. Kroll (1980) reported a 1.35:1 ratio of junipers (40+ years old) to Bigelow oak (Quercus durandii) in habitat at Meridian State Park (northern portion of the range). At Kerr Wildlife Management Area, in the west-central portion of the range, Ladd (1985) found warblers preferred mixed stands of Ashe juniper and Texas oak. Ladd (1985) also described other plant associations favored as habitat by the warbler, all contained Ashe juniper with various species of oak. These vegetative composition descriptions are at odds with Pulich's (1976a) reference to warbler habitat as "dense cedar breaks".

Probably not all of the habitat identified is suitable and certainly not all of it is utilized. This classification has merely identified areas containing mature Ashe juniper and varying proportions of deciduous hardwoods. However, these results are likely to include all potential habitat, and thus provide a baseline for initial analyses and assessment.

For species facing habitat reduction and fragmentation, such as the Golden-cheeked Warbler, their conservation will require further understanding of nesting requirements. This must include minimal area as well as structural characteristics of potential habitat. The means to measure some of these spatial attributes have been developed here. As this information becomes available, the spatial data base generated here may be used to narrow down the definition of potential habitat for the species.

In recent years there has much been work in the area of habitat fragmentation and its effect on biological diversity, particularly for breeding bird populations (Forman et al. 1976; Whitcomb 1977; Robbins 1980; Lynch 1987). These have contributed supporting evidence that area and isolation are important considerations for habitat occupancy. Additional studies (Preston 1962, MacArthur and Wilson 1963,1967) have addressed spatial attributes such as area and isolation as they affect species diversity and abundance on islands. However, all these studies address the issue from a species diversity standpoint rather than in consideration of the ecological requirements of an individual species.

In a recent study, Robbins et al. (1989) identified bird species for which forest area was a predictor of relative occurrence during the breeding season. To accomplish this, data were obtained on the minimum area required by each species. They concluded that, for most neotropical migrant species, probability of occurrence increased with the area. For example, any wooded patch of at least 100 ha, regardless of location and forest type was likely have at least one pair of Red-eyed Vireos (Vireo olivaceus).

However, patch size alone is not adequate information to plan for protection of a species. Another consideration is the ratio of edge to area, as can be measured with the CI. A patch may be of sufficient size but may be unsuitable if it is long and linear in configuration. Robbins et al. (1989) have suggested several factors that may render small patches unsuitable, I propose that the same concerns be extended for large patches with high CI values. The first problem of such patches is the inherent proximity to a habitat edge, depending on the species requirements, this may reduce the effectiveness of that portion of forest. Another factor is that predation and brood parasitism appear to be higher for smaller patches than large. Wilcove (1985) documented significantly higher rates of nest predation and Cowbird parasitism for small forest patches. Cowbirds are a problem for Golden-cheeked Warblers. Pulich (1976a) found Brown-headed Cowbirds (Molothrus ater) parasitized 19 of 33 nests observed, he attributed 54.5% of egg losses to this. Brittingham and Temple (1983) found that nest parasitism by Brown-headed Cowbirds decreased with distance from forest edge, but extended greater than 300 m into the forest. Threats from predators which prey on eggs and nestlings are also augmented for small patches. Robbins (1980) and Wilcove (1985) have reported that avian predators such as

American Crows (Corvus brachyrhynchos) and Blue Jays (Cyanocitta cristata) may be more common along forest edges than in the interior. These threats may reduce both the rates of return by adult birds and colonization by first-time breeders (Robbins et al. 1989).

There are factors other than size which must be considered in an evaluation of habitat. These include patch isolation, corridor availability, and adjacent landuse. As information about the tolerance of Golden-cheeked Warblers for these variables becomes available, remote sensing and GIS will be useful for assessing impact and identifying areas to be set aside which will provide protection for the gene pool.

However, there are some limitations to the remote sensing technology which must be addressed. For this particular study the age of the digital data was a limitation. These data are already dated and much of the identified habitat may have already been cleared. Additionally, regardless of age, there is variability between scenes which can be attributed to climatic and seasonal influences. This may influence the results of the classification. Finally, consideration must be given to the resolution of the spatial data. At 80 m, this resolution has limitations with respect to the treatment of habitat edge, this may contribute to classification error. Additionally, small patches may be missed.

Despite these limitations, there are many advantages to this type of study. First, relatively inexpensive data can be obtained and analyzed for parts of the breeding range that are not easily accessible (much of the study area is under private ownership and therefore difficult to reach). Secondly, the data base can be used for comparisons with future studies and temporal changes can be monitored. In the long run, this technology may allow for improved estimates of spatial distribution and temporal dynamics of the habitat for this species.

CHAPTER V

BLACK-CAPPED VIREO HABITAT
HABITAT CHARACTERIZATION

The Black-capped Vireo (*Vireo atricapillus*) was listed as an endangered species by the U.S. Federal government in 1987 (52 FR 37420-37423 [6 October 1987]). This affords the species full protection under the 1973 Endangered Species Act. Section 7 of this Act mandates responsible actions to insure protection of endangered and threatened species and their critical habitat (USFWS 1987a). The identification and appraisal of this habitat is imperative to this mandate. The primary objective of this portion of the research was to assess the integrated use of remote sensing and GIS(s) to assess habitat availability for the Black-capped Vireo.

Nesting habitat of the Black-capped Vireo is primarily heterogenous scrub characterized by a patchy distribution of shrub clumps and thickets with a few scattered trees and abundant dense hardwood foliage to ground level. Throughout the breeding range of the Black-capped Vireo (Fig. 2), the species that comprise these vegetative communities vary across gradients of climatic and edaphic conditions. This variability, compounded by the patchy nature of the habitat makes it difficult to characterize exclusively on the basis of vegetative descriptions as viewed by remote sensing imagery. For these reasons, a stratified analysis for Camp Bullis was developed which considered not only vegetative composition but also factors such as underlying geologic formation, slope and aspect upon which the habitat is found. The strategy for this approach consisted of an on-site survey of the species, discrimination of potential habitat from satellite imagery and integration of these data with ancillary data bases of geology, slope and aspect (Appendix E).

Study Area

The study area for this research was Camp Bullis, Fort Sam Houston, Texas. Camp Bullis is located north of San Antonio, Texas in Bexar and Comal counties (Fig. 27). The 11,287 ha installation is approximately 16 km long and 6.4 km wide. The military activities on Camp Bullis include range, field and assault training exercises. A variety of weapons are used including pistols, rifles, machine guns, mortars, anti-tank weapons and grenade launchers. Field training maneuvers are also practiced over the installation. Leased grazing is practiced over the northern two thirds of the installation. The land surrounding Camp Bullis is primarily rural with some strip and clustered development around the perimeter.

The climate of this area is characterized by long hot summers, and short mild winters. January is the coldest

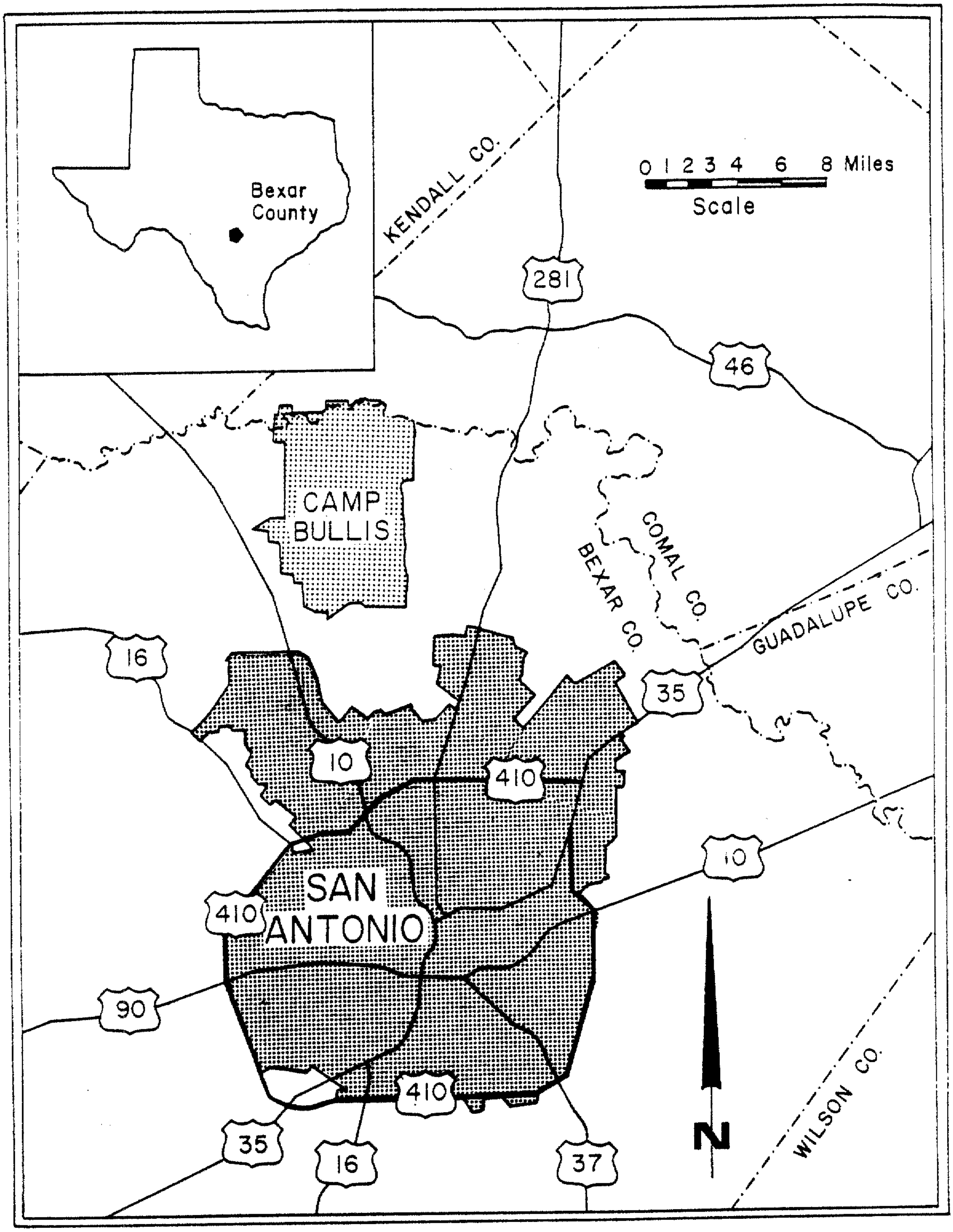


Figure 1. Location of Camp Bullis, Fort Sam Houston, Texas.

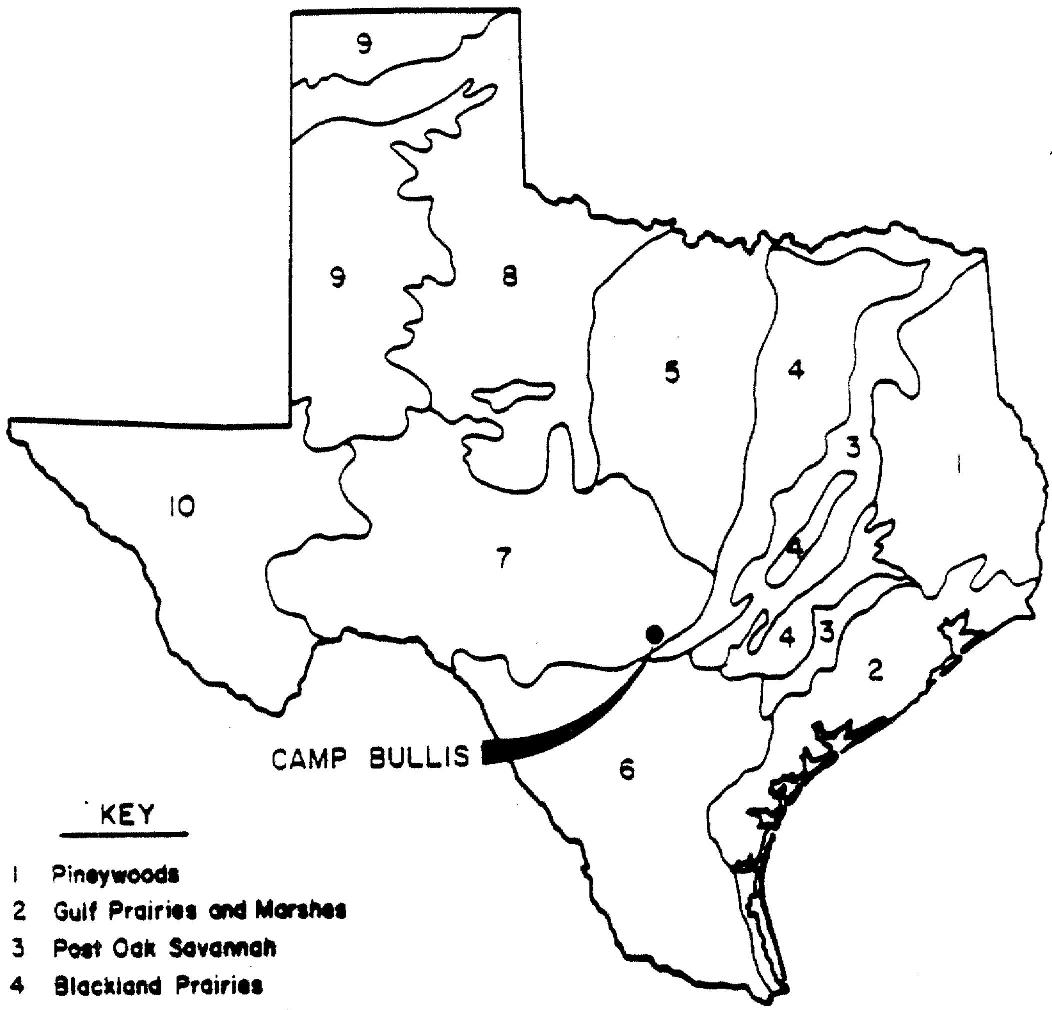
month, with an average monthly temperature of 11°F, July is the warmest month, averaging 29°F. The average precipitation is about 80 cm and is well distributed throughout the year (Larkin and Bomar 1983).

Geology

Camp Bullis lies within the Edwards Plateau ecological area on the northwestern edge of the Balcones escarpment (Fig. 28). The regional physiography of this area is governed by the Balcones Escarpment, a broad area of faulted limestone forming the southern and eastern edges of the Edwards Plateau. Topographically, the region consists of steep sparsely-vegetated slopes on limestone bedrock. There is no permanent water; intermittent streams drain to the south and east (Caran and Baker 1986). Elevations on Camp Bullis range from 305 to 465 m.

With respect to major geologic formations, Camp Bullis is underlain by the Upper and Lower members of Glen Rose Limestone. The Glen Rose Formation consists of beds of moderately resistant and massive chalky limestone alternating with beds of less resistant marly limestone. The erosional differences in these two layers has formed a terrace type topography in the area. Overlying the Glen Rose Limestone is Edwards Limestone. This formation consists of gray to white, dense, hard, semicrystalline limestone. Edwards Limestone outcrops are found exposed on

ECOLOGICAL AREAS OF TEXAS



KEY

1 Pineywoods
2 Gulf Prairies and Marshes
3 Post Oak Savannah
4 Blackland Prairies
5 Cross Timbers and Prairies
6 South Texas Plains
7 Edwards Plateau
8 Rolling Plains
9 High Plains
10 Trans-Pecos, Mountains and Basins

FIGURE 28. Location of Camp Bullis, Texas on the Edwards Plateau ecological area.

hilltops in the southcentral and southeastern portions of Camp Bullis.

Vegetation

Prior to settlement this portion of the Edwards Plateau was grass covered and the juniper and oak woodlands were restricted to deeply eroded slopes and canyon walls (Bray 1904). The replacement of prairies by woody plants, associated with intensive grazing by livestock in the latter 1800s and the cessation of range fires was detailed by Buechner (1944) and Pulich (1976a). Ford and Van Auken (1982) described the vegetation of the southern and eastern portions of the Edwards Plateau as a scrub forest of juniper, evergreen oak (live oak) and Mexican persimmon (Dixon 1989). Riskind and Diamond (1986) have more specifically categorized the dominant vegetative communities of this region from the perspective of physiographic divisions. Two of these, floodplain forests and steep slopes are relevant for Camp Bullis. Floodplain forests are areas subjected to periodic flooding. They are dominated by a combination of oak-elm and hackberry (Celtis sp.) forests. These mixed forests may include species such as ash (Fraxinus pensylvanica), soapberry (Sapindus sp.), ashe juniper (Juniperis asheii), pecan (Carya illinoensis), eastern cottonwood (Populus deltoides), American elm (Ulmus americana) and red mulberry (Morus rubra). Floodplain forests are usually bi-layered containing an understory comprised of species such as deciduous holly (Ilex decidua), roughleaf dogwood (Cornus drummondii), elderberry (Sambucus sp.), agaritos (Berberis trifoliolata) and Mexican plum (Prunus mexicana) (Riskind and Diamond 1986).

The vegetation of the steep slopes of this area support short-stature woodlands composed primarily of ashe juniper and juniper-oak woodlands. It is primarily on these slopes that Black-capped Vireo habitat is found. The structure of the vegetative communities on these slopes are influenced by exposure, slope, microclimate as well as edaphic factors. Riskind and Diamond (1986) have described distinct vegetative communities based on these distinctions. On north and east facing slopes (deep soils) they report Spanish oak (Quercus texana), ashe juniper, black cherry (Prunus serotina), Arizona walnut (Juglans major), cedar elm (Ulmus crassifolia) and ash. On south and west aspects (shallow soils) they identified ashe juniper, live oak (Quercus fusiformis), Texas persimmon (Diospyros texana), mescal-bean sophora (Sophora secundiflora), Texas mulberry (Morus microphylla) and sotol (Dasylirion texanum). It has also been recognized by other authors (Anderson 1904, Cuyler 1931, Tharpe 1939) that the dominant vegetation in this area is influenced by the substrate. For example, open stands of ashe juniper are often found on terraces of the Glenrose Formation and liveoak and ashe juniper are typically located on the Edwards formation.

With respect to vegetation specific to Camp Bullis, the predominant woody species are; live oak and Ashe juniper, with minor amounts of Spanish oak, scrub oak (Q. sinuata), post oak (Q. stellata), blackjack oak (Q. marilandica), cedar elm, ash, black cherry, Texas walnut (Juglans microcarapa) and shin oak (Quercus havardii). Common shrubs consist of agaritas, evergreen sumac (Rhus sp.) and mesquite (Prosopis glandulosa) (Bruns 1988).

Methodolgy

This portion of the research included three major components. The first was an on-ground survey for Black-capped Vireo at Camp Bullis during the 1989 breeding season, this was done to affirm their presence and to estimate population size. The second component was classification of major landcover types on Camp Bullis. This included the attempted identification of potential habitat for the Black-capped Vireo from digital imagery based on spectral reflectances . The third component of the study was the integration of data from the classified image and locations of vireo sightings with additional factors (i.e. installation activities and physiographic features) into a GIS.

Vireo Census

Black-capped Vireo surveys were conducted on Camp Bullis from 24 - 27 April and 23 - 25 May 1989. This was during the described breeding period for the species. Search areas included for the survey were selected based on knowledge of the habitat requirements of the Black-capped Vireo, aerial photographs and helicopter reconnaissance. The portions of the installation visually inspected and sampled (using taped Black-capped Vireo calls) are shown in Figure 29.

Presence or absence of Black-capped Vireo for the areas sampled, was documented by playing a tape recording of the male Black-capped Vireo territory advertisement song. If male vireos were in the vicinity, they would respond to this playback with song and "shradding" calls, as if responding to the presence of another male Black-capped Vireo in its territory. Lack of response within a ten to twenty minute period was a good, although not absolute, indication that the species was absent from the immediate area. Also, during this survey observations were made concerning the presence or absence of Brown-headed Cowbirds in the vicinity of vireo habitat.

Landcover Classification

The second component involved analysis of digital LANDSAT satellite imagery. Through the classification of

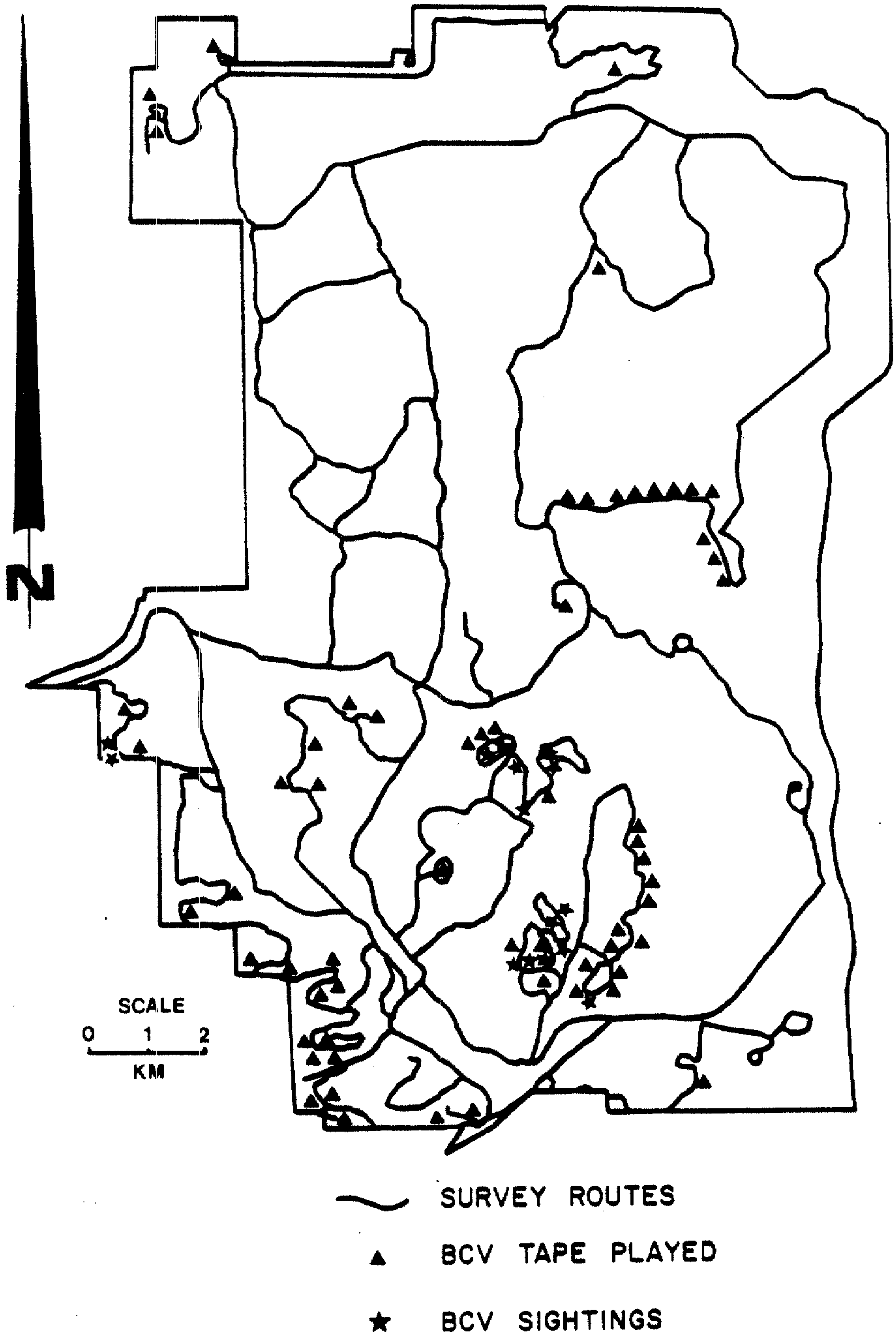


FIGURE 29. Areas surveyed for Black-capped Vireo on Camp Bullis, Texas in 1989.

satellite imagery major vegetative communities, potential Black-capped Vireo habitat and other landcover categories were distinguished on Camp Bullis. A digital Landsat Thematic Mapper (TM) scene of 20 April, 1988 (ID 51511-16330) was acquired for this study. TM data has 30 m resolution and records spectral reflectances in 7 portions of the electromagnetic spectrum. Principal component analysis (PCA) was performed on this data and the first three resulting transformed bands were used in the analyses. These first three PCA bands represented 98.8% of the variation in the original six bands.

The image was classified with a combination of supervised and unsupervised classification techniques. Supervised classification required the identification of training fields from which spectral signatures for a particular cover type was extracted. This process included extraction of signatures from several sites at which Black-capped Vireos had been identified. These signatures were combined to form a "catalog" of landcover categories. A preliminary unsupervised classification was then used to generate a second catalog of signatures obtained with a clustering technique, independent of operator input. The two signature catalogs were then merged and the entire image was classified with respect to the landcover categories available in the catalog. The result of this process was a preliminary landcover map of Camp Bullis. The preliminary map was used for ground truthing the classification.

The classified image was ground truthed in order to assess its reliability. Two separate visits were made to Camp Bullis for this purpose. In preparation for these visits, landcover maps were prepared at a scale of 1:24,000 to be used for comparison with actual landcover. Accuracy assessments for each landcover category were determined by evaluation of 100 randomly selected points within the study area. These points were visited and their actual landcover was compared with the results of the classification. This process was aided by reference to a set of 1:3200 aerial photographs (provided by the Agricultural Stabilization and Conservation Service [ASCS] office in San Antonio) as well as with a helicopter reconnaissance flight over Camp Bullis.

GIS Analyses

GIS analyses were conducted with ERDAS and ARC/INFO systems. These analyses were employed to integrate data from the field census with the classified image and other spatial data. Specifically, GIS was used to describe the location of the vireos and their habitat with respect to geologic strata, slope, aspect and military activities.

Major geologic formations on Camp Bullis were manually digitized from a 1:25,000 USGS map of the study area (Fig. 30). These data were overlain with the locations of the bird sightings in order to identify any correlation between

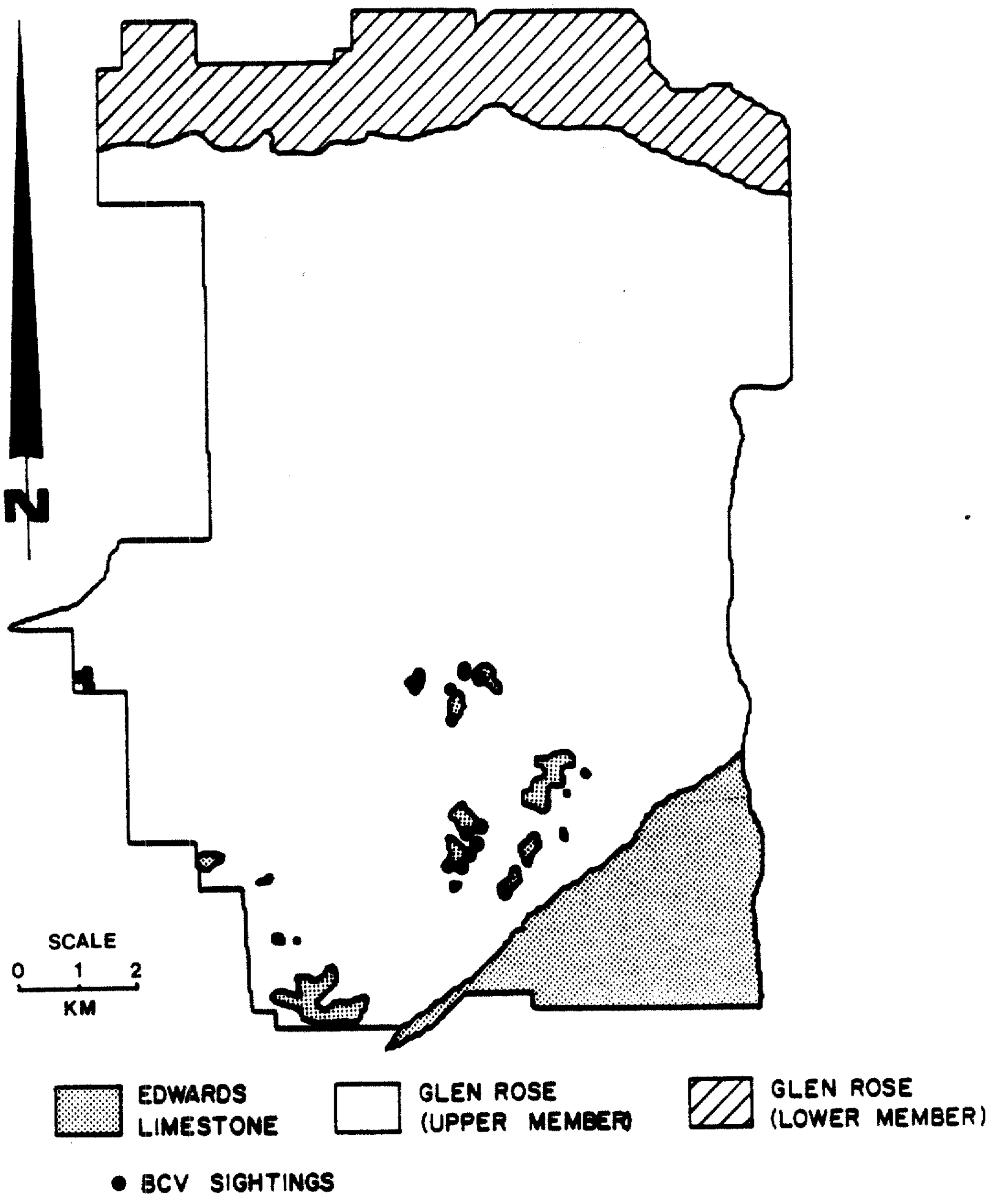


FIGURE 30. Major geological formations and Black-capped Vireo sightings on Camp Bullis, Texas.

their occurrence and surface geology. Slope and aspect information were generated from USGS digital elevation model data (DEM). These terrain data were produced by the U.S. Defense Mapping Agency (DMA) at a scale of 1:250,000 with contour intervals of 61 m. Slope increments of 4% and eight primary compass directions were used to characterize the topography of the habitat for the vireo.

Results

Vireo Census

Fifteen Black-capped Vireo were located during the census of Camp Bullis. Table 13 is a summary of the inventory. The actual number of territories (15), represents the number of singing males observed, exclusive of possible duplications. The potential number (24), is the highest number of territories that might be expected based on an estimation of suitable habitat within the areas searched (this includes possible duplication) (Tazik 1989). A mid-range compromise of 20 territories is a reasonable approximation of the number of territories on Camp Bullis. With this estimate, assuming 80% of the males were mated (an approximate average for Texas based on data from Grzbowski [1988] and Tazik and Grzbowski [1988]), the population of Black-capped Vireos on Camp Bullis, during the 1989 survey amounts to 16 mated pairs plus 4 unmated males, a total of 36 adults. Tazik (1989) reported that, based on bird

TABLE 13. Black-capped Vireo sightings made during the 1989 survey at Camp Bullis, Texas.

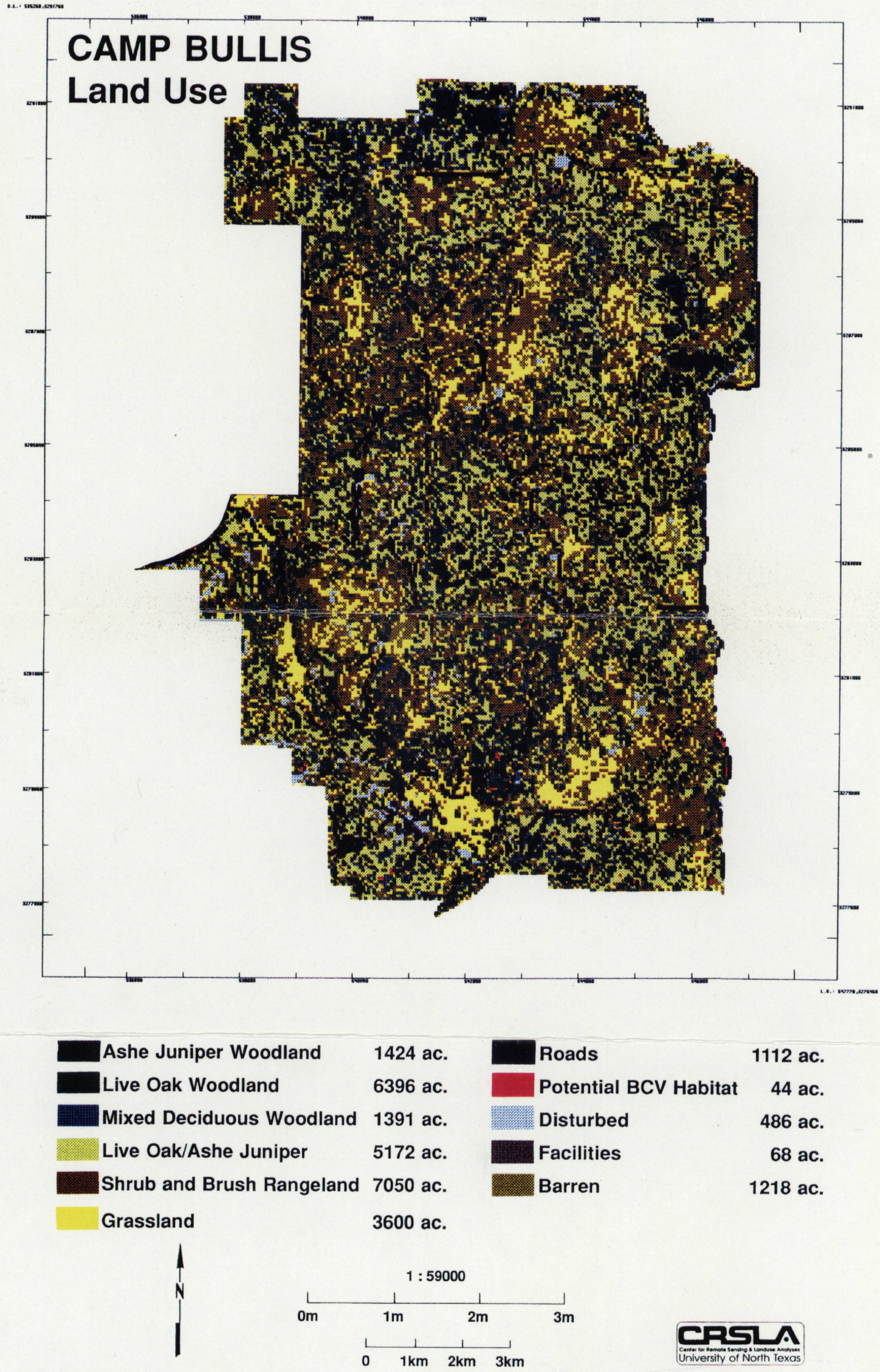
	NUMBER OF TERRITORIES	
	ACTUAL	POTENTIAL
AUE HILL	2	3
HILL 1465	2	2
LEON HILL	1	2
OTIS RIDGE	2	4
HOGAN RIDGE	7	11
DAVIS RIDGE	1	2
TOTAL	15	24

sightings, habitat on Camp Bullis was similar in structure to habitat elsewhere in the vireo's range. It was described as a heterogeneous mix of hardwood scrub species including ashe juniper and large clumps of evergreen sumac. Vegetation measured approximately 3 m in height and exhibited uneven distribution in both horizontal cover and vertical height.

Landuse Classification

Eleven major landcover categories and vegetative communities were identified on Camp Bullis (Fig. 31). The predominant covertype was identified as a Shrub and Brush Rangeland (25.3%). This category consisted of a variety of young trees and shrubs mixed with patches of herbaceous vegetation. Typical hardwood species in this area were young live oak, mesquite, evergreen sumac, young ashe juniper and cedar elm. The second largest covertype category was a Live Oak Woodland (22.9%). This category was composed of mature, fairly homogenous stands of live oak. The third largest division of landuse was a Live Oak/Ashe Juniper mixed woodland. Other categories that were identified were; Mixed Deciduous Woodland (comprised of cedar elm, live oak, Texas oak and blackjack oak), Grassland, Disturbed (areas of limestone exposed either from natural causes or construction activities), Barren Land (areas of minimal vegetation, generally patchy herbaceous

FIGURE 31. Landcover classification map for Camp Bullis, Texas (1989).


CAMP BULLIS
Land Use
Ashe Juniper Woodland 1424 ac.
Live Oak Woodland 6396 ac.
Mixed Deciduous Woodland 1391 ac.
Live Oak/Ashe Juniper 5172 ac.
Shrub and Brush Rangeland 7050 ac.
Grassland 3600 ac.
Roads 1112 ac.
Potential BCV Habitat 44 ac.
Disturbed 486 ac.
Facilities 68 ac.
Barren 1218 ac.
N
1 : 59000
0m
1m
2m
3m
0
1km
2km
3km
CRSLA
Center for Remote Sensing & Landuse Analyses
University of North Texas

vegetation in limestone soils) and potential habitat for the Black-capped Vireo. A total of 303 ha of potential habitat for the Black-capped Vireo were identified using this method. This resulted in an overestimation of potential habitat. Many of the incorrectly identified areas were unsuitable due lack of appropriate understory or unsuitable vegetative communities. These results indicated that there was considerable spectral variation between areas where vireo had been sighted. To assess this, a statistical comparison was made of the spectral characteristics of locations on which the Black-capped Vireos had been sighted. For each of the 15 sites, 25 pixels were identified around the point at which each of the vireo had been identified. Analysis of variance indicated that there were significant spectral differences between each of the 15 sites ($P > 0.0001$, $n=1043$).

Classification Accuracy Assessment

The overall accuracy of the landcover classification was estimated to be 89% (Table 14). The majority of error occurred in distinguishing the category of Live Oak/Ashe Juniper Woodland from the categories of predominately Live Oak Woodland and predominately Ashe Juniper Woodland. Discrepancies also occurred in distinguishing categories of Shrub and Brush Rangeland, Live Oak Woodland and Grassland categories. These difficulties were attributed to the mixed

TABLE 14. Results of accuracy assessment for landcover classification at Camp Bullis, Texas (1989).

Landcover categories	Points checked	Points verified	Accuracy percentage
Ashe Juniper	11	11	100
Live Oak	17	17	100
Deciduous Mix	11	9	82
Live Oak/ Ashe Juniper	22	19	86
Shrub and Brush Rangeland	14	11	78
Grassland	10	9	90
Roads	5	4	80
Disturbed	4	3	75
Facilities	2	2	100
Barren	4	4	100
Total	100	89	89

stages of development and succession found within and between these categories.

GIS Analyses

GIS analyses were used to refine the discrimination of potential habitat for the vireo and to describe the location of potential threat with respect to military activities. Identification of potential habitat was redefined as areas that were both spectrally appropriate and located on the Edwards Limestone formation. A total of 18 ha met these criteria (Fig. 32). All 15 of the vireo sightings fell on or within 50 m of these areas. Based on these criteria, potential habitat was also identified in the southeastern corner of Camp Bullis, but no birds were observed there.

Although not used as criteria to identify potential habitat, slope and aspect of each of the locations of Black-capped Vireo were determined. These are summarized in Figure 33. Eighty-seven percent (13) of the birds sighted were on south or south west facing slopes. Slopes on which they were located ranged between 8 and 32%.

Assessment of habitat with respect to military activities indicated potential habitat and 13 of the 15 sightings were in the Impact Area. This area is subject to periodic artillery firing, shelling and fires. Fires are likely to maintain habitat for the vireo on camp Bullis. Research at Ft. Hood, Texas, indicates that fires probably

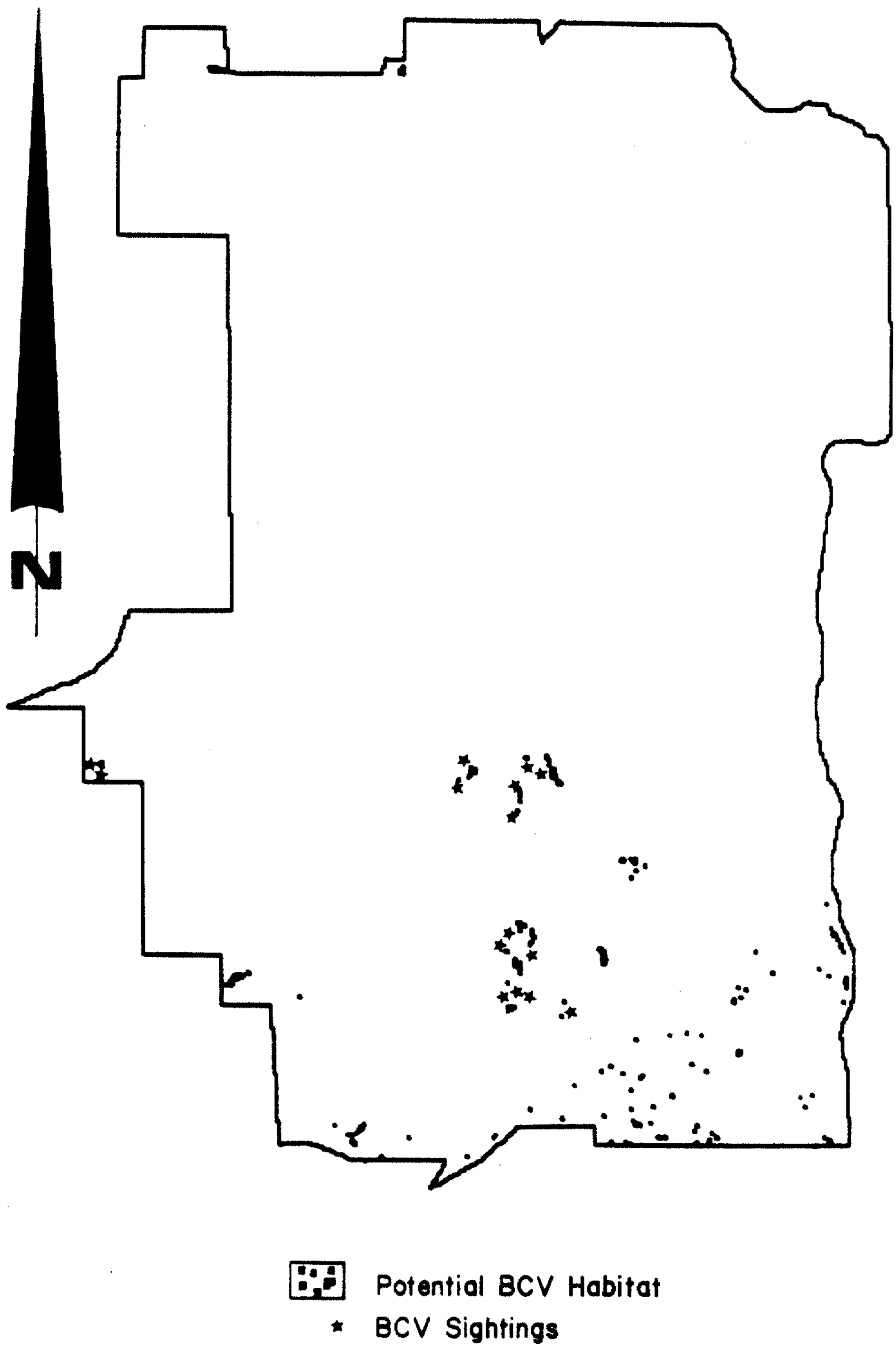
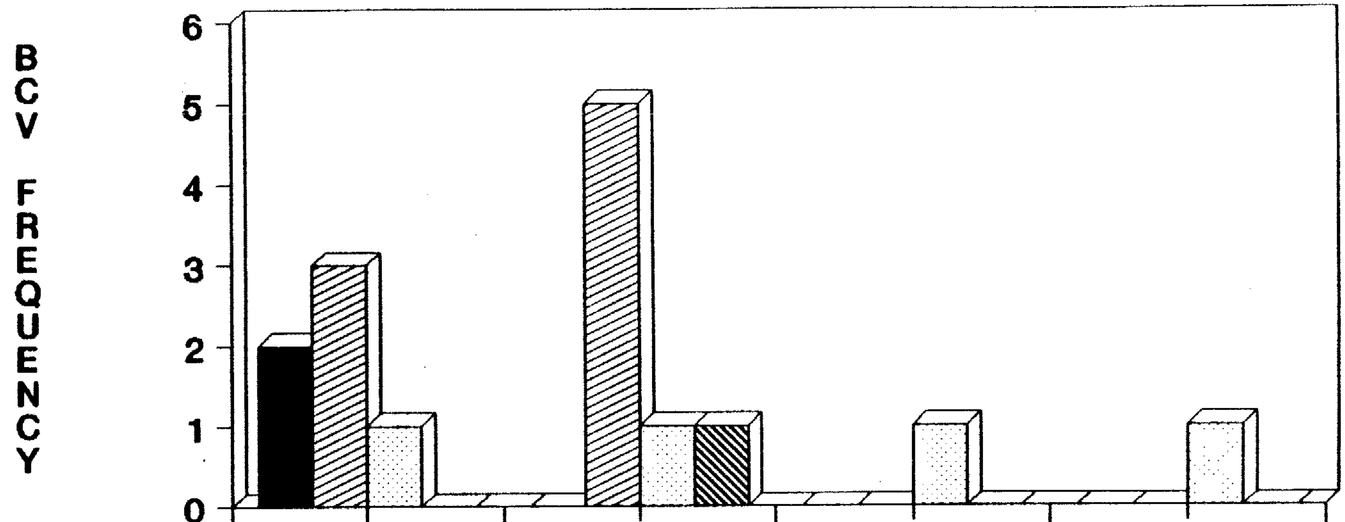


FIGURE 32. Location of potential Black-capped Vireo habitat located on Camp Bullis, Texas (1989).



	S**	SW	E	SE
0-10*	2	0	0	0
11-20	3	5	0	0
21-30	1	1	1	1
31-40	0	1	0	0

ASPECT AND SLOPE

* percent slope
** aspect

FIGURE 33. Slope and aspect descriptions for the locations of the fifteen Black-capped Vireo identified on Camp Bullis during the 1989 survey.

enhance potential habitat for the Black-capped Vireo (Tazik 1988). Two vireo were sighted off the impact area in a unit field training area on which cattle are periodically grazed (Fig. 34).

Discussion

Conservation of an endangered species requires the preservation of adequate habitat. However, for species such the Black-capped Vireo the identification of such habitat on a large scale is difficult. Through the combined use of field survey, remote sensing and GIS a potential means to achieve this was developed for Camp Bullis, Texas.

A field survey in 1989 for Black-capped Vireo confirmed the presence of the species on the installation, population size was estimated to be 36 adults. The only other report of the vireo on Camp Bullis was in 1976 by Pulich (1976b) who reported a bird in the northern part of the installation. This portion of Camp Bullis was surveyed in 1989 and was judged to be no longer suitable. The vegetation was dominated by ashe juniper and juniper/live oak woodlands, and there was evidence of heavy browsing by deer which has destroyed the undergrowth. For all of Bexar County, the only other recent records of the species are from the Friedrich Park Wilderness Area where they have been recorded in small numbers (four to ten pairs) with regularity (Sexton et al. 1989).

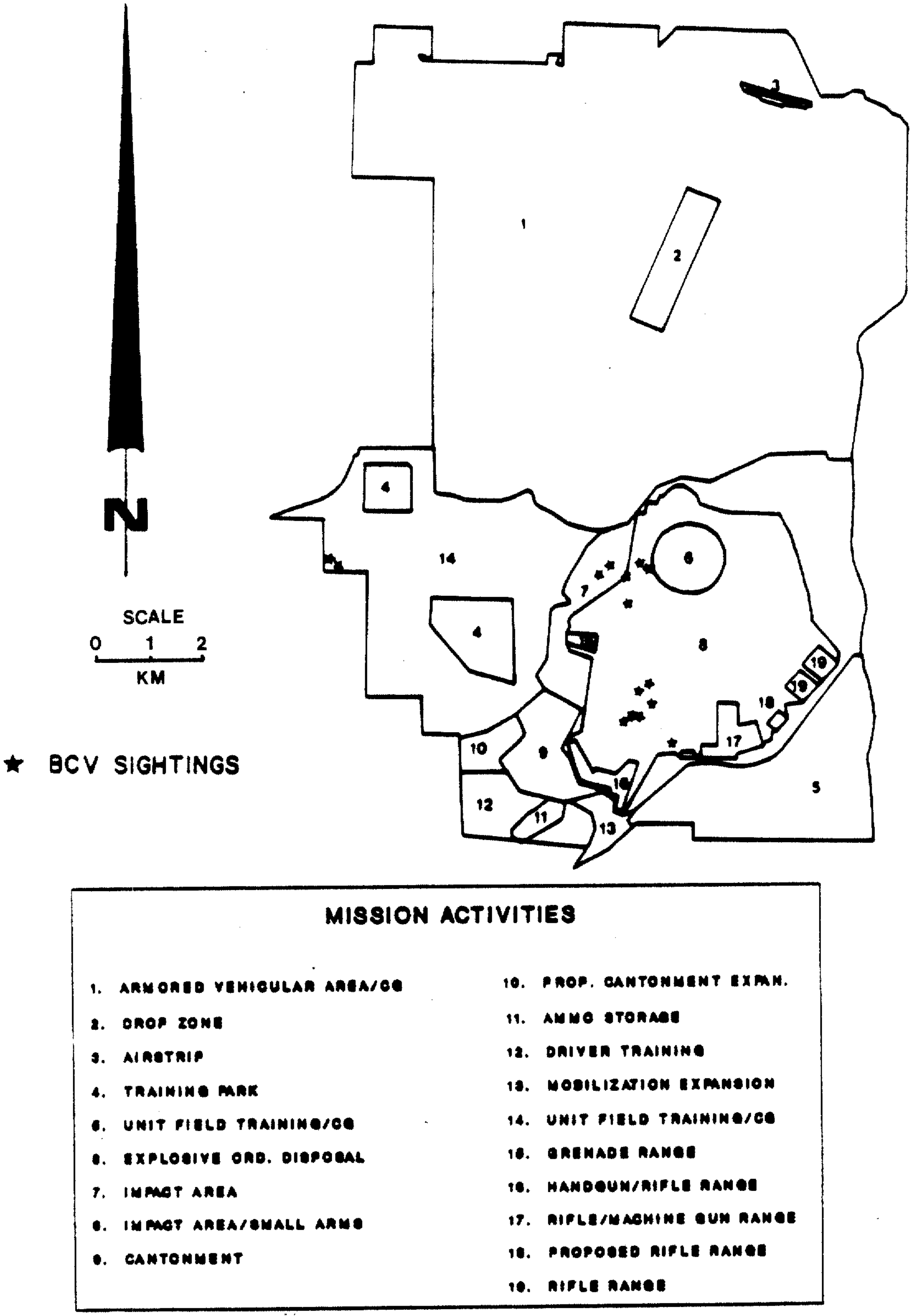


FIGURE 34. Training activities and Black-capped Vireo sightings at Camp Bullis, Texas (1989).

Potential habitat for the Black-capped Vireo on Camp Bullis could not be discriminated on the basis of spectral reflectance with TM 30 m resolution data. This can probably be attributed to variation in vegetative species composition as well as to spatial differences with respect to size and shape of patches of suitable vegetation. Classification using spectral signatures drawn from several of these sites severely overestimated the potential habitat on Camp Bullis. Despite this problem, the classification was useful for eliminating landcover areas that were entirely inappropriate such as forested areas, cleared areas and grasslands.

Once the inappropriate areas were eliminated habitat identification was refined based on geologic formation. Previous investigations of Black-capped Vireo by Sexton (1988) had suggested that the distribution of breeding populations of the Black-capped Vireo appeared to be correlated with only a few relatively narrow strata of limestone, especially the Fredericksburg group (contains the Edwards Limestone formation). When this information was used to filter the identified habitat, the results were 18 ha of potential habitat which were identified with respect to spectral reflectance and geology.

Through this method of habitat identification, several areas on Camp Bullis were identified as potential habitat but no vireo were heard. This may be due to several factors such as; inadequate time spent sampling at these locations, too few birds to utilize all the potential habitat, or these areas may be inappropriate due to a characteristic of habitat (i.e. shape or configuration) yet to be identified.

Black-capped Vireo prefer early successional hardwood scrub habitat. Therefore, land management actions that suppress juniper and encourage low hardwood growth would be beneficial. Fire in mixed juniper/deciduous hardwood stands often produces Black-capped Vireo habitat within about five years. Such areas may remain suitable for 15 to 20 years after a fire (Grzbowski 1988).

This research has established criteria for Black-capped Vireo habitat as determined by geology and landuse. This method of habitat delineation will certainly evolve as more applications and tests are developed. Given the range of climatic, edaphic and vegetative communities over which the Black-capped Vireo is found, these criteria may be appropriate for only a small portion of the range of the Black-capped Vireo. Additional studies are needed to identify analogous criteria for other portions of the Edwards Plateau. Such studies will regionally "tune" for particular vegetative communities, climatic conditions and edaphic factors.

CHAPTER VI

HABITAT CHARACTERIZATION FOR THE TEXAS KANGAROO RAT

Introduction

A simple empirical model is developed that utilizes GIS and remote sensing to predict habitat suitability for the Texas kangaroo rat for a portion of their range. Specifically, three major objectives were identified. The first was the establishment of a spatial digital data base for the study area. This data base was comprised of the following: kangaroo rat collection sites; major soil associations; major geologic formations; slope description and landuse. A second objective was the evaluation of these data and subsequent development of a suitability map for kangaroo rat habitat, indicating areas most likely to contain kangaroo rats. The third objective was an evaluation of historic landuse information for the study area. These data were summarized to identify major landuse trends which may impact potential habitat for the Texas kangaroo rat.

Study Area

An area of 300,885 ha in north central Texas was selected as the study area (Fig. 35). This area is

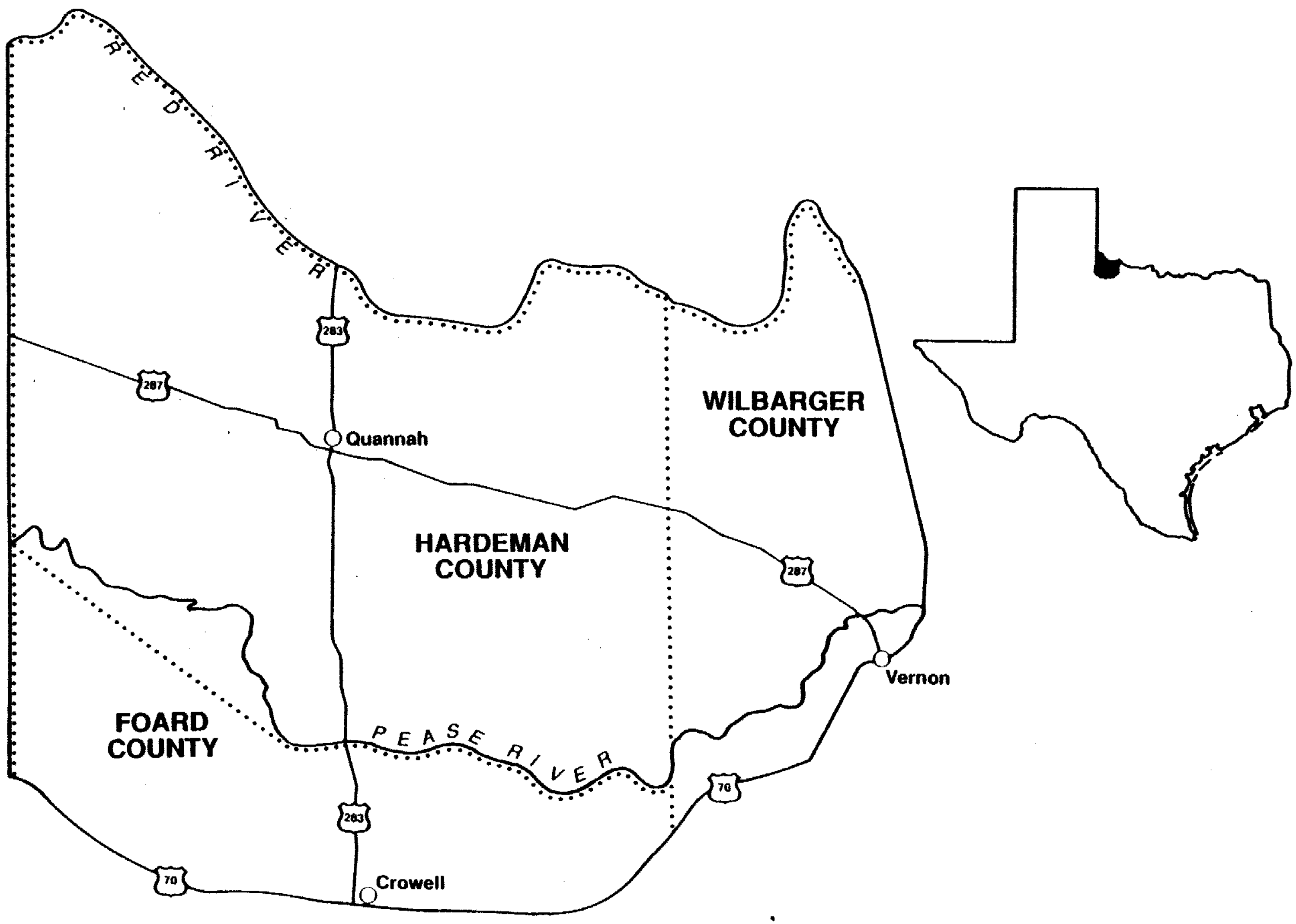


FIGURE 35. Location of the Texas kangaroo rat study area.

within the range of the Texas kangaroo rat and was chosen because of the availability of data pertaining to kangaroo rat collections and sightings. This area is within the Texas counties of Hardeman, Foard and Wilbarger. It is bounded by the Red River to the north, and by State Highways 283 and 70 to the west and south, respectively. The eastern limit of the study area is the eastern boundary of Hardeman county.

The study area is within the Red River basin, in the north-central portion of the Rolling Plains ecological area of Texas (Fig. 36). The climate is subtropical subhumid, with dry winters and low summer humidity. Rainfall ranges from 56 to 67 cm annually. The regional topography is dissected by many narrow intermittent streams in the plains, and by undulating grasslands in nearly level valleys and prairies. Elevations range from 245 to 915 m (USACE 1976).

Soils and Geology

The study area is underlain by geology of the Permian Formation, consisting mainly of rocks of the Double Mountain Group. This group consists of interbedded gypsum, dolomite and red shale with layers of sandstone and shale in the lower parts. Permian rocks are exposed over portions of the central and southern parts of the study area. In the northern and east-central portions of the study area, a mantle of outwash materials was deposited over the Permian

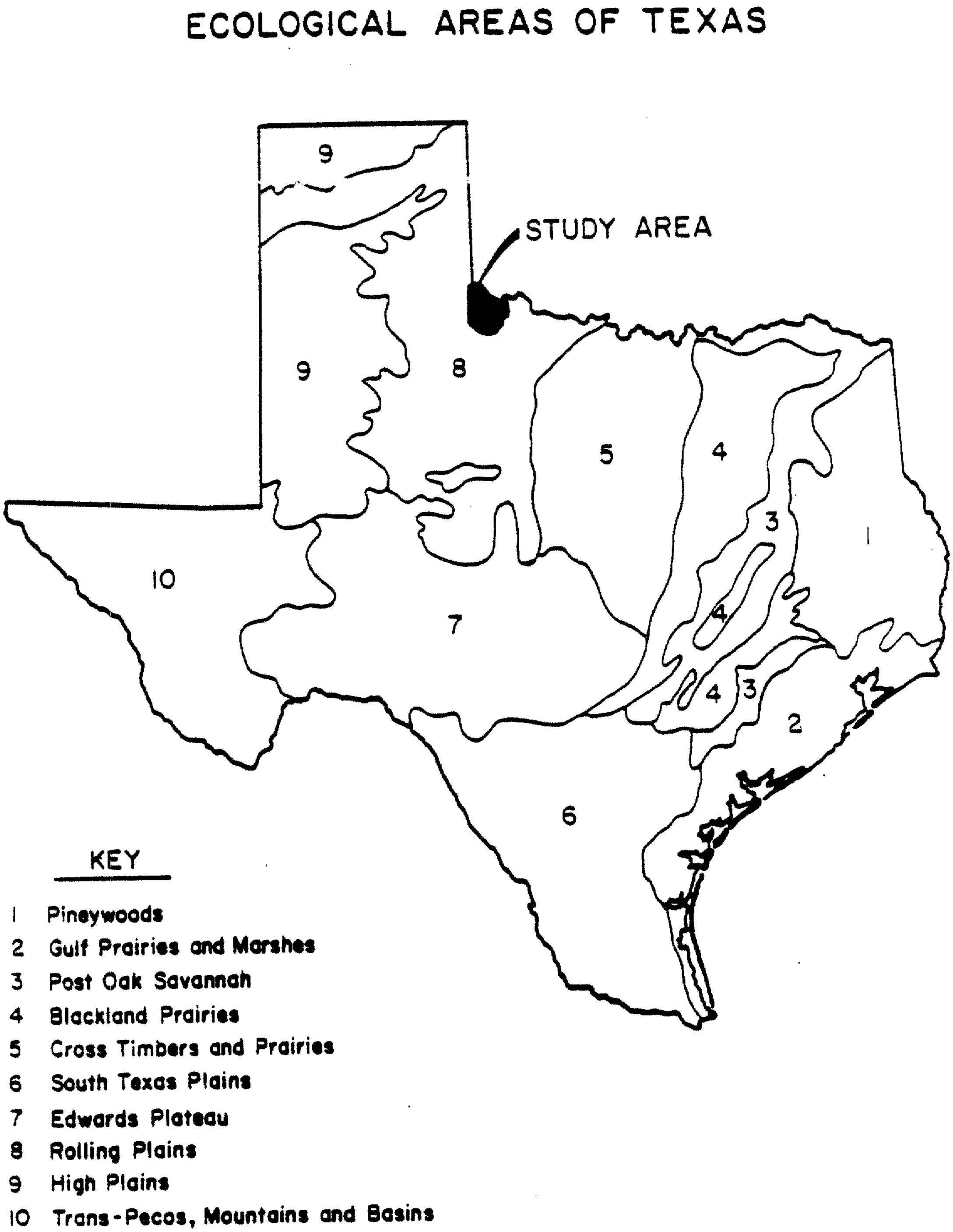


FIGURE 36. Location of the study area in the Rolling Plains ecological area.

Red Beds from the Pliocene to Pleistocene periods. These outwash deposits, the Seymour Formation, rest directly on top of the Permian Red Beds and vary from a few meters to about 15 m in thickness and range in texture from clayey to silty and sandy (Sellards et al. 1932).

Soils in this area have developed from four types of parent material: residuum derived from Permian shale, (sandstone, limestone and gypsum); sandy to clayey outwash or old alluvium; recent alluvium and; recent eolian materials. Eolian materials are mostly along tributaries of the Red River. These materials were deposited in a relatively narrow band parallel to the river. Soils in the plains vary from sands to tight clays or red bed clays that are slightly acidic to moderately alkaline. Upland soils are composed of slightly acidic silty or sandy loam. These soils are usually deeper and have more distinct horizons than sloping soils on hilltops and ridges. The flatter soils receive additional water, have less runoff and are subject to less erosion (USDA 1972).

Due to the combination of climate and substrate, this area is subject to extensive soil erosion. Wind and water induced erosion have caused extensive soil loss and subsequent reduction in the productivity. Incidents of sheet erosion exceeding 5 tons/acre/year occur in the area, particularly on sandy soils. As much as 49 million tons of soil annually are moved by erosion for all of the Red River basin and over 120 ha are lost to streambank and gully erosion yearly (USDA 1977).

Vegetation

Five major vegetative groups are identified within the study area (McMahan et al. 1984). The most prominent is cropland. Major crops in this area are wheat, cotton and sorghum. The second largest vegetative type is described as a mesquite-juniper brushland. The dominant species of this community are mesquite (Prosopis glandulosa), Pinchot juniper (Juniperus pinchotii), lotebush (Ziziphus obtusifolia), sumac (Rhus sp.), Texas pricklypear (Opuntia lindheimeri), tasajillo (Opuntia kleiniae) and catclaw (Acacia greggii). This vegetative association is located predominately in the eastern and southeastern portions of the study area.

The third vegetative community is described as a cottonwood-hackberry-saltcedar brush/woodlands. The common plants are cottonwood (Populus deltoides), black willow (Salix nigra), buttonbush (Cephalanthus sp.), rough-leaf dogwood (Cornus drummondii), Panhandle grape (Vitis acerifolia), and groundsel-tree (Baccharis sp.). This community is located primarily along the Pease River in the southern portion of the study area. The fourth community, a Mesquite-Lotebush Shrubland consists of mesquite (Prosopis glandulosa), yucca (Yucca sp.), skunkbush sumac (Rhus sp.), agarita (*Berberis* sp.), elbowbush (*Forestiera pubescens*), juniper (*Juniperis* sp.) and tasajillo. This community is located in the southeastern corner of the study area. The fifth vegetative community is a mesquite brushland, composed of mesquite, yucca, pricklypear and Pinchot juniper. This brushland community is located in the far northwest portion of the study area (McMahan et al. 1984).

Methodology

The digital data base for the study area was comprised of spatial information for five variables; locations of Texas kangaroo rat collection sites, major soil associations, major geologic formations, slope descriptions and landuse. These data were acquired in digital format or manually digitized (Appendix E).

Geology and Soils

Geology data for the study area were manually digitized from the Texas Bureau of Economic Geology Wichita Falls/Lawton 1:250,000 sheet (BEG 1987). These maps provided locations and descriptions of the major geologic formations. Nine different formations were located in the study area. Brief descriptions of each of these are found in Appendix F. Soils information was manually digitized from Soil Conservation Service (SCS), general soil maps of Hardeman, Foard and Wilbarger Counties (USDA 1972, USDA

1961, USDA 1981). Only the 13 major associations were considered. Brief descriptions of these associations are provided in Appendix G.

Slope

Data for the factor were generated from U.S. Geological Survey (USGS) Digital Elevation Model data (DEM). The information provided land surface elevation values for each pixel in the study area. A slope value for each pixel was calculated by comparing each pixel's elevation to its neighbors' elevation, thus estimating "percent slope". The result of these calculations were a data base where the attribute is the percent slope for each pixel.

Landuse Classification

A Landsat MSS scene (18 June 1986) was classified to obtain landuse information for the study area. The image was classified using a combination of supervised and unsupervised classification as described in Chapter 3. Eight major landuse categories were identified; mesquite pasture, mesquite woodland, grassland, badlands (areas of severe erosional sculpturing and sparse vegetation), water, urban/barren, agriculture, mesquite juniper woodlands and deciduous woodlands.

Texas Kangaroo Rat Locations

Locations of previously reported and/or collected kangaroo rats were provided by Martin (1989). The information provided included date of capture or sighting as well as the location (Appendix H). These data were predominately from museum collections at Texas Tech University (Lubbock, Texas) and Midwestern University (Wichita Falls, Texas). Data were collected from 1969 to 1974. Seventy-seven different collection points were identified in the study area. For several of these sites, more than one rat had been collected, but these sites were considered to be equal weight with the other points.

Suitability Model

The suitability of any portion of the study area for Texas kangaroo rats was determined from comparison of known kangaroo rat locations, to a combination of the previously described variables (i.e. slope, geology, soil and landuse). For this stage, the development of the model, 46 collections sites (60%) were randomly selected. The remaining 31 points were used to test it. The development of the model was achieved in three steps. The first step was an assessment the actual distribution of the rats for each variable class (i.e. the number of rats reported from Quanah-Talpa soil formation). This was compared with the number of rats expected (per class), if this were a random distribution.

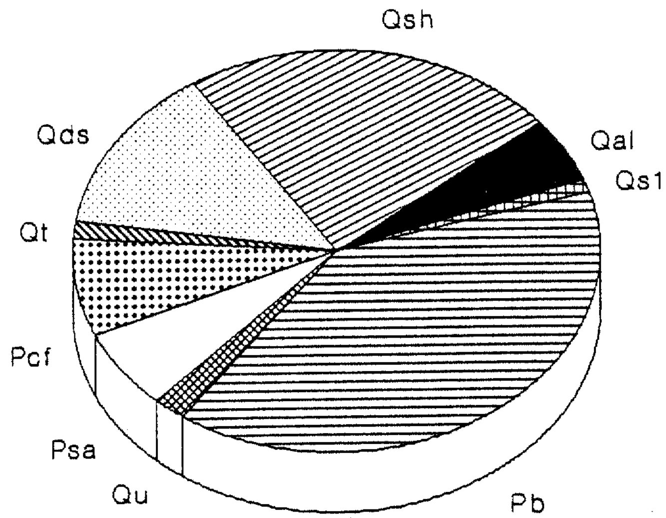
For each variable, a chi-square test was employed to determine if there was a significant deviation from the expected distribution. If there was, the variable was included in the model. If there was not a significant deviation from a random distribution, the variable was not included.

The second step for the development of the model was the assignment of weights to each variable class. The weight for each class was determined as the number of rats observed divided by the number of rats expected (for a given class). Each of these variable layer (composed of weighted classes) were added together in a pixel by pixel addition. The result was the generation of a habitat suitability map with the highest values indicating the most suitable habitat. The final step in the model development was a test of the suitability map with the remaining 31 points. This was done as a comparison of the collection sites with respect to the suitability value assigned to that location.

Results

Geology and Soils

Nine specific geologic formations were identified within the study area, the proportions of each are illustrated in Figure 37. The comparison of the spatial geologic data with 46 randomly selected records of the kangaroo rat found they had been observed or collected in



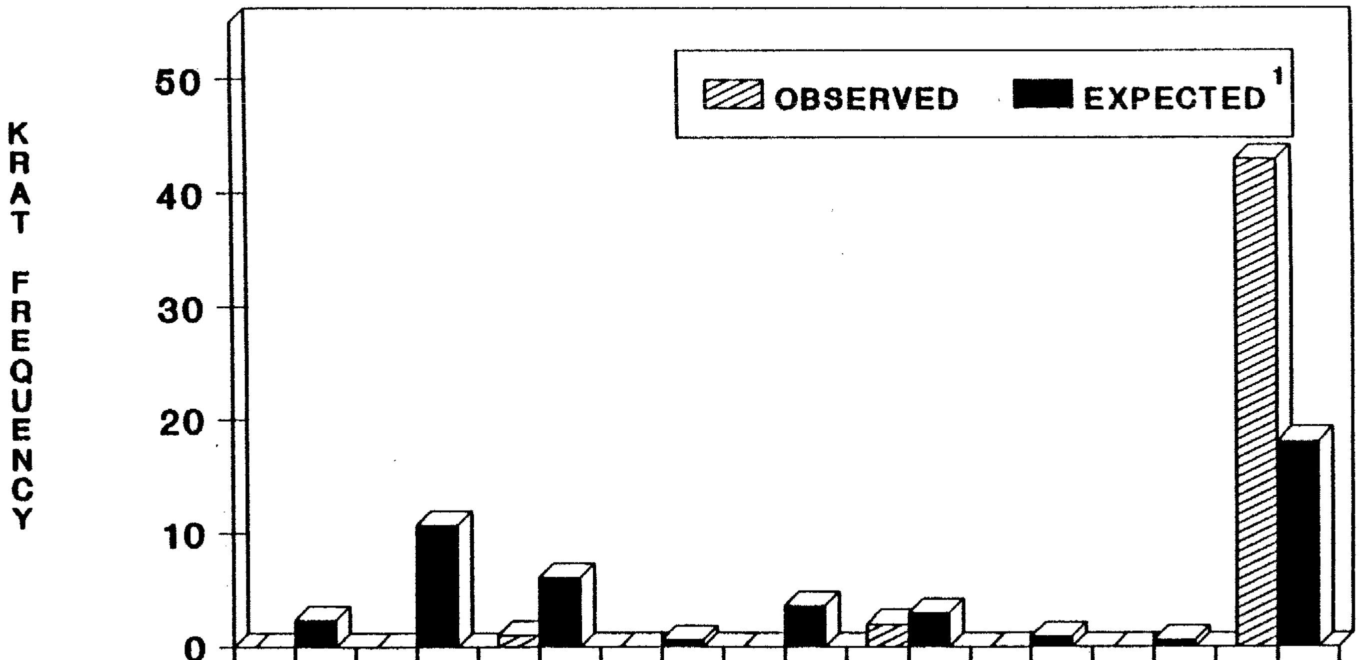
Formation	%	ha.
Qal	5.3	16097
Qsh	23.2	69669
Qds	13.3	40042
Qt	1.4	4150
Pcf	7.8	23491
Psa	6.5	19396
Qu	2.0	6007
Qs1	1.0	3060
Pb	39.5	118973

FIGURE 37. Major geologic formations within the Texas kangaroo rat study area.

only three of the nine formations, Qds, Psa and Pb. Forty-three (93.5%) of the rats were reported from Permian Blain Formation (Pb). The formation comprises 39.4% of the study area (118,965 ha), and is typified by mudstone, gypsum, dolomite and sandstone deposits. One observation was reported from the Quaternary dune sands (Qds), which accounts for 13.3% of the study area (40,042 ha). Qds is characterized by eolian sand and silt and sheetwash slope deposits.

Two of the 46 (4.3%) kangaroo rat records were reported from the Permian sandstone Formation (Psa). The formation comprises 6.5% of the study area (19396 ha). Psa is characterized by mudstone, sandstone, siltstone and gypsum (BEG 1987). This distribution of kangaroo rats was significantly different from random ($x^2 = 36.3, P < 0.001$). This was determined from a comparison of observed versus the expected rats normalized for formation area (Fig. 38). If there was no relationship between the distribution and a particular formation, there would not be a significant difference between the observed and expected.

Fifteen major soil categories were identified in the study area. Figure 39 illustrates their proportion in the study area. Of these, six associations with were combined into a category "other". No rats were reported from these relatively small areas. Kangaroo rats had been collected in

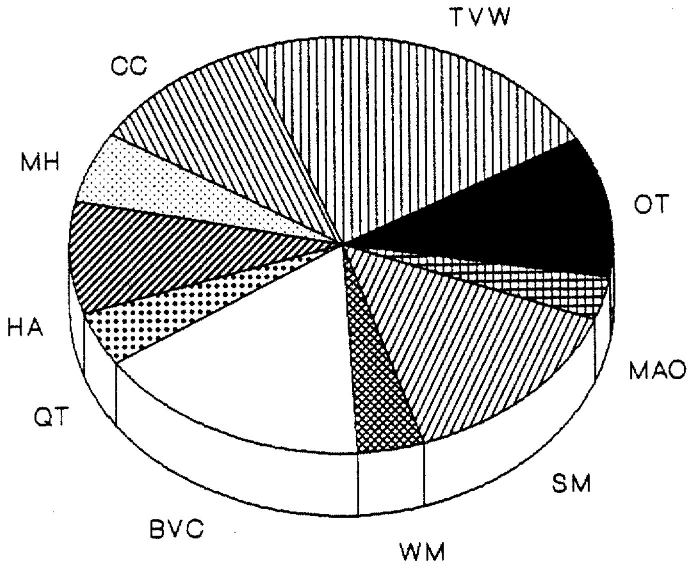


	Qal	Qsh	Qds	Qt	Pcf	Psa	Qu	Qs1	Pb
OBSERVED	0	0	1	0	0	2	0	0	43
EXPECTED[1]	2.4	10.7	6.1	0.6	3.6	3	0.9	0.6	18.1

FORMATION

[1] Assuming a random distribution

FIGURE 38. Observed and expected distribution of Texas kangaroo rats with respect to major geologic formations.



	Association	%	ha.
TVW	Tillman-Vernon-Weymouth	24.6	73721
CC	Cobb-Cosh	1.1	3451
MH	Miles-Hardy	6.0	18065
HA	Hollister-Abilene	9.7	29056
QT	Quanah-Talpa	4.7	14001
BVC	Badlands-Vernon-Cottonwood	18.1	54517
WM	Wichita-Miles	4.3	13213
SM	Springer-Miles	15.7	47099
MAO	Miles-Acuf-Olton	3.7	11042
OT Other:			
	Yomont-Lincoln	1.1	3525
	Rotan-Hollister	3.0	9116
	Tivoli-Enterprise	0.5	1480
	LaCasa-Ector	2.6	7859
	Tivoli-Hardeman	2.6	7916
	Enterprise-Tipton	2.3	6824
	TOTAL	100.0	300885

FIGURE 39. Major soil associations within the Texas kangaroo rat study area.

five of the fifteen soil associations. Thirty-five (76%) were reported from areas underlain by the Tillman-Vernon-Weymouth soil association. The association comprises 24.6% of the study area. Another soil association in which kangaroo rats were reported was the Hollister-Abilene. Four kangaroo rats (8.7%) were reported from the association. The association represents 9.7% of the study area. Five rats (10.9%) were located on the Quanah-Talpa soil association. This represents 4.7% of the study area. One rat was located in both the Cobb-Cosh and Badlands-Vernon-Cottonwood associations (1.1 and 18.1% of the area respectively).

As with geologic formations, in a comparison of observed versus expected, the distribution of kangaroo rats was significantly different than a random (proportional) distribution of rats across all soil associations (x^2 = 52.7, $P < 0.001$) (Fig. 40).

Slope and Landuse

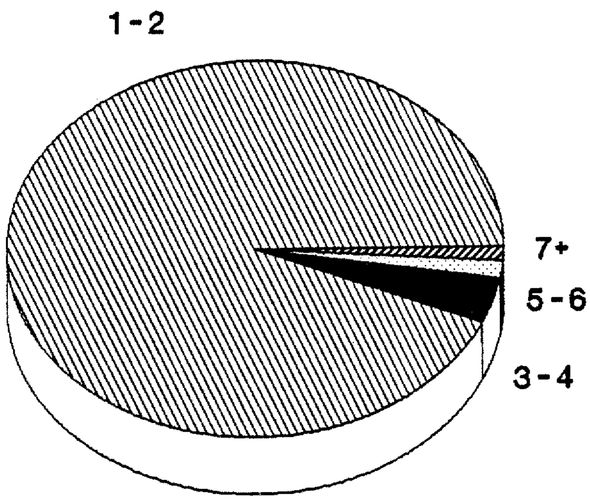
Slope was calculated for the study area and compared with the locations of the kangaroo rats. Within the study area, slope ranged from 0 - 15% (Fig. 41). A comparison of observed and expected kangaroo rats found no significant difference in the distribution of kangaroo rats and distribution of slope (x^2 = .56) (Fig. 42). For this reason slope was not considered as a variable in the suitability

	TVW	CC	MH	HA	QT	BVC	WM	SM	MAO	OT
OBSERVED	35	1	0	4	5	1	0	0	0	0
EXPECTED[1]	11.3	0.5	2.8	4.5	2.1	8.3	2	7.2	1.7	5.6

SOIL ASSOCIATION

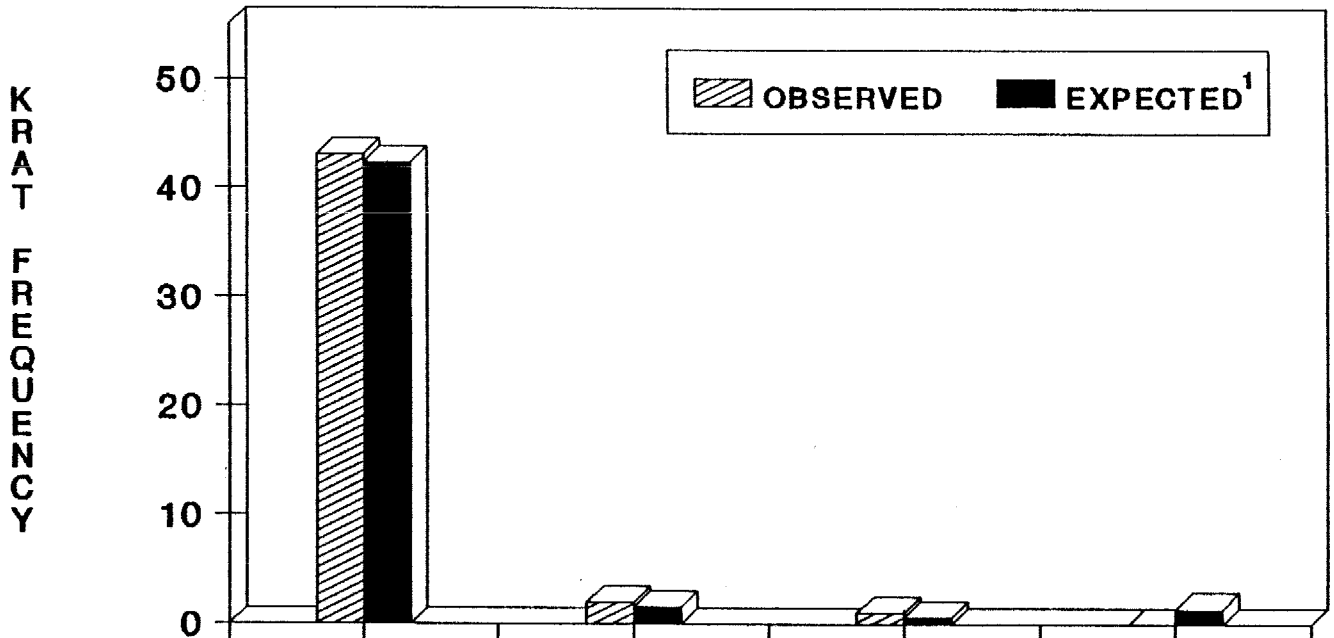
[1]Assuming a random distribution

FIGURE 40. Observed and expected distribution of Texas kangaroo rats with respect to major soil associations.



Slope	%	ha.
0 - 2	91.9	276513
3 - 4	3.5	10531
5 - 6	1.3	3912
7+	3.3	9929
TOTAL	100.0	300885

FIGURE 41. Distribution of slope within the Texas kangaroo rat study area.



	0-2	3-4	5-6	7+
OBSERVED	43	2	1	0
EXPECTED[1]	42.3	1.6	0.6	1.4

SLOPE (PERCENT)

[1] Assuming a random distribution

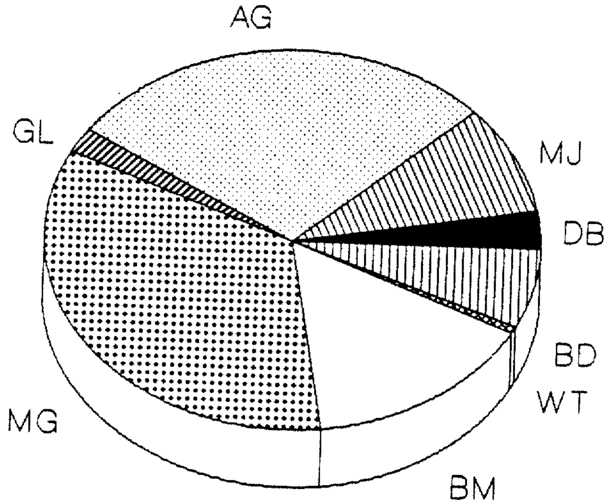
FIGURE 42. Observed and expected distribution of Texas kangaroo rats with respect to slope.

model.

Eight major landuse categories were identified within the study area. With respect to coverage they ranged from 34.5% of the area (mesquite grassland) to 0.6% of the area (water) (Fig. 43). A comparison of the kangaroo rat collection sites found their distribution to be significantly different from a random, with respect to these landuse categories (x^2 = 14.5, $P < 0.05$) (Fig. 44). From these analyses, I conclude that geology, soil and landuse exert an influence on the distribution of the Texas kangaroo rat.

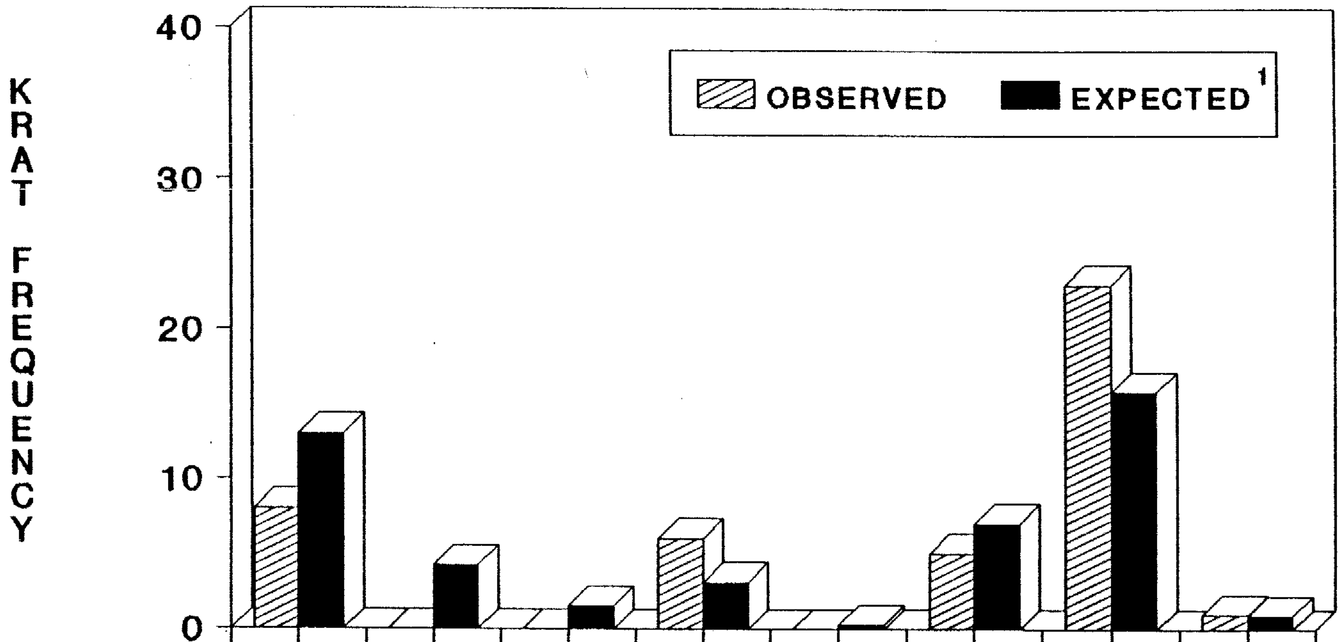
Habitat Suitability Map

The variables in the model (geology, soil and landuse) were equally weighted, and each was considered to have the same importance for the distribution of the Texas kangaroo rat. The justification for this was that there was not sufficient information with which to weight the variables. Within each of the variables, the value assigned to individual classes (e.g. specific soil formations) was determined as the number of observed rats divided by the number of expected rats. For example, in the HA (Hollister-Abilene) soil association, 4 rats were observed, based on proportional area and a random distribution, 4.5 rats would be expected. The value assigned to the HA association was .89 (4/4.5). Using the GIS capabilities of the ERDAS



	Landuse	%	ha.
AG	Agriculture	28.2	84895
MJ	Mesquite-Juniper Woodland	9.2	27681
DB	Developed/Barren	3.3	9898
BD	Badlands	6.8	20576
WT	Water	0.6	1996
BM	Bottomland Hardwoods	15.3	45878
MG	Mesquite Grassland	34.5	103730
GL	Grassland	2.1	6231
	TOTAL	100.0	300885

FIGURE 43. Distribution of landuse categories within the Texas kangraoo rat study area.



	AG	MJ	DB	BD	WT	BM	MG	GL
OBSERVED	8	0	0	6	0	5	23	1
EXPECTED[1]	13	4.2	1.5	3.1	0.3	7	15.8	0.9

LANDUSE

[1]Assuming a random distribution

FIGURE 44. Observed and expected distribution of Texas kangaroo rats with respect to landuse categories.

software, these layers of variables were added together. The values of the resulting suitability map was condensed to 5 categories, where 1 was least and 5 most likely to contain kangaroo rats (Fig. 45). Specifically, 18.1% (53283 ha) of the study area was rated as "most likely" (to contain kangaroo rats) (5), 3.17% (9329 ha) was rated as "likely" (4), 19.7% (57951 ha) was rated as "less likely", 15.7% (46409 ha) as "unlikely" and 43.3% (127756 ha) were rated as "least likely".

When the suitability map was tested with the 31 additional locational points, results supported the validity of the model for the variables tested. Fifty-five percent (17) of the rat locations were within the "most likely" areas, 6 (19%) were located in areas classified as "likely", 5 rats were located within areas designated as "less likely", and 3 were located in "unlikely" areas. No rats were reported from the "least likely" areas (Fig. 46). A Chi-square test (normalized for area) found the distribution of kangaroo rats was significantly different than the distribution of habitat categories ($x^2 = 62.3$, $P < .001$).

The areas rated highest for Texas kangaroo rats were located on soils of the TVW (Tillman-Vernon-Weymouth association). Tillman series soils are typically deep, nearly level to gently sloping, composed of reddish-brown to brown clay loams with a slowly permeable lower layer.

FIGURE 45. Texas kangaroo rat habitat suitability map. Habitat suitability ranked 1-5; Areas designated as 1 are least likely, areas of 5 are most likely to contain Texas kangaroo rats.

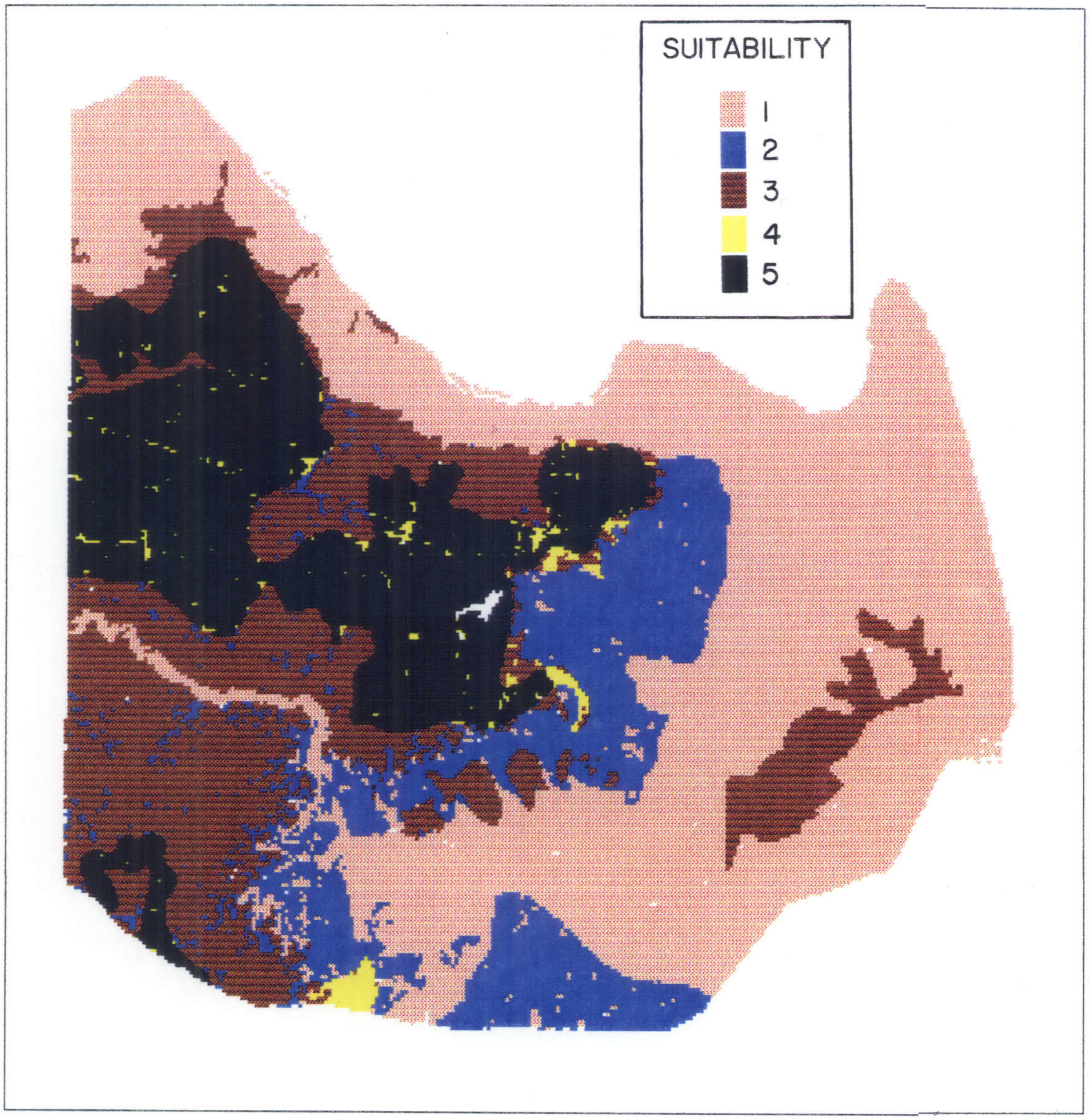
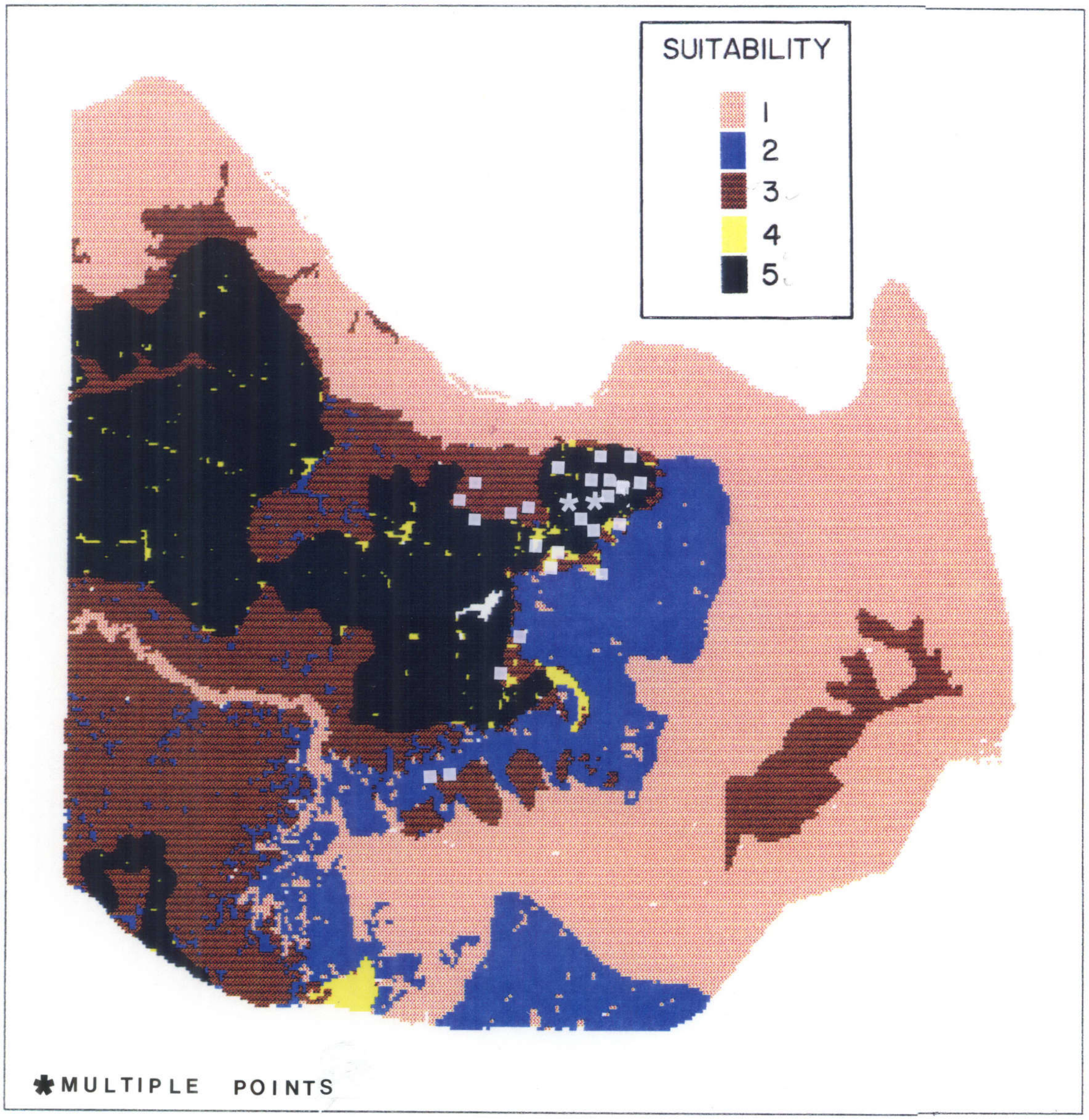

SUITABILITY
1
2
3
4
5

FIGURE 46. Location of the 31 Texas kangaroo rat test locations on the habitat suitability map.


SUITABILITY
1
2
3
4
5
*MULTIPLE POINTS

Vernon series soils consist of well-drained calcareous soils that are clayey below the surface layer. Weymouth soils consist of well-drained sloping calcareous soils on uplands. They formed from calcareous moderately fine textured red beds or in old alluvium that contains red-bed material consisting primarily of clay loam (USDA 1972). The geology underlying the best habitat is primarily of the Pb (Permian-Blaine) formation. The formation is composed primarily of mudstone, gypsum, dolomite and sandstone. The landuse of the highest rated region is a mesquite-grassland.

Discussion

This habitat model was developed and implemented to identify areas of suitable habitat for the Texas kangaroo rat. Preliminary test results indicate that the model provides a realistic appraisal of the suitability of Texas kangaroo rat habitat for the study area. Through the development and implementation of the model, variables (i.e. geology, soils and landuse) were identified which appear to be correlated spatially with the current distribution of the Texas kangaroo rat. More research is needed to investigate these relationships. The research has also established a digital data base for the study area which may be used for future research in the area.

Several difficulties were encountered in the course of the research. First, with respect to landuse classification, during June (when the image was taken) many of the agricultural fields were fallow. These were difficult to classify. Another problem was with the location of collection sites for the kangaroo rats. Most of the sites were located near the boundary of two landuses (i.e. roads and agriculture). Because of the resolution of the Landsat MSS data (80 m), and the spectral variation of these areas, these areas may have been misclassified with respect to landuse.

In terms of potential threat to the identified habitat, the only concern was from landuse change. Most of the land in the study area is privately owned and has been modified for agricultural production and grazing. Cultivation was introduced to this area about 1880, prior to this most of the area was native rangeland (USDA 1974). Over the past 50 years there has been a trend away from agriculture and towards rangeland (Fig. 47) (USDA 1974). This trend may benefit the kangaroo rat, given the prevalence of the rat in rangeland (mesquite grassland) as opposed to agricultural areas. Hamilton et al. (1987) suggested that habitat alteration such as clear cutting and brush control for agricultural development, may reduce available habitat for the species. Additionally, Martin and Matocha (1972) suggested the extensive modification of mesquite pastures or conversion of pastures to monoculture may adversely affect the kangaroo rat. However, Martin and Matocha (1972)

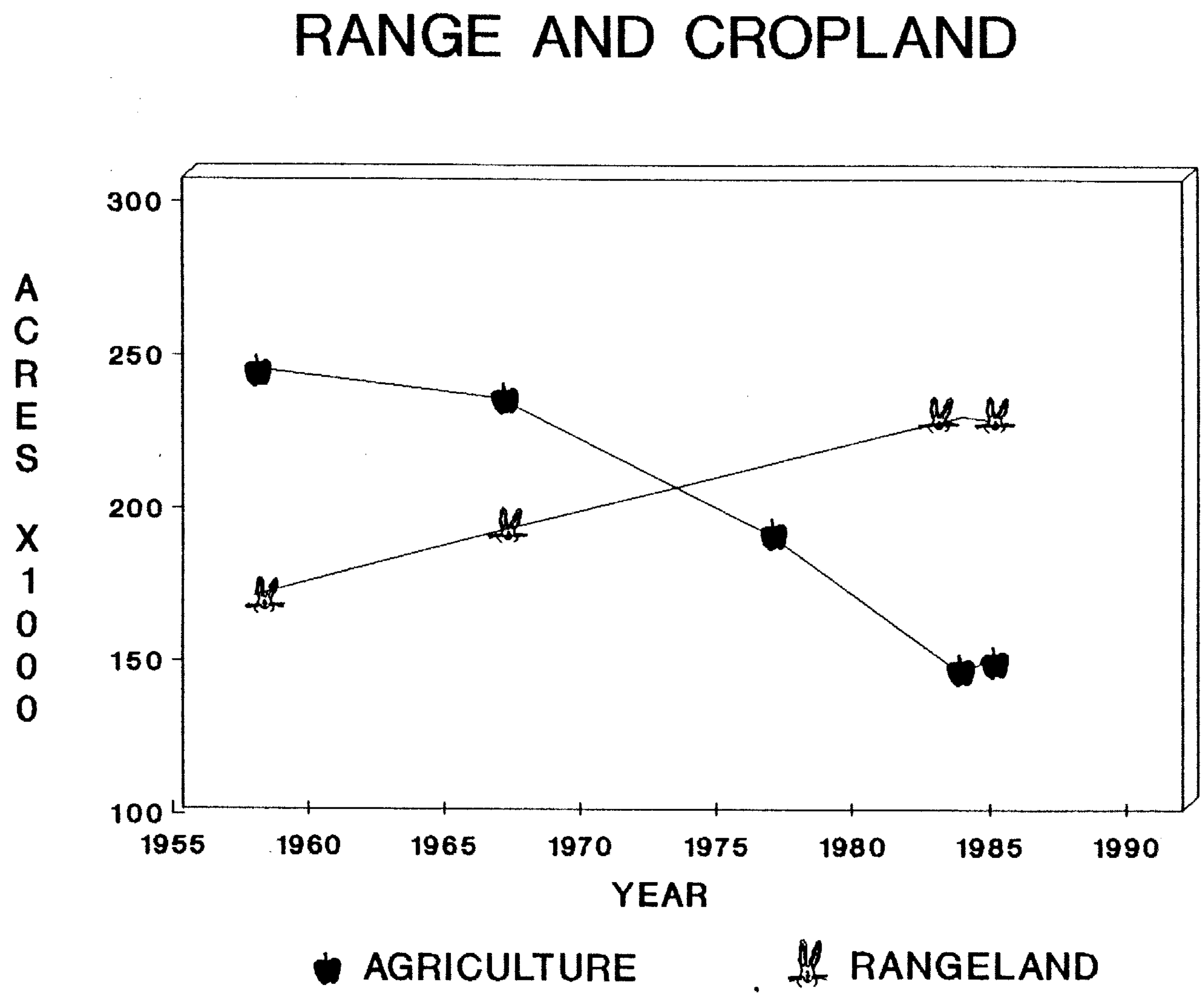


FIGURE 47. Trends in agriculture and rangeland for the past 30 years in the Texas kangaroo rat study area.

pointed out agricultural practices need not limit the distribution of the kangaroo rat if cultivated areas are interspersed with mesquite pastures and shrubby fence rows. Aside from agricultural impacts, tolerance of the Texas kangaroo rat to land development with regards to buildings and roadway impacts are not known, although Martin and Matocha (1972) suggested that urbanization and cultivation apparently limit the habitat available to the species.

CHAPTER VII

CONCLUSIONS AND SUMMARY

Geographic information systems and the computer analysis of remotely sensed data are tools which have emerged as a means to assemble and evaluate spatially oriented information. For the research described in the dissertation, these tools were used to analyze data with more variables and for larger areas than would be possible with traditional methods. Given the inherent complexity of ecological systems, use of these tools offered a means for systematic research into spatial habitat characterization.

This chapter describes a general approach to be used for subsequent ecological studies and identifies some of the current technological limitations. The chapter also serves as a summary of the overall strategy used in this research.

General Procedure

This procedure is a guide for projects which implement GIS and remote sensing for habitat characterization. Its purpose is to serve as a general guideline for subsequent spatially-oriented habitat studies. The general approach can be broken into four major components: problem definition, data collection, data manipulation and final assessment (Table 15).

Problem Definition

During this stage, important decisions must be made pertaining to: scale of interest, spatial extent of the study area and the resolution of data. Once these are decided, specific research objectives can be identified. Prior to making any choices, however, a thorough knowledge of the species of interest should be gained. This knowledge should include not only biological factors but also physical habitat and environmental characteristics. For example, many of the variables addressed in this research were not confined to biological phenomena but dealt with geologic, climatologic and physical issues.

Once the background information is amassed specific questions can be addressed. One of these is the matter of scale. The areal scale on which a biological system is viewed will have major effects on patterns that are detected and how they are interpreted. Weins et al. (1985) suggested that when habitat selection (by a species) is considered, it is through a filter affected by human perceptions and preconceptions of nature. This may lead us to ignore the fact that patterns in nature are sensitive to the scale on which they are viewed by the respective organisms (Allen and Starr 1982). For example, the scale of analysis that was useful for Black-capped Vireo habitat on Camp Bullis, Texas,

TABLE 15. Outline of the general approach for GIS based research.

I. Problem Definition
   a. scale
   b. study area
   c. resolution

II. Data Entry
   a. assess data availability
   b. data acquisition
   c. manual digitization
   d. digital data input

III. Data Analysis and Manipulation
   a. overlay analyses
   b. proximity anayses
   c. areal and linear calculations

IV. Data Display
   a. maps
   b. data tables
   c. figures

is not appropriate for habitat analyses for Red-tailed Hawks (*Buteo jamaicensis*) inhabiting the same general area.

The extent of the study area and resolution of the data are also important criteria. These are closely related; one will usually determine the other. For example, with a large scale project, such as the Golden-cheeked Warbler, the resolution (80 m) was decided by limitations posed by data volume, processing time and cost. Conversely, the small study area identified for the Black-Capped Vireo research afforded the option of higher resolution data and more intensive analyses. In general, the greater the extent of the study area; the less attention and time can be dedicated to detail.

Data Entry

The second phase of this procedure is data entry. This is a very important and labor intensive component. For this research, input and preprocessing of data was the major expense with respect to time and cost. The concerns which are addressed at this level are: data availability, data format (digital, or is manual input required), cost, and level of effort required to convert the data to a usable format.

For the research described here, data for several variables were acquired in digital format (satellite data, elevation data) and several were input manually (county boundaries, geology and soils). A list of the sources of these data (both manual and digital) are provided in Appendix E. Through the course of this research, it became apparent that improvements were needed in this aspect, particularly in the establishment of data standards and in the provision of estimations of accuracy and precision. If the data that are input contain errors, these errors will be passed on in cumulative and compounded fashion to the final results. Standards for data accuracy would alleviate some of the problem. A further need that was recognized is for the establishment of regional repositories for digital data. This would prevent duplicated effort.

Currently, digital data may be acquired from a variety of federal, state and local sources. USGS (1989) has compiled a nationwide inventory of digital spatial data sets generated by federal agencies. The costs of these data vary as does available coverage (with respect to time and geographic area).

Data Analysis and Manipulation

Data analysis and manipulation in a GIS are the process by which the data bases are queried. An extensive review of data manipulations available on most GIS systems can be found in Dangermond (1983). Some of the spatial analyses employed in the research include computations such as overlay, proximity analyses, and measurement. Overlay analyses are used to integrate two or more data sets in order to create a new one. Overlay was used to integrate the variable of landuse with the variable of geologic formations to describe Black-capped Vireo habitat on a particular geologic formations. Proximity analyses are performed by comparisons of adjacent pixels within one GIS layer. These types of analyses were used for the calculation of slope and aspect from DEM data. Measurement or linear calculations are used to quantify shapes and sizes. These calculations include perimeter and areal estimations for example, the area-to-perimeter ratios that were used to relate patch shape to size for habitat of Golden-cheeked Warbler.

Data Display

Clear and effective graphic output is important for communicating results of this type of research. GIS systems generally include the capability for displaying maps, charts, graphs and tabular information. For this research, data charts were produced as well as maps and 3-d images.

The technological limitations encountered at this stage of research were with the generation of accurate maps. Despite calculations which indicated data were correctly registered, maps produced were not correctly aligned with respect to features on the map. This type of problem may be one of both software and hardware limitations.

Summary

GIS and remote sensing were used to describe some of the environmental variables which compose the habitat of the Golden-cheeked Warbler, Black-capped Vireo and Texas kangaroo rat. An individual approach was developed for each species. For the Golden-cheeked Warbler, potential nesting habitat was identified based upon presence of an appropriate vegetative community (Ashe juniper/deciduous hardwood forest). This was accomplished through the classification of remotely sensed digital imagery. A GIS was used to quantify the habitat and describe the spatial relationships between habitat patches.

Black-capped Vireo, habitat was identified with a combination of digital satellite imagery and geologic substrate. Classification of digital satellite imagery was used to eliminate some areas, but owing to the nature of the habitat the tool could not be used to identify specific areas. GIS was then used to identify the relationship between the locations of nesting vireo on Camp Bullis and geology. GIS was also used to generate a final map indicating potential habitat as areas of appropriate landuse and correct geologic substrate.

For Texas kangaroo rat, GIS was used to identify variables significant to the distribution of the species. A set of variables were tested with known locations of kangaroo rats to identify any spatial relationships. The result was a spatial model which used geology, soils and landuse to predict the likelihood of finding the species in any given area.

For all three species, the underlying assumption throughout the research has been that measurements for a set of habitat attributes (i.e. landuse, aspect or elevation) can be used to predict presence or abundance of a species. Further effort is needed for each of these species to identify the relationship between spatial habitat characteristics and occupancy. If these relationships were known, the areas identified for each of the species could be refined by the elimination of sites which met physical criteria but not the specific spatial requirements of the species.

APPENDIX A

DESCRIPTIONS OF ERDAS PROGRAMS UTILIZED (ERDAS 1976).

CLUSTR - CLUSTR is used to classify an input raw image and creates an output GIS file. This is a type of "unsupervised" classification. The computer creates the signatures and defines the clusters. This program uses a two-pass sequential clustering algorithm. In the first pass, a set of clusters are built, based on parameters selected by the user. These clusters become the signatures used to assign classes in the output GIS file. In the second pass, each pixel is classified, or assigned to a particular class. This is based on the spectral distance between the pixel and the mean value for every cluster. The pixel is then assigned to the class (cluster) with the minimum or shortest spectral distance.

COORD2 - This program is run after GCP and calculates a transformation matrix that is used to rectify an image. This program is the second step in the geo-referencing process. The resulting is a matrix of six coefficients that are calculated from the ground control points using a least squares regression.

ELLIPSE - Used to plot a given set of signatures on top of a scatterplot of the pixel values. When plotting the probability curve for two of the channels in a given signature, the result will be an ellipse.

FIELD - Used to identify training fields. Specific areas on an image are identified and a signatures calculated based on the reflectance values of all the pixels for all the bands within the delineated area. Specifically, signatures are based on a covariance matrix, means and standard deviations.

GCP - Is used to create a set of points which represents the same location in two sets of corresponding data (an image and a map). Points are identified on an image and a map, the x,y, coordinates (row and column) and the map coordinates (northing and easting) are saved.

<u>MAXCLAS</u> - A supervised classification procedure. An input image is analyzed with respect to a group of signatures. The procedure operates by considering every pixel and comparing it to all signatures in all bands. The resulting output image has every pixel assigned to a particular class.

<u>PRINCE</u> - PRINCE creates an output file whose bands are the principal components of the bands in the input image. The channels are output in order from contain the most to the least variation. PRINCE is a two pass program. In the first pass, the statistics are calculated for the computation of the covariance matrix. In the second pass the eigenvectors of the covariance matrix are calculated.

<u>RECTIFY</u> - Transforms an unrectified image (input) so that the output pixels correspond to points in a specific map system. RECTIFY computations involve resampling and rotation of the original data. These computations are accomplished with a coefficient transformation matrix computed with the COORD2 program.

<u>SLOPE</u> - SLOPE program can compute slope and/or aspect of a topographic image file (DEM data). The resulting file contains slope values, in percents or degrees, or aspect values in twelve major compass headings.

<u>STATCL</u> - This program provides the signatures that are calculated from an unsupervised classification. The program uses a one-pass moving 3x3 window that is used to generate up to 49 spectrally distinct classes. The criteria which define new clusters (divergence measure, standard deviation, and covariance) are specified by the user.

<u>SUMMARY</u> - This program calculates cross tabulation that compare class values areas between two GIS files of the same size. The resulting table includes the number of points in common, the number of acres in common, number of acres in common and percentages.

APPENDIX B

SPECIES NAMES

Common Name	Scientific Name
agarita	*Berberis trifoliolata*
American elm	*Ulmus americana*
Arizona walnut	*Juglans major*
ash (var)	*Fraxinus* spp.
Ashe juniper	*Juniperus ashei*
bald cypress	*Taxodium distichum*
big bluestem	*Andropogon gerardii*
black cherry	*Prunus serotina*
black willow	*Salix nigra*
blue grama	*Bouteloua gracilis*
bluestem (var)	*Bothriochloa* spp.
box elder	*Acer negundo*
buffalo grass	*Buchloe dactyloides*
cedar elm	*U. crassifolia*
curlymesquite	*Hilaria belangeri*
grama (var)	*Bouteloua* spp.
hairy tridens	*Erioneuron pilosum*
indian grass	*Sorghastrum nutans*
Lacey oak	*Quercus glaucoides*
little bluestem	*Schizachyrium scoparium*
mesquite	*Prosopis glandulosa*
mountain laurel	*Sophora secundiflora*
muhly (var)	*Muhlenbergia* spp.
oak (var)	*Q.* spp.
pecan	*Carya illinoensis*
plateau live oak	*Q. fusiformis*
sand dropseed	*Sporobolus cryptandrus*
scalybark oak	*Q. sinuata*
seep muhly	*M. reverchonii*
sideoats grama	*B. curtipendula*
silver grama	*B. saccharoides*
sugarberry	*Celtis laevigata*
sumac (var)	*Rhus* spp.
tall dropseed	*S. asper*
Texas oak	*Q. texana*
Texas grama	*B. rigidiseta*
Texas persimmon	*Diospyros texana*
Texas wintergrass	*Stipa leucptricha*
Texas cupgrass	*Eriochloa sericea*
threeawn (var)	*Aristida* spp.
tobosa	*H. mutica*

APPENDIX C

POTENTIAL GOLDEN-CHEEKED WARBLER HABITAT BY COUNTY

COUNTY	SIZE (AC)	HABITAT (AC)	PORTION OF COUNTY IN STUDY
BANDERA	524295	53429	100
BELL	697323	20427	89.5
BEXAR	802777	21682	66.2
BLANCO	453693	24284	100
BOSQUE	635021	15782	100
BROWN	616340	0	1.2
BURNET	651392	46549	100
COMAL	368881	61247	93.8
COMMANCHE	613570	39	66
CORYELL	675878	20487	100
EASTLAND	594506	157	68.6
EDWARDS	1341929	42457	88.5
ELLIS	612053	0	5.5
ERATH	702326	1728	100
FALLS	496529	2	5.5

GILLESPIE	681560	20193	100
GUADALUPE	456320	463	16
HAMILTON	537922	854	100
HAYS	434910	50625	86.4
HILL	637543	1815	73
HOOD	27603	1647	51
JOHNSON	467840	4062	44
KENDALL	424557	32839	100
KERR	683867	44864	100
KIMBLE	800000	31531	100
KINNEY	868058	6064	26.3
LAMPASAS	453997	1336	100
LLANO	615939	18352	100
MASON	594427	26756	100
MCCLENNAN	682187	5015	73
MCCULOCH	689362	1405	12.2
MEDINA	852878	12049	63.7
MENARD	580320	5015	80.8
MILLS	479734	129	86.5

PALO PINTO	607360	37	1.0
REAL	445249	66152	100
SAN SABA	728561	5626	58.3
SCHLEICHER	846556	190	23.5
SOMERVELL	120320	4715	100
SUTTON	911395	648	41.7
TRAVIS	654575	106453	72
UVALDE	1000960	40858	47
WILLIAMSON	724177	37023	50.9
TOTAL	27043120	835,970	

APPENDIX D

CLIFTON

	DENSITY Ind./Ha.	RELATIVE COVER (%) 3M	5M	>5.5M	AVG. HT. (M)
Ashe Juniper *Juniperus ashei*	298.8	54.0	51.0	47.4	6.2
Texas Oak *Quercus texana*	441.1	31.9	28.7	16.8	4.5
Live Oak *Q. fusiformis*					
Lacey Oak *Q. laceyi*					
Scrub Oak *Q. sinuata*	71.1	2.1	2.1	3.3	4.4
Arizona Walnut *Juglans major*					
Texas Ash *Fraxinus texensis*	185.0	7.6	11.0	16.8	5.4
Cedar Elm *Ulmus crassifolia*					
Hackberry *Celtis laevigata*					
Chokecherry *Prunus virginiana*					
Mexican Buckeye *Ungnadia speciosa*					
Redbud *Cercis canadensis*	57.0	1.1	-	-	3.4
Gum Bumelia *Bumelia lanuginosa*	28.0	-	6.5	15.5	11.1
Mexican Persimmon *Diospyros texana*					
Total Cover by strata (sq.M./ha.)		6180	4297	2996	

EMMA LONG CITY PARK

	DENSITY Ind./Ha.	RELATIVE COVER (%) 3M	5M	>5.5M	AVG. HT. (M)
Ashe Juniper *Juniperus ashei*	56.2	59.7	48.3	36.0	7.0
Texas Oak *Quercus texana*	99.3	11.7	27.2	20.0	10.9
Live Oak *Q. fusiformis*					
Lacey Oak *Q. laceyi*					
Scrub Oak *Q. sinuata*	66.2	5.7	3.4	2.5	7.8
Arizona Walnut *Juglans major*					
Texas Ash *Fraxinus texensis*	66.2	1.9	.4	2.3	7.8
Cedar Elm *Ulmus crassifolia*	132.3	3.8	4.1	25.6	12.4
Hackberry *Celtis laevigata*	99.3	3.4	10.4	9.9	9.5
Chokecherry *Prunus virginiana*	16.5	-	-	.3	8.3
Mexican Buckeye *Ungnadia speciosa*	16.5	3.8	.1	-	5.1
Chinaberry *Melia azedarach*	33.1	8.2	5.0	3.2	16.4
Soapberry *Sapindus drummondii*					
Deciduous Holly *Ilex decidua*					
Total Cover by strata (sq.M./ha.)		7465	13860	19996	

FORT HOOD

	DENSITY Ind./Ha.	RELATIVE COVER (%) 3M	5M	>5.5M	AVG. HT. (M)
Ashe Juniper *Juniperus ashei*	474.5	75.6	64.6	55.6	4.5
Texas Oak *Quercus texana*					
Live Oak *Q. fusiformis*	100.9	6.6	5.9	6.3	4.8
Lacey Oak *Q. laceyi*					
Scrub Oak *Q. sinuata*	151.4	7.5	3.3	1.2	3.8
Arizona Walnut *Juglans major*					
Texas Ash *Fraxinus texensis*	70.6	1.9	.5	7.8	4.8
Cedar Elm *Ulmus crassifolia*	10.1	8.1	21.0	28.9	7.5
Hackberry *Celtis laevigata*					
Total Cover by strata (sq.M./ha.)		6198	2717	1383	

GARNER STATE PARK

	DENSITY Ind./Ha.	RELATIVE COVER (%) 3M	5M	>5.5M	AVG. HT. (M)
Ashe Juniper *Juniperus ashei*	1097.8	69.3	54.1	46.5	5.4
Texas Oak *Quercus texana*	91.5	6.6	14.6	26.0	8.5
Live Oak *Q. fusiformis*					
Lacey Oak *Q. laceyi*	219.6	23.2	31.2	27.4	6.3
Scrub Oak *Q. sinuata*					
Arizona Walnut *Juglans major*					
Texas Ash *Fraxinus texensis*					
Cedar Elm *Ulmus crassifolia*					
Hackberry *Celtis laevigata*					
Total Cover by strata (sq.M./ha.)		11725	15492	10329	

GUADALUPE RIVER STATE PARK

	DENSITY Ind./Ha.	RELATIVE COVER (%) 3M	5M	>5.5M	AVG. HT. (M)
Ashe Juniper *Juniperus ashei*	628.3	41.1	62.8	64.4	7.6
Texas Oak *Quercus texana*	66.8	4.4	5.7	10.9	9.3
Live Oak *Q. fusiformis*	66.8	24.9	13.3	8.1	7.5
Lacey Oak *Q. laceyi*					
Scrub Oak *Q. sinuata*	13.4	-	-	-	5.0
Arizona Walnut *Juglans major*					
Texas Ash *Fraxinus texensis*	13.4	-	.9	5.4	13.3
Cedar Elm *Ulmus crassifolia*	120.3	19.1	11.4	7.2	7.6
Hackberry *Celtis laevigata*	26.7	5.8	4.7	3.6	10.0
Chokecherry *Prunus virginiana*					
Mexican Buckeye *Ungnadia speciosa*					
Deciduous Holly *Ilex decidua*					
Mexican Persimmon *Diospyros texana*	133.7	4.4	.9	.3	4.6

KERRVILLE STATE PARK

	DENSITY Ind./Ha.	RELATIVE COVER (%) 3M	5M	>5.5M	AVG. HT. (M)
Ashe Juniper *Juniperus ashei*	1015.2	78.2	25.7	16.5	4.1
Texas Oak *Quercus texana*	14.1	4.5	5.9	3.7	5.8
Live Oak *Q. fusiformis*	84.6	11.8	57.2	73.6	6.4
Lacey Oak *Q. laceyi*					
Scrub Oak *Q. sinuata*	14.1	5.4	11.0	6.0	6.5
Arizona Walnut *Juglans major*					
Texas Ash *Fraxinus texensis*					
Cedar Elm *Ulmus crassifolia*					
Hackberry *Celtis laevigata*					
Total Cover by strata (sq.M./ha.)		7640	6242	4695	

LOST MAPLES SNA

	DENSITY Ind./Ha.	RELATIVE COVER (%) 3M	5M	>5.5M	AVG. HT. (M)
Ashe Juniper *Juniperus ashei*	89.5	9.1	2.2	1.3	4.5
Texas Oak *Quercus texana*	39.7	12.0	23.4	22.7	11.1
Live Oak *Q. fusiformis*	4.9	2.5	1.0	.6	6.5
Lacey Oak *Q. laceyi*	84.5	16.9	17.0	16.8	8.0
Scrub Oak *Q. sinuata*	4.9	.3	.3	.3	7.0
Big-tooth Maple *Acer grandidentatum*	89.5	37.3	34.6	32.0	10.7
Chinkapin Oak *Quercus muehlenbergii*	4.9	-	-	-	14.0
Arizona Walnut *Juglans major*	14.9	8.5	1.0	4.0	7.1
Texas Ash *Fraxinus texensis*					
Cedar Elm *Ulmus crassifolia*					
Hackberry *Celtis laevigata*	9.9	1.6	-	-	3.9
Chokecherry *Prunus virginiana*	14.9	6.0	8.6	6.4	8.7
Total Cover by strata (sq.M./ha.)		7306	10786	14550	

MERIDIAN STATE PARK

	DENSITY Ind./Ha.	RELATIVE COVER (%) 3M	5M	>5.5M	AVG. HT. (M)
Ashe Juniper *Juniperus ashei*	887.7	85.3	80.3	49.6	5.4
Texas Oak *Quercus texana*	32.8	6.3	4.0	3.0	5.4
Live Oak *Q. fusiformis*	16.4	-	-	-	3.3
Lacey Oak *Q. laceyi*					
Scrub Oak *Q. sinuata*	230.1	2.7	5.0	3.6	3.8
Arizona Walnut *Juglans major*					
Texas Ash *Fraxinus texensis*	147.9	5.5	10.6	11.9	4.3
Cedar Elm *Ulmus crassifolia*					
Hackberry *Celtis laevigata*					
Total Cover by strata (sq.M./ha.)		9294	5163	3519	

TRAVIS COUNTY AUDUBON PRESERVE

	DENSITY Ind./Ha.	RELATIVE COVER (%) 3M	5M	>5.5M	AVG. HT. (M)
Ashe Juniper <u>Juniperus ashei</u>	460.6	58.9	28.9	6.2	4.7
Texas Oak <u>Quercus texana</u>	60.8	16.0	19.9	8.5	6.5
Live Oak <u>Q. fusiformis</u>	52.1	16.0	24.3	8.9	6.4
Lacey Oak <u>Q. laceyi</u>					
Scrub Oak <u>Q. sinuata</u>	26.0	5.0	.1	-	3.7
Arizona Walnut <u>Juglans major</u>	26.0	.9	26.6	74.1	20.1
Texas Ash <u>Fraxinus texensis</u>	8.7	-	-	-	11.3
Cedar Elm <u>Ulmus crassifolia</u>	17.4	2.2	3.7	2.8	8.1
Hackberry <u>Celtis laevigata</u>					
Chokecherry <u>Prunus virginiana</u>					
Mexican Buckeye <u>Ungnadia speciosa</u>					
Soapberry <u>Sapindus drummondii</u>	17.4	1.2	4.1	2.5	6.9
Deciduous Holly <u>Ilex decidua</u>	17.4	2.2	-	-	4.5
Mexican Persimmon <u>Diospyros texana</u>					
Total Cover by strata (sq.M./ha.)		5980	5607	5120	

APPENDIX E

DATA DICTIONARY

GOLDEN-CHEEKED WARBLER

LAYER	SOURCE	SCALE	ENTRY	DESCRIPTION
COUNTY	USGS	1:250000	DIGITIZED	COUNTY BOUNDARIES
SLOPE	USGS	1:250000	DIGITAL	SLOPE PERCENT
HABITAT	MSS	1:250000	DIGITAL	CLASSIFIED IMAGE
PATCH	MSS	1:250000	DIGITAL	HABITAT PATCHES
BIRDS	TP&W	1:24000	DIGITIZED	GCW HABITAT

BLACK-CAPPED VIREO

LAYER	SOURCE	SCALE	ENTRY	DESCRIPTION
STAREA	USGS	1:24000	DIGITIZED	STUDY AREA BOUNDS
GEOLOGY	BEG	1:250000	DIGITIZED	MAJOR FORMATIONS
HABITAT	TM	1:24000	DIGITAL	CLASSIFIED IMAGE
ACTIVITY	USACOE	1:25000	DIGITIZED	MISSION ACTIVITIES
BIRDS	SURVEY	1:24000	DIGITIZED	BCV SITINGS
ROADS	US ARMY	1:25000	DIGITIZED	BASE ROADS
CENSUS	SURVEY	1:24000	DIGITIZED	SURVEY ROUTE
LANDUSE	TM	1:24000	DIGITAL	BASE LANDUSE

TEXAS KANGAROO RAT

LAYER	SOURCE	SCALE	ENTRY	DESCRIPTION
COUNTY	USGS	1:250000	DIGITIZED	COUNTY BOUNDARIES
SLOPE	USGS	1:250000	DIGITAL	SLOPE PERCENT
LANDUSE	MSS	1:24000	DIGITAL	CLASSIFIED IMAGE
GEOLOGY	BEG	1:250000	DIGITIZED	MAJOR FORMATIONS
KRATS	MARTIN	1:24000	DIGITAL	KRAT SITES
SOILS	SCS	1:163000	DIGITIZED	SOIL TYPES
STUDAR	USGS	1:250000	DIGITIZED	STUDY AREA
ROADS	USGS	1:250000	DIGITIZED	STUDY AREA ROADS

KEY FOR DATA DICTIONARY	
USGS	U.S. Geologic Survey
TP&W	Texas Parks and Wildlife
BEG	Texas Bureau of Economic Geology
USACOE	U.S. Army Corps of Engineers
TM	Thematic Mapper Landsat Data
MSS	Multispectral Scanner Landsat Data
GCW	Golden-cheeked Warbler
BCV	Black-capped Vireo
KRAT	Texas Kangaroo Rat

APPENDIX F

Description of Major Geologic Formations*

Qal - (Quaternary, Holocene) Floodplain and channel deposits: sand, silt, clay and gravel near floodplain levee. Locally developed eolian dunes of sand and silt, bedrock locally in stream channels. Thickness of alluvium of to 30 feet.

Qsh - (Quaternary Holocene and/or Pleistocene) Windblown deposits, dunes and dune ridges; sand, silt and clay, orange-brown, massive with crude vertical joints and buried soils. Thickness of sheets up to 20 feet.

Qds - (Quaternary Holocene and/or Pleistocene) Windblown deposits, dunes and dune ridges; sand and silt, orange-brown, massive, local low-angle crossbeds; best developed on floodplains, fluviatile terraces and Seymour Formation. Thickness of dune ridges up to 25 feet.

Qt - (Quaternary Holocene and/or Pleistocene) Fluviatile terrace gravel, sandy lenticular, stratified, crossbedded, locally cemented by calcite, clasts granule to cobble-size, well-rounded to subangular, composed of quartzite and other metamorphic rocks, milky quartz, chert and fine grained igneous rocks from westerly sources.

Pcf - (Permian) Mudstone, siltstone, dolomite, limestone and gypsum. Mostly mudstone, commonly silty, brownish-red, minor gray and green, calcareous nodules abundant in lower part. Siltstone in units 1 to 3 feet thick distributed throughout.

Psa - (Permian) Mudstone, sandstone, siltstone and gypsum. Thickness of formation 90 to 120 feet.

Qu - (Quaternary) Alluvium surficial deposits; sand, clay, silt, caliche and gravel; includes thin remnants of older terraces, lag gravel, windblown sand and silt, residual soil and colluvium commonly cemented by caliche. Thickness of surficial deposits up to 10 feet.

Qsl - (Quaternary Pleistocene) Surficial deposits, thin deposits; sand, silty orange-brown massive; thin gravel locally in basal part, generally massive to crudely stratified, rarely crossbedded, locally cemented by calcite; clasts granule to pebble-size, angular to rounded, composed predominately of limestone with minor clasts of quartzite, milky quartz, sandstone and siltstone. Thickness of deposits 1 to 10 feet.

Pb - (Permian) Mudstone, gypsum, dolomite and sandstone; laterally persistent and prominent dolomite beds. Mudstone, locally silty, brownish-red and gray -green. Gypsum typically of nodular alabaster, friable, white, dolomitic beds; units pinch out locally in outcrop owing to dissolution.

* From BEG 1987

APPENDIX G

Soil Association Descriptions*

Tillman-Vernon-Weymouth - This association is a large, irregular shaped, nearly level to sloping, upland plain. It is on a broad divide between the rivers and adjoins most of the other associations. It is characterized by deep to shallow, nearly level to gently sloping soils that have a surface layer of clay loam and slowly to moderately permeable lower layers.

About 70% of this association is cultivated, 30% is in native range. Wheat, cotton and sorghum are the principal crops. This association covers about 34% of the total study area. Tillman soils make up about 38%, Vernon soils about 15% and Weymouth soils 11%. The remaining soils are scattered areas of Hollister, Olton, Colorado, Spur and Mangum soils.

Tillman soils are deep, nearly level to gently sloping, reddish-brown to brown clay loams with a slowly permeable lower layer. They are usually found on smoother ridges and upland divides. Vernon soils are gently sloping, reddish brown with a slowly permeable clayey lower layer. They are shallow and underlain by redbed clay or shale. Weymouth soils are deep, gently sloping, brown to reddish-brown clay loams with a moderately permeable clay loam lower layer. Weymouth and Vernon soils are found on the more prominent ridges, hilltops and side slopes flanking creeks and natural drains.

Badland-Vernon-Cottonwood - This association consists of very shallow rough lands in breaks lying below the adjoining soil associations. The topography of this associations is steep escarpments and benchlike areas dissected by drainage channels and gullies. The soil is characterized as nearly barren red-bed shale and clay with shallow to very shallow soils with a clay or clay loam surface layer and lower layers of clay or gypsum.

This association is approximately 18% of the study area. Little of this association is cultivated, it is used mainly for range.

Springer-Miles - These soils form an undulating to hummocky sandy plain that covers about 16% of the study area. These soils are deep, neutral and have a very friable fine sandy loam lower layer. The underlying material is loamy fine sand to fine sand.

About 75% of this association is cultivated and about 25% is in native range. The principal crops are wheat, cotton, guar and sorghum. These soils are susceptible to wind erosion.

Hollister-Abilene - These soils form a nearly level to gently sloping upland plain that occupies about 10% of the study area. The association is characterized by deep nearly level to gently sloping soils that have a clay loam surface layer and lower layers of clay, silty clay, or silty clay loam.

About 90% of this association is cultivated; 10% is in native range. Wheat, sorghum and cotton are cultivated on this association.

Miles-Acuff-Olton - This soil comprises about 8% of the study area and occupies nearly level to gently sloping uplands. The soils are characterized by deep, nearly level to gently sloping soils that have a surface layer of loam to clay loam and lower layers of sandy clay loam and clay loam to silty clay loam.

About 85% of this association is in cultivation and about 15% is native range. The major crops are wheat, sorghum and cotton.

Quanah-Talpa - This soil occupies about 7% of the study area. It is about 56% gently sloping Quanah soils and about 30% gently sloping to steep Talpa soils. The association is characterized by deep and very shallow, gently sloping to steep soils that have a surface layer of clay loam over moderately permeable layers.

About 10% of this association is cultivated, and about 90% is native range. Cultivation is primarily on the Quanah soils, Talpa soils are too shallow and stony.

Tivoli-Hardeman - These soils are duny and undulating. They comprise about 5% of the study area. The association is characterized by deep, nearly undulating, dunned and steep soils that have a surface layer of fine sand to fine sandy loam and lower layers of fine sand and fine sandy loam. The Tivoli soils (50%) are deep duned soils of the uplands. They are rapidly permeable fine sand throughout. They are generally adjacent to flood plains. The Hardeman soils are deep, nearly level to steep soils with fine sandy loam throughout.

About 30% of this association is cultivated and 70% in native range. Cultivated areas are confined almost entirely to the Hardeman soils. Wheat and cotton are the principal crops.

Cobb-Cosh - This association occupies gently sloping uplands and comprises less than 2% of the study area. The soils are characterized by moderately deep to shallow, gently sloping soils that have a surface layer of fine sandy loam and lower layers of sandy clay loam over sandstone.

About 80% of this association is cultivated and 20% is in native range. Wheat and sorghum are the principal crops.

* From USDA 1972

APPENDIX H

COLLECTION SITES FOR KANGAROO RATS

RAT NUMBER	CATALOG #	UTM X COORD.	UTM Y COORD.	YEAR	MON	DAY
1	24798	431916.00	3779073.00	69	10	9
2	13532	432720.65	3787119.50	69	10	9
3	13535	433525.30	3785510.20	69	10	9
4	13534	434329.95	3787119.50	69	10	9
5	13536	435134.60	3777463.70	69	10	9
6	13533	435134.60	3777463.70	69	10	9
7	8824	435536.93	3799189.25	69	7	15
8	24793	435939.25	3787119.50	69	10	9
9	9610	435939.25	3797579.95	69	12	17
10	11434	435939.25	3797579.95	70	4	4
11	13547	435939.25	3797579.95	70	6	5
12	11780	435939.25	3797579.95	70	7	1
13	11435	435939.25	3797579.95	70	4	4
14	11430	435939.25	3797579.95	70	2	11
15	24756	435939.25	3797579.95	70	1	8
16	9926	435939.25	3797579.95	70	2	10
17	11429	435939.25	3797579.95	70	2	11
18	24744	435939.25	3797579.95	69	11	6
19	9758	435939.25	3797579.95	70	1	13
20	24747	435939.25	3797579.95	70	7	1
21	9571	435939.25	3797579.95	69	12	17
22	24748	435939.25	3797579.95	69	11	7
23	24764	435939.25	3797579.95	70	4	4
24	12080	435939.25	3797579.95	70	5	9
25	24742	435939.25	3797579.95	69	11	6
26	9608	435939.25	3797579.95	69	12	17
27	11779	435939.25	3797579.95	70	7	1
28	10275	435939.25	3797579.95	70	5	9
29	24750	435939.25	3797579.95	70	7	2
30	24739	435939.25	3797579.95	70	1	13
31	24737	435939.25	3797579.95	70	2	11
32	24757	435939.25	3797579.95	70	1	8
33	24804	435939.25	3797579.95	70	2	11
34	11781	435939.25	3797579.95	70	7	2
35	24746	435939.25	3797579.95	69	11	6
36	24751	435939.25	3797579.95	70	2	10
37	9612	435939.25	3797579.95	69	12	17
38	24741	435939.25	3797579.95	70	1	12
39	24805	435939.25	3797579.95	70	4	4
40	9759	435939.25	3797579.95	70	1	12
41	24762	435939.25	3797579.95	70	4	4
42	9609	435939.25	3797579.95	69	12	17
43	24738	435939.25	3797579.95	70	2	11
44	24754	435939.25	3797579.95	70	5	9
45	9573	435939.25	3797579.95	69	12	17
46	24765	435939.25	3797579.95	70	4	4
47	9611	435939.25	3797579.95	69	12	17
48	24752	435939.25	3797579.95	70	2	10
49	11431	435939.25	3797579.95	69	11	6
50	24806	435939.25	3797579.95	70	6	5
51	10194	435939.25	3797579.95	70	5	9
52	9572	435939.25	3797579.95	69	12	17
53	10195	435939.25	3797579.95	70	5	9

54	24755	435939.25	3797579.95	70	5	9
55	11778	435939.25	3797579.95	70	7	1
56	24745	435939.25	3797579.95	69	11	6
57	11782	435939.25	3797579.95	70	7	2
58	11447	435939.25	3797579.95	70	7	2
59	24766	435939.25	3797579.95	70	4	4
60	11777	435939.25	3797579.95	70	7	1
61	11783	435939.25	3797579.95	70	7	2
62	12079	435939.25	3797579.95	70	5	9
63	10196	435939.25	3797579.95	70	5	9
64	24749	435939.25	3797579.95	70	7	2
65	10274	435939.25	3797579.95	70	5	9
66	24761	435939.25	3797579.95	70	4	4
67	11425	435939.25	3797579.95	70	5	9
68	24758	435939.25	3797579.95	70	1	12
69	9760	435939.25	3797579.95	70	1	9
70	24763	435939.25	3797579.95	70	4	4
71	11448	435939.25	3797579.95	70	7	2
72	24743	435939.25	3797579.95	69	11	6
73	24740	435939.25	3797579.95	70	1	13
74	24760	435939.25	3797579.95	70	6	4
75	11444	435939.25	3797579.95	70	7	1
76	11432	435939.25	3797579.95	69	11	6
77	24759	435939.25	3797579.95	70	1	13
78	10276	435939.25	3797579.95	70	5	9
79	9570	435939.25	3797579.95	69	12	17
80	11428	435939.25	3797579.95	70	2	11
81	11427	435939.25	3797579.95	70	2	11
82	11433	435939.25	3797579.95	69	11	6
83	11426	435939.25	3797579.95	70	5	8
84	11445	435939.25	3797579.95	70	7	1
85	11446	435939.25	3797579.95	70	7	2
86	24768	436743.90	3796936.23	69	7	14
87	13545	437076.94	3795222.39	69	9	19
88	13527	437146.23	3799189.25	69	7	15
89	13521	437237.87	3795383.32	69	9	19
90	24794	437548.55	3787119.50	69	10	9
91	13546	438203.45	3795544.20	69	9	19
92	13548	438353.20	3785510.20	69	10	9
93	13537	438353.20	3785510.20	69	10	9
94	13538	438686.24	3795544.25	69	9	19
95	24795	439157.85	3787119.50	69	10	9
96	13520	439490.89	3795544.25	69	9	19
97	11440	439560.18	3793959.03	70	6	5
98	13524	439560.18	3799189.25	69	7	15
99	13550	439962.50	3778268.35	69	10	10
100	24797	439962.50	3785510.20	69	10	9
101	24727	440364.83	3799189.25	70	2	5
102	13542	440617.40	3798762.85	69	9	19
103	13551	440767.15	3787119.50	69	10	9
104	24796	440767.15	3787119.50	69	10	9
105	13549	442376.45	3780279.98	69	10	9
106	13525	442376.45	3799189.25	69	7	15
107	24726	442698.31	3799350.18	70	2	5
108	24728	443583.43	3799189.25	69	7	15
109	12078	443836.00	3795544.20	69	9	19

110	11443	443836.00	3795544.25	70	6	5
111	24801	443836.00	3796509.83	69	7	14
112	13544	443836.00	3799084.70	69	9	19
113	24792	443985.75	3794763.68	69	8	11
114	24772	443985.75	3796775.30	69	7	14
115	24771	443985.75	3796775.30	69	7	14
116	13539	443985.75	3798786.93	69	9	19
117	13528	443985.75	3799189.25	69	7	15
118	13530	443985.75	3800798.55	69	11	7
119	24788	444388.08	3795568.33	70	6	5
120	13540	444962.51	3796670.76	69	9	19
121	24773	445192.73	3796775.30	69	8	11
122	24774	445273.19	3796775.30	69	7	14
123	24775	445273.19	3796775.30	69	7	14
124	11441	445445.30	3796670.76	70	6	5
125	24789	445595.05	3795166.00	69	7	14
126	24776	445595.05	3796775.30	69	7	14
127	24777	445595.05	3796775.30	69	8	11
128	24784	445755.98	3796614.37	69	8	11
129	11442	445767.16	3796670.76	70	6	5
130	24800	445767.16	3796670.76	69	7	15
131	24802	445928.09	3796509.83	69	7	14
132	24790	445997.38	3795166.00	69	8	11
133	24778	445997.38	3796775.30	69	8	11
134	24767	445997.38	3797177.63	69	8	11
135	24731	445997.38	3798384.60	69	7	5
136	24729	445997.38	3798786.93	70	2	6
137	24734	446077.84	3797740.88	69	7	15
138	24735	446077.84	3797740.88	69	7	15
139	24736	446077.84	3797740.88	69	7	15
140	24791	446399.70	3795166.00	69	8	11
141	24779	446399.70	3796775.30	69	8	11
142	24780	446399.70	3796775.30	69	8	11
143	24781	446399.70	3796775.30	69	8	11
144	24803	446571.81	3796509.83	69	7	14
145	24769	446721.56	3796936.23	69	7	14
146	13522	446732.74	3796670.76	69	9	19
147	24782	446802.03	3796775.30	69	8	11
148	24730	446802.03	3798786.93	69	8	11
149	11436	446893.67	3796348.90	69	11	7
150	13519	446893.67	3796670.76	69	9	19
151	13541	446893.67	3796670.76	69	9	19
152	24808	447204.35	3794361.35	70	6	5
153	24787	447204.35	3795970.65	69	8	11
154	24786	447204.35	3796372.98	69	8	11
155	24785	447204.35	3796372.98	69	8	11
156	24783	447204.35	3796775.30	70	6	5
157	24807	447204.35	3797579.95	70	6	5
158	24732	447204.35	3798384.60	69	7	15
159	24733	447204.35	3798384.60	69	11	7
160	13531	447204.35	3799591.58	69	9	19
161	13543	447204.35	3800396.23	69	9	19
162	24799	447215.53	3798280.06	69	9	19
163	24770	447365.28	3796936.23	69	7	15
164	12077	447376.46	3798280.06	69	9	19

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