University of Redlands

**Fragmentation and Loss:
A GIS View of
The Mojave Desert Tortoise Habitat**

A Major Individual Project submitted in partial satisfaction of the requirements
for the degree of Master of Science in Geographic Information Systems

By

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December 2006

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Fragmentation and Loss

In the Mojave Desert Tortoise Habitat

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The report of Linda J. Wallers is approved.

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December 2006

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I had never aspired to a Masters degree. But, after listening for two years (2003-4) about NGA's plans for GIS in my directorate and seeing a few of our geospatial analysts at work, curiosity lead me to take the GIS certificate course offered at George Mason University. I became more excited about the possibilities of GIS for intelligence analysis after each class. When the announcement for the MS GIS program was published, in late winter of 2005, I decided that the program might be just what I needed to enhance my skills as an intelligence analyst and gain a degree in the process. I was surprised and delighted when I was one of the few selected to attend the program. Little did I know what was in store for me over the next 11 months. I am grateful to the following people for making the MS GIS experience possible and rewarding:

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ABSTRACT

Fragmentation and Loss

In the Mojave Desert Tortoise Habitat

By

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Landscapes are ever changing or being changed by natural forces or by human activities. The changes, over time, frequently result in more complex and fragmented landscape structures. Much of the fragmentation is due to human activities, primarily roads. Landscape indices, tools that identify and quantify landscape structure, provide statistical analysis of how the landscape is fragmented by roads and what, if any, habitat loss resulting from road-avoidance behavior might be present. The interpretation of the landscape indices can give scientists clues to where limited resources can be directed to preserve the habitat.

The desert tortoise habitat was chosen as the subject for a baseline assessment of fragmentation and habitat loss in the Mojave Desert. The desert tortoise is highly sensitive to changes in its environment. In 1990, the tortoise was listed as Threatened due to dramatic decreases in its population over only a few decades. The reasons for the listing included deterioration and loss of habitat. The desert tortoise continues to be studied for changes in population that might indicate broader problems for all species in the Mojave Desert.

This project involved the statistical analysis of the desert tortoise habitat, using Patch Analyst 3.1, a landscape analysis program incorporating landscape indices, ArcView 3.3, and ArcGIS 9.1 to model the desert tortoise habitat and provide a baseline assessment of fragmentation due to roads and potential for habitat loss resulting from road-avoidance behavior in the desert tortoise habitat. Preliminary analysis of the landscape-level statistics suggests that the Mojave Desert is highly fragmented, particularly in the western Mojave Desert of California. Roads, particularly highways and secondary roads impose significant barriers to movement, although how this might affect the desert tortoise, with its small home range, remains to be determined. The evidence of greater road-avoidance

distances based on the figures from a von Seckendorff Hoff and Marlowe (2002) study, produced evidence of loss of habitat, especially for near highways and secondary roads. Overall, it appears that the Mojave Desert tortoise habitat is extremely fragmented, with large potential for significant habitat loss resulting from the human need for more roads.

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List of Acronyms

ACEC	Area Of Critical Environmental Concern
AWMSI	Area Weighted Mean Shape Index
CAI	Total Core Area Index
CFCC	Census Feature Class Code
DEM	Digital Elevation Data
DLG	Digital Line Graphic
DSS	Decision Support System
DTP	Desert Tortoise Project
DWMA	Desert Wildlife Management Areas
ED	Edge Density
EMDS	Ecosystem Management Decision Support
EROS	Earth Resources Observation And Science
ESRI	Environmental Systems Research Institute
FGDC	Federal Geographic Data Committee
GIS	Geographic Information System
HPKB	Habitat Potential Knowledge Base
HSI	Habitat Suitability Index
MDEP	Mojave Desert Ecosystem Program
MPS	Mean Patch Size
MSI	Mean Shape Index
NumP	Number Of Patches
ORV	Off-Road Vehicle

Pclass	Patch Class
PSCoV	Patch Size Coefficient Of Variance
PSSD	Patch Size Standard Deviation
PType	Period or Age of Rock Type
SDI	Shannon's Diversity Index
SEI	Shannon's Evenness Index
SRTM	Shuttle Radar Topography Mission
SSURGO	Soil Survey Geographic
STATSGO	State Soil Geographic
TE	Total Edge
TLA	Total Landscape Area
TNF	Tahoe National Forest

1. Project Background

Habitat fragmentation is a serious problem with potentially devastating effects for biological diversity. The issue of fragmentation has been identified recently as one of the most pressing issues in wildlife management and the conservation of biodiversity. Habitat fragmentation refers to a phenomenon where habitats are broken up into small, isolated pieces that result in new landscapes being developed that differ substantially from the previous landscape. The shape, size, proximity, and contrast of each new landscape piece determine how the fragmented habitat affects wildlife. . . (U. S. Fish and Wildlife Service, 2006).

A landscape is a heterogeneous mosaic of discrete, dynamic, homogeneous patches, continually changing, as with the seasons, and/or being changed by natural forces, such as water, or by humans (McGarigal & Marks, 1995). The more patches in the landscape, the more fragmented the landscape is considered to be. It is not enough to say that the landscape is a changing patchwork, though. What does that pattern imply about the landscape and the forces acting upon it? “Landscape structure must be identified and quantified in meaningful ways before the interaction between landscape patterns and ecological processes can be understood” (Turner, 1989, p.171). Identification and quantification of landscapes, landscape pattern analysis, is accomplished using landscape indices.

Landscape indices are tools used to identify and quantify landscape structure. As there are hundreds of such indices (McGarigal, 2002), many providing redundant data, how does a researcher select those indices relevant to the issue under study? For some analyses, that work has already been accomplished by McGarigal, Marks, Ene, & Holmes (n.d.) who devised FRAGSTATS, a software program for quantifying landscape structure. The FRAGSTATS program consists of a variety of metrics, analyzed for their utility in various applications, and automated statistical analysis to simplify the search for and use of metrics for landscape analysis. The relevance of metrics selected for a specific purpose is dependent on the scale or level of the analysis.

Landscapes are measured at various levels from patch or class to landscape, depending on the issue under scrutiny. Patch-level indices measure every patch in the landscape returning information on the “spatial character and context of individual patches” (McGarigal, 2002, p. 2) and on how each patch composition varies from the class and landscape norms. Class-level indices measure the distribution of landscape patches that have similar characteristics (class), such as size or shape. Landscape-level indices, used to assess fragmentation and habitat loss, measure the characteristics of composition and configuration across all patches in all classes over the entire landscape (McGarigal, 2002). The landscape-level metrics measure the pattern and process relationships of fragmentation, relationships that change over time.

Landscape pattern analysis and GIS combine in a powerful partnership enabling researchers to import or create datasets, store, display, manipulate, analyze, and share them, as well as a means to produce graphical representations of the resulting analysis.

Statistics are useful for telling the story of fragmentation and habitat loss, but a picture is still worth a thousand words.

The Mojave Desert occupies an area of approximately 57,000 sq km between California, Arizona, Nevada, and Utah (Figure 1). It is an arid place with rainfall generally less than 6 inches per year and, in summer, there is the extreme heat, greater than 120 degrees in Death Valley. The desert is dotted with towns and cities along the major highways and is home to a variety of plant and animal species, among them, the desert tortoise.

Figure 1. The Mojave Desert.

Gopherus agassizii (Figure 2), listed as a threatened species at the state and federal levels (Boarman, n.d.), is a land-dwelling turtle, one of three species of tortoise in North America, and is found in the Mojave and Sonoran Deserts of California, Arizona, Nevada, Utah, and Mexico (Berry, 1990). The desert tortoise home range is between 300 m and 2 sq. km. with overlapping home ranges being common (Duda, Krzysik, & Meloche, 2002). Within the home range, the tortoise maintains a system of burrows between which it will move, depending on food availability or climate during a season (Duda et al., 2002).

Figure 2. Tortoise walking (Massar, 2002, Redlands Institute).

The Desert Tortoise Habitat Potential Knowledge Base (HPKB), compiled by the Redlands Institute Decision Support Team (2004) and based on the knowledge of desert tortoise experts, establishes a baseline for a suitable desert tortoise habitat based on observed tortoise preferences for such factors as elevation, slope, geomorphology/soil for burrows, and vegetation for both food and retreat sites. Some of this information was used to prepare a desert tortoise potential habitat area model that serves as the foundation for this inquiry. I will provide more detail in a later section.

“To survive the harsh environment of the hot, dry desert, desert tortoises spend much of the year in burrows dug under shrubs or in caliche caves.” (Berry, 1990, para. 3; U.S. Fish and Wildlife Service, 1998, para. 3). They hibernate in their underground burrows between late fall (October) and late winter (February – March) and are most active in the spring when they come out of their burrows to feast on tender spring annual and perennial flowers and grasses and to reproduce (U. S. Fish & Wildlife Service, 1998, para. 3). In the heat of the summer, they return to the burrow, coming out in the early morning, late evening, or after a rain (Berry, 1990). The Wildlife Fact Sheet states that the burrowing and spring feeding make the desert tortoise “vulnerable to any activity that disturbs the earth or changes their habitat,” (U. S. Fish & Wildlife Service, 1998, p 1). These activities include construction/urbanization, agriculture, and mining that cause significant habitat losses. They also include military maneuvers and ORV activities that unintentionally cause burrows to collapse or destroy tortoise food sources (U. S. Fish & Wildlife Service, 1998, Fact Sheet).

The desert tortoise has been called the "flagship species of the Mojave Desert" (Spotila, 1999, para. 2). Highly sensitive to changes in its environment, declines in the desert tortoise population indicate broader problems in the ecosystem of the Mojave Desert. Declines, resulting from increasing human activities in the region, were first recognized during the 1970s, with organized efforts to protect the desert tortoise, specifically the Mojave population, originating in the 1980s (Berry, 1997). The desert tortoise, was listed as “Threatened” “over 30% of its geographic range” by the U.S. Fish & Wildlife Service (USFWS) in 1990 (Berry, 1997, p. 1; Boarman, Sazaki, & Jennings, 1997, p. 54). The reasons for the listing included deterioration and loss of habitat, elevated levels of predation, loss from disease, human collection of tortoises, and inadequate laws to protect the species (Fish & Wildlife Service, 1994). The Desert Tortoise 1994 Recovery Plan (Fish & Wildlife Service, 1994) was the first of many efforts to preserve and manage the

species, as well as providing a springboard for research to help managers formulate policies based on science as opposed to emotion and anecdotes.

Research and conservation efforts on behalf of the desert tortoise have followed similar paths (Lovich, 1999). As awareness of the decline in desert population increased, so did the efforts to find causes of the decline and ways to mitigate it so that the species would continue into the future. Roads and their effects on the desert tortoise habitat have been a consistent focus of that research. That focus, as I will explain in the literature review has been primarily on the direct effects of roads - tortoise mortality (Boarman & Sazaki, 1996; Boarman, Sazaki, & Jennings, 1997; Jennings, 1997). Very little has been written on the indirect effects of roads on the desert tortoise habitat, and most of those have been focused on off-road vehicle (ORV) activities (Brooks & Lair, 2005; Webb & Wilshire, 1983). Studies of the indirect effects of paved and unpaved roads across the entire Mojave Desert are needed to build a picture of how roads change the habitat and what results from those changes.

To begin an analysis of the effects of roads in the Mojave Desert, it is necessary to first identify and characterize roads. A pilot study conducted by McIntosh (n.d.) proposed “a methodology to characterize fragmentation by roads” (McIntosh, n.d., para. 3) in the desert tortoise habitat. The study area included the Fremont-Karner, Superior-Cronese, and Ord-Rodman Desert Wildlife Management Areas (DWMA) of the western Mojave and used landscape indices to “assess fragmentation of desert tortoise habitat” (McIntosh, n.d., para. 3). This paper will expand on that pilot study, using geographic information systems and landscape indices to characterize the regional road fragmentation and habitat loss in the Mojave Desert with a brief discussion of the additional potential for fragmentation due to ORV activity. This study uses an historical data set, so the current status of road fragmentation and loss of habitat will not be reflected. Instead, it can serve as a baseline for future research.

1.1. The Client

Research efforts continued under Dr. Thomas Leuteritz, formerly conservation ecologist with the Redlands Institute and director of the Desert Tortoise Project (DTP). The Redlands Institute Desert Tortoise Project is using Ecosystem Management Decision Support (EMDS) (Heaton, Davenport, Inman, & Burgess, 2004) to assist scientists and managers in understanding the interrelationships, uncertainty, and relative influence of scientific knowledge on modeling desert tortoise habitat. In my initial interview in February 2006, Dr. Leuteritz indicated to me that he had surveyed the desert tortoise community, early in his tenure, asking the community to prioritize the issues that concerned them. One of the high priority issues was to investigate road fragmentation in the Mojave Desert as an initial step to the subsequent analysis of its effects on the desert tortoise.

1.2. Problem Statement

There is no question about whether the Mojave Desert tortoise habitat is fragmented by roads. The question, however, is how fragmented is it? Have roads caused more

fragmentation and loss of habitat in some areas than in others? Do all roads inhibit movement between patches (connectivity)? How are habitat patch sizes and shapes distributed in the Mojave Desert? To answer these questions, it is necessary to understand the nature of road fragmentation in the Mojave Desert. My major independent project will use landscape indices incorporated into Patch Analyst© 3.1 ARC View extension is a geographic information system with techniques to identify, characterize, describe, and quantify road fragmentation as the initial step to assessing the consequences of the Mojave Desert road fragmentation and habitat loss. Patch Analyst 3.1, a tool for quantifying landscape structure, is an extension to ArcView GIS that facilitates spatial analysis of landscape patches, and modeling of attributes associated with patches. Patch Analyst and Patch Analyst (Grid) are not public domain, but may be used free of charge under their attached license agreements. (Elkie, Rempel, & Carr, 1999)

1.3. Scope of Work Overview

This project results from a survey of the desert tortoise community, conducted early in 2005 by my client, to discover and prioritize research areas. A study of road fragmentation in the desert tortoise habitat ranked high on the list of research topics that needed to be done. Dr. Leuteritz requested a study of characterization of the habitat patches by size, shape, composition, and patch connectivity. This project will support the Desert Tortoise Project, a multi-year, multi-million dollar effort, to develop a GIS-based program using advanced sensor technologies and spatial data analysis techniques to support desert tortoise monitoring efforts (The Redlands Institute, n.d.) while creating a baseline for subsequent research. Additionally, it can be incorporated into the Desert Tortoise Decision Support System (DSS).

1.4. Literature Review

1.4.1. Fragmentation and Habitat Loss

Think of a pane of tempered glass as an unbroken landscape. If an object were to hit the glass, it would fracture immediately, with the smallest pieces located near the impact area. Habitats, like panes of glass, are subject to fragmentation, especially where humans are involved. A secondary effect of the fragmentation is edge avoidance. Broken glass results in many sharp edges that can potentially inflict damage. Habitat loss has a similar effect. A fragmented habitat has more edges and some edges, like those near roads, can pose dangers to a broader area of a habitat. Among those dangers posed by increased fragmentation by roads are the reduction and/or replacement by invasive species of food sources, toxic pollutants entering the food chain, and increased opportunities for vehicular homicide. Those edges are avoided, to one degree or another depending on species, resulting in less useable habitat.

Unlike the second that it takes to break glass, fragmentation and habitat loss evolve over time (McGarigal et al., 2006; Turner, 1989). Fragmentation and habitat loss are the results of ecological processes. Ecological processes are the continuous actions and reactions of the landscape to the basic elements of earth (landslides, earthquakes), water (rain), fire, air (wind), along with temperature and human activities. These elements work to reshape, build, erode, fragment, and revitalize the constantly evolving landscape structure.

Fahrig (2003) found that there are many ways to define habitat fragmentation when it comes to studies on biodiversity, including some that take account of the effects of habitat loss. Nevertheless, in her conclusion, she suggests that fragmentation and habitat loss should be viewed separately because the consequences of each are not the same. For example, natural fragmentation occurs when heavy rains cause gullies or washes in the landscape. These forms of fragmentation usually cause temporary problems within a habitat – gullies or washes can be crossed, once the rain ends. The results of fragmentation can result in good, bad, or inconsequential effects.

Unnatural fragmentation is the result of human activity, such as paved-road construction. These forms of fragmentation cause more severe and permanent damage to the landscape because they tend to result in habitat loss. The permanent loss of habitat is largely the result of human activity (McGarigal & Marks, 1995) and it has “has large, consistently negative effects on biodiversity” (Fahrig, 2003).

Forman & Alexander (1998) studied the issue of “local hydrologic and erosion effects,” and at the chemical affects of run-off from roads. Nevertheless, the consequences of traffic, noise, and chemicals from cars, trucks, and motorcycles extend beyond a road into a “road-effect zone” (Forman & Alexander, 1998, Abstract; see also Forman & Deblinger, 2000). This zone, which can vary in width along the length of a road, is an area that wildlife will avoid, thereby reducing the amount of useable habitat. Forman & Deblinger (2000) determined that the road-effect zone for one road in Massachusetts extended approximately 0.6 km for direct effects to nearby streams and native plants, and also for indirect road-avoidance effects.

Von Seckendorff Hoff & Marlow (2002) conducted an investigation into desert tortoise road-avoidance distances in southern Nevada. They selected five paved (US 95, SR163, SR 164, SR 165, and Loran) and two unpaved (graded)roads (BC 1 and BC 2) “in relatively homogeneous creosote scrub habitat, with a low elevational gradient and, where possible, out of proximity to roads other than the one defining the site,” (p. 450). Data for traffic density on four of the paved roads, monitored by the Nevada Department of Transportation over a decade (1982-1992) was used to assess the impact of increased traffic on road avoidance. Their conclusion described a direct correlation between higher traffic levels (220 – 5000 average vehicles per day) (p. 454) and greater road avoidance distances. A more startling finding was that the avoidance distances extended out to over 4000m from the more highly trafficked roads (see Table 1).

Table 1. Degradation of suitability from Seckendorff Hoff & Marlow (p. 455).

Road	Distance through conserved tortoise area (km)	Detectable reduction distance from the road (km)	Total impacted area both sides of the road (ha)	Road type
US 95	61.6	4.25	51,414	paved, multi[lane
SR 163	22.08	3.15	13,606	paved, multilane
SR 164	27.84	2.15	11,842	paved, dual lanes
SR 165	21.28	2.25	9,323	paved, dual lanes
Loran		0	0	paved, dual lanes
BC1	41.6	1.39	11,087	unpaved, dual lanes
BC 2	23.2	1.09	5,115	unpaved, dual lanes
Total			102,387	

Another cause of habitat loss is urbanization (van Dorp & Opdam, 1987). One development, in Coyote Springs, Nevada will occupy “a 67 square miles tract of empty desert . . . that, until recently, its best use was thought to be as a weapons range” (Neubauer & Cooper, 2006, p. C1). Nearly one-third of the site is under “title” to the federal government “to maintain a preserve for the desert tortoise” (Neubauer & Cooper, 2006, p. C9). That is equivalent to approximately 22 square miles of desert tortoise habitat lost. The article indicated that a land swap had been negotiated and the desert tortoises would be moved to another location. However, Neubauer and Cooper (2006) indicated that there was no federal appraisal conducted to “determine whether the [new] land . . . was equal in value to the land” (p. C9) given up by the government. There was no mention of whether the land was comparable for tortoise habitat.

Not all roads pose the same problems in a given habitat. The effects of road fragmentation and habitat loss can be ranked from least to greatest impacts. Paved roads (Figure 3) would fall under the greatest impacts because they are permanent, well traveled, frequently at high speed, and act as barriers to most wildlife. Unpaved or gravel roads would have fewer impacts because they are used less, usually at somewhat lower speeds, and because they do not necessarily create insurmountable obstacles to wildlife. Dirt tracks, like those used for ORV, would fall towards the greatest impacts because of the damage such vehicles inflict on the habitat and wildlife (Brooks & Lair, 2005; Jones, 1999).

Figure 3. Desert road (Redlands Institute).

GIS has proved to be a useful tool to analyze the indirect effects of roads. Forman delved into the width and density discussion of the “road-effect zone” with two articles. In the first, Forman (2000) estimated the amount of US land ecologically impacted within the road-effect zone, a zone of negative and indirect effects that extend outward an estimated 100 meters or more from the roads. This ecological zone, he indicates, is fertile ground for invasive plants, run-off of salts and other pollutants, and reconfiguring of drainage patterns. In the second, Forman & Deblinger (2000) applied GIS to the road-effect zone along a suburban Massachusetts highway that was part of an earlier study (Forman & Deblinger, 1998, as cited in 2000), providing a more focused assessment of the problem. They found that the road-effect zone varied in width, from 100 meters to over 300 meters, along the length of their subject road. Road noise and traffic kills also affect species, primarily large mammals (moose and deer populations) which can change their behaviors (road avoidance), extending the road-effect zones even further.

Girvetz and Shilling (2003) developed a means to analyze road systems for environmental impact. The Ecosystem Management Decision Support (EMDS¹) program, a custom-made knowledge base tested in the Tahoe National Forest (TNF), determined the effectiveness of the model at identifying roads that were or potentially could cause environmental harm to the Tahoe habitats. The model brought together TNF-owned spatial data sets (road [1:24,000], streams, digital elevation data (DEM) soils, and biological data), the EMDS, a set of experts (TNF managers) who were able to contribute to the knowledge base, and a second set of experts (transportation engineers) who evaluated and verified the results. The powerful combination of GIS tools, a knowledge base, and expertise resulted in an assessment that the TNF road network was larger than necessary.

¹ “The Ecosystem Management Decision Support (EMDS) system is an application framework for knowledge-based decision support of ecological assessments at any geographic scale. The system integrates state-of-the-art geographic information system (GIS) as well as knowledge-based reasoning and decision modeling technologies in the Microsoft Windows® (hereafter, Windows) environment to provide decision support for a substantial portion of the adaptive management process of ecosystem management.” From <http://www.institute.redlands.edu/emds/>

Road fragmentation studies are enhanced by the application of landscape indices and metrics, along with GIS techniques to assess the impacts on habitats. In a Wilderness Society report (Thomson, Weller, & Severtsen, 2003), landscape metrics were used to measure the impact of “human-induced disturbances” (p. 13) in a forest habitat in the northern Cascade Range. The authors applied edge density, mean patch size, and core area metrics with GIS to determine the “degree of fragmentation that stems from clear-cutting and road construction . . .,” (p. 13) and then compared their findings with historical data. The authors applied auto-correlation techniques at coarse and fine scales to show the differences and similarities in the road effects. This technique worked well for forested areas, allowing them to see the visible scars of logging roads and clear-cut areas and logging on the landscape. The application of a similar technique to the more subtle desert landscape may be less successful.

Deuling, Woudsma, and Franklin (2000) integrated remote sensing techniques, landscape models, and GIS to assess changes in the habitat composition between 1975 and 1997 in the early winter habitat for woodland caribou. Their study area, near Revelstoke, British Columbia, was an area of timber harvesting and wildfires. Using a habitat suitability index (HSI), along with patch and core area metrics, they were able to quantify a decrease in habitat area of over 8% in the 22-year period, along with changes in “geometric complexity and interior core area” (p. 1). At the same time, they noted increases in “patch abundance, patch density, and edge density” (p. 1). “The value of this work can be recognized on a number of fronts. It represents further support for the need to manage more effectively resource extractive activities. It provides a methodology that can now be used for future environmental monitoring by park managers. Finally, it represents an example of the value of using integrated spatial models in a temporal analysis of environmental change” (p. 8).

1.4.2. Off-road Vehicles (ORV)

“Physical and biological effects of ORVs range from reduction of soil stability to destruction of vegetation, wild animals, and their habitat. The capability of modern ORVs to damage the environment varies according to vehicle design, but it is not possible to drive vehicles on natural terrain that has a soil cover without causing damage, no matter how careful the vehicle operator” (Jones, 1999, section 1.0, para. 1). The American Association for the Advancement of Science Committee on Arid Lands concluded in their 1974 report that “unregulated ORV use of arid areas is ‘a serious threat to the preservation of the environment in a desirable and stable condition’” (1974, as referenced by Webb & Wilshire, 1983, p. 1).

The affordability of ORVs has made them popular toys for weekend warriors. Special areas, like Jawbone Canyon (Figure 4), have been set aside for use by ORV enthusiasts. However, the desire for free space to ride ORV brings many off-roadies to other areas in the desert where there are few inhibitions and insufficient law-enforcement personnel to enforce federal and state regulations protecting the fragile desert ecosystem from ORV-inflicted damage. ORV tire treads, designed for traction, tear at the soil, resulting in increased soil compaction and erosion, changed drainage patterns due to destruction of vegetation – particularly on uphill slopes, transfer of non-native plants into the habitat, and potential fire (Jennings, 1997). Eventually, the “web-like networks of ORV trails

coalesce into broad areas largely denuded of vegetation” (Jones, 1999, Desert Biota section, para. 1). There is also the intentional destruction of wildlife when ORV drivers run over small animals, destroy burrows (Boarman & Sazaki, 1996), or use wildlife for target practice (Boarman, n.d.). Noise, noxious fumes, and air-borne dust levels rise wherever ORV enthusiasts gather, contributing to the deterioration of the habitat.

Figure 4. Jawbone Canyon ORV trails (Redlands Institute).

Brooks and Lair (2005) addressed the impact of off-road vehicle traffic, more commonly known as ORV trails on the desert ecosystem. ORV trails are under-represented in official road databases, leading to an underestimation of the number of roads and, consequently, an underestimation of the effects of roads on ecosystems. The study provides an example of the problem, “habitat fragmentation is often cited as an ecological effect of vehicular routes, but his effect may be more pronounced where routes create major structural gaps in forests than where the contrast between vehicular route corridors and the surrounding landscape are more subtle, such as shrublands” (p. 2). The population growth in southern California has resulted in increased tourism in the Mojave Desert.

Because vehicular routes facilitate people’s access to the landscape, the presence of routes exacerbates all human mediated disturbances. In fact, the intensity of disturbance within and adjacent to vehicular routes, coupled with recurrent disturbance along routes that have high rates of vehicular travel and repeated disturbance from regular route maintenance, make vehicular routes one of the most intense and pervasive forms of anthropogenic disturbance in the Mojave Desert. (p. 3)

The “conceptual framework [created by Brooks & Lair (2005)] describing the ecological characteristics of various types of vehicular routes from [ORV] trails to limited-access highways” which includes a look at the effects at three spatial scales, is an excellent foundation upon which to build further research on this issue.

1.4.3. Landscape Indices

GIS is a window through which we can display, manipulate, visualize, analyze, and document the results of research in ways that are relatively easy to understand and, if prepared correctly, to interpret. However, some studies, such as fragmentation and habitat loss, require additional tools to understand the landscape. Among these additional tools are FRAGSTATS (McGarigal, et al., n.d.) and Patch Analyst (Elkie, Rempel, & Carr, 1999). Both tools use mechanisms to measure or quantify and analyze aspects of landscape structure and to enhance land use decision-making. These mechanisms are landscape indices.

“Landscape ecology, if not ecology in general, is largely founded on the notion that environmental patterns strongly influence ecological processes” (Turner, 1989). McGarigal, et al. (2006) identifies processes that are related to habitat fragmentation, resulting in changing landscape patterns, as follows:

. . . Habitat fragmentation creates discontinuities (i.e., patchiness) in the distribution of critical resources (e.g., food, cover, water) and environmental conditions (e.g., microclimates), and these patterns change over time in response to the fragmentation process. From the perspective of an organism, these discontinuities create variability in the distribution of suitable habitat, where suitable habitat is the combination of food, cover, water, and space necessary to sustain an individual. Ultimately, physical changes in the extent and connectivity of suitable habitat conditions affect many processes that influence the behavior and spatial habitat use patterns of individuals, and alter intra- and inter-specific interactions that influence population persistence and community structure and dynamics (McGarigal, et al., 2006, p.14)

Landscape pattern analysis is a method of quantifying the patterns and changes in the landscape (McGarigal, 2002) by means of hundreds of landscape indices (McGarigal, 2002). There are three levels of landscape metrics: patch-level, class-level, and landscape-level. McGarigal (2002) explained the differences as follows:

1. *patch-level* metrics are defined for individual patches, and characterize the spatial character and context of patches;
2. *class-level* metrics are integrated over all the patches of a given type. These may be integrated by simple averaging, or through some sort of weighted-averaging scheme that biases estimate to reflect the greater contribution of large patches to the overall index. There are additional aggregate properties at the class level that result from the unique configuration of patches across the landscape;
3. *landscape-level* metrics are integrated over all patch types or classes over the full extent of the data (i.e., the entire landscape). Like class metrics, these may be integrated by a simple or weighted average, or may reflect aggregate properties of the patch mosaic. (p. 2)

Rutledge (2003) characterized indices as either non-spatial or spatial. Non-spatial indices “describe landscape composition and include measurements of the number of patch classes or proportions of total area” (p.10). Spatial indices “describe patch attributes and

contain information relevant to measuring fragmentation” (p. 11) He also categorizes spatial indices into three groups that “describe patch composition, shape, and configuration,” (p. 11) concluding that patch composition indices are most relevant to the discussion of fragmentation, but traditionalists would include all three sub-categories, along with habitat loss.

Patch composition indices (Figure 5) “describe the basic characteristics of fragmentation” (Rutledge, 2003, p. 11) looking at the number, area, and density of patches and the core area of the patches. These types of indices are “based on an organism’s space requirements” (McIntosh, n.d., p. 2), although patch number and density may not be tied to an ecological process. Core area, and the core area index, may better reflect ecological processes affecting movement between core areas (Rutledge, 2003, p. 13).

Name	Symbol	Value	Description	Formula	Scale
Number of Patches	NP	$1 \leq NP \leq N_{max}$	Number of patches (by class)	-	class or landscape
Mean Patch Size	MPS	$A_{min} < MPS \leq A_{tot}$	Average area of a patch (by class)	$MPS = \sum_{i=1}^n AREA_i / n$	class or landscape
Largest Patch Index	LPI	$0 < LPI \leq 1$	Percentage of the total landscape area occupied by the largest patch (by class)	$LPI = \frac{\max(a_{ij})}{A} (100)$	landscape
Patch Density	PD	$0 \leq PD$	Number of patches per unit area (by class)	$PD = \frac{N}{A}$ where N = the total number of patches and A is the total landscape area. Fragstats outputs in number of patches per 100 hectares	class or landscape
Splitting Index	S	$0 < S \leq N_{max}$	Number of equal sized patches of a class required to produce a specified degree of landscape division.	$S = \frac{A^2}{\sum_{j=1}^n a_{ij}^2}$ A is total landscape area and a_{ij} is the area of patch ij	class or landscape
Effective Mesh Size	m	$A_{min} < m \leq A_{tot}$	Area of the equal sized patches of a class required to produce a specified degree of landscape division. Related to the Splitting Index.	$m = \frac{\sum_{j=1}^n a_{ij}^2}{A}$ a_{ij} is the area of patch ij and A is the total landscape area	class or landscape
Average Patch Carrying Capacity	K_{avg}	$0 < K_{avg} < K_{max}$	the number of pairs sustained by the average patch size (by class)	$K_{avg} = \sum_{i=1}^n (AREA_i / IAR_s) / n$ Where IAR_s is the area requirement for a reproductive unit and $AREA_i$ is the area of the patch i	class
Core Area	$CORE$	$CORE \geq 0$	Area whose boundary is a specified distance inwards from the patch edge	-	patch or class
Core Area Index	CAI	$0 \leq CAI \leq 1$	percentage of the area of a patch that is core area.	$CAI = \frac{a_{ij}^c}{a_{ij}} (100)$ where a_{ij}^c is the core area of a patch and a_{ij} is the total area of the patch	patch or class

Figure 5. Composition indices (modified from Rutledge, 2003, as cited in McIntosh, n.d., p. 2).

Shape indices (Figure 6) describe patch complexity and may reflect ecological processes (Rutledge, 2003). The circle and square are simple compact shapes with minimal edge and maximum core area, according to Rutledge. However, linear features, like rivers, are

more complex, long and narrow, shapes with maximum edge but relatively little core area in comparison to total area (p. 13). Many patch shape measurements consider the “perimeter-to-area ratio” which “suffers from a negative relationship with size, given the same shape” (Rutledge, 2003, p. 13). A patch shape index compares the perimeter-to-area ratio to a simple compact shape, solving the size problem, albeit forcing the user to select either a circle or square as a reference shape.

Name	Symbol	Value	Description	Formula	Scale
Perimeter:area ratio	P/A	$0 \leq P/A$	Ratio of perimeter to area. For a given shape, depends on patch area. For example the area perimeter ratio of a 1x1 square is 1/4 while the area perimeter ratio of a 4x4 square is 1.	$PARA = \frac{P_{ij}}{a_{ij}}$	Patch or class
Shape Index	SI	$1 \leq SI$	Ratio of perimeter to area adjusted by a constant to account for a particular patch shape (usually a square). Not dependent on patch area	$SHAPE = \frac{P_{ij}}{\min(p_{ij})}$ where $\min(p_{ij})$ is the perimeter of a square patch of the same area.	patch, class, or landscape
Fractal Dimension Index	$FRAC$	$1 \leq FRAC \leq 2$	Fractal Dimension. Similar to the perimeter to area ratio but does not depend on patch area	$FRAC = \frac{2 \ln(.25 p_{ij})}{\ln a_{ij}}$	landscape
Square Pixel	SqP	$0 \leq SqP \leq 1$	measures the deviation from a square shape	$SqP = 1 - (4 * A^{1/2} / p)$ Where A = total area, and P is the total perimeter of all pixels in the study area	landscape

Figure 6. Shape indices (modified from Rutledge, 2003, as cited in McIntosh, n.d., p. 3).

Configuration indices (Figure 7) describe, “how connected or isolated patches are relative to other patches in the landscape” (McIntosh, n.d., p. 3). Rutledge (2003) classifies configuration indices into two groups; those that describe “distances between patches” and those that describe “the overall spatial pattern” (p. 14) or texture of the landscape. “Distance-based configurations range from a simple edge-to-edge distance to more complex metrics [that] incorporate other factors such as size of the nearby patches” (McIntosh, n.d., p. 3).

Name	Symbol	Value	Description	Formula	Scale
Nearest Neighbor	d_{ij}	$0 < d_{ij} < D_{max}$	Distance from patch i to the nearest occupied patch j	-	patch, mean nearest neighbor for class and landscape
Proximity Index	$PROX$	$PROX \geq 0$	Sum of the area of all patches within a given distance of a focal patch normalized by the square of the distance between the patch and focal patch edge	$PROX = \sum_{i=1}^n \frac{a_{ij}}{h_{ij}^2}$ where a_{ij} is the area of a patch ijs within a specified neighborhood of patch ij and h_{ij} is the edge to edge distance between the patches	Patch, Mean proximity index for class and landscape
Connectance Index	$CONNECT$	$0 \leq s_i \leq s_{i,max}$	Measures the connectedness of the focal patch to all possible source populations	$CONNECT = \left[\frac{\sum_{j=1}^n c_{jk}}{n_i(n_i - 1)} \right] * (100)$ where c_{jk} is a binary (0=unjoined and 1=joined) between patch j and k and n_i is the number of patches in the landscape of the corresponding patch type(class)	class and landscape, formula for class shown
Patch Cohesion	$COHESION$	$0 \leq PC \leq 100$	Proportional to area weighted perimeter:area ratio divided by the area weighted mean shape index	$COHESION = 1 - \left[\frac{\sum_{i=1}^n p_{ij}}{\sum_{i=1}^n p_{ij} \sqrt{a_{ij}}} \right] * \left[1 - \frac{1}{\sqrt{A}} \right]^{-1} * 100$ p_{ij} = perimeter of patch ij in terms of number of cell surfaces, a_{ij} = area of patch ij in terms of number of cells, and A = total number of cells in the landscape.	class and landscape (formula for class shown)
Contagion	$CONTAG$	$0 < CONTAG \leq 100$	Measures the degree of adjacency or clumpiness of a map based on adjacency of cells. Note: different patterns can produce the same index value.	$CONTAG = \left[1 + \frac{\sum_{i=1}^m \sum_{k=1}^m p_i \left(\frac{g_{ik}}{\sum_{k=1}^m g_{ik}} \right) * \left[\ln \left(\frac{g_{ik}}{\sum_{k=1}^m g_{ik}} \right) \right]}{2 \ln(m)} \right] * 100$ where P_i =proportion of the landscape occupied by patch type (class) i, g_{ik} =number of adjacencies (joins) between pixels of patch types (classes) i and k based on the double-count method and m =number of patch types (classes) present in the landscape, including the landscape border if present.	Landscape
Interspersion/Juxtaposition	IJI	$0 \leq IJI \leq 100$	measures the degree of aggregation or clumpiness of a map based on adjacency of patches	$IJI = \frac{\sum_{k=1}^n \left[\left(\frac{e_{ik}}{\sum_{k=1}^n e_{ik}} \right) \ln \left(\frac{e_{ik}}{\sum_{k=1}^n e_{ik}} \right) \right]}{\ln(m-1)} * 100$ e_{ik} = total length (m) of edges in landscape between patch types (classes) i and k, m = number of patch types (classes) present in the landscape, including the landscape border, if present, and E= total length of edge in the landscape excluding background.	class and landscape (formula for class shown)
Landscape Division Index	$DIVISION$	$0 \leq Division \leq 1$	probability that two randomly selected places in a landscape are not in the same patch	$DIVISION = \left[1 - \sum_{i=1}^m \left(\frac{a_{ij}}{A} \right)^2 \right]$ a_{ij} = area (m^2) of patch ij and A = total landscape area (m^2).	class and landscape (formula for class shown)
Lacunarity	L	$1/P < L < 1$	A measure of image texture.	See Plotnick et al 1993 for details on the gliding box algorithm	Landscape
Graph Theory	various	-	measure the connectness of patches based as nodes in a graph		

Figure 7. Configuration indices (modified from Rutledge, 2003, as cited in McIntosh, n.d., p. 4).

With hundreds of indices to choose from, how does a user determine which of the many landscape indices will be useful for a particular analysis? McGarigal (2002) includes a lengthy discussion on the “limitations in the use and interpretation of metrics” (p. 5), where he indicates that there have been attempts (Li & Reynolds, 1994; McGarigal & McComb, 1995; Ritters, et al., 1995, as cited in McGarigal, 2002) to “identify the major components of landscape pattern for the purpose of identifying a parsimonious suite of independent metrics” (p. 5). However, the community of users has not agreed to any of the resulting choices. Rather, McGarigal proposes that, “the choice of metrics should

explicitly reflect some hypothesis about the observed landscape pattern and what processes or constraints might be responsible for that pattern, and how that pattern relates to the process under investigation.

1.5. Analysis Tools

A number of tools have been developed over the last two decades, such as FRAGSTATS, and Patch Analyst, to make the task of selecting and processing landscape indices easier. FRAGSTATS, a spatial analysis program for categorical maps, is “a computer software program designed to compute a wide variety of landscape metrics for categorical map patterns,” (McGarigal, et al., n.d.). The FRAGSTATS User Guide includes discussions on how to use and interpret indices, along with some of the limitations and pitfalls of interpreting them. FRAGSTATS is a sophisticated program, with a wide variety of indices from which to choose. It is a tool requiring more training and some experience to fully understand and correctly interpret the resulting data (McGarigal, et al., n.d., Abstract), suggesting that it is intended for researchers in ecology fields rather than GIS professionals. FRAGSTATS comes as a stand-alone application or as an extension to ArcView 3. The program can compute 14 patch indices, 40 class indices, and 46 landscape indices in a relatively user-friendly interface. Figure 8 shows the initial FRAGSTATS user interface. Additional workboxes for class, landscape, and patch metrics allow the user to tailor the available metrics to the particular issue under study.

Figure 8. FRAGSTATS interface and run parameters workbox (FRAGSTATS 3.3, 2002, August).

Elkie, Rempel, & Carr (1999) developed Patch Analyst, another software program that incorporates aspects of the FRAGSTATS program into an ArcView extension, allowing

for broader use of landscape metrics by GIS professionals. The full version of Patch Analyst allows the user to analyze both vector and raster data structures, but it requires the ESRI Spatial Analyst extension. Elkie, et al. (1999) explained Patch Analyst's capabilities as follows:

Patch Analyst 3 contains analysis and modeling functions related to polygons, while Patch Analyst (Grid) 3 extends analysis capabilities to grids and, therefore, requires Spatial Analyst. Patch Analyst (Grid) includes a user interface to the PC raster version of FRAGSTATS 2, as well as separate Avenue based spatial analysis functions. . . . Numerous patch metrics are calculated, and these include mean and median patch size, patch size coefficient of variance, edge density, mean shape index, fractal dimension, interspersions and juxtaposition, Shannon's diversity index, and core area index. Summary statistics are reported at the patch or landscape scale. The various patch metrics follow the definitions in FRAGSTATS (McGarigal & Marks 1993). Processing of grid format themes is done through either Avenue code, or through an interface to a specially compiled version of the PC version of FRAGSTATS 2 (from <http://flash.lakeheadu.ca/~rrempe/p/patch/>)

Figure 9 shows the ArcView 3.3 interface with the Patch Analyst extension polygon analysis menu active. Figure 10 shows the same interface with the Patch Analyst extension GRID analysis menu active. Figure 11 is the Spatial Statistics Workbox that allows the user to tailor metrics for particular issues under study.

Figure 9. Patch Analyst Extension for Vector/Polygon analysis in Arc View 3.3.

Figure 10. Patch Analyst Extension for ArcGRID analysis in ArcView 3.3.

Figure 11. Patch Analyst spatial statistic workbook.

1.6. Proposed Solution

Fragmentation and habitat loss are processes that evolve with time. A homogeneous area can be dissected by natural processes, such as rain (flooding), fire, and changes in the earth (earthquakes), or unnatural processes that result from human activity. Nevertheless, these processes can only be observed as discrete points in time. It is through the compilation of those discrete points in time, into a comprehensive analysis, that the effects of fragmentation and habitat loss be visualized and used to support land management decisions (land-use planning), base expansion, and conservation effort. This project is the first step in that analysis.

McIntosh (n. d.) conducted a pilot study to establish a conceptual model for analysis of fragmentation in the Mojave Desert tortoise habitat. He incorporated landscape indices to characterize changes in the habitat, and GIS to illustrate the results of his findings. My major independent project will expand on that pilot study to cover the broader desert tortoise habitat in the Mojave Desert, combining the capabilities of ArcGIS 9.1©, ArcView 3.3, and the vector analysis tools in Patch Analyst 3.1. One part of this analysis will include building a habitat suitability model in ArcGIS 9.1, using data from the shuttle radar topography mission (SRTM), the Mojave Desert Ecosystem Program (MDEP) and the Desert Tortoise Project Habitat Potential Knowledge Base (HPKB) (Redlands Institute Decision Support Team, 2004) so as to determine the extent of the potential desert tortoise habitat within the Mojave Desert. The second part of the analysis will use Patch Analyst 3.1© to characterize the landscape defined as the potential habitat extent, along with the size, shape, composition, and connectivity of patches resulting from the road network in the Mojave Desert. The third part will apply the techniques used in part two to a subset of the Mojave Desert designated for ORV use to characterize the resulting landscape. ArcGIS 9.1© will be used to display and produce maps that document the findings from this project.

2. Project Development and Methodology

This project did not involve the design or development of software. It was undertaken to discover and learn how to apply GIS capabilities to answer a question. As a result, the project management aspects were not as involved as they might have been for another project. I have included those elements of project management that I felt were most important to this project.

2.1. System Requirements

There is no specific hardware requirement for this project. Since the primary software that will be used for the project is ArcGIS, there is a requirement for a geodatabase, which will be discussed in more detail in section 2.4.

2.2. System Description

The personal geodatabase is structured within ArcGIS for archiving, manipulating, and displaying the original input data and output results gathered from the analysis of the desert tortoise habitat, including the results derived from statistical analysis, all in one compact container with all relevant domains, a standardized spatial reference, projection, and format. For this project, two personal geodatabases will contain all of the project data. Upon completion of the project, those geodatabases will be retrievable from the Redlands Institute server. A user electing to create a follow-on project will not need to hunt for datasets in numerous disparate files, instead, users will find all of the project data in two geodatabases and will be able to select and display datasets, manipulate (add, delete, modify) datasets, create new datasets, store topology, change symbology, label or annotate, and run datasets through spatial and/or statistical analysis tools for further research.

2.3. System Environment

The Redlands Institute “maintains a fully networked, multi-operating system, state-of-the-art computing [environment] . . . with 30 XP-based workstations for the laboratory and staff and over 4 TB of on-line storage and high-speed tape backup with off-site media storage” (J. Laska, personal communication, June 22, 2006). This network is separate from that of the University of Redlands. The personal geodatabases will reside on one of the network enterprise servers and will be accessible from any workstation that is equipped with GIS software within the Redlands Institute. Users will access the geodatabase by first logging into the RI network. The geodatabase can store up to 2 gigabytes of information.

2.4. Geodatabase Design

The geodatabase framework, based on Microsoft Access, provides storage for geographic information allowing large datasets to be stored, retrieved, and analyzed with associated

data models, topology, relationship and annotation classes, domains, and attribute tables from a single source. For this study, two personal geodatabases were constructed in order to avoid exceeding the Microsoft Access 2 gigabyte size limitation for the large foundational MDEP datasets and the many follow-on datasets created as a result of the analysis. One geodatabase was designed to store primarily raster data for the suitable habitat analysis, and the second geodatabase was designed to store the feature datasets used and/or created from the analysis. The feature and raster datasets share the same projection and coordinate systems. Federal Geographic Data Committee (FGDC) standards were imposed on all metadata.

Figure 12. Project geodatabase design.

The functional design requirements for the construction of the geodatabases are listed in Table 2.

Table 2. Geodatabase Functional Design.

Function	Output
Data Input	Environmental Data
Extension	Patch Analyst
Display	Operator Interface
Product Statistical Analysis	Display Graphics
Product Output	Tables
Product Output	Report
Product Output	Paper Maps
Product Output	Poster
Product Output	CD

Environmental data is based on the Habitat Potential Knowledge Base, which summarizes “the knowledge and data collected and synthesized in support of the Desert Tortoise Project (DTP) Decision Support System (DSS) team’s desert tortoise habitat modeling efforts. The purpose of this paper is to provide desert tortoise scientists and Mojave land managers with the knowledge, data, and methods used by the DSS team to model knowledge about desert tortoise habitat and to evaluate that knowledge in a geographic information system (GIS). This information is intended to help (a) identify gaps in knowledge and data regarding desert tortoise habitat, (b) enhance the knowledge and data resources available to the desert tortoise community, (c) provide a baseline for evaluating threats to habitat and (d) support decisions that would contribute to species recovery” (Redlands Institute Decision Support Team, 2004).

2.5. Project Implementation

Project implementation was conducted in three phases. The first phase was to establish the final study area. The second phase was to prepare the suitable habitat data for analysis. Phase three involved Patch Analyst and the statistical analysis of the suitable habitat data. Data for this project (Table 3) included Digital elevation models from the US Geological Survey, coverages from the MDEP, and road data from the Census TIGER Line.

Twenty DEM, covering the California, Arizona, Nevada, and Utah portions of the Mojave extent, were retrieved from the USGS Earth Resources Observation and Science (EROS) Geographic Data Download website (<http://edc.usgs.gov/geodata/>). The 30-meter/1-arc-second raster datasets were collected in 2000 as part of the SRTM Dataset.

The MDEP was the source of the Mojave extent, geomorphology, land cover, and soil datasets. These datasets were retrieved from the set of eight CD-ROMs, along with a copy of the report, in a portfolio borrowed from the ESRI Library. The data is also available from the official MDEP website.

A road dataset compiled by the Census Bureau and conforming to the Census Feature Class Code (CFCC) system was retrieved from the Redlands Institute data archives. A road dataset was available within the MDEP. However, the digital line graphic (DLG) road coding system was used for that project and was found to be unworkable for this study.

Table 3. Project foundation datasets.

Data Type	Feature Class	Feature Type	Geometry type	Notes
BOUNDARY Personal geodatabase feature class	The following dataset contains the boundary of the Mojave Desert: ba322_polygon_extent	coverage	polygon	Source: R. G. Bailey Ecosystems of the United States (1994), as referenced in the MDEP) and is taken from the Mojave Desert Ecosystem Program (MDEP) data CD's borrowed from the ESRI Library.
GEOMORPHOLOGY Personal geodatabase feature class	This dataset contains information on the geomorphology (age and major composition) of the Mojave Desert: MojGeomorph	coverage	polygon	Source: US Geological Survey/MDEP. The MDEP Geological Dataset was compiled at a scale of 1:500,000 using geological maps of California, Nevada, Arizona, and Utah. Collected: Unknown. Created: 09/20/2006.
LAND COVER Personal geodatabase feature class	This dataset contains information on land cover formations and vegetation in the Mojave Desert: mojveg5a_polygon	coverage	polygon	Source: USGS. Biological Resource Division GAP Vegetation Database (California, Nevada, Arizona, and Utah) at a scale of 1:250,000/MDEP. Collected: Beginning date Unknown. End date 5/15/1998. Created: 09/20/2006.
SOIL Personal geodatabase feature class	This dataset contains information on the soil composition in the Mojave Desert: soils1_polygon	coverage	polygon	Source: National Resources Conservation Service – STATSGO soils database/MDEP. The MDEP Soils Dataset was compiled at a scale of 1:250,000 covering California, Nevada, Arizona, and Utah. The soil attributes are extensive so 5 datasets, each with a different set of related attributes, were included in the MDEP. Collected: Unknown. Created: 09/20/2006.
ROADS Personal geodatabase feature class	This dataset contains information on the road network in the Mojave Desert: MojRoads_cfcc	vector	polyline	Source: Census TIGER Line files. The data was compiled at a scale of 1:50,000 covering Arizona, California, Nevada, and Utah portions of the Mojave Desert. Publication date: 2002.
DEM Personal Geodatabase raster dataset	This dataset consists of digital elevation models that cover the Mojave Desert: 7NovDEM	raster	polygon	Source: NASA/NGA Shuttle Radar Topography Mission. Datasets collected in 2000 at 1 ARC Second (30 by 30 m cells) over Arizona, California, Nevada, and Utah.

Ancillary information was found in the Desert Tortoise Habitat Potential Knowledge Base (Redlands Institute Decision Support Team, 2004), and in documents found in the literature review. More detail is provided in the relevant sections of this chapter.

The project data is archived in two geodatabases. The SuitHabModel database (Figure 13) contains foundational and derived datasets used to produce the potential suitable habitat map. The final suitable habitat data was used to clip all subsequent data sets. The Frag_LossProj database (Figure 14) contains foundational and derived datasets used for the road fragmentation portion of the project. The MDEP datasets were projected in the

NAD_1983_UTM_Zone_11N coordinate system. The geographic datum was North_American 1983 (NAD83).

Figure 13. Potential suitable habitat geodatabase structure.

Figure 14. Fragmentation and loss geodatabase structure.

2.5.1. MDEP Data

The MDEP was a cooperative effort, using the expertise of personnel from the Department of Defense, the U. S. Geological Survey, the Bureau of Land Management, and Utah State University to assemble and integrate the data into the program's database (From www.mojavedata.gov). As mentioned earlier, there are eight CD-ROMs in the MDEP archive, including vector and raster GIS data, tables, a viewing application, and metadata. The Mojave Desert extent, defined by Bailey (1993, as cited in the MDEP), is buffered by 50 km in the MDEP to ensure complete coverage of the area. The Mojave Desert Extent in the MDEP totals approximately 80,000 square miles (MDEP). The buffer was not needed for the current project. The Mojave extent, with road network applied, is shown in Figure 15.

Figure 15. The Mojave Desert road network.

2.5.2. Potential Habitat Suitability Model

Before beginning the fragmentation and loss analysis, it was necessary to define the Mojave Desert boundary for the study area. ArcGIS Model Builder was selected for this task. Model Builder simplifies and automates complex workflows involving multiple datasets, parameters, and processes or tools. The DEM was the source data for the

potential suitable habitat model. Twenty DEM over the study area were downloaded from the MDEP website and imported into Model Builder. The following tools were used in the model:

- Mosaic Data Management – Raster tools
- Extract By Mask (3) Spatial Analyst – Extraction tools
- Reclassify (2) Spatial Analyst – Reclass tools
- Slope Spatial Analyst – Surface tools
- Hillshade Spatial Analyst – Surface tools

Criteria for the model were extracted from the Habitat Potential Knowledge Base (HPKB) (The Redlands Institute Decision Support Team, 2002). The HPKB is a summary of what is currently known about the desert tortoise and its habitat. It is part of a larger Decision Support System (DSS) modeling effort for the Western Mojave habitat. It is “intended to help (a) identify gaps in knowledge and data regarding desert tortoise habitat, (b) enhance the knowledge and data resources available to the desert tortoise community, (c) provide a baseline for evaluating threats to habitat and (d) support decisions that would contribute to species recovery” (Redlands Institute Decision Support Team, 2004, p. v).

According to the HPKB, the highest preferred elevations of the desert tortoise vary by latitude with tortoises found at higher elevations in lower latitudes and lower elevations at higher latitudes. “There is no minimum elevation range, but there is an optimum range dependent on the latitude. Optimum range at low latitudes is between 356 to 1,524 meters. Optimum range at higher latitudes is between 243 to 1,219 meters” (Nussear et al., [personal communication] 2003, as cited in Redlands Institute Decision Support Team, 2004, p.29). Optimum slopes are below 33 degrees (Gardener, T. J. and Brodie, E. D., Jr., 1998 as cited in Redlands Institute Decision Support Team, 2002, Appendix B, p.29).

For the current project, the Western Mojave and the Mojave Desert are considered the same. The models elevation ranged between 243 m for the lowest parameter and 1524 m for the highest. The initial model processes (Figure 16) involved mosaicking nineteen DEM, covering the Mojave Desert extent, between Arizona, California, Nevada, and Utah into a single dataset, masking out the unsuitable elevations and clipping the dataset to the Mojave extent. The second part of the model (Figure 17) involved creating suitable slopes of 33 degrees or less, masking out all unsuitable slopes above 33 degrees. The model result is shown in Figure 18.

Figure 16. Potential suitable habitat model_1.

Figure 17. Potential suitable habitat model_2.

Figure 18. Potential suitable habitat model result. This result represents the selection of elevations between 243 m and 1,524 m in elevation and slopes of 33 degrees or less.

The model result was reclassified so that the value for the habitat was "1" and all other values were "NoData." The Data Management/Features tool, Features to Polygon, was used to create a vector dataset to make clipping subsequent vector format datasets, such as the exclusion datasets in the next step, easier. Using a model to process this data was relatively easy. However, numerous anomalies appeared in the final dataset that would later affect the analysis. Efforts were made to eliminate or, at least reduce, the anomalies were unsuccessful.

2.5.3. Exclusion Datasets

To complete the potential suitable habitat, the desert tortoise preferences for geomorphology, land cover, and soils needed to be considered. "Throughout their range, desert tortoises occur on valley bottoms and bajadas, but may also occur on hillsides and rocky substrates" (Germano et al., 1994, as cited in Redlands Institute Decision Support Team, 2004, p.25). The connection between geomorphology and desert tortoise habitat is still under discussion in the desert tortoise community. Still, "several studies note associations between tortoise presence and physiography" (Germano et al., 1994, Luckenbach 1982, as cited in Redlands Institute Decision Support Team, 2004, p. 25).

Figure 19 is a reproduction of a table from the HPKB (p.25) showing landform type by potential to support desert tortoise habitat.

Habitat Potential	Landform Type*	Comments
High	Alluvial Plains, alluvial fans, bajada, canyon bottomland, fluvial floodplain, fluvial terrace, intramontain alluvial plain, intermontane undifferentiated, and wash.	These landforms or terms synonymous for these landforms were identified by numerous authors and publications (Appendix XX) as suitable desert tortoise habitat.
Moderate	Lacustrine terrace, sand sheet, undifferentiated sediment.	These landforms were listed by one or more authors (Appendix XX) as having tortoises present, but were not highlighted as good tortoise habitat.
Undetermined	Intramontane Undifferentiated, unmapped	Insufficient information was available for these landforms to determine their habitat potential.
Poor	Dune, bedrock plain, Erosional highland, fluvial channel, Inselberg, lava field, alluvial deposit	These landforms were sporadically mentioned, if at all as having the occasional tortoise present, but they are not thought to be important habitats.
None	Playa, reservoir, volcanic highlands	These landforms do not support habitat for the desert tortoise.

Figure 19. Landform type by potential to support desert tortoise habitat (From Heaton, personal communication, as cited in Redlands Institute Decision Support team, 2004, p. 25).

The MDEP geomorphology dataset attributes do not correspond directly to the information in the Figure 17 HPKB table. Nevertheless, it was possible to create an exclusion dataset based on that information in the HPKB by creating a table-join with the geomorphology descriptions table and the dataset attribute table from the MDEP (Table 4). PType is a mapping code that represents the age or geologic period of the rock formation and its composition and/or origin (volcanic, metamorphic, or sedimentary. For example, Jg is Jurassic granite (volcanic) and granitoid, Qp is Quaternary playa (sedimentary), and Tbr is Triassic breccia (metamorphic). The Geomorphology exclusion dataset is illustrated in Figure 20.

Table 4. Geomorphology descriptions by PType.

PType	DESCRIPTION
Jg	Granitoid plutons (Jurassic) Mostly granite and granodiorite.
KJd	Diorite and gabbro plutons (Cretaceous and Jurassic).
Kg	Granitoid plutons (Cretaceous) Mostly granite and granodiorite.
PzXu	Undivided metasedimentary and metavolcanic rocks of great variety (Paleozoic to Early Proterozoic) Slate, quartzite, hornfels, chert, phyllite, mylonite, schist, gneiss, and minor marble, primarily in roof pendants in the Sierra Nevada and eastern California
Qp	Playa deposits (Holocene and Pleistocene) Playa, marsh, and alluvial-flat deposits consisting of silt, clay, salts, and sand; locally includes lacustrine deposits.
TKg	Granitoid plutons (early Tertiary to Late Cretaceous; 55 to 85 Ma) Generally metaluminous granite to diorite and subvolcanic porphyry.
TRg	Mt. Lowe Granodiorite (Triassic) Granitoid rocks and gneiss in the San Gabriel Mountains.
Tao	Older andesite (middle Miocene to Oligocene) Flows and volcanic breccias composed of andesite and related rocks of intermediate composition.
Tay	Young andesite flows (late to middle Miocene) Flows and volcanic breccias composed of andesite and related rocks of intermediate composition.
Tb	Youngest basaltic rocks (Pliocene to late Miocene; 4 to 8 Ma).
Tbay	Young andesite and basalt flows (late to middle Miocene) Interlayered basalt and andesite lava flows. Mostly in ~17 to ~6 m.y. age range. May include rocks younger than 6 m.y. in places.
Tbr	Breccia Volcanic, thrust, and jasperoid breccia and landslide megabreccia.
Tby	Young basaltic rocks (late to middle Miocene; 8 to 17 Ma) Units, such as the Hickey Formation, erupted after most mid-Tertiary volcanism and tectonism.
Tg	Granitoid plutons (Miocene to latest Eocene; 14 to 38 Ma) Mostly granite and granodiorite.
Try	Young rhyolitic flows (late to middle Miocene) Includes shallow intrusive rhyolite locally. Includes andesitic rocks interlayered with rhyolite in Arizona.
Two	Older volcanic rocks (middle Miocene to Oligocene; 15 to 38 Ma) Undivided rhyolitic to basaltic lava flows and pyroclastic rocks; includes some subvolcanic intrusions.
Xg	Granitoid rocks (Early Proterozoic; 1650 to 1750 Ma) Granite, granodiorite, tonalite, quartz diorite, diorite, and gabbro; commonly foliated.
Xm	Metamorphic rocks (Early Proterozoic; 1650 to 1800 Ma) Undivided metasedimentary, metavolcanic, and gneissic rocks, including locally abundant amphibolite, marble, and pegmatite. In places may represent late Proterozoic strata or Mesozoic granitoids met
Xms	Metasedimentary rocks (Early Proterozoic; 1650 to 1800 Ma) Includes Vishnu Schist.
Xmv	Metavolcanic rocks (Early Proterozoic; 1650 to 1800 Ma).
Yg	Granitoid rocks (Middle Proterozoic) Typically porphyritic rapakivi granite; about 1400 Ma.

Figure 20. Geomorphology exclusion dataset.

The soil criteria for the desert tortoise involve “conditions suitable for burrowing or geomorphologic type is suited to the formation of caves, overhangs, or rock outcroppings that the tortoise could use for shelter” (Redlands Institute Decision Support Team, 2004, p. 16). “Desert tortoises often construct their burrows under caliche overhangs exposed in the banks of washes. Caliche overhangs are “hardpan” soil horizons of calcium carbonate crust that form in some desert areas. These layers cement the gravels and cobbles in the soil together, forming a matrix almost as hard as concrete” (Lovich & Daniels 2000, p. 720). Loamy soils (soils with varying percentages of sand, clay, and organic materials), especially sandy-loamy soils, are preferred by the desert tortoise (Duda et al., 2002; Krzysik, 2005).

Soils are complex structures. The US Department of Agriculture, Natural Resources Conservation Service maintains soil data for the United States in two forms, the Soil Survey Geographic (SSURGO 2.2) database, and the State Soil Geographic (STATSGO) Database. Both include spatial and attribute data from the soil survey area; SSURGO data is typically at either 1:12,000 or 1:24,000 scale of mapping. SSURGO data is available for only a limited area (the far southwest corner of San Bernardino County). STATSGO data is available for the Mojave, but at an extremely coarse grain and, with 19 different variables in up to 160 combinations, the data was difficult to interpret. The HPKB did not provide any useful criteria for soils. However, the MDEP Soils1 dataset included fields that described soil content (loamy, sandy, or clay) and an aspect of composition (gravelly,

stony, or rocky). These attributes were used to select the soil exclusion dataset (Figure 21).

The soil exclusion map suggests that soils in California are less suitable for the desert tortoise than the soils of Nevada, Arizona, and Utah. Indeed, Mojave Desert soils of California consist of more sand (too porous) or clay (too compact), many of the areas with large rocks or stones. In Nevada, Utah, and Arizona, the Mojave soils are predominantly loamy with a cobble or gravel content.

Figure 21. Soil exclusion dataset.

The final exclusion dataset consists of land cover types that would be unsuitable for desert tortoise habitat. Those included areas that are under agriculture, barren, playa, urban, sparsely vegetated sand dunes, semi-permanent flooded tall grassland, and bodies of water, along with areas where invasive exotic plants may be found (Figure 22).

Figure 22. Land cover exclusion dataset.

The three exclusion datasets were joined and then clipped to the potential suitable habitat model result. Figure 23 illustrates the final potential suitable desert tortoise habitat study area.

Figure 23. Final suitable habitat area.

2.5.4. Road Fragmentation Datasets

Once the study area had been established, the focus shifted to the road fragmentation data preprocessing. This consisted of three steps. The first step was to create the Mojave Desert patch structure. Next, the roads within the Mojave road network were identified and classified according to a simple classification scheme. Finally, The patch structure and classified roads were used to create classes of patches that corresponded to the road classes.

The foundation dataset for the road fragmentation and habitat loss analysis consisted of 589116 polylines representing roads in and around the Mojave Desert extent and classified according to the Census Feature Class Code (CFCC) system (see Appendix A). The CFCC classifies roads into seven categories, based on characteristics such as who has jurisdiction over road maintenance (federal, state, local), whether the road is multi-lane or dual lanes, whether the road is divided or undivided (for multi-lane roads), and whether the road is paved or unpaved. For the purpose of this project, the Mojave roads were classed as Primary or Class 1 (light yellow), secondary or Class 2 (light green), and tertiary or Class 3 (light blue) to simplify the analysis (Table 5). The three road classes (Figure 24) will be used to look at road-avoidance behavior in a later part of the analysis, and also will provide the classification for the next step, creating the landscape patches.

Table 5. CFCC groupings with descriptions.

Code	Description
A 10	Primary Highway With Limited Access; Interstate highways and some toll highways are in this category (A1) and are distinguished by the presence of interchanges. These highways are accessed by way of ramps and have multiple lanes of traffic. The opposing traffic lanes are divided by a median strip
A 20	Primary Road Without Limited Access; This category includes nationally and regionally important highways that do not have limited access as required by category A1. It consists mainly of US highways, but may include some state highways and county highways that connect cities and larger towns. A road in this category must be hard-surface (concrete or asphalt). It has intersections with other roads, may be divided or undivided, and have multi-lane or single-lane characteristics
A 30	Secondary and Connecting Road; This category (A3) includes mostly state highways, but may include some county highways that connect smaller towns, subdivisions, and neighborhoods. The roads in this category generally are smaller than roads in Category A2, must be hard surface (concrete or asphalt), and are usually undivided with single-lane characteristics. These roads usually have a local name along with a route number and intersect with many other roads and driveways.
A 40	Local, Neighborhood, and Rural Road; A road in this category (A4) is used for local traffic and usually has a single lane of traffic in each direction. In an urban area, this feature is a neighborhood road and street that is not a thorough-fare belonging in categories A2 or A3. In a rural area, this is a short-distance road connecting the smallest towns; the road may or may not have a state or county route number. Scenic park roads, unimproved or unpaved roads, and industrial roads are included in this category. Most roads in the United States are classified as A4 roads
A 50	Vehicular Trail; A road in this category (A5) is usable only by four-wheel drive vehicles, is usually a one-lane dirt trail, and is found almost exclusively in very rural areas. Sometimes the road is called a fire road or logging road and may include an abandoned railroad grade where the tracks have been removed. Minor, unpaved roads usable by ordinary cars and trucks belong in category A4, not A5
A 70	Road as Other Thoroughfare; A road in this category (A7) is not part of the vehicular highway system. It is used by bicyclists or pedestrians, and is typically inaccessible to mainstream motor traffic except for private owner and service vehicles. This category includes foot and hiking trails located on park and forest land, as well as stairs or walkways that follow a road right-of-way and have names similar to road names.

Figure 24. Unique Mojave Desert road classes.

The Mojave landscape patches are, essentially, areas or polygons bounded by roads. Initially, a road dataset that was larger than the Mojave Desert extent was converted from polylines (Figure 25) to polygons. That produced large gap areas along the northern and eastern boundary of the Mojave extent because not all of the lines at the boundary closed to form polygons (Figure 26). Analysis of the vector polygons would have produced erroneous results by under-representing the number, size and shape of patches along the boundary.

Figure 25. Census Road Network with Mojave Desert Extent

Figure 26. Vector polyline to polygon conversion - incomplete polygons.

Converting the road network to raster format proved to be a better method for creating complete polygons to the boundary of the Mojave Desert. Raster format automatically creates polygons using the extent boundary to close the loop. The raster dataset was created using a small cell size (10 meters) to reduce area loss resulting from the square-shaped cell extending beyond the width of the linear feature while retaining a good resolution. The raster boundary was set by masking out all but the Mojave Desert extent. Then, the raster was converted back into a vector shape file. Shape files display faster than raster files, generally occupy less storage space -- a key factor for large datasets such as those used in this project, and are easier to interpret. Figure 27 illustrates an area of the patch structures in the central Mojave Desert, prior to the application of the final study area extent. Two of the patches are highlighted. Finally, the Mojave Desert patch structure shape file was clipped to the final study area so that datasets created from the patch structure would consist only of potential suitable habitat areas.

Figure 27. Mojave roads as polygons.

The final step involved creation of patch classes, for the statistical analysis and as a baseline for an investigation into road-avoidance that would correspond to the road classes. A distance of 500m from a road class was arbitrarily selected after testing distances of 100m, 300m, 500m, and 1000m and finding no striking differences between the results. The 500m distance represents a zone of direct influence produced by particular road class. Since the patches were defined by the road structure, all patches

were near at least one class of roads. Therefore, no patch within the study area could be left out of the analysis.

To create the patch classes, the road classes were overlaid on the patch structure and the Select by Location query was used to draw patches within a defined distance, in this case 500 m, from each road class. The newly defined patch classes (Pclass) were then converted to new datasets. Three patch classes resulted from this process: Pclass 1 represents suitable habitat patches within 500m of highways, Pclass 2 represents suitable habitat patches within 500m of secondary roads and streets, and Pclass 3 represents suitable habitat patches within 500 m of tertiary roads and trails. The queries resulted in significant patch overlap because secondary and tertiary roads branch off or intersect primary roads, as well as each other so that patches could be within 500m of all three types of roads simultaneously. To handle the overlap, a priority was given to each patch class. Pclass 1 was given the highest priority because the influence of highways was expected to be greater than for other roads. Pclass 3 was given the lowest priority because the influence of dirt roads and trails was expected to be less significant than for highways or secondary roads and streets. Prioritizing the patch classes allowed each class to be clipped to the class or classes with higher priorities, thus creating unique patch classes where each patch was assigned to one and only one of the three patch classes (Figure 28). This completed the preprocessing of the suitable habitat data so that analysis could begin.

Figure 28. Mojave patch classes.

2.5.5. Patch Analyst

The GIS analysis was accomplished using the vector analysis tools in Patch Analyst 3.1, an extension for ArcView 3.3. Landscape-level spatial statistics were processed for all three patch classes. The statistics included Patch and Density Metrics, Edge Metrics, and Shape metrics were selects, as shown in Figure 29. Landscape spatial statistics produce a new dataset, along with the statistics in an attribute table. The statistics are reported in hectares. For this project, with few exceptions, areas will be reported as hectares. The new dataset is the source for the next process, the creation of core areas. All statistics were exported to Microsoft Excel for further analysis.

“A core area is the interior area of a landscape patch and is defined by a core area buffer distance” (Elkie, Rempel, & Carr, 1999, p. 6). In this project, core areas represent a loss of available habitat area within a patch. To investigate the potential for loss in the desert tortoise habitat, road-avoidance distances were applied to each of the patch classes. The road-avoidance distances from Table 1 (Von Seckendorff Hoff & Marlow, 2002) were modified for use in this portion of the analysis.

Figure 29. Spatial Statistics workbook.

Three sets of core areas (Table 6) were created for each class to reflect a best case or least amount of habitat loss due to road-avoidance, a midrange case, and a worst case or greatest amount of potential loss due to road-avoidance.

Table 6. Project road-avoidance distances.

Road	Avoidance Distance (m)
Class 1	2,650
	3,150
	4,250
Class 2	2,150
	2,250
	2,650
Class 3	1,090
	1,390
	1,575

The Patch Analyst workbox for core area processing is shown in Figure 30. Datasets resulting from the creation for core areas, along with the associated statistics, are automatically saved with a prefix CA or CAP to distinguish them from the landscape data.

Figure 30. Core Area workbox.

2.6. Problems and solutions

Initially, FRAGSTAS was chosen as the landscape analysis tool for this project. However, installation proved to be more complicated than anticipated. After several failed attempts at installing the package, it became clear that an alternative was needed. Patch Analyst, with a FRAGSTATS component, was selected. Patch Analyst was easy to install, and relatively easy to learn and use. Additional training was required to learn ArcView 3.3, which has similar capabilities to ArcGIS 9.1, but uses different terminology and menu selections. ESRI on-line training was the solution to that problem.

A second problem was identified when the author attempted to convert the original vector formatted road dataset into polygons using the Data Management/Feature, Feature to Polygon tool. Areas where roads did not cross to create polygons, along the boundary of the extent, became large gaps in the data set and would have skewed the statistical data and final analysis. On the recommendation of Mr. E. Carreras, a fellow GIS analyst, the road dataset was converted to raster, as described in section 2.5.4. This significantly improved the output dataset, creating polygons in the entire extent - without any gaps.

A larger problem was identified with the chosen software for the analysis after visualizing the results of the analysis in ArcMap. Patch Analyst calculates any and all edges, regardless of origin, when running the analysis. In this study, the desired outcome of the fragmentation and loss analysis should only include roads. However, anomalies that resulted during the suitable habitat analysis also were considered in the calculations, skewing the analysis towards less available habitat than might actually exist. The preferred solution for this problem was to rerun the analysis with the Buffer tool in ARCMAP.

3. Analysis Results Summary

Two sets of statistics, using Patch Analyst, were collected for the analysis. The first set consisted of spatial statistics at the landscape-level. Fragmentation also can occur at the patch-level or within a class, but, those are not the focus of this project. The second set of statistics involved road-avoidance distances to assess the potential for habitat loss due to roads. A third set of data, not statistics, was derived from the buffered roads analysis.

3.1. Patch Analyst Results

Spatial statistics for the total landscape suggest that the Mojave Desert is highly fragmented by roads. This is evidenced by the 18,000 suitable habitat patches across the landscape. Each patch class appeared to have a smaller patch size than the class above it. Each patch class also appeared to increase in complexity or heterogeneity, from the lowest value (Pclass 1) to the highest value (Pclass 3). Pclass 2 and 3 patches show more diversity across the landscape than those belonging to Pclass 1. However, Pclass 3 patches appeared less evenly distributed across the landscape than both Pclass 1 and 2 patches.

Road-avoidance distances, modified from the von Seckendorff Hoff & Marlow (2002) study, applied to each of the suitable habitat patch classes suggested that the loss of desert tortoise habitat is greater than anticipated, especially for patches near primary and secondary roads (Pclasses 1 and 2). For Pclass 1 and 2, connectivity appeared to be a serious issue. Connectivity did not appear to be a large issue for Pclass 3, with two exceptions. First, movement from one patch to another is impeded by high berms. the tortoise is able to climb the berm, but as it goes down the other side, there is potential for the tortoise to flip over onto its shell. Unable to right itself, it becomes easy prey for predators. The second exception is for areas that are heavily trafficked by illegal off-road activities. I use, such as for ORV activities. There are areas of driving, for dirt roads or trails that included high berms on either side. Connectivity appeared to be a serious issue between Pclass 1 and 2, but less so for Pclass 3, suggesting a potential follow-up study to determine the extent of the problem.

The findings that follow are preliminary and basic, based on limited knowledge gained from readings and study of landscape metrics for this project. The interpretation of landscape metrics is difficult, even for those knowledgeable in habitat analysis. Such metrics are easily misunderstood and/or misapplied. The final interpretation of the landscape and core area statistics is best left to experts in the field who are more familiar with landscape metrics, how they apply to habitats, and what they imply for the desert tortoise habitat. All of the landscape-level spatial statistics are shown in table 7.

Table 7. Patch Analyst landscape spatial statistics.

	Total landscape area (TLA)	Number of patches (NumP)	Mean patch size (MPS)	Patch size co-efficient of variance PSCoV	Patch size standard deviation (PSSD)	Total edge (TE)	Edge density (ED)	
Pclass 1	2,788,110	2,680	1,040	896	9,323	66,013,595	23.68	Distances
Pclass 2	2,776,079	13,624	204	1,142	2,328	124,779,375	44.95	in hectares
Pclass 3	129,856	1,640	79	1,298	1,028	3,988,998	30.72	
	Mean Patch edge (MPE)	Mean shape index (MSI)	Area-weighted mean shape index (AWMSI)	Mean perimeter area ratio (MPAR)	Mean patch fractal dimension (MPFD)	Area-weighted mean patch fractal dimension (AWMPFD)	Shannon's diversity index	Shannon's evenness index
Pclass 1	24,632	2.36	14.73	5,514	1.43	1.36	5.00	1.00
Pclass 2	9,159	2.49	18.11	30,559	1.41	1.36	5.91	1.00
Pclass 3	2,432	2.08	2.75	1,701	1.40	1.25	5.98	0.82

3.2. Mojave Desert Landscape Metrics

The original Mojave Desert landscape areas and the potential suitable habitat landscape including each of the patch classes are compared in Table 8. The table also includes the amount of reduction and percentage of decrease at each level. Total landscape area is the sum of the areas of all patches in the landscape.

Table 8. Comparison of the landscape area: the original Mojave to the patch classes

Extent	sq ha	sq km	Habitat Reduction (ha)	sq km	% Decrease
Mojave Desert (as defined by Bailey, 1994)	7,081,100	70,811			
Mojave patches with unsuitable areas removed	5,694,046	56,940	1,387,054	13,871	0.20
Pclass 1 - patches within 500 m of primary roads	2,788,110	27,881	2,905,935	29,059	0.49
Pclass 2 - patches within 500 m of secondary roads	2,776,079	27,761	2,917,966	29,180	0.49
Pclass 3 - patches within 500 m of tertiary roads	129,856	1,299	5,564,189	55,642	0.02

The total landscape area for the Mojave Desert was approximately 71,000 sq km (44,000 sq miles). After applying the potential suitable habitat study area (with unsuitable areas removed), the landscape area was approximately 57,000 sq km, a loss of about 14,000 sq km of the Mojave landscape. The patches in Pclass 1 and 2 dominate the landscape, each with almost half of the study area. Pclass 1, representing suitable habitat patches within 500 m of primary roads, consisted of approximately 27,900 sq km or 49% of the landscape. Pclass 2, representing patches within 500 m of secondary roads, consisted of approximately 27,800 sq km or 49 % of the landscape. Pclass 3, representing patches within 500 m of tertiary roads, consisted of approximately 1,300 sq km or 2 % of the

study area. A comparison of the Pclass areas, in hectares, is illustrated in Figure 31. All of the definitions for the following sections were taken from Appendix II of the Patch Analyst Users Manual (Elkie, et al., 1999).

Figure 31. Landscape area, by class percentages.

3.2.1. Number of Patches (NumP)

Total number of patches in the landscape if 'Analyze by Landscape' is selected.

The number of patches created in the Mojave extent was approximately 18,000. There were approximately 2,700 patches in the Pclass 1 dataset or approximately 27 patches per 100 hectares, about 15 percent of the total number of patches in the landscape. The Pclass 2 dataset contained approximately 13,600 patches or 136 patches per 100 hectares, over 75 percent of the total number of patches. Pclass 3 contained approximately 1640 patches or 16 patches per 100 hectares, less than 10 percent of the total number of patches in the landscape (Figure 32).

Figure 32. Number of patches by Pclass.

3.2.2. Mean Patch Size (MPS)

Average patch size.

The Mean Shape Size (MPS) was largest (1,040 ha) in Pclass 1 and the smallest (79 ha) in Pclass 3 (Figure 33). Pclass 1, the highways, were assessed to have considerable influence in the habitat, due to the amount and types of traffic, as well as the speeds of vehicles. Therefore, Pclass 1 had first priority on the patch assignment, gaining 15% of all patches in the landscape. Pclass 3, with the lowest priority for patch assignment, made up only 9% of all landscape patches.

Figure 33. Mean Patch Size.

3.2.3. Patch Size Coefficient of Variance (PSCoV)

Coefficient of variation of patches.

$$\text{PSCoV} = \text{PSSD}/\text{MPS}$$

The Patch Size Coefficient of Variation (PSCoV) is the result of dividing Patch Size Standard Deviation (PSSD) by MPS. Landscapes with greater PSCoV tend towards heterogeneity or greater patchiness while landscapes with lower PSCoV are more homogeneous. For this study, it suggested greater patchiness in Pclasses 2 and 3 than in Pclass 1 (Figure 34) (Elkie, et al., 1999, p.16). This would be true because road Classes 2 and 3 created almost 86% of the patches in the landscape and all of those were smaller than those created by Class 1 roads.

Figure 34. Patch size co-efficient of variation.

3.2.4. Mean Shape Index (MSI)/Area Weighted Mean Shape Index (AWMSI)

Shape Complexity.

MSI = sum of each patch perimeter divided by the square root of patch area (hectares)

for all patches (Landscape level), and adjusted for circular standard (polygons) divided by the number of patches. MSI is normally greater than one. MSI equals one when all patches are circular. AWMSI is the average perimeter-to-area ratio for a class, weighted by the size of its patches.

The Mean Shape Index (MSI) for all three patch classes ranged from 2.0 to 2.5, suggesting that the patches were somewhat irregular or complex and, therefore, slightly dissimilar from the reference shape (circle). The AWMSI, which calculates the index, is weighted by patch area to give larger patches more weight and possibly a truer picture of patch complexity. The Area-weighted MSI for Pclasses 1 and 2 show a significant change in value for AWMSI, and greater patch complexity, while the change in value for Pclass 3 is far less significant (Figure 35) (Elkie, et al., 1999, p. 17).

Figure 35. Shape index compared to the area-weighted mean shape index.

3.2.5. Total Edge (TE)

Perimeter of patches.

TE = Sum of perimeter of all patches.

Pclass 2, with the greatest number of patches also has the edge on Total Edge (Figure 36). But TE is best viewed in comparison to Edge Density (ED) or the *amount of edge relative to the landscape area* or $ED = TE / TLA$. Figure 37 shows the comparison between TE and ED for all patch classes. The take-away from these metrics is that more edges and greater edge density mean higher levels of habitat fragmentation, which subsequently suggests greater habitat loss.

Figure 36. Total edge.

Figure 37. Comparison of total edge-to-edge density.

3.2.6. Shannon's Diversity Index (SDI)/Shannon's Evenness Index (SEI)

SDI is the measure of relative patch diversity.

Shannon's diversity index is only available at the landscape level and is a relative measure of patch diversity. The index will equal zero when there is only one patch in the landscape and increases as the number of patch types or proportional distribution of patch types increases.

SEI is the measure of patch distribution and abundance.

Shannon's evenness index is equal to zero when the observed patch distribution is low and approaches one when the distribution of patch types becomes more even. Shannon's

evenness index is only available at the landscape level.

Shannon's Diversity Index (SDI) and Shannon's Evenness Index (SEI) are illustrated in Figure 38. For this study, the SDI is above zero, so the landscape patch structure displays increasing diversity from Pclass 1 through Pclass 3. SEI, nearing or equal to one, suggests that the landscape patch structure is evenly distributed. These indexes are not truly meaningful by themselves, however. The best way to understand the SDI and SEI is in comparison with another landscape or with the same landscape at another time. So, while not useful for this particular study, this data can be a baseline for comparison with an historical or future Mojave Desert study.

Figure 38. Comparison of Shannon's diversity and evenness indices.

3.3. Road Avoidance

According to the Department of Transportation, Federal Highway Administration (<http://www.fhwa.dot.gov/environment/htnoise.htm>), high traffic density, at high speeds, creates noise levels that, for humans 150m or less from the road, are at or over the threshold for hearing loss with only hours of extended exposure. Add exhaust fumes, damage or total destruction of native plants that may have been tortoise food sources, and noise generated by traffic - all may contribute to road avoidance by tortoises. Road-avoidance means just that – keep some distance away from the road and, thereby, losing

the use of the habitat for that distance. Road avoidance, then, reduces a whole patch to some core suitable habitat area. Core areas in the Mojave Desert represent potentially what remains of suitable desert tortoise habitat near Mojave Desert roads.

The road avoidance distances used in this part of the analysis appear in Table 6 on page 49. To briefly review, according to the work of von Seckendorff Hoff & Marlow (2002), the desert tortoise exhibits significant road avoidance behavior near primary roads or highways (multi-lane, paved roads), moderate avoidance near secondary roads and streets (generally single-lane, paved), and lesser avoidance of tertiary roads (graded dirt or graveled roads). The patch classes for this project correspond to highways (Pclass 1), secondary roads and streets, (Pclass 2), and tertiary roads (Pclass 3) so road avoidance distances similar to those used by von Seckendorff Hoff and Marlow may have value in understanding potential habitat loss related to the desert tortoise in the Mojave Desert.

Two trials were conducted on road avoidance distances during this study. Each trial produced sets of core areas for each Pclass. Core areas are those areas that remain useable habitat when road-avoidance behavior is taken into account. The two trials, both conducted using Patch Analyst, differed as to when the final suitable habitat area was introduced to the analysis.

3.3.1. First Patch Analyst Trial

The first Patch Analyst trial used Pclasses that had been clipped to the suitable habitat dataset. These were the same unique Pclasses, used for the statistical analysis. The Pclasses were reduced to only those that were equal to or greater than 10 km². The minimum patch size of 10 sq km was established for two reasons. First, it was considered, by the analyst, to be the smallest possible patch for the success of a small group of individuals, given 1 sq km per individual. Second, it was established to reduce the number of patches to ensure the successful run of the analysis on limited computer resources.

Core areas were created for each Pclass at each avoidance distance to arrive at new datasets and statistics for total core area (TCA), number of patches (Nump), and the total core area index (TCAI). From this information, core areas were combined into least road avoidance distances (Pcls1 – 2650m, Pcls2 – 2150m, and Pcls3 – 1090m) for a best case and most road avoidance distances (Pcls1 – 4250m, Pcls2 – 2650m, and Pcls3 – 1575m) for a worst case for the potential suitable habitat area in the Mojave Desert.

According to the first analysis, the best case (least road avoidance distances) for desert tortoise potential available habitat is equal to just over 1630 km² with 174 core areas equal to about 5% (TCAI) of the total patch area. The worst-case scenario (most road avoidance distances) is about 630 km² with only 75 core areas making up approximately 1% (TCAI) of the total patch area (Table 9).

The Total Core Area Index (TCAI), a measure of the percentage of core area to the total patch area, illustrates a problem with the way that Patch Analyst calculates edges. In calculating the suitable habitat area model, small artifacts were created across the Mojave study area resulting from anomalous areas of elevation and/or slope that occurred within the final suitable habitat area. Such areas occurred in all of the Pclasses. Figure 39 shows one such area within a Pclass 2 patch. The artifact edges (within the green circle) were

included in the Patch Analyst calculations so that the resulting core areas reflected all edges (note the indentation of the core areas in Figure 39), not just road edges. What this means is that roads were not the only consideration in the calculations of core areas and, it follows that the resulting analysis did not portray the true potential for habitat loss in the Mojave Desert. At the suggestion of Dr. Westmoreland and Dr. Leuteritz, the author undertook two other approaches to determining better information on the habitat loss.

Table 9. First patch analyst trial statistics.

First Patch Analyst Trial			
Core Areas of Least Avoidance	NUMP	TCA (km²)	TCAI (Av)
Pclass 1 - 2650m	53	623	4
Pclass 2 - 2150m	95	970	5
Pclass 3 - 1090m	26	38	5
Totals	174	1631	5
Core Areas of Most Avoidance	NUMP	TCA (km²)	TCAI (Av)
Pclass 1 - 4250m	12	85	0
Pclass 2 - 2650m	55	543	3
Pclass 3 - 1575m	8	6	1
Totals	75	634	1

Figure 39. Example of artifact in the first analysis.

3.3.2. Second Patch Analyst Trial

A second trial was conducted using Patch Analyst and the original Mojave Desert patch dataset, reduced to only those patches equal to or greater than 10 km², not yet clipped to the suitable habitat dataset. From there, new Pclasses were selected for each road class to provide base datasets without artifacts for the analysis. As in the previous trial, each Pclass dataset was processed through Patch Analyst for core areas and statistics. From this information, core areas were combined into least road avoidance distances (Pcls1 – 2650m, Pcls2 – 2150m, and Pcls3 – 1090m) for a best case and most road avoidance distances (Pcls1 – 4250m, Pcls2 – 2650m, and Pcls3 – 1575m) for a worst case for the potential suitable habitat area in the Mojave Desert.

According to the second analysis, the best case (least road avoidance distances) for potential available habitat is equal to over 30,350 km² with 434 core areas and making up about 34% (TCAI) of the total patch area. The worst case (most road avoidance distances) is approximately 19,700 km² with 296 core areas making up about 24% (TCAI) of the total patch area. The comparison between the first and second trial statistics was surprising in that so small a change as creating the core areas before correcting for suitable habitat could result in such significant differences.

Table 10. Second patch analyst trial statistics.

Second Patch Analyst Trial			
Core Areas of Least Avoidance	NUMP	TCA (km²)	TCAI (Av)
Pclass 1 - 2650m	33	281	31.68
Pclass 2 - 2150m	237	13363	34.85
Pclass 3 - 1090m	164	16715	34.67
Totals	434	30359	34
Core Areas of Most Avoidance	NUMP	TCA (km²)	TCAI (Av)
Pclass 1 - 4250m	23	148	22
Pclass 2 - 2650m	186	10358	28
Pclass 3 - 1575m	87	9226	21
Totals	296	19732	24

The second trial probably represents a more accurate assessment of potential Mojave Desert tortoise habitat, after accounting for road avoidance distances. Figures 40 and 41 show what the core areas, minus the portions that were unsuitable for tortoise habitat. Of course, the truth of these figures for potential available habitat can only be determined by fieldwork similar to that of Von Seckendorff Hoff & Marlow (2002).

Figure 40. Best case scenario.

Figure 41. Worst case scenario.

3.4. Connectivity

The connectivity between core areas may be a moot point since the desert tortoise range appears to be between 300 and 1000m of its system of home burrows (Redlands Institute Decision Support Team, 2004, Appendix B, pp 1-2), although there are recorded exceptions. Movement between some of the suitable habitat core areas is hampered by their distribution between primary and secondary roads in most areas. Smaller core areas that are near larger homogeneous core areas may be candidates for corridors. Corridors between the more isolated core areas probably would be less desirable than moving any individuals to larger territory.

The majority of core areas, in Pclass 1 and Pclass 2, are found between paved roads. Class 1 roads, such as Interstate 40, act as permanent barriers to between-patch or core area movement from one side of the highway to the other. Class 2 roads also serve as barriers. However, traffic density, and its associated problems, is a key factor in determining whether the barrier is permanent or breachable. Additionally, culverts, placed in a few areas along California State Route 58, in the Mojave Desert, have shown some success (Boarman, Sazaki, & Jennings, 1997) when paired with fences to funnel the tortoise safely from one side of a highway to the other, or from one Pclass 2 core area to

another. State Route 58 is a four-lane (two in each direction) expressway running between Bakersfield and the town of Mojave. The Pclass 3 core areas are few and generally not near to another. There appears to be little potential for connectivity between core areas unless they are clustered together.

3.5. ORV Analysis

Fragmentation and habitat loss also occur within patches. While this project was aimed at assessing the fragmentation and potential habitat loss at the landscape level, it is worthwhile to discuss, briefly, the potential for additional fragmentation at the patch-level. Such fragmentation would not be detected at the landscape level.

Brooks and Lair (2005) indicated that legal and illegal ORV trails are under-represented in official road databases, like the Census TIGER Line data, leading to an underestimation of the number of roads and, consequently, an underestimation of the effects of roads on ecosystems. If true, then the core areas described in the last section may be smaller than this project suggests which means less potential habitat area for the desert tortoise and greater danger of continuing population decreases. The possibility also exists that the core areas, at least in some patches, are non-existent due to under-reported roads or trails created by illegal recreational use of the desert tortoise habitat.

To illustrate the potential problem, and because finding illegal ORV trafficked areas is difficult, an established ORV area was selected as a sample. The selected area, the Jawbone Canyon Area of Critical Environmental Concern (ACEC), also known as Dove Springs ORV area, is approximately 20 miles north of the town of Mojave, off Route 14, near Red Rock Canyon (Figure 42). A digital orthophoto of a sub-area, representing a single patch, was retrieved from the imagery archives residing at the University of California, Davis and pre-processed to determine feasibility of analysis at the patch level (Figure 43). A sub-patch structure made up of ORV trails is clear. It is this sub-patch structure that is of concern since it would have serious implications for the desert tortoise and usable habitat areas. This sub-patch analysis was beyond the scope of this study and should be considered as a future subject for analysis.

Jawbone Canyon ORV Area

The Jawbone/Dove Springs ORV areas, north of the city of Mojave, CA., consist of approximately 35 sq km (8500 acres) of open ORV trails.

Figure 42. Jawbone ORV area locator.

Figure 43. ORV area image subset.

4. Discussion

This project represents the first step in the GIS analysis of the potential affects of roads, in terms of fragmentation/connectivity and habitat loss, on the desert tortoise habitat. The purpose of this project was threefold:

- (1) To characterize the regional road fragmentation and habitat loss in the Mojave Desert, in support of the desert tortoise project, to aid decision-makers in determining the areas where limited resources should be applied first,
- (2) To briefly look at the potential of ORVs to cause further fragmentation and loss of habitat, and
- (3) To bring all of the data for the analysis into a geodatabase structure for future researchers.

The author believes that all items have been successful and will serve as a starting point for future work on the subject of road fragmentation and habitat loss in the Mojave Desert tortoise habitat.

4.1. In Review

Coming from an intelligence background, I knew little about conservation, animal habitats, what might imperil them, and less about the Mojave Desert and the desert tortoise. I knew a little about GIS, most importantly that it was a new and potentially important way to visualize problems and possible solutions and that I wanted to know more. Each step in the completion of this project has added new knowledge and an appreciation for habitats of all kinds.

The literature review provided the foundation for building knowledge about conservation and conservation techniques, the Mojave Desert environment, and the desert tortoise. GIS, in conjunction with Patch Analyst, provided the tools to visualize the desert tortoise habitat along with the road network that runs through it. The Patch Analyst roads analyses put that habitat in a different context to the roads, showing the potential fragmentation and loss.

After completing this study, I believe that there is reason to fear for the desert tortoise. As human beings, we observe the landscape through a soda straw – only a small portion at a time. When we think about how roads may cross the landscape, we imagine that animals have the entirety of the remaining area to wander and forage. While driving Route 40 from Virginia to California, I gave little thought to the landscape beyond the highway. We fail to consider other factors, such as pollution and litter that may poison or otherwise further reduce the area that animals may inhabit. Nevertheless, I also believe there is reason to hope that there is still time and land enough for scientists to take steps to mitigate the damage of our passage. My return trip to Virginia was more careful and appreciative of what might be going on not far from the highway.

This study concludes my involvement, at least for now, with the desert tortoise. But, I hope it marks a starting point for future research to answer the question of how roads in the Mojave Desert may impact the desert tortoise habitat.

4.2. In Conclusion

Based on the GIS analysis, along with the Patch Analyst landscape spatial statistics, the Mojave Desert tortoise habitat appears to be significantly fragmented. The author expected a reduction in potential habitat area at the beginning of the first Patch Analyst analysis. However, as analysis proceeded, the degree of fragmentation and loss turned out to be more significant than the author had anticipated. The initial reduction in the habitat area, from the application of tortoise preferences for elevation, slope, geomorphological formations, land cover, and soils removed approximately half of the original extent as unsuitable habitat area and added a large number of artifacts that skewed the analysis towards a severe loss of habitat.

The second Patch Analyst analysis produced a very different picture of the desert tortoise habitat. While still very fragmented, the habitat loss was not nearly as great as the first analysis, though that loss was still significant when compared to the total area of the Mojave Desert. The second analysis resulted in more than twice the amount of available habitat for the areas where there is potentially least road avoidance and nearly four times the amount of available habitat where there is potentially greatest road avoidance. Where almost all of the core areas were isolated from each other in the first Patch Analyst trial, there were many clusters of patches resulting from the second Patch Analyst trial that would give corridors and tortoise relocation efforts more opportunities for success.

I have little doubt that unpaved roads and off road activities pose threats to the desert tortoise, especially in unregulated areas of the desert. But, how significant those threats may be can only be determined by field studies on road-avoidance distances, traffic density on the lesser used roads, vegetation and drainage patterns from off road activities, suspended dust from vehicles speeding through the desert, and toxic contamination due to exhaust, oil leaks or spilled gasoline on Mojave Desert roads. As more vehicles use the same trails, more damage is done to tortoise food sources and to drainage patterns. Combined with the noise, dust suspended in the air, toxic contamination, and litter that may lead to increases in certain predators such as the ravens, all contribute to tortoise mortality.

4.3. In Future Work

This project was intended to baseline the Mojave Desert tortoise habitat at one point in time, for use by future researchers. Future work on fragmentation and habitat loss will further aid decision-makers in protecting the desert tortoise habitat. Ideas for future projects include fieldwork. The von Seckendorff Hoff and Marlow road-avoidance data should be tested in several other areas of the Mojave to establish a set of road-avoidance

distances that can serve as ground truth for analysis. Verification of core areas found in this project also should be undertaken to determine whether they are or are not untouched by more than limited human activity.

Analysis at a patch-level, particularly where heavy recreational activity is located, could provide a source of data on potential habitat loss that generally goes unrecorded and unrecognized in most of the literature. As an example, a detailed analysis of ORV trails, characterizing one or more of the larger existing ORV areas would provide insight into the potential for habitat loss by illegal ORV use in open unregulated areas of the Mojave Desert. The analysis could focus on categorizing ORV trail use by investigating the degree of vegetation loss and soil erosion resulting from ORV usage. A model of vegetation loss and erosion might aid decision-makers and policing authorities to identify illegal ORV trails, from overhead imagery, so that limited resources can be better distributed.

A subsequent analysis of other historical road data could be conducted or perhaps near the end of the decade, to compare differences in the levels of fragmentation and habitat loss over a 10-year period. Fragmentation is a temporal phenomenon that is best understood in comparison to another dataset. Such a project would do well to include traffic density data to enhance the analysis, especially since there appears to be a correlation between traffic density and connectivity (McGregor, Derrane, Bender, & Fahrig, 2003).

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Appendix A: Census Feature Class Codes (CFCCs)

A census feature class code (CFCC) is used to identify the most noticeable characteristic of a feature. The CFCC is applied only once to a chain or landmark with preference given to classifications that cover features that are visible to an observer and a part of the ground transportation network. Thus, a road that is also the boundary of a town would have a CFCC describing its road characteristics, not its boundary characteristics. The CFCC, as used in the TIGER/Line files, is a three-character code. The first character is a letter describing the feature class; the second character is a number describing the major category; and the third character is a number describing the minor category. Not all CFCCs listed currently appear in the TIGER/Line files.

The U.S. Census Bureau has created some CFCCs in preparation for collecting additional information for identifying and classifying features in future operations. The TIGER/Line files contain sporadic occurrences of road segments with a misclassified CFCC. The result is that complete chains for the affected road features will have segments with different CFCC values assigned erroneously. This problem could affect applications that use the CFCC values for network analysis, routing, or for assigning symbology to a feature when creating a map. Some street features in the TIGER/Line files that normally would be classified as "A" class features may now be coded with a "P" instead of the "A" to indicate that the feature is a "provisional" feature. The numeric portion of the CFCC still classifies the street as if an "A" were preceding it. Provisional features are those streets that were added from reference sources or other programs in preparation for Census 2000, but were not aerial photography or imagery. As these features are verified in future operations, the provisional flag will be removed for subsequent TIGER Line file releases. Features that still have the provisional flag at the time the U.S. Census Bureau assigned the Census 2000 tabulation block numbers were not held as Census 2000 tabulation block boundaries.

Feature Class A, Road

The U.S. Census Bureau uses the term *divided* to refer to a road with opposing traffic lanes separated by any size median, and *separated* to refer to lanes that are represented in the Census TIGER database as two distinct complete chains. The term, *rail line in center*, indicates that a rail line shares the road right-of-way. The rail line may follow the center of the road or be directly next to the road; representation is dependent upon the available source used during the update. The rail line can represent a railroad, a streetcar line, or other rail line.

Census Feature Class Codes	
Code	Description
A 10	Primary Highway With Limited Access; <i>Interstate highways and some toll highways are in this category (A1) and are distinguished by the presence of interchanges. These highways are accessed by way of ramps and have multiple lanes of traffic. The opposing traffic lanes are divided by a median strip. Paved and maintained.</i>
A 11	Primary road with limited access or interstate highway, unseparated
A 12	Primary road with limited access or interstate highway, unseparated, in tunnel
A 13	Primary road with limited access or interstate highway, unseparated, underpassing
A 14	Primary road with limited access or interstate highway, unseparated, with rail line in center
A 15	Primary road with limited access or interstate highway, separated
A 16	Primary road with limited access or interstate highway, separated, in tunnel
A 17	Primary road with limited access or interstate highway, separated, underpassing
A 18	Primary road with limited access or interstate highway, separated, with rail line in center
A 19	Primary road with limited access or interstate highway, bridge
A 20	Primary Road Without Limited Access; <i>This category includes nationally and regionally important highways that do not have limited access as required by category A1. It consists mainly of US highways, but may include some state highways and county highways that connect cities and larger towns. A road in this category must be hard-surface (concrete or asphalt). It has intersections with other roads, may be divided or undivided, and have multi-lane or single-lane characteristic. Paved and maintained</i>
A 21	Primary road without limited access, US highways, unseparated,
A 22	Primary road without limited access, US highways, unseparated, in tunnel
A 23	Primary road without limited access, US highways, unseparated, underpassing
A 24	Primary road without limited access, US highways, unseparated, with rail line in center
A 25	Primary road without limited access, US highways, separated
A 26	Primary road without limited access, US highways, separated, in tunnel
A 27	Primary road without limited access, US highways, separated, underpassing
A 28	Primary road without limited access, US highways, separated, with rail line in center

A 29	Primary road without limited access, US highways, bridge.
A 30	Secondary and Connecting Road; <i>This category (A3) includes mostly state highways, but may include some county highways that connect smaller towns, subdivisions, and neighborhoods. The roads in this category generally are smaller than roads in Category A2, must be hard surface (concrete or asphalt), and are usually undivided with single-lane characteristics. These roads usually have a local name along with a route number and intersect with many other roads and driveway.. Paved and maintained</i>
A 31	Secondary and connecting road, state and county highways, unseparated
A 32	Secondary and connecting road, state and county highways, unseparated, in tunnel
A 33	Secondary and connecting road, state and county highways, separated, underpassing
A 34	Secondary and connecting road, state and county highways, unseparated, with rail line in center
A 35	Secondary and connecting road, state and county highways, separated
A 36	Secondary and connecting road, state and county highways, separated, in tunnel
A 37	Secondary and connecting road, state and county highways, separated, underpassing
A 38	Secondary and connecting road, state and county highway, separated, with rail line in center
A 39	Secondary and connecting road, state and county highways, bridge

Code	Description
A 40	Local, Neighborhood, and Rural Road; <i>A road in this category (A4) is used for local traffic and usually has a single lane of traffic in each direction. In an urban area, this feature is a neighborhood road and street that is not a thorough-fare belonging in categories A2 or A3. In a rural area, this is a short-distance road connecting the smallest towns; the road may or may not have a state or county route number. Scenic park roads, unimproved or unpaved roads, and industrial roads are included in this category. Most roads in the United States are classified as A4 roads. Paved and maintained</i>
A 41	Local, neighborhood, and rural road, city street, unseparated
A 42	Local, neighborhood, and rural road, city street, unseparated, in tunnel
A 43	Local, neighborhood, and rural road, city street, unseparated, underpassing
A 44	Local, neighborhood, and rural road, city street, unseparated, with rail line in center
A 45	Local, neighborhood, and rural road, city street, separated
A 46	Local, neighborhood, and rural road, city street, separated, in tunnel
A 47	Local, neighborhood, and rural road, city street, separated, underpassing
A 48	Local, neighborhood, and rural road, city street, separated, with rail line in center
A 49	Local, neighborhood, and rural road, city street, bridge
A 50	Vehicular Trail; <i>A road in this category (A5) is usable only by four-wheel drive vehicles, is usually a one-lane dirt trail, and is found almost exclusively in very rural areas. Sometimes the road is called a fire road or logging road and may include an abandoned railroad grade where the tracks have been removed. Minor, unpaved roads usable by ordinary cars and trucks belong in category A4, not A5. Unpaved, may or may not be maintained.</i>
A 51	Vehicular trail, road passable only by 4WD vehicle, unseparated
A 52	Vehicular trail, road passable only by 4WD vehicle, unseparated, in tunnel
A 53	Vehicular trail, road passable only by 4WD vehicle, unseparated, underpassing
A 60	Road with Special Characteristics; <i>This category (A6) includes roads, portions of a road, intersections of a road, or the ends of a road that are parts of the vehicular highway system and have separately identifiable characteristics. Paved and maintained.</i>
A 70	Road as Other Thoroughfare; <i>A road in this category (A7) is not part of the vehicular highway system. It is used by bicyclists or pedestrians, and is typically inaccessible to mainstream motor traffic except for private owner and service vehicles. This category includes foot and hiking trails located on park and forest land, as well as stairs or walkways that follow a road right-of-way and have names similar to road names. Unpaved, may or may not be maintained.</i>

Appendix B: Instructions for installing Patch Analyst

The Patch Analyst extension and other necessary scripts are contained in [a] zip archive file named *patch.zip*. Within the zipped file, several files need to be installed. Installation includes unzipping the *patch.zip* file into a chosen directory. Once the files have been unzipped, double click on the *install.apr* file. This will copy the Patch Analyst extension into the “C:\ESRI\AV_GIS30\ARCVIEW\EXT32” directory. If you are using the vector and grid version, *Fragstats.exe* and *Trimgrid.exe* will also be copied into the “EXT32” directory. The install routine will also copy parts of the Dialogue Designer extension, if not already there, into the ArcView directory structure. An alternative method of installation is a manual installation, *i.e.*, unzipping the *bin*, *lib*, *ext.zip* files to their respective ArcView directories.

The respective ArcView directories include:

- C:\ESRI\AV_GIS30\ARCVIEW\BIN32 for bin.zip
- C:\ESRI\AV_GIS30\ARCVIEW\LIB32 for lib.zip
- C:\ESRI\AV_GIS30\ARCVIEW\EXT32 for ext.zip

Either method is valid and will install the Patch Analyst extension properly. Once the extension is installed, start ArcView, open a view, choose *Extensions* from the Views file menu, and ensure that the Patch Analyst extension is enabled. The *Patch* menu is now available and Patch Analyst is ready for use (Elkie, Rempel, & Carr, 1999, p. 1).

Appendix C: Landscape Indices for the Current Project

	Class 1	Class 2	Class 3
Class area (CA)	2,788,110	2,776,079	181,896
Total landscape area (TLA)	2,788,110	2,776,079	181,896
Number of patches (NumP)	2,680	13,624	34,442
Mean patch size (MPS)	1,040	204	5
Patch size co-efficient of variance PSCoV)	896	1,142	4,260
Patch size standard deviation (PSSD)	9,323	2,328	225
Total edge (TE)	66,013,595	124,779,375	107,497,623
	Class 1	Class 2	Class 3
Edge density (ED)	24	45	591
Mean Patch edge (MPE)	24,632	9,159	3,121
Mean shape index (MSI)	2	2	5
Area-weighted mean shape index (AWMSI)	15	18	9
Mean perimeter area ratio (MPAR)	5,514	30,559	9,774
Mean patch fractal dimension (MPFD)	1	1	2
Area-weighted mean patch fractal dimension (AWMPFD)	1	1	1
Shannon's diversity index	5	6	9
Shannon's evenness index	1	1	1