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MODELING BIGHORN SHEEP HABITAT IN NORTHWEST NEBRASKA

Kyle M. Forbes
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MODELING BIGHORN SHEEP HABITAT IN NORTHWEST NEBRASKA

By

Kyle M. Forbes

A THESIS

Presented to the Faculty of
The Graduate College at the University of Nebraska
In Partial Fulfillment of the Requirements
For the Degree of Master of Arts

Major: Geography

Under the Supervision of Professor James W. Merchant

Lincoln, Nebraska

November, 2001
MODELING BIGHORN SHEEP HABITAT IN NORTHWEST NEBRASKA

Kyle Forbes, M.A.

University of Nebraska, 2001

Advisor: James W. Merchant

In recent years geographic information system (GIS) and remote sensing technologies have been used extensively in habitat suitability modeling. By incorporating these technologies, scientists often gain the ability to formulate and implement a more detailed habitat suitability model with the addition of more detailed spatial information. A habitat suitability model was developed to quantify and describe the available suitable Rocky Mountain bighorn sheep (Ovis canadensis canadensis) habitat in the Pine Ridge of Northwestern Nebraska and determine if a minimum viable population (MVP) of this species can be supported naturally in the region. The model included a strong spatial analysis component, extensively utilizing satellite imagery as an input to the strong spatial analysis capabilities of the GIS. A spatial juxtaposition algorithm was developed to analyze the spatial configuration of escape terrain around each pixel of potential habitat in the study area. Landscape metrics were computed and suitable habitat was quantified in five suitability intervals for 1) the entire study area, 2) three focus areas (subdivisions) within the study area, and 3) six population locales (possible herd locations). Quantity of habitat, mean nearest neighbor, and contagion landscape metrics were used to rank each of the six population locales from most to least likely to support a herd of bighorn sheep. Results from the model indicated that
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ACKNOWLEDGMENTS

Special thanks to Darryl Williams of the U.S. Geological Survey in Rolla, Missouri and Josh Lear and Dan Kloch of the Nebraska Natural Resources Commission who graciously provided crucial data for this project. My sincere appreciation goes to the many officials at the Nebraska Game and Parks Commission (Kevin Church, Lon Lemmon, Karl Menzel, Gary Schlichtemeier) and the USDA Forest Service (Jeff Abegglen) in the Pine Ridge for providing their expertise, advice, and enormous cooperation on this project. I thank my masters committee (Dr. James Merchant, Dr. Kevin Church, Dr. Scott Hygnstrom, Dr. Sunil Narumalani) for being patient with me, providing valuable advice, and spending a substantial amount of time reading my many manuscripts. My wife Michèle deserves an enormous amount of credit as my motivation for finalizing my thesis manuscript and pushing ahead to the finish line. Special thanks also to the flora and fauna of the Pine Ridge for allowing me to hike and drive on and near them.
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CHAPTER I: INTRODUCTION

1.1 Introduction

The study of wildlife populations is partially based upon the ability to derive some understanding about the relationship between the species and the habitat in which it resides. Traditionally, wildlife populations and habitat were tracked and delineated using paper maps and notes written in notebooks. Unfortunately, these methods proved to be cumbersome and difficult to manage. Paper maps are rarely up-to-date, hand-drawn boundaries are typically inaccurate, and the ability to study multiple spatial variables influencing a population is greatly limited. Furthermore, it is difficult to quantify important habitat properties such as patch size and land cover interspersion when using paper maps.

Extensive amounts of time were once required to study the flora and fauna of a region, map areas, and track animals. Now, satellite-borne remote sensing systems can produce multi-band images that can be processed with relative ease to extract information about the land cover types over large geographic areas. Multiple layers of information can be stored and processed within a geographic information system (GIS) to derive new and meaningful information regarding wildlife habitat. In situ data collection is no longer the primary means for obtaining information about a region, but rather one of many tools that can be used to support such a study (see, for example, Trotter 1991, Herr and Queen 1993, Homer et al. 1997). While they are by no means perfect solutions, remote sensing and GIS have solved many of the former difficulties by allowing the frequent updating of maps without the need to reprint the map, the acquisition and storage of large amounts of
data with less field work, the analysis of multiple variables influencing a population, and
the quantification of spatial structure. For these reasons and more, GIS and remote
sensing have become increasingly more common tools in wildlife research.

This thesis focuses on the management of bighorn sheep (*Ovis canadensis*) in
Nebraska. Remote sensing and GIS are used to demonstrate how these tools can be
integrated to provide critical information to wildlife managers. I focus on bighorn sheep
because of a growing interest by the Nebraska Game and Parks Commission to determine
whether the available habitat within the northwest region of the state can support a
minimum viable population (MVP). A MVP is defined as the smallest population having
at least a 99% chance of surviving 1000 years (Nunney and Campbell 1993). The MVP
for bighorn sheep must include at least 125 individuals (Van Dyke et al. 1983, Berger
1990, Smith et al. 1991). This is a good opportunity to apply the aforementioned
technologies to provide the state with the information it desires since limited staff is
available to address this problem and to analyze the large amount of land.

Bighorn sheep were once abundant throughout the Great Plains and western
mountain regions of the continental United States, but over the last century their numbers
have declined considerably. The Audubon bighorn sheep (*O. c. auduboni*) historically
inhabited the Northern Great Plains, but the last of its kind was seen near Magpie Creek,
South Dakota in 1905 (Jones et al. 1983). Management of the remaining herds in our
altered landscapes is critical as home ranges of bighorn sheep herds steadily decrease and
the distance between neighboring populations increases. In recent decades wildlife
biologists have undertaken programs to reestablish bighorn sheep in their once native
ranges and, in the case of Nebraska, the former range of the Audubon subspecies.
Rocky Mountain bighorn sheep (*O. c. canadensis*) were reintroduced to the Pine Ridge region of northwest Nebraska in 1981. Despite a growing population within the region, it is not known to what extent this species can establish itself within the former range of the Audubon bighorn. Fairbanks et al. (1987) gathered data pertaining to the distribution of bighorns in the original Pine Ridge enclosure, but the enclosure has since been removed, allowing the sheep to move freely about the region. Bighorn sheep are considered a "wilderness species" and generally require contiguous regions of suitable habitat (Van Dyke et al. 1983). It is, therefore, important to understand the spatial structure of suitable bighorn sheep habitat across the study area. Although the Audubon subspecies found habitat conditions within the Pine Ridge favorable to colonization, there is no guarantee that those same conditions exist today. Despite the short-term success of the reintroduced herd, wildlife biologists are not certain that bighorn sheep in the can survive in the Pine Ridge without human intervention. These biologists lack two crucial pieces of information – how much suitable habitat exists for Rocky Mountain bighorn sheep in the Pine Ridge of Nebraska, and what is the spatial structure of that suitable habitat?

Landsat satellite imagery will be employed in this study to provide a layer of data representing the vegetation found throughout the study area. A GIS will be used to store and analyze these and other data (e.g. elevation, hydrology, road networks). A spatial model will be developed to evaluate suitable bighorn sheep habitat in the Pine Ridge of Nebraska. This model will emphasize the spatial structure of the suitable habitat in the region, based on landscape metrics.
1.2 Statement of Objectives

Seventeen years after bighorn sheep were reintroduced within the borders of Nebraska, the Nebraska Game and Parks Commission and United States Department of Agriculture Forest Service (USFS) wish to determine whether the establishment of a MVP of bighorn sheep is possible within the Pine Ridge of Nebraska.

The objectives of this study are to:

1) develop and implement a habitat suitability model for bighorn sheep in the Pine Ridge of Nebraska,

2) develop a GIS model to compare and associate factors relating to the spatial configuration of bighorn sheep habitat,

3) assess the spatial structure of suitable habitat within the Pine Ridge and relate these metrics to results obtained from the GIS model, and

4) determine if the Pine Ridge has sufficient habitat to support a minimum viable population of bighorn sheep.

1.3 Study Area

The study area encompasses a 4,263-km² subset of northwest Nebraska, commonly referred to as the Pine Ridge (Figure 1). The stony, pine-covered escarpments of this region cover 3,885 km² (Tolstead 1947). Areas characterized by rocky buttes extending upward from steep slopes are covered primarily by open stands of ponderosa pine (*Pinus ponderosa*). A mixture of grasses and forbs characterizes the plant communities on the ridge-tops and flat lands, while the lowland, riparian areas contain a few species of grasses, deciduous trees and shrubs (Table 1).

The study area boundary follows the boundaries of 30 United States Geological Survey (USGS) 1:24,000 scale (7.5 minute) topographic quadrangles (Figure 2), which were selected visually by overlaying a vector layer of quadrangle boundaries on Landsat
Figure 1. The Pine Ridge study area encompasses 4263 km² of northwest Nebraska. The region was divided into three main focus areas, believing sheep would be reluctant to traverse regions between focus areas. Shaded regions indicate public land.
Thematic Mapper (TM) images and elevation maps and choosing quadrangles containing both forested regions and substantial change in elevation (indicating potential bighorn sheep habitat). Corresponding quadrangles are listed in Table 2. Within the boundary, state and federal ownership is intermixed with privately owned land. Of particular importance is Fort Robinson State Park, located west of Crawford, where bighorn sheep were reintroduced into Nebraska.

Table 1. Shrub and pine sapling abundance in the Pine Ridge of Nebraska (Tolstead 1947).

<table>
<thead>
<tr>
<th>Species</th>
<th>Density of Pine Stand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scattered</td>
</tr>
<tr>
<td>Symphoricarpos occidentalis</td>
<td>37.1</td>
</tr>
<tr>
<td>Rhus trilobata</td>
<td>21.4</td>
</tr>
<tr>
<td>Pinus scopulorum seedlings</td>
<td>10.3</td>
</tr>
<tr>
<td>Rosa arkansana</td>
<td>8.8</td>
</tr>
<tr>
<td>Rhus toxicodendron</td>
<td>6.2</td>
</tr>
<tr>
<td>Yucca glauca</td>
<td>6.4</td>
</tr>
<tr>
<td>Artemisia frigida</td>
<td>5.0</td>
</tr>
<tr>
<td>Rosa woodsii</td>
<td>2.3</td>
</tr>
<tr>
<td>Amelanchier alnifolia</td>
<td>1.1</td>
</tr>
<tr>
<td>Prunus melanocarpa</td>
<td>0.7</td>
</tr>
<tr>
<td>Gutierrezia sarothrae</td>
<td>0.3</td>
</tr>
<tr>
<td>Prunus americana</td>
<td>0.3</td>
</tr>
<tr>
<td>Prunus besseyi</td>
<td>0.1</td>
</tr>
<tr>
<td>Ribes odoratum</td>
<td>T</td>
</tr>
<tr>
<td>Ribes inebrians</td>
<td>T</td>
</tr>
<tr>
<td>Berberis aquifolium</td>
<td>7.1</td>
</tr>
<tr>
<td>Symphoricarpos albus</td>
<td>T</td>
</tr>
<tr>
<td>Ribes oxyacanthoides</td>
<td>T</td>
</tr>
</tbody>
</table>

<sup>1</sup> T denotes trace amounts in the total sample.

Focus areas were subdivided into population locales that could potentially support a subpopulation of bighorn sheep within the framework of a metapopulation (Figure 3,
Figure 2. Map of thirty, 7.5 minute USGS quadrangles used to delineate the Pine Ridge study area. Corresponding quadrangle names are listed in table 2.
discussed later in greater detail). Population locales were visually delineated on the maps after the habitat and landscape analysis procedures were completed. Each locale focuses on a region of seemingly contiguous, suitable habitat within a focus area. Focus area 1 was divided into three population locales, labeled Gilbert-Baker, Roundtop, and Fort Robinson. Focus area 2 was not further divided, and focus area 3 was divided into two population locales, labeled Beaver-Wall and Ponderosa.

Table 2. List of quadrangle names used to delineate the Pine Ridge study area.

<table>
<thead>
<tr>
<th>Quadrangle ID</th>
<th>Quadrangle Name</th>
<th>Quadrangle ID</th>
<th>Quadrangle Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Clinton NE</td>
<td>16</td>
<td>Chadron 3 NE</td>
</tr>
<tr>
<td>2</td>
<td>Clinton NW</td>
<td>17</td>
<td>Chadron 3 NW</td>
</tr>
<tr>
<td>3</td>
<td>Whiteclay</td>
<td>18</td>
<td>Coffee Mill Butte</td>
</tr>
<tr>
<td>4</td>
<td>Beaver Wall</td>
<td>19</td>
<td>Chimney Butte</td>
</tr>
<tr>
<td>5</td>
<td>Clinton SW</td>
<td>20</td>
<td>Crow Butte</td>
</tr>
<tr>
<td>6</td>
<td>Whiteclay SE</td>
<td>21</td>
<td>Crawford</td>
</tr>
<tr>
<td>7</td>
<td>Whiteclay SW</td>
<td>22</td>
<td>Smiley Canyon</td>
</tr>
<tr>
<td>8</td>
<td>Bordeaux</td>
<td>23</td>
<td>Andrews</td>
</tr>
<tr>
<td>9</td>
<td>Chadron East</td>
<td>24</td>
<td>Harrison East</td>
</tr>
<tr>
<td>10</td>
<td>Chadron West</td>
<td>25</td>
<td>Harrison West</td>
</tr>
<tr>
<td>11</td>
<td>Roundtop</td>
<td>26</td>
<td>Coffee Mill B. SW</td>
</tr>
<tr>
<td>12</td>
<td>Five Points</td>
<td>27</td>
<td>Belmont</td>
</tr>
<tr>
<td>13</td>
<td>Bodarc</td>
<td>28</td>
<td>Dead Mans Creek</td>
</tr>
<tr>
<td>14</td>
<td>Warbon. Ranch</td>
<td>29</td>
<td>Glen</td>
</tr>
<tr>
<td>15</td>
<td>Hay Springs</td>
<td>30</td>
<td>Kyle Creek</td>
</tr>
</tbody>
</table>

1.4 Thesis Organization

The thesis is organized into five chapters, introducing the problem (Chapter 1); a literature and background review of bighorn sheep, their habitat requirements, and various issues regarding the use of GIS and remote sensing to study wildlife habitat (Chapter 2); methods used to develop the habitat model and innovations used for the
CHAPTER II: BACKGROUND

2.1 Introduction

Habitat suitability models have been derived for numerous species since the middle of the 20th century. These models, often formulated as mathematical equations that compute a habitat suitability index (HSI), assess the habitat requirements and preferences of a species to derive an evaluation of areas with regard to their ability to support a population. In recent years GIS and remote sensing technologies have been used extensively in habitat suitability modeling (Pereira and Itami 1991, Sweanor et al. 1994, Gudorf et al. 1995, Ockenfels et al. 1996, Conway 1996, Van Deelen et al. 1997, Bian and West 1997, Van Manen and Pelton 1997). By incorporating these technologies, scientists often gain the ability to formulate and implement a more detailed habitat suitability model.

Population models that attempt to describe the dynamics of a species over time often complement habitat models. Habitat models focus on the environment in which the population exists, whereas population models emphasize the rhythms of the population due to density, carrying capacity of the habitat, birth and death, movements, and abundance. Whereas these two approaches are clearly synergistic, habitat modeling tends to be spatially oriented, considering relative distances to food and water sources, patch sizes, and other geospatial factors. Population models describe the population’s trend over time, while often considering the abundance of resources as inputs to a spatially inexplicit model.

As the use of geospatial information technologies has become more prevalent in wildlife studies, the ability to perform comprehensive habitat modeling has increased.
Computing habitat suitability is now a relatively simple matter of implementing the model within a GIS, providing the necessary inputs (e.g. land cover), and instructing the computer on how to run the model. The spatial extent of the model becomes relatively inconsequential in terms of processing demands.

Smith et al. (1991) proposed a GIS-based habitat evaluation procedure (HEP) for Rocky Mountain bighorn sheep. This HEP was designed to provide “(1) estimates of the quantity and quality of occupied, or proposed, bighorn ranges, (2) predictions of a site’s ability to support at least a [minimum viable population estimate] (MVPE) of bighorn sheep, (3) an identification of population limiting factors, (4) an estimation of the effects of management activities on bighorn habitat, (5) identification of cost-effective habitat management strategies, and (6) [a method for the] use of geographic information systems (GIS) technology for habitat evaluations (Smith et al. 1991:206).” The authors described informational layers that should be included within a model, how the layers should interact within the model, and how the results from the model should be interpreted to obtain an estimate of stocking levels in a study area. The general approach described in this HEP formed the basis of the model for habitat suitability in the Pine Ridge of Nebraska, with modifications to account for differences in descriptions of favorable vegetation types and escape terrain.

Development of a GIS-based habitat model for bighorn sheep has been based on an extensive review of the wildlife literature. This chapter will review the current literature pertaining to not only bighorn sheep and their habitat preferences, but also habitat modeling techniques, GIS modeling, and the use of remotely-sensed data in habitat models for wildlife.
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CHAPTER I: INTRODUCTION

1.1 Introduction

The study of wildlife populations is partially based upon the ability to derive some understanding about the relationship between the species and the habitat in which it resides. Traditionally, wildlife populations and habitat were tracked and delineated using paper maps and notes written in notebooks. Unfortunately, these methods proved to be cumbersome and difficult to manage. Paper maps are rarely up-to-date, hand-drawn boundaries are typically inaccurate, and the ability to study multiple spatial variables influencing a population is greatly limited. Furthermore, it is difficult to quantify important habitat properties such as patch size and land cover interspersion when using paper maps.

Extensive amounts of time were once required to study the flora and fauna of a region, map areas, and track animals. Now, satellite-borne remote sensing systems can produce multi-band images that can be processed with relative ease to extract information about the land cover types over large geographic areas. Multiple layers of information can be stored and processed within a geographic information system (GIS) to derive new and meaningful information regarding wildlife habitat. In situ data collection is no longer the primary means for obtaining information about a region, but rather one of many tools that can be used to support such a study (see, for example, Trotter 1991, Herr and Queen 1993, Homer et al. 1997). While they are by no means perfect solutions, remote sensing and GIS have solved many of the former difficulties by allowing the frequent updating of maps without the need to reprint the map, the acquisition and storage of large amounts of
data with less field work, the analysis of multiple variables influencing a population, and the quantification of spatial structure. For these reasons and more, GIS and remote sensing have become increasingly more common tools in wildlife research.

This thesis focuses on the management of bighorn sheep (*Ovis canadensis*) in Nebraska. Remote sensing and GIS are used to demonstrate how these tools can be integrated to provide critical information to wildlife managers. I focus on bighorn sheep because of a growing interest by the Nebraska Game and Parks Commission to determine whether the available habitat within the northwest region of the state can support a minimum viable population (MVP). A MVP is defined as the smallest population having at least a 99% change of surviving 1000 years (Nunney and Campbell 1993). The MVP for bighorn sheep must include at least 125 individuals (Van Dyke et al. 1983, Berger 1990, Smith et al. 1991). This is a good opportunity to apply the aforementioned technologies to provide the state with the information it desires since limited staff is available to address this problem and to analyze the large amount of land.

Bighorn sheep were once abundant throughout the Great Plains and western mountain regions of the continental United States, but over the last century their numbers have declined considerably. The Audubon bighorn sheep (*O. c. auduboni*) historically inhabited the Northern Great Plains, but the last of its kind was seen near Magpie Creek, South Dakota in 1905 (Jones et al. 1983). Management of the remaining herds in our altered landscapes is critical as home ranges of bighorn sheep herds steadily decrease and the distance between neighboring populations increases. In recent decades wildlife biologists have undertaken programs to reestablish bighorn sheep in their once native ranges and, in the case of Nebraska, the former range of the Audubon subspecies.
Rocky Mountain bighorn sheep (*O. c. canadensis*) were reintroduced to the Pine Ridge region of northwest Nebraska in 1981. Despite a growing population within the region, it is not known to what extent this species can establish itself within the former range of the Audubon bighorn. Fairbanks et al. (1987) gathered data pertaining to the distribution of bighorns in the original Pine Ridge enclosure, but the enclosure has since been removed, allowing the sheep to move freely about the region. Bighorn sheep are considered a “wilderness species” and generally require contiguous regions of suitable habitat (Van Dyke et al. 1983). It is, therefore, important to understand the spatial structure of suitable bighorn sheep habitat across the study area. Although the Audubon subspecies found habitat conditions within the Pine Ridge favorable to colonization, there is no guarantee that those same conditions exist today. Despite the short-term success of the reintroduced herd, wildlife biologists are not certain that bighorn sheep in the can survive in the Pine Ridge without human intervention. These biologists lack two crucial pieces of information – how much suitable habitat exists for Rocky Mountain bighorn sheep in the Pine Ridge of Nebraska, and what is the spatial structure of that suitable habitat?

Landsat satellite imagery will be employed in this study to provide a layer of data representing the vegetation found throughout the study area. A GIS will be used to store and analyze these and other data (e.g. elevation, hydrology, road networks). A spatial model will be developed to evaluate suitable bighorn sheep habitat in the Pine Ridge of Nebraska. This model will emphasize the spatial structure of the suitable habitat in the region, based on landscape metrics.
1.2 Statement of Objectives

Seventeen years after bighorn sheep were reintroduced within the borders of Nebraska, the Nebraska Game and Parks Commission and United States Department of Agriculture Forest Service (USFS) wish to determine whether the establishment of a MVP of bighorn sheep is possible within the Pine Ridge of Nebraska.

The objectives of this study are to:

1) develop and implement a habitat suitability model for bighorn sheep in the Pine Ridge of Nebraska,

2) develop a GIS model to compare and associate factors relating to the spatial configuration of bighorn sheep habitat,

3) assess the spatial structure of suitable habitat within the Pine Ridge and relate these metrics to results obtained from the GIS model, and

4) determine if the Pine Ridge has sufficient habitat to support a minimum viable population of bighorn sheep.

1.3 Study Area

The study area encompasses a 4,263-km² subset of northwest Nebraska, commonly referred to as the Pine Ridge (Figure 1). The stony, pine-covered escarpments of this region cover 3,885 km² (Tolstead 1947). Areas characterized by rocky buttes extending upward from steep slopes are covered primarily by open stands of ponderosa pine (*Pinus ponderosa*). A mixture of grasses and forbs characterizes the plant communities on the ridge-tops and flat lands, while the lowland, riparian areas contain a few species of grasses, deciduous trees and shrubs (Table 1).

The study area boundary follows the boundaries of 30 United States Geological Survey (USGS) 1:24,000 scale (7.5 minute) topographic quadrangles (Figure 2), which were selected visually by overlaying a vector layer of quadrangle boundaries on Landsat
Figure 1. The Pine Ridge study area encompasses 4263 km² of northwest Nebraska. The region was divided into three main focus areas, believing sheep would be reluctant to traverse regions between focus areas. Shaded regions indicate public land.
Thematic Mapper (TM) images and elevation maps and choosing quadrangles containing both forested regions and substantial change in elevation (indicating potential bighorn sheep habitat). Corresponding quadrangles are listed in Table 2. Within the boundary, state and federal ownership is intermixed with privately owned land. Of particular importance is Fort Robinson State Park, located west of Crawford, where bighorn sheep were reintroduced into Nebraska.

Table 1. Shrub and pine sapling abundance in the Pine Ridge of Nebraska (Tolstead 1947).

<table>
<thead>
<tr>
<th>Species</th>
<th>Density of Pine Stand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scattered</td>
</tr>
<tr>
<td>Symphoricarpos occidentalis</td>
<td>37.1</td>
</tr>
<tr>
<td>Rhus trilobata</td>
<td>21.4</td>
</tr>
<tr>
<td>Pinus scopulorum seedlings</td>
<td>10.3</td>
</tr>
<tr>
<td>Rosa arkansana</td>
<td>8.8</td>
</tr>
<tr>
<td>Rhus toxicodendron</td>
<td>6.2</td>
</tr>
<tr>
<td>Yucca glauca</td>
<td>6.4</td>
</tr>
<tr>
<td>Artemisia frigida</td>
<td>5.0</td>
</tr>
<tr>
<td>Rosa woodsii</td>
<td>2.3</td>
</tr>
<tr>
<td>Amelanchier alnifolia</td>
<td>1.1</td>
</tr>
<tr>
<td>Prunus melanocarpa</td>
<td>0.7</td>
</tr>
<tr>
<td>Gutierrezia sarothrae</td>
<td>0.3</td>
</tr>
<tr>
<td>Prunus americana</td>
<td>0.3</td>
</tr>
<tr>
<td>Prunus besseyi</td>
<td>0.1</td>
</tr>
<tr>
<td>Ribes odoratum</td>
<td>T</td>
</tr>
<tr>
<td>Ribes inebrians</td>
<td>T</td>
</tr>
<tr>
<td>Berberis aquifolium</td>
<td>7.1</td>
</tr>
<tr>
<td>Symphoricarpos albus</td>
<td>T</td>
</tr>
<tr>
<td>Ribes oxyacanthoides</td>
<td>T</td>
</tr>
</tbody>
</table>

1 T denotes trace amounts in the total sample.

Focus areas were subdivided into population locales that could potentially support a subpopulation of bighorn sheep within the framework of a metapopulation (Figure 3,
7.5 Minute Quadrangles Defining the Pine Ridge Study Area

Figure 2. Map of thirty, 7.5 minute USGS quadrangles used to delineate the Pine Ridge study area. Corresponding quadrangle names are listed in table 2.
discussed later in greater detail). Population locales were visually delineated on the maps after the habitat and landscape analysis procedures were completed. Each locale focuses on a region of seemingly contiguous, suitable habitat within a focus area. Focus area 1 was divided into three population locales, labeled Gilbert-Baker, Roundtop, and Fort Robinson. Focus area 2 was not further divided, and focus area 3 was divided into two population locales, labeled Beaver-Wall and Ponderosa.

Table 2. List of quadrangle names used to delineate the Pine Ridge study area.

<table>
<thead>
<tr>
<th>Quadrangle ID</th>
<th>Quadrangle Name</th>
<th>Quadrangle ID</th>
<th>Quadrangle Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Clinton NE</td>
<td>16</td>
<td>Chadron 3 NE</td>
</tr>
<tr>
<td>2</td>
<td>Clinton NW</td>
<td>17</td>
<td>Chadron 3 NW</td>
</tr>
<tr>
<td>3</td>
<td>Whiteclay</td>
<td>18</td>
<td>Coffee Mill Butte</td>
</tr>
<tr>
<td>4</td>
<td>Beaver Wall</td>
<td>19</td>
<td>Chimney Butte</td>
</tr>
<tr>
<td>5</td>
<td>Clinton SW</td>
<td>20</td>
<td>Crow Butte</td>
</tr>
<tr>
<td>6</td>
<td>Whiteclay SE</td>
<td>21</td>
<td>Crawford</td>
</tr>
<tr>
<td>7</td>
<td>Whiteclay SW</td>
<td>22</td>
<td>Smiley Canyon</td>
</tr>
<tr>
<td>8</td>
<td>Bordeaux</td>
<td>23</td>
<td>Andrews</td>
</tr>
<tr>
<td>9</td>
<td>Chadron East</td>
<td>24</td>
<td>Harrison East</td>
</tr>
<tr>
<td>10</td>
<td>Chadron West</td>
<td>25</td>
<td>Harrison West</td>
</tr>
<tr>
<td>11</td>
<td>Roundtop</td>
<td>26</td>
<td>Coffee Mill B. SW</td>
</tr>
<tr>
<td>12</td>
<td>Five Points</td>
<td>27</td>
<td>Belmont</td>
</tr>
<tr>
<td>13</td>
<td>Bodarc</td>
<td>28</td>
<td>Dead Mans Creek</td>
</tr>
<tr>
<td>14</td>
<td>Warbon. Ranch</td>
<td>29</td>
<td>Glen</td>
</tr>
<tr>
<td>15</td>
<td>Hay Springs</td>
<td>30</td>
<td>Kyle Creek</td>
</tr>
</tbody>
</table>

1.4 Thesis Organization

The thesis is organized into five chapters, introducing the problem (Chapter 1); a literature and background review of bighorn sheep, their habitat requirements, and various issues regarding the use of GIS and remote sensing to study wildlife habitat (Chapter 2); methods used to develop the habitat model and innovations used for the
habitat analysis (Chapter 3); results of the study and a discussion of the implications of these results (Chapter 4); and the conclusions derived from this research (Chapter 5).
Figure 3. Map of six regions that were visually delineated from the Pine Ridge study area as potential population locales for bighorn sheep.
CHAPTER II: BACKGROUND

2.1 Introduction

Habitat suitability models have been derived for numerous species since the middle of the 20th century. These models, often formulated as mathematical equations that compute a habitat suitability index (HSI), assess the habitat requirements and preferences of a species to derive an evaluation of areas with regard to their ability to support a population. In recent years GIS and remote sensing technologies have been used extensively in habitat suitability modeling (Pereira and Itami 1991, Sweanor et al. 1994, Gudorf et al. 1995, Ockenfels et al. 1996, Conway 1996, Van Deelen et al. 1997, Bian and West 1997, Van Manen and Pelton 1997). By incorporating these technologies, scientists often gain the ability to formulate and implement a more detailed habitat suitability model.

Population models that attempt to describe the dynamics of a species over time often complement habitat models. Habitat models focus on the environment in which the population exists, whereas population models emphasize the rhythms of the population due to density, carrying capacity of the habitat, birth and death, movements, and abundance. Whereas these two approaches are clearly synergistic, habitat modeling tends to be spatially oriented, considering relative distances to food and water sources, patch sizes, and other geospatial factors. Population models describe the population’s trend over time, while often considering the abundance of resources as inputs to a spatially inexplicit model.

As the use of geospatial information technologies has become more prevalent in wildlife studies, the ability to perform comprehensive habitat modeling has increased.
Computing habitat suitability is now a relatively simple matter of implementing the model within a GIS, providing the necessary inputs (e.g. land cover), and instructing the computer on how to run the model. The spatial extent of the model becomes relatively inconsequential in terms of processing demands.

Smith et al. (1991) proposed a GIS-based habitat evaluation procedure (HEP) for Rocky Mountain bighorn sheep. This HEP was designed to provide "(1) estimates of the quantity and quality of occupied, or proposed, bighorn ranges, (2) predictions of a site's ability to support at least a [minimum viable population estimate] (MVPE) of bighorn sheep, (3) an identification of population limiting factors, (4) an estimation of the effects of management activities on bighorn habitat, (5) identification of cost-effective habitat management strategies, and (6) [a method for the] use of geographic information systems (GIS) technology for habitat evaluations (Smith et al. 1991:206)." The authors described informational layers that should be included within a model, how the layers should interact within the model, and how the results from the model should be interpreted to obtain an estimate of stocking levels in a study area. The general approach described in this HEP formed the basis of the model for habitat suitability in the Pine Ridge of Nebraska, with modifications to account for differences in descriptions of favorable vegetation types and escape terrain.

Development of a GIS-based habitat model for bighorn sheep has been based on an extensive review of the wildlife literature. This chapter will review the current literature pertaining to not only bighorn sheep and their habitat preferences, but also habitat modeling techniques, GIS modeling, and the use of remotely-sensed data in habitat models for wildlife.
2.2 GIS in Wildlife Studies

Relatively few studies have been conducted on habitat for bighorn sheep using GIS and remote sensing. Smith et al. (1991) proposed a GIS-based modeling procedure for evaluating Rocky Mountain bighorn sheep habitat in the intermountain west. As with most studies of bighorn sheep, their model addressed the primary habitat requirements (general, foraging, lambing, and thermal) and related this to the needs of a MVP. The model, however, is based on decision rules rather than a deterministic habitat suitability index (HSI). Further, at the time this model was proposed, GIS technology was still in its infancy.

A habitat suitability model that attempts to rate areas of land with respect to their ability to support bighorn sheep will be developed. Traditionally, such suitability models are implemented as habitat suitability indices (HSI), typically equations that account for important components of the species' habitat. However, suitability models may also take a less deterministic form and be implemented as decision-rule models, wherein they evaluate potential habitat through a series of rules before ultimately assigning a rating to the habitat. It is this latter form of model that will be implemented for bighorn sheep in the Pine Ridge.

In 1994 the National Park Service (NPS) conducted a GIS analysis for bighorn sheep habitat in the Greater Theodore Roosevelt National Park Area. They conducted a similar study in 1995 in the Colorado National Monument Area (Sweanor et al. 1994, Gudorf et al. 1995). These studies included habitat as well as anthropogenic factors to evaluate focus areas located within the study region with regard to their ability to support
bighorn sheep and a minimum viable population of 125 individuals. Modeling of habitat was conducted in vector format with land cover information derived from digitized Bureau of Land Management (BLM) maps at a scale of 1:24,000. The NPS concluded that the Greater Theodore Roosevelt National Park Area contained too little habitat in too many patches to support a MVP of bighorn sheep, while the Colorado National Monument Area contained sufficient habitat for a MVP. These studies provide a good basis for a GIS study of bighorn sheep habitat in the state of Nebraska.

GIS and remote sensing studies of other species and habitat have also been valuable to wildlife managers. Bian and West (1997) conducted an analysis of elk (*Cervus elaphus*) calving habitat using GIS modeling and statistics. In this study a logistic regression model was used to produce a map of probabilities of habitat use by elk for calving. The model also accounted for anthropogenic factors such as oil and gas wells that create wildlife-disturbing noises, an aspect not always considered by wildlife models. The model accurately predicted the use of already known calving sites with a 93.6% success rate while predicting non-calving sites with an accuracy of 82.8%. Similarly, Van Manen and Pelton (1997) used GIS logistic modeling to produce a predictive model for black bears (*Ursus americanus*). This model incorporated such data parameters as overstory vegetation type, proximity to streams, and forest stand age richness.

Mladenoff (see Conway 1996) developed a GIS-based habitat model for gray wolves (*Canus lupus*) in the Great Lakes region. Mladenoff initially used radio-telemetry data to map the locations and movements of the wolf packs in the region. Then, using land-use/land-cover and road information extracted from U.S. Bureau of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER) system data,
they statistically determined the critical factors that influence the presence of wolves.

From this, they were able to apply the model of wolf presence probability to Minnesota, Wisconsin, and Michigan to locate areas of favorable wolf habitat.

Whereas these models focused on different species and incorporated a variety of modeling techniques, they provide a solid foundation for modeling bighorn sheep habitat in Nebraska. For example, water is typically analyzed as a “distance from feature” basis. As distance from water increases, the suitability of habitat decreases in some fashion (e.g. linear, exponentially). Studies often incorporate vegetation information on a discrete basis. For example, Van Manen and Pelton’s (1997) model of black predicted the presence or absence of black bears in the Appalachian mountains by incorporating overstory vegetation types. A logistic regression comparing random locations to known bear locations produced “weights” for the influence of each vegetation type on the presence of bears. When incorporated into the model, the type of vegetation at a given location helped to predict whether bears would be present or not.

Whereas logistic modeling is frequently used for the analysis of wildlife habitat, it has one limitation: data must be available to describe the presence or absence of a species as well as the various habitat features found in the area. In a study incorporating a logistic model, the data are collected and then analyzed using a logistic regression to derive coefficients for each of the variables. For example, a 1998 study of elk habitat in the Pine Ridge of Nebraska required that radio-telemetry be utilized to determine areas used by the collared individuals. Data regarding overstory, lateral visibility, distance from water, and other landscape features were then collected at numerous locations within the home ranges of the individuals (Cover, 2000). Unfortunately, it is not always
possible to use radio telemetry or to collect field data at known locations. It is time consuming, may span many seasons, and is labor-intensive.

Hepinstall et al. (1996) used a neighborhood analysis, based on a moving window, in their study of moose (*Alces alces*) habitat in Minnesota. They used an existing HSI for moose and modified it for use within a GIS to take a more spatial approach to modeling the habitat. They determined that a 50% moving window overlap was sufficient to capture variability in landscape spatial structure. This approach will be adapted to provide an assessment of the roads in the Pine Ridge of Nebraska, which are assumed to provide some measure of human disturbance in the region. By incorporating a neighborhood analysis, feature (road) density can be assessed across the region.

Incorporating GIS into wildlife modeling can assist in policy-making. For example, the University of Arizona Natural Resources Department conducted a habitat impact assessment for the Mt. Graham Red Squirrel at the request of the USDA Forest Service (Pereira and Itami 1991). In this study the University of Arizona wanted to construct a new astronomical observatory on Mt. Graham, the location of a rare species of squirrel. The Natural Resources Department used GIS and logistic modeling to develop a habitat suitability model for the region. Once this was completed, the construction plans were analyzed in combination with the habitat suitability maps to determine the amount of red squirrel habitat that would be eliminated by the proposed construction. From the analysis, an assessment of the population impact was derived. Based on the results of this study, the University was required to modify its construction plans to have a lesser impact. In this study of bighorn sheep, assessment of roads will be incorporated into the study to determine whether certain roads may need to be closed
temporarily during the lambing season.

For well-researched species, habitat data (e.g. preferred vegetation, access to water, and urban influences) may be available. In the study of the gray wolves (Conway 1996), radio-telemetry data were available to give the GIS analysts information about where wolves were located. These data were analyzed using multiple regression to develop a deterministic regression equation used within the GIS to assign a probability of presence or absence of the species for a given area of land. Whereas such models are often very accurate, they are only as good as the data upon which they are built. Having more data available to initially develop the regression coefficients can lead to a more accurate model. Unfortunately, little of this information exists for bighorn sheep, especially in the Pine Ridge of Nebraska. Thus, it is necessary to build an empirical model using a less statistically based approach, but incorporating prior observations of species absence/presence to fine-tune the model.

2.3 Remote Sensing in Wildlife Studies

Remote sensing and GIS analysis techniques are often used in combination. Herr and Queen (1993), for example, used GIS and remote sensing to identify potential greater sandhill crane (Grus canadensis tabida) nesting habitat in northwestern Minnesota. Landsat Thematic Mapper (TM) data were used to produce a land cover classification that was used to identify favorable and unfavorable vegetation types for nesting. The classification was combined with several anthropogenic layers including highways, urban structures, and agricultural land. Each layer was assigned ratings, indicating areas more or less favorable for crane nesting. This study is somewhat unique in that it used a “zone
of influence" technique to evaluate the influence of various factors on potential nesting sites. These zones are implemented as concentric circles of influence as distance increases from a feature. For example, a building has different levels of influence over the suitability of habitat proportional to distance. As distance increased from the building, disturbance decreased. The authors note that satellite imagery may often have a spatial resolution too coarse for use in modeling the habitat of some wildlife species.

Herr and Queen (1993) realized this when determining that many of their vegetation categories were incorrectly classified due to their inability to detect different patches of vegetation on such a small geographic scale. While this concern should always be considered when using satellite imagery for habitat modeling, it is not a concern for modeling bighorn sheep habitat. Areas used by bighorn sheep are relatively large. The minimum area used by an individual bighorn sheep is, in fact, the size of one pixel (28.5 m x 28.5 m) of a Landsat TM image.

Aspinall and Veitch (1993) used a Bayesian modeling approach to incorporate satellite imagery in their wildlife study of curlews (Numenius arquata) in Scotland. They noted that habitat maps produced with satellite imagery are usually based on a spectral classification of "ecologically meaningful classes" relevant to the species of interest. It is not necessary to produce a classification of all vegetation types, but rather only those vegetation types that have some relevance to the species of interest. The Bayesian approach used in their study, however, requires training data to produce a model of absence and presence predictions. Training data is used in a supervised image classification procedure to indicate to the software which pixels are known to belong to specific classes. The software can then use this information to classify unknown pixels.
To obtain training data, they conducted a bird survey on a small portion of the study area. This process, however, can be time consuming for species that are not abundant, such as bighorn sheep. Once their model was developed with this sample of training data, it was possible to apply the model to the entire study area. Their approach produced noteworthy success, though they stated that the model would have been more accurate had elevation data been incorporated.

Ormsby and Lunetta (1987) also used Landsat TM data in their study of food availability for whitetail deer (*Odocoileus virginia*) in Michigan. Once again the satellite imagery was used to produce a land cover map of the region, which was subsequently used as an input to a GIS model. In this case, however, areas of escape terrain were the primary focus of the study. A similarity between their study of deer and this study of bighorn sheep exists in the focus on escape terrain. Ormsby and Lunetta (1987) took a slightly different approach by delineating zones around escape terrain and assigning them values based on distance from the core. Thus, as distance increased from escape terrain, suitability of the food source decreased. In the bighorn model that will be developed in this study, the juxtaposition of escape terrain will be accounted for, but it will be done so using a neighborhood analysis. Although maximum distance from escape terrain is important for bighorn sheep habitat, the spatial configuration of the escape terrain around the habitat is of greater importance.

### 2.4 Wildlife, Landscape Structure, and Metapopulation Theory

As human influence on the landscape increases over time, wilderness species are placed under increasing stress. The amount of wilderness habitat decreases with an
increase in human disturbance, which is a possible cause of declining numbers of bighorn sheep (Bleich et al. 1996). Levins (1970) coined the term “metapopulation,” a population of populations of a species, and developed the metapopulation model. The metapopulation model suggests a different perspective for population modeling. Prior to its existence, most wildlife population researchers believed that the persistence of a species’ population was dependent on the availability of resources. The metapopulation model, however, suggests that the spatial configuration of the species’ habitat across the landscape is fundamentally important, primarily for species exhibiting territoriality or population distributions over relatively large geographic regions. “In the broadest sense, metapopulations simply are sets of subdivided populations in which rates of mating, competition, and other interactions are much higher within than among populations (Gutiérrez and Harrison 1996:168).” It is believed that metapopulations are more persistent than single- or subpopulations and allow the continuance of the species within a geographic region (Wiens 1996).

Not all populations, however, fit into the framework of the metapopulation. For example, the spotted owl (Strix occidentalis) in California and neighboring areas exhibits territorial behavior and occurs in isolated populations that interact very seldom over the long term (Gutiérrez and Harris 1996). Biologists have found that bighorn sheep fit very well into the metapopulation model, establishing many smaller populations within a geographic range of similar habitat. Diseases greatly impact bighorn sheep populations (Van Dyke et al. 1983), and the separation between subpopulations of a metapopulation protects each from the diseases that may be affecting a local subpopulation. Often, a single herd of sheep will occupy a small area, such as a specific mountain (Bleich et al. 1996).
1996). Given this information, it is important for biologists to consider the spatial
distribution of bighorn herds across the landscape. Something as simple as the
construction of a road between two mountains can effectively isolate two neighboring
bighorn herds from each other, destroying the connectivity of the metapopulation.

Bleich et al. (1996) conducted a study of mountain sheep populations in southern
California to better understand the distribution of populations in this region. Sheep that
occupied territories no more than 7.5 km from other sheep were found to be part of the
same metapopulation. It was also determined that the mean number of populations per
metapopulation in the region had declined from 7.7 to 4.0 from 1850 to 1970. From 1970
to the present, the mean number of populations dropped to a low of 2.6. It is believed
that this is due to an increase in habitat fragmentation across the landscape, caused by the
expansion of the interstate highway system.

Many indices have been developed to describe the structure and fragmentation of
landscapes. These include such measures as contagion, nearest neighbor, and proximity.
Wiens (1996) addressed the issue of dispersal, patch isolation and local population
dynamics. In general, as the landscape becomes more heavily fragmented and patches
become smaller and more isolated, the probability of a given animal of a species
dispersing to one of these patches decreases. The flow of genes between separated
populations is greatly impacted by the structure of the landscape. Despite the existence
of many patches of habitat that could each support a population, genetic bottlenecks can
occur within the entire population. In this case the landscape may be so fragmented that
genetic flow between the patches is limited (Hedrick 1996).

Gustafson and Parker (1992) conducted a study of the relationships between
landscape structure and indices of spatial pattern (contagion, nearest neighbor, and proximity), which is important to a proper evaluation of the results of a habitat model. They simulated two types of landscapes: random pixel and random clump. Random pixel landscapes were those in which each pixel had a certain probability of being suitable habitat, and the total landscape occupied by suitable habitat did not exceed a threshold value. Random clump landscapes were those in which pixels were aggregated into clumps and the total landscape occupied by suitable habitat did not exceed a threshold value. They found that some landscape indices (contagion, for example) did not perform as one might expect for the two landscape structures.

Contagion measures the interspersion of patches of habitat across the landscape. Disregarding other factors, landscapes where patches of habitat are well interspersed will have low contagion values, while landscapes with a lower level of patch interspersion will have higher contagion values (McGarigal and Marks 1993). Gustafson and Parker (1992) showed that, in a randomly generated image of pixels (a landscape), as the proportion of the landscape occupied by favorable habitat patches increased, the contagion curve conformed to a concave parabolic function. In contrast, contagion for a randomly generated image of pixel clumps resulted in a linearly decreasing contagion function. It is, therefore, important to pay careful attention to the structure of the landscape in which the species of interest resides and the impact that changes in the landscape can have on populations and distributions of that species. With bighorn sheep, for example, decreased patch size may render the habitat patch incapable of supporting any sheep at all. Increasing the distance between neighboring patches of habitat may effectively isolate herds of bighorn sheep or make it more difficult for migrating sheep to
successfully locate remote patches.

2.5 Rocky Mountain Bighorn Sheep

2.5.1 History of the Species

The Rocky Mountain bighorn sheep subspecies is found throughout the western regions of the continental United States. Historically, it inhabited mountainous regions of the West, ranging from Canada to Mexico, Montana to California, and even the foothills of the plains states. Until the early part of the 20th century, the Audubon subspecies inhabited the Northern Great Plains region. This subspecies was driven to extinction, however, just after the turn of the century by unregulated hunting from settlers expanding westward (Jones et al., 1983). The last of its kind was sighted near Magpie Creek, South Dakota in 1905. As populations of bighorn sheep have declined in numbers over the last few decades, wildlife biologists have begun looking into methods for stabilizing this species. Several Rocky Mountain bighorn sheep were transplanted to Custer State Park, South Dakota in 1964, and several additional, successful transplants in other regions followed over the next decades (Bear and Jones, 1973).

Bighorn sheep were first reintroduced to the Pine Ridge in 1981 by the Nebraska Game and Parks Commission when 4 ewes and 2 rams were relocated from Custer State Park in South Dakota to an enclosure in Fort Robinson State Park (Fairbanks et al. 1987). Two additional rams were introduced late in 1981, but did not survive (Menzel, pers. comm.). In 1982, 4 more individuals from Custer State Park were introduced into the enclosure. The initial plan was to maintain a parent population of 25 individuals within the enclosure, and to release any surplus sheep into the surrounding landscape (Fairbanks
Twenty-two sheep were released from the enclosure in 1988, and the remainder of the sheep was released when the enclosure was removed in 1993 (Grier 1999). An aerial survey of the Pine Ridge revealed 17 individuals (Grier 1995), but the current herd size is believed to contain approximately 70 individuals after approximately 11 individuals died from malnutrition or starvation during the winter of 1983-84 (Menzel pers. comm.). Rams have been reportedly sighted throughout the delineated study area, indicating extensive migration; but ewes are thought to remain within or near to the original enclosure on Fort Robinson. This concurs with other studies (Tilton and Willard 1982, Gionfriddo and Krausman 1986) that have documented the difference of habitat use and mobility between genders in bighorn sheep. Rams tend to explore their surroundings more and travel greater distances from their core habitats, while females show a higher level of fidelity to the core habitat.

Bighorn sheep are considered by biologists to be a “wilderness species.” That is, they often avoid areas of human disturbance and may flee from a vehicle or human observed at more than 2 km (Van Dyke et al. 1983). Given this behavior, they tend to occupy the more remote areas of habitat. Bissonette and Steinkamp (1996) conducted a study of bighorn sheep response to ephemeral habitat fragmentation by cattle. They found that the grazing herds of cattle excluded bighorn herds from parts of their normal habitat range, effectively fragmenting their home ranges. The model developed in this study incorporates the idea of habitat remoteness by adding a layer of urban influence (road density) as a measure of remoteness of lambing habitat.
2.5.2 Habitat Selection Criteria

Several studies (Shannon et al. 1975, Risenhoover and Bailey 1985, Krausman and Leopold 1986, Fairbanks et al. 1987) have focused on habitat factors that play a role in the distribution of bighorn sheep. Requirements of bighorn sheep change from season to season (Oldemeyer et al. 1971, Tilton and Willard 1982, Gionfriddo and Krausman 1986). During the summer months, rams can be found at higher elevations and grazing in open grasslands, while the ewes remain more within the high relief terrain. Herds migrate to lower elevations during the winter months to avoid deep snow cover and find available forage. The rutting season begins in the fall, and sheep will use lower elevations less for foraging and more for the purpose of breeding. From April to June, ewes give birth to lambs and raise them through the summer. During this time they require a greater amount of protection from predators. It is important to note, however, that, apart from a few mountain lions, only coyotes and some wild dogs may present a threat of predation to young lambs in the Pine Ridge. Of these, the mountain lion is considered most capable of killing an adult bighorn sheep (Buechner 1960), and predation is most successful in areas where escape terrain is limited (Blaisdell 1961). Whether the predator rule fully applies to the Pine Ridge or not is currently unknown.

Mountain sheep wintering in the area of Thompson Falls, Montana had a preference for shrubland-grassland and open forests, but tended to avoid closed canopy forests (Tilton and Willard 1982). Sheep avoided upper slopes and drainage bottoms while preferring cliffs. These results concur with similar reports by Oldemeyer et al. (1971), who conducted a study of bighorn sheep in Yellowstone National Park.

Gionfriddo and Krausman (1986) found that bighorn sheep moved to slightly
higher elevations during the summer months and to preferred more northerly-facing slopes. It is believed that these cooler areas are used as a means of thermoregulation. The upper slopes of drainages were also preferred during this time, though ewes and lambs remained more within the middle slopes and rugged terrain for protection.

Bighorn sheep are very strongly influenced by elevation during the mid-summer months, though biotic factors (availability of forage) may be an underlying cause. The association between bighorn sheep and their preference for certain elevations may be more strongly influenced by the vegetation that is present at those elevations, and not a preference for the elevation itself (Shannon et al. 1975).

It is not known to what extent the bighorn sheep currently inhabiting the Pine Ridge are migrating and dispersing throughout the matrix of suitable and unsuitable habitat. Bleich et al. (1996) found that herds in southern California generally occupy a small area with infrequent migration. Despite the initial transplanting of bighorn sheep to the Pine Ridge at Fort Robinson State Park, rams have been observed throughout the study area. Interestingly, though, state biologists reported only one sighting of a ewe outside of the state park. Rams are known to be more mobile than ewes and lambs, and thus it is not surprising that a difference in dispersal would exist between the genders. Studies have also shown that highly mobile rams will typically return to their own herds, despite extensive migration (Geist 1971). A comparison of dispersal patterns between the Pine Ridge bighorns and those in other studies seems to indicate that the Pine Ridge herd may still occupy a relatively small geographic region, adhering to the concept of the metapopulation.

Habitat fragmentation plays a role in a species' ability to successfully utilize the
suitable habitat contained within its home range. While some species, such as the brown-headed cowbird (*Molothrus ater*), thrive in habitat that is heavily fragmented, many species prefer habitat that is connected and offers more protection when traversing a region. Bighorn sheep are adversely affected by the fragmentation of habitat at the landscape level (Bleich et al. 1996). Urban development, timber harvesting, and other such activities can lead to a matrix of habitat that is incapable of supporting a viable population of bighorn sheep.

In this study, habitat requirements for bighorn sheep in the Pine Ridge area will be reduced to four categories: General, Forage, Thermal Protection, and Lambing; which encompass both the daily and seasonal activities of individuals (Table 3). The most broad and non-specific of the four categories is the “General” habitat category, which encompasses all general use habitat for movement by individuals and all non-specific activities. The “Forage” habitat category encompasses all areas used primarily for foraging as described below. The “Thermal Protection” category encompasses those areas used during the winter to assist in thermoregulation (maintaining body temperature). Finally, the “Lambing” category encompasses habitat where ewes will give birth to and rear lambs during lambing season.

2.5.3 Foraging Behavior

Many studies addressed the composition of diet for bighorn sheep at different times of the year. Bighorn sheep primarily rely on grasslands as a source of forage, though Rominger et al. (1988) found a greater amount of shrub leaves in the diet of sheep during the summer at Waterton Canyon, Colorado. Risenhoover and Bailey (1985)
describe the optimal forage habitat for bighorn sheep as “large open areas near escape terrain.” These areas provide a mix of grasses and forbs that are the mainstay of the bighorn diet (Todd 1975, Van Dyke et al. 1983, and Risenhoover and Bailey 1985). Van Dyke et al. (1983) consider suitable forage habitat to consist of open grasslands containing a variety of grasses. Many taxa of grasses and forbs are consumed by grazing mountain sheep. Miller and Gaud (1989) reported that desert bighorn sheep (Ovis canadensis mexicana) consumed almost all plant species present in their study area.

Table 3. Habitat requirements of Rocky Mountain bighorn sheep (Ovis canadensis canadensis) (Van Dyke et al. 1983).

<table>
<thead>
<tr>
<th>Habitat Category</th>
<th>Minimum Specifications</th>
</tr>
</thead>
</table>
| General          | Roads and open water excluded  
|                  | Minimum patch size of 0.16 ha  
|                  | Within 300 m of escape terrain  
|                  | Within 3 km of a water source  |
| Forage           | Grasslands  
|                  | Minimum patch size of 0.16 ha  
|                  | Within 300 m of escape terrain  
|                  | Within 3 km of a water source  
|                  | Preferably bordered on multiple sides with escape terrain  |
| Thermal Protection | Areas free of dense shrubs but with protection from tree canopies  
|                   | South facing slopes of escape terrain  
|                   | Minimum patch size of 0.16 ha  
|                   | Within 3 km of a water source  |
| Lambing          | Remote grasslands and mature forests  
|                  | Minimum patch size of 2 ha  
|                  | Located within escape terrain  
|                  | Within 1 km of a water source  
|                  | No north facing slopes  |

2.5.4 Escape Terrain

Some studies (Shannon et al. 1975, Fairbanks et al. 1987) have found that bighorn
sheep frequently distribute no farther than 300 m from escape terrain. Risenhoover and Bailey (1985) defined escape terrain as “rocky and broken ground with a slope greater than 200%.” Van Dyke et al. (1983:4) added that “cliffs with traversable terraces are desirable; sheer, vertical cliffs are not.” Sheep use this terrain to escape from predators, but from region to region the distance that sheep will venture from escape terrain seems to vary. Use of a site by bighorn sheep differs as a function of distance from nearby escape terrain (Figure 4). The function is nonlinear and takes the form of an inverted logistic equation. Most of the habitat use occurs within 400 m of the escape terrain. Fairbanks et al. (1987) found virtually no use of areas that were farther than 300 m from escape terrain in the Pine Ridge, except in some observations during the summer. Tilton and Willard (1982) also found little use of sites beyond 320 m from escape terrain. Further, approximately 90% of observations within the 300 m distance limit generally occurred within 100 m of escape terrain.

![Graph showing habitat use by bighorn sheep as a function of distance from escape terrain.](image)

**Figure 4.** Use of habitat by bighorn sheep as a function of distance from escape terrain (Van Dyke et al. 1983).
Few studies have addressed the issue of spatial juxtaposition of escape routes (routes that sheep might used to access escape terrain) with regard to forage areas, though Van Dyke et al. (1983) recognized the benefit of multiple escape routes (access to escape terrain) distributed around a forage area. In this study the model incorporates the concept that routes to multiple areas of escape terrain assist the sheep in evading a predator that may be blocking access to a given area of escape terrain. Thus, an area that has only one route to nearby escape terrain is not as suitable as a site that is surrounded by escape terrain.

The concept of spatial juxtaposition states that multiple escape routes increase the suitability of a site when the sheep are outside of escape terrain (Figure 5, Van Dyke et al. 1983). Note the foraging sheep in the center and the predator entering from the upper right quadrant. Escape terrain is located in three of the quadrants 1, 3, and 4 of the circle surrounding the sheep with a radius of 300 m. Recall that for a foraging site to be considered suitable, escape terrain must be located somewhere within 300 m of the forage site. We might imagine, though, that the areas of escape terrain in quadrants 3 and 4 do not exist, and escape terrain is only present in quadrant 1. The predator enters this quadrant between the sheep and the escape terrain, effectively blocking the sheep's route to the escape terrain. This site, then, is questionable with regard to its ability to support bighorn sheep in the presence of a predator. Clearly multiple areas of escape terrain surrounding this site would increase its suitability.

The optimal configuration for escape terrain around a site would be to have the site surrounded by escape terrain no matter where the sheep may flee. However, this may be a rare configuration of escape terrain. Some insight into animal behavior may provide
an alternate optimal condition. If a predator enters an area where the sheep is foraging, the sheep would have many options for an escape route, including running toward the predator. Sheep are not aggressive animals, though, and this would probably not be the exhibited behavior in such a scenario. All things being equal, the sheep would likely run in the opposite direction from where the predator was standing, increasing the probability of placing distance between predator and prey. Fleeing along any other angle from where the predator stands would increase the predator’s chance of gaining ground on the sheep.

Figure 5. Diagrammatic view of how multiple escape routes play an important role in defining the suitability of habitat for bighorn sheep.

In a scenario where two predators enter the area, one in front and one behind, we must again determine where the prey would attempt to flee. Again it is believed that the angle placing maximum distance between the predators and prey would be the most desirable, and this limits the choices to two angles which are orthogonal to the two predators. A pattern begins to form here, but one piece of information is lacking. How
much area can a predator impact, such that the prey will not utilize that area to escape?

A radius of 300 m produces a circle with a circumference of 1885 m surrounding the theoretical foraging site. Sheep may forage <300 m from escape terrain, and in one case 90% of the habitat used was within 100 m of escape terrain (Fairbanks et al. 1987). A circle with a 100-m radius has with a circumference of 628 m.

However, the threat of the predator extends far beyond its physical position and has an impact on a substantial area surrounding it. The extended threat comes from the mobility of the predator and the perception on the part of the prey that the predator may be able to catch it and bring it down. Because of the short radius between a sheep and its maximum distance from escape terrain, it seems likely that a predator could eliminate one quarter of the circular area surrounding that sheep. If the distance between the sheep and the escape terrain lessens, the ability of a predator to cover a larger portion of that circular area increases. The optimal configuration of escape terrain around a site, then, is to have four areas of escape terrain located orthogonal to each other. This provides a configuration such that a sheep could flee directly along the maximum angle from predators to escape terrain. This optimal condition is neither lessened nor strengthened as the area of the regions of escape terrain increases or decreases.

2.5.5 Water Preferences

The role that water plays in the distribution of bighorn sheep is uncertain and subject to debate in the literature. Van Dyke et al. (1983) suggested that the influence that water has on habitat selection is dependent upon the quality of the forage consumed by the sheep. Sheep that consume dried forage may drink more water, and vice versa.
select areas on south-facing slopes since these generally receive the most sunlight throughout the day (Oldemeyer et al. 1971, Tilton and Willard 1982). In the summer, however, use of areas may shift to those sites located on, or at the base of north-facing slopes to take advantage of the relatively cool, moist areas. Rocky cliffs and sparse, open-canopy forests can also provide thermal habitat during both the warm and cool seasons (Van Dyke et al. 1983).

2.6 Minimum Viable Populations and Stocking Densities

Reports of population density for bighorn sheep vary from region to region and are dependent on the availability of suitable habitat. The proximity of urban or human-made features also influence densities. Habitat near urban environments may require a lower stocking density and more area per sheep, while remotely located areas may allow for a much higher density of sheep. Densities of bighorn sheep vary during seasons. Van Dyke et al. (1983) suggested a maximum density of 1.9 bighorns/km² over an entire range. However, Demarchi (1965) reported over 27 bighorns/km². Smith et al. (1991) reviewed previous studies of bighorn sheep densities and determined that these studies often did not account for only those areas of land that were suitable for habitat, which possibly resulted in erroneously low densities reports. Thus, they suggested that a range (including unsuitable areas) should not be expected to support densities greater than 3.9/km². After deducting unsuitable portions of the range, densities of 7.7/km² may be expected.

Determining the required MVP for a population is no easy task. When the concept of MVP was first discussed, it was defined as the level at which a population has
CHAPTER III: METHODS

3.1 Data Acquisition

Data pertaining to land cover, elevation, water availability, and human structures were collected from a variety of sources (Table 4). Four of the six data sources were obtained for the U.S. Geological Survey (USGS). Road data were obtained from U.S. Bureau of Census Topographically Integrated Geographic Encoding and Referencing system (TIGER) files, and satellite imagery was extracted from the Nebraska Gap Analysis Program (GAP) archive. The ability to detect local habitat components for bighorn sheep necessitated the acquisition of data at the finest spatial resolution available. Studies of bighorn sheep habitat have included such parameters as barriers to sheep movement (rivers, fences, highways) (Sweanor et al. 1994, Gudorf et al. 1995). These features are not present in abundance within the Pine Ridge, and data pertaining to them are incomplete. The difficulty of obtaining these data and the belief by Nebraska Game and Parks biologists that they would not have a significant impact within the analysis resulted in the exclusion of these types of data from the model. Although road data will be used in this study, roads will not be used to represent barriers to bighorn sheep movement, but rather as measures of human disturbance.

3.1.1 Land Cover Mapping

The vegetative cover in the study area is a crucial component within the model, fundamentally influencing where sheep will be distributed throughout the region. However, it is not necessary that the land cover provide detail beyond basic vegetation
types, as sheep are generalists with regard to what cover types they will use. Landsat TM data were used to map eight classes of land cover: Dense Pine Forest, Sparse Pine Forest, Riparian, Deciduous Woodland, Grassland, Agriculture and Sparse Vegetation, and Open Water. Image processing was conducted with a combination of the ERDAS Imagine and ESRI ArcInfo (GRID) software.

Table 4. Data layers used in the bighorn sheep model for the Pine Ridge of Nebraska.

<table>
<thead>
<tr>
<th>Parameter Value</th>
<th>Data Source</th>
<th>Scale/Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land cover</td>
<td>Landsat-5 Thematic Mapper (TM) Imagery</td>
<td>30 m</td>
</tr>
<tr>
<td>Escape Terrain</td>
<td>USGS Digital Elevation Models</td>
<td>30 m</td>
</tr>
<tr>
<td>Distance to Water</td>
<td>USGS Digital Line Graphs (DLG)</td>
<td>1:100,000</td>
</tr>
<tr>
<td>Slope</td>
<td>USGS Digital Elevation Models</td>
<td>30 m</td>
</tr>
<tr>
<td>Aspect</td>
<td>USGS Digital Elevation Models</td>
<td>30 m</td>
</tr>
<tr>
<td>Human Disturbance</td>
<td>U.S. Bureau of Census TIGER Files</td>
<td>1:100,000</td>
</tr>
</tbody>
</table>

Two Landsat-5 Thematic Mapper (TM) scenes were obtained for the study area (Path-row 33/30, scene 5280917001X0 5/11/1992 and path-row 32/30, scene 5300216535X0 5/20/1992). These scenes were mosaicked, utilizing a maximum value assignment method in the overlap areas and histogram matching between scenes. Scenes originally came in the Universal Transverse Mercator (UTM) projection, and scene 33/30 was not in the same UTM zone as 32/30. Thus a reprojection of scene 32/30 was required before the mosaic could be constructed. These scenes were originally in the North American Datum (NAD) of 1983 (NAD83), while all other input data for the study were obtained in NAD 1927 (NAD27). Rather than reprojecting all other study data from
NAD27 to NAD83, the satellite imagery was reprojected to NAD27. This served to minimize error in the overall dataset that resulted from the reprojection process. Shifting the datum from NAD83 to NAD27 was accomplished concurrently with the reprojection process before mosaicking.

Six of the seven TM spectral bands were extracted from the image data (Table 5). The thermal band (6) was not used. Several trial classifications were produced with various combinations of these six bands. These trial classifications indicated that the more shadowed areas of the high relief, forested areas became easily confused with water bodies. To reduce this problem, the water areas were masked from the imagery, and the imagery was reclassified.

Table 5. Seven band characteristics of Landsat-5 Thematic Mapper (TM) images.

<table>
<thead>
<tr>
<th>Band</th>
<th>Spectral Range</th>
<th>Spectral Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.45-0.52 μm</td>
<td>Blue</td>
</tr>
<tr>
<td>2</td>
<td>0.52-0.60 μm</td>
<td>Green</td>
</tr>
<tr>
<td>3</td>
<td>0.63-0.69 μm</td>
<td>Red</td>
</tr>
<tr>
<td>4</td>
<td>0.76-0.90 μm</td>
<td>Near Infrared</td>
</tr>
<tr>
<td>5</td>
<td>1.55-1.75 μm</td>
<td>Shortwave Infrared</td>
</tr>
<tr>
<td>6</td>
<td>10.4-12.5 μm</td>
<td>Thermal Infrared</td>
</tr>
<tr>
<td>7</td>
<td>2.08-2.35 μm</td>
<td>Shortwave Infrared</td>
</tr>
</tbody>
</table>

A Tasseled Cap Transformation (TCT) was used to derive a moisture image of the Pine Ridge that was used to mask water from the mosaic. The TCT in the ERDAS Imagine image processing software uses a linear combination of the TM bands to
produce four new images of brightness, greenness, wetness, and haze. It is a type of
principal components analysis (PCA) where the coefficients for the bands are known \textit{a priori} for each of the desired outputs (ERDAS 1997). The moisture output image can be
used to select those areas composed primarily of water, of which we would expect open
water to be included. A binary mask was produced by setting a brightness threshold,
labeling everything above the threshold as water (a value of 0) and everything below as
non-water (a value of 1). This binary image was then multiplied with the original mosaic
to mask out the majority of water present.

After comparing the cluster separability amongst the trial classifications, it was
decided that TM bands 1 through 4 (blue through near-infrared (NIR)) were optimal for
producing a set of distinguishable clusters for the Pine Ridge vegetation. An
unsupervised classification algorithm was used to produce twenty-five output clusters,
which were then aggregated, with the help of on site vegetation data collected during
three ground truthing sessions in the Pine Ridge. The twenty-five clusters were
aggregated to produce seven vegetation classes: Dense Pine Forest, Sparse Pine Forest,
Riparian, Deciduous Woodland, Grassland, Agriculture and Sparse Vegetation. After the
aggregation process was completed, the water mask was stitched back into the
classification to produce the eighth class: Open Water.

Since the vegetation requirements for bighorn sheep fall into broad categories, the
level of detail of the land cover map reflected this generality as well. As previously
mentioned, forage habitat for bighorn sheep consists of open grasslands containing a
variety of grasses and forbs. Sheep will generally avoid dense forests and areas with low
lateral visibility, such as areas with a high density of deciduous shrubs. Thus, it was only necessary to distinguish between general land cover types within the model.

3.1.2 Field Work and Accuracy Assessment

Data describing vegetative land cover were collected throughout the Pine Ridge during the summer of 1997 to assist in accurately producing a land cover map from satellite data. I traversed the area by vehicle and foot, stopping at points where vegetation changed from one distinct type to another and where large areas of homogenous vegetation occurred. Areas where vegetation types were intermixed were not sampled since satellite imagery is often too coarse in resolution to properly detect the different vegetation types in these areas. Type of vegetation present, slope, and aspect of the site were recorded at each stop. Coordinates were recorded using a Trimble GPS unit in UTM projection, zone 13. Approximately 100 data points were obtained through this field work and through field work that was concurrently being undertaken for the Nebraska Gap Analysis Project (GAP). Data collection methods were identical for the two projects. Data points were chosen based on the characteristics (size of area and homogeneity of vegetation) of areas while driving and walking through the study area or based on areas of the initial land cover maps for which the land cover type had not yet been identified. These data were then entered into the ArcInfo GIS software, and a program was written to compare the data points to the land cover classification to support the labeling of the land cover classes. A visual comparison of the land cover classification with the actual land cover types present in the study area was conducted during subsequent visits to the Pine Ridge by stopping at areas of homogenous vegetation
and comparing with the land cover map on paper to ensure agreement between the two. Areas of inconsistency between vegetation shown on the paper map and actual vegetation in the field were drawn and noted on the map for later refinement of the classification.

3.1.3 Acquisition of Elevation Data

Elevation data play an important role in the habitat model, since they control the ability to detect the cliffs and slopes that are a vital component of bighorn sheep habitat. USGS digital elevation models (DEM), in a 30-m format (produced from 1:24,000 quadrangle contour maps), were available for approximately half of the study area. The Nebraska Natural Resources Commission (NRC), which was concurrently undertaking a project to produce 30-m DEMs for the state of Nebraska, produced the needed elevation data for the remainder of the study area. Four additional DEMs were produced by the USGS when it was discovered that the NRC did not possess the hypsography to produce data for these areas. Once elevation data were obtained for all quadrangles, they were mosaicked to produce a contiguous layer of elevation for the region.

3.1.4 Acquisition of Water Data

Although sheep will make use of water available in streams, rivers, and water tanks for cattle, only data pertaining to lakes, streams, and rivers were available for the Pine Ridge. These were obtained in digital line graph (DLG) format (a vector format) from the USGS. Features were originally digitized from 1:100,000 scale maps and all features contained in the DLG water data were assumed to be valid water sources for bighorn sheep.
3.1.5 Acquisition of Human Disturbance Data

Road data were used as a measure of human disturbance and were obtained in vector format from the 1992 U.S. Bureau of TIGER files. These files contain a variety of information collected by the U.S. Bureau of Census, ranging from political boundaries to road locations and types. Roads contained within, and surrounding, the Pine Ridge were extracted from the TIGER files along with information about their type (two-track, paved road, neighborhood road, small highway, and major highway).

3.2 Data Entry and Manipulation

All data required at least some preprocessing before they could be used as parameter layers within the GIS habitat model. Water features were extracted from the DLG files; satellite imagery required mosaicking, and DEMs were imported and mosaicked. Reprojection and resampling of images was conducted only as needed so as to reduce propagation of spatial error. The ArcInfo GRID module performed better for some image processing tasks than the ERDAS Imagine software. Therefore, ArcInfo was used when reprojection and resampling were required, and ERDAS Imagine was used for the mosaicking process. Arc Macro Language (AML) programs were written to analyze field data in conjunction with image data, which facilitated an assessment of the land cover classification.

3.2.1 Land Cover Analysis

Multiple land cover layers were produced from the land cover map, each representing a "habitat use" category for bighorn sheep (Table 6). In most cases each
categorical image contained 1’s for pixels of suitable vegetation for bighorn sheep and 0’s for pixels of unsuitable vegetation. In some cases pixels received fractional values to indicate that they are suboptimal for use by bighorn sheep. For example, Sparse Pine Forest is considered a suitable forage habitat, but Grassland is considered optimal for this use. Thus, Sparse Pine Forest was assigned a suboptimal value (0.5) for the “Forage” category.

Table 6. Habitat use categories for bighorn sheep and suitability ratings for each land cover type. Numbers in parentheses indicate the suitability coefficient applied to the specified land cover type while modeling habitat suitability for the specified habitat use category.

<table>
<thead>
<tr>
<th>Habitat Use</th>
<th>Suitable Land Cover Types (Rating)</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
<td>Sparse Pine Forest (1), Grassland (1), Sparse Vegetation (1), Agriculture (0.5), Deciduous Woodland (0.3)</td>
</tr>
<tr>
<td>Forage</td>
<td>Grassland (1), Sparse Pine Forest (0.5)</td>
</tr>
<tr>
<td>Lambing</td>
<td>Sparse Pine Forest (1), Grassland (0.5), Sparse Vegetation (0.5)</td>
</tr>
<tr>
<td>Thermal</td>
<td>Sparse Pine Forest (1), Grassland (0.5), Sparse Vegetation (0.5)</td>
</tr>
</tbody>
</table>

These coefficients were created based on a review of existing literature regarding the use of habitat as a factor of vegetation present and also based upon literature regarding the diet composition for bighorn sheep. For land cover types to which bighorn sheep readily associate, a value of 1.0 was used as a suitability coefficient. For land cover types to which bighorn sheep associate, but less strongly, a suitability coefficient of 0.5 was assigned. In the case where bighorn sheep are likely to make use of a given land cover type, but may do so rarely or only under unusual circumstances, a minimal
suitability coefficient of 0.3 was assigned. All other habitat types were considered unsuitable for the given habitat use category and assigned a coefficient of 0.0.

A minimum patch size (MPS) was enforced for each of the four land cover layers in accordance with the MPS requirements found in Van Dyke et al. (1983) for each of the habitat use categories. A 0.18-ha MPS was used for the general, thermal, and forage categories, while a 2.0-ha MPS was enforced for lambing habitat. Although bighorn sheep generally require a 0.16-ha MPS for the three former categories, two, 30 m pixels cover an area of 0.18 ha. Enforcing a 0.16-ha MPS would require resampling all data to an artificial spatial resolution such that a given number of pixels would cover an area of this size. The difference between 0.16 ha and 0.18 ha, however, seemed negligible; and a 0.18-ha MPS appeared sufficient. Twenty-two pixels of a 30-m resolution TM image cover an area of 2 ha, and this number of pixels was used to determine the MPS for lambing habitat (Van Dyke et al. 1983).

The MPS analysis was accomplished by grouping pixels within each land cover image with the Arc/Info REGIONGROUP command. The output from this command is a raster grid where all adjoining pixels are grouped as a single patch. All pixels in the patch are assigned a patch value, which is unique among all patches in the image. The INFO table associated with this grid contains a listing of each unique patch and the number of pixels belonging to those patches. By eliminating all patches containing 2 pixels or less, a MPS of 0.18 ha was enforced. Similarly, in the case of lambing, any groups containing 22 pixels or less were eliminated from the image. All pixels remaining after elimination were assigned a value of 1, and all eliminated or NULL pixels were assigned a value of 0 to produce a binary filter (mask) for the 0.18 ha and 2 ha MPS. The
eliminated as potential lambing habitat, while aspects between 225° and 135° were classified as optimal for thermal habitat.

\[
1 - \frac{1}{1 + 333 \times e^{-0.44d}}
\]  

(1)

3.2.3 Analysis of Water Data

Since the water data layer was initially obtained in vector format, it was subsequently rasterized at a 90-m spatial resolution and then resampled to 30 m. This process of resampling was necessary due to the sometimes-poor translation that occurs with linear features during a vector-raster conversion. By using a more coarse resolution to convert to raster, the linear features were consistently retained within the raster image. Resampling to a finer resolution allowed the layer to be used in combination with other, 30-m resolution layers such as the elevation data. Buffers of 1, 2, and 3 km were created around water features and assigned zonal values of 1.0, 0.66, and 0.33 respectively. All area outside of 3 km was assigned a suitability value of 0.

3.2.4 Analysis of Road Data

Road data were processed to derive a layer of human disturbance. Van Dyke et al. (1983) and Smith et al. (1991) indicated that bighorn sheep flee at the sight of a vehicle or other perceived threat even when it is as much as 2 km away. An assumption in this study is that roads could provide a substantial measure of habitat disturbance by humans. This assumption was made after assessing the data available for human-made features in the Pine Ridge and determining which data might best summarize the amount
of human disturbance in a region. Van Deelen et al. (1997) also used road density as a measure of disturbance to potential release sites for elk in southern Illinois. Vector data for roads in the study area were readily available in TIGER format, while only incomplete and very little data were available for other features such as houses and land use.

Roads were extracted from the TIGER files and assigned a rating from 1 – 5, where 1 indicated an infrequently traveled road (a two-track) and 5 indicated a heavily traveled road (four-lane highway). The idea that a two-track road represents less human influence in an area than a four-lane highway is based on the concept of cars per minute, a measurement of road use. A two-track road may receive some use during the day, but it receives relatively little use in comparison to a four-lane highway, which has a much higher cars per minute rating during both the daylight and nighttime hours.

The vector layer of roads was rasterized, and the resulting pixels comprising each road were assigned their respective disturbance ratings. This layer was then processed using a neighborhood analysis to provide a summary of road density as a function of number of pixels and intensity of those pixels. A circular kernel with a 2-km radius was used to summarize pixels within the neighborhood. The sum of the pixels was assigned to the pixel central to the neighborhood. The maximum value within the layer resulting from this process was recorded, and all pixels within the layer were divided by this value and subtracted from 1. This procedure produced a raster image in which pixels with higher values indicated lower road density in the surrounding area, and pixels with lower values indicated higher road density. This layer was subsequently multiplied with the output lambing habitat layer to produce a new, descriptive layer of lambing habitat.
remoteness. Higher values indicated that the habitat is more isolated from human influence, while lower values indicated more human influence in the surrounding area.

3.3 Model Construction

A raster model was constructed in the ArcInfo GRID module using a combination of boolean decision rules and linear combination method to produce an output map of habitat suitability. The conceptual model (Figure 6) includes land cover information qualitative criteria such as spatial juxtaposition and remoteness. Note that some steps are not applicable for all habitat use categories. For example, aspect does not play a role in the determination of suitable general and forage habitat, while it does play a significant role for lambing and thermal habitat suitability. Similarly, the analysis of slope configuration is only used for habitat areas where sheep may venture some distance from escape terrain, as in the general and forage habitat categories.

Procedurally, the model is employed by processing and analyzing each input layer of data to produce an output layer with pixel values ranging from 0.0 to 1.0 (Figure 7). The parameter layers used within the model and the possible ratings that they may contribute at various stages in the model are summarized in Table 7. Note how features are preprocessed through the decision rules and eventually combined to produce an output layer, wherein each category is assigned a value from 0 – 1. A value of 0 indicates that the area is unsuitable for supporting bighorn sheep and a value of 1 indicates optimal suitability for supporting bighorn sheep. As an example, note that elevation data is processed to produce a layer of slopes. Those slopes favorable to bighorn sheep are retained, while all others are excluded as potential bighorn sheep habitat. In the case of
general habitat these slopes are buffered to 300 m and assigned a rating from 0.0 – 1.0 based on the previously described inverted logistic model.

Figure 6. Conceptual overview of the habitat suitability model for bighorn sheep in Nebraska. From top to bottom, criteria combine in a process of eliminating unsuitable habitat and rating remaining habitat by suitability.
Figure 7. Implementation of the bighorn sheep model for the Pine Ridge of Nebraska.
Table 7. Parameter layers used within the GIS model for bighorn sheep habitat in the Pine Ridge and their possible suitability ratings.

<table>
<thead>
<tr>
<th>Parameter Layer</th>
<th>Description</th>
<th>Possible Ratings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land cover</td>
<td>Vegetation covering the pixel of interest.</td>
<td>1.0 – Optimal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5 – Suboptimal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.3 – Minimally suitable</td>
</tr>
<tr>
<td>Escape</td>
<td>Distance to a pixel of escape terrain, scaled to 0 – 1 range.</td>
<td>0 – 1, inclusive, where 1 is within escape terrain and 0 is beyond maximum distance.</td>
</tr>
<tr>
<td>Aspect</td>
<td>Binary layer of suitable/unsuitable aspects.</td>
<td>[0,1], where 1 is a suitable aspect and 0 is unsuitable.</td>
</tr>
<tr>
<td>Roads</td>
<td>Density of roads present in the study area.</td>
<td>1 – 5, inclusive, where 1 is a low impact road and 5 is a high impact road (highway).</td>
</tr>
<tr>
<td>Juxtaposition</td>
<td>Number of quadrants containing nearby escape terrain, scaled to 0 - 1.</td>
<td>0 – 1, inclusive, where 1 is completely surrounded and 0 indicates absence of escape terrain.</td>
</tr>
</tbody>
</table>

Other parameters are processed in a similar fashion and ultimately receive pixel values from 0 – 1. What remains, then is to simply sum these layers and divide by the number of layers to derive a measure of suitability as a function of all habitat parameters included. This process, however, assumes that all habitat parameters are of equal importance and that specific features such as water are not significantly more important than features such as escape terrain. If this were true, then weights would need to be applied during the final processing stage so that features that are more important to bighorn sheep are weighed more heavily in the output layer of habitat suitability. Given the habitat requirements for bighorn sheep, the assumption of feature equality appears to be valid.
3.4 Spatial Juxtaposition

Based on the logic and the assumptions outlined in section 2.5.4, spatial juxtaposition of escape terrain was modeled as shown in Figure 8. The binary raster layer of slope was summarized using two rules, each with four analyses. The Arc/Info FOCALMAX command was used with the WEDGE option to examine each pixel in the study area to determine if escape terrain existed within each of the four quadrants surrounding the pixel.

Figure 8. Use of a Cartesian and rotated coordinate system to quantify the spatial juxtaposition of escape terrain for bighorn sheep.

In each use of the FOCALMAX command, a 90° area (one quadrant) was specified, hence requiring four analyses per rule. This procedure produced a new raster layer for each of the quadrant analyses. Each layer contained pixels with a value of 1 indicating that escape terrain occurred within 300 m and the specified quadrant surrounding that pixel and 0's when these two conditions were not met. Summing across these four layers and dividing by 4 produced a final raster layer in which pixels with a
value of 1 indicated portions of the study area conforming to optimal configuration
criteria and pixels with a value of 0 indicated that escape terrain was not present. Values
between these two extremes indicated that two or three zones of escape terrain were
present in some configuration around the pixel of interest.

Problems with this analysis arise, however, when one area of escape terrain spans
the border between two quadrants. Although this is only one area of escape terrain and
has, in effect, only one escape route associated with it, the pixel central to those quadrants
will receive a contribution of two suitability levels from that escape terrain because it is
located in two quadrants. Rule 2 solves this problem by rotating the quadrants 45°. With
this approach zones of escape terrain that previously bordered quadrants will be located
in only one quadrant. Analysis of juxtaposition by this rule alone is insufficient because
the same border conditions can arise with the rotated system. The two rules must be used
in combination to classify pixels appropriately. The correct classification is
accomplished by first performing rule 1, subsequently performing rule 2, and obtaining
the minimum juxtaposition value from these two rules on a pixel by pixel basis. The
minimum value for each pixel, then, is divided by 4 (Equation 2) to derive the proper
pixel values for suitability as a function of spatial juxtaposition.

\[
\text{Suitability} = \min \left( \frac{\text{Rule}_1, \text{Rule}_2}{4.0} \right)
\]

where \text{Rule}_1 is the 0.0 - 4.0 value of each pixel in the resultant image from the
juxtaposition analysis using the Cartesian coordinate system and \text{Rule}_2 is the 0.0 - 4.0
value of each pixel in the resultant image from the juxtaposition analysis using a rotated
coordinate system.
3.5 Analysis of Landscape Structure

Due to the lack of information regarding the dispersion of bighorn sheep within the Pine Ridge, landscape analyses were conducted on two scales. Three focus areas were delineated within the boundaries of the study area, each consisting of habitat groups that were seemingly isolated from habitat in the other focus areas. Focus areas were then further divided into population locales. These were relatively contiguous areas of habitat, seemingly isolated from other contiguous groups of habitat. In a study of elk restoration in southern Illinois, areas similar to population locales were referred to as "potential release sites," which were areas of contiguous, "most suitable habitat" where elk could potentially be restored to the state (Van Deelen et al. 1997). Three metrics were applied at the focus area and population locale scales to quantify the landscape structure. Until more information is obtained regarding the scale at which a herd of bighorn sheep will establish within the Pine Ridge, it is believed that either the focus area or population locale scale could be appropriate for the establishment of a subpopulation.

3.5.1 Quantity of Habitat

The quantity and spatial distribution of suitable habitat ultimately determines whether a herd of bighorn sheep can exist within a region. Optimally suitable habitat cannot be expected to support more than 7.7 bighorns per km² (Smith et al. 1991). Quantification of total habitat area was conducted at the level of the study area, focus areas, and population locales. I used the statistics procedure available in ArcInfo to sum the total area of pixels for the study area, each focus area, and each population locale.
Statistics were only calculated for the General habitat suitability layer, since the desire was to gain a better understanding of habitat structure regardless of habitat use, and the General habitat category includes suitable habitat from the other categories.

3.5.2 Habitat Fragmentation

Contagion is a landscape index that measures the interspersion of patches within an area, and it can be used as a measure of habitat fragmentation. Focus areas and population locales were evaluated with the contagion index to derive a measure of habitat contiguity (connectivity). The “General” habitat suitability layer was used to extract additional layers for each area of interest (focus area or population locale). Each subset layer was subsequently analyzed using the FRAGSTATS 2.0 software (McGarigal and Marks 1993) to produce a contagion statistic for the layer.

3.5.3 Habitat Isolation

Nearest neighbor, or mean nearest neighbor (MNN), is an index that quantifies the habitat structure within a landscape with regard to the average distance between contiguous patches of habitat. Greater distances indicate a lower probability that a given patch will be colonized by the species. Focus areas and population locales were evaluated with regard to MNN. The General suitability layer was subset to produce an individual layer for each area of interest. These subset layers were then processed using the FRAGSTATS software to produce a MNN statistic for the layer.

Since population locales were believed to be the more appropriate scale at which the establishment of a subpopulation is possible, the three landscape metrics (area,
contagion, and MNN) were used to rank the six population locales. Each locale could receive from 1 to 6 points for each parameter based on how it compared to the other locales. Once each locale was ranked for each metric, the rankings were combined linearly to derive an overall site ranking (Equation 3). $R$ is the overall ranking for the locale; $Q$ is ranking of the locale for quantity of habitat; $C$ is the ranking for the locale with respect to the contagion index; and $N$ is the MNN ranking for the locale. While all metrics are important for determining the suitability of a region for supporting a herd of bighorn sheep, quantity of habitat weighs as more important, and MNN appears to be less important than contagion (e.g. Smith et al. 1991).

$$ R = 1.1Q + 1.0C + 0.9N $$  \hspace{1cm} (3)

3.6 Model Validation

Official distribution data do not exist for bighorn sheep in the Pine Ridge, and what data do exist are based on sightings by local inhabitants and biologists in the region. For these reasons, it was not possible to validate the habitat suitability model by comparing resulting habitat maps to data of known bighorn habitat usage. To validate the model, discussions were held with NGPC and USFS biologists who are familiar with the bighorn herd in the Pine Ridge. Discussions with the biologists regarding current habitat use by bighorns in the Pine Ridge in comparison to output suitability maps from the model were used to refine the modeling criteria. While this leaves the validation of the model to the perceptions of the biologists, their knowledge of the behavior of the Pine Ridge bighorns was extensive and helped to provide information about parameters within the model and how they play a role for bighorns in the Pine Ridge.
CHAPTER IV: RESULTS AND DISCUSSION

4.1 Quantification of Study Area

Bighorn sheep habitat for the entire study area was divided into five suitability classes, and the area for each specific use category was calculated (Table 8). The five output suitability classes represent optimal suitability (1.0 – 0.81), sub-optimal suitability (0.80 – 0.61), moderate suitability (0.60 – 0.41), low suitability (0.40 – 0.21), and marginal suitability (0.20 – 0.01) for the habitat in each class. The use of five output classes provides a level of detail sufficient to detect subtle changes in suitability of habitat over a region without overly describing the region and providing more information than can really be digested. In the General and Forage use categories, a substantial amount of habitat (216 km² and 178 km²) exists across the region. However, lambing and thermal habitats exist only in small quantities, scattered across the study area. The requirements for lambing and thermal habitat are much more stringent than for the general and forage use categories. Both lambing and thermal categories require that habitat be located within the confines of escape terrain to provide protection for lambs and ewes (lambing habitat) or to provide bedding areas where sheep can absorb heat from the sun (thermal habitat). While much land area exists with the 300-m buffer around escape terrain, there is very little actual escape terrain within the study area. Thus, the requirement of lambing and thermal habitat to occur within these areas greatly reduces the final area of habitat in these categories. This reduction of habitat is more easily demonstrated by a detailed view of habitat quantity at each step during the model (Table...
9). In many cases quantity of habitat is greatly reduced by the application of a modeling rule, yet this is not true for all rules.

Table 8. Quantity and quality of bighorn sheep habitat in the Pine Ridge of Nebraska, by habitat use category.

<table>
<thead>
<tr>
<th>Habitat Use Suitability Category</th>
<th>General (km²)</th>
<th>Forage (km²)</th>
<th>Lambing (km²)</th>
<th>Thermal (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.81 - 1.0</td>
<td>32</td>
<td>26</td>
<td>2</td>
<td>&lt;1</td>
</tr>
<tr>
<td>0.61 - 0.80</td>
<td>66</td>
<td>57</td>
<td>1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>0.41 - 0.60</td>
<td>103</td>
<td>90</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.21 - 0.40</td>
<td>15</td>
<td>5</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.01 - 0.20</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Totals</td>
<td>216</td>
<td>178</td>
<td>3</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>

For each of the specific use categories, escape terrain is the limiting factor controlling the amount of available bighorn sheep habitat, especially for the lambing and thermal habitats. Without the 300-m buffer used for general and forage habitat selection, a total of 10 km² (1000 ha) of escape terrain exists throughout the Pine Ridge. With the 300-m buffer, a total of 334 km² of buffered escape terrain exists. Recall that Lambing habitat and Thermal habitat must reside within escape, not within the 300-m buffer around the terrain. This requirement, then, imposes strict limitations on the distribution of suitable habitat for these two categories and ultimately eliminates a large area of land that does not reside within escape terrain. In the Thermal habitat category, slope aspect also plays a role in eliminating a substantial portion (4 km²) of the remaining 5 km² of
suitable habitat after the application of the escape terrain rule. Thermal habitat is restricted to south-facing slopes, which are generally warmer and provide bighorn sheep with some additional heat during the winter months. Many slopes in the Pine Ridge are covered with either dense stands of Ponderosa pine or some form of deciduous cover and thus are not suitable as lambing or thermal cover. Escape terrain is already in limited quantity in the Pine Ridge, so restricting Thermal habitat to only south-facing slopes within escape terrain results in a total area less than 1 km$^2$ of suitable Thermal habitat.

Table 9. Bighorn habitat remaining after each model selection criterion is enforced. Final numbers indicate amount of habitat for the specific use category across the Pine Ridge of Nebraska.

<table>
<thead>
<tr>
<th>Selection Criterion</th>
<th>General Habitat Remaining (km$^2$)</th>
<th>Forage Habitat Remaining (km$^2$)</th>
<th>Lambing Habitat Remaining (km$^2$)</th>
<th>Thermal Habitat Remaining (km$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Area</td>
<td>4262</td>
<td>4262</td>
<td>4262</td>
<td>4262</td>
</tr>
<tr>
<td>Land Cover</td>
<td>3888</td>
<td>2827</td>
<td>3479</td>
<td>3479</td>
</tr>
<tr>
<td>Minimum Patch Size</td>
<td>3887</td>
<td>2822</td>
<td>3457</td>
<td>3476</td>
</tr>
<tr>
<td>Escape Terrain</td>
<td>216</td>
<td>178</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Hydrology</td>
<td>216</td>
<td>178</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Aspect</td>
<td>N/A</td>
<td>N/A</td>
<td>3</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Final</td>
<td>216</td>
<td>178</td>
<td>3</td>
<td>&lt; 1</td>
</tr>
</tbody>
</table>

The MPS plays a minor role in the selection process. In the General, Forage, and Thermal categories, a maximum 5 km$^2$ of land is eliminated as potential habitat due to the 0.18 ha MPS threshold. However, I assigned a substantially larger MPS (2 ha) for
lambing habitat. In cases where lambing habitat is very remote, the patch size can
decrease to 1 ha; but it is generally accepted that lambing habitat should be of at least 2
ha in size (Van Dyke et al. 1983). The enforcement of this MPS eliminates 22 km² of
potential habitat. Water availability also played a role in the lambing category due to the
1-km maximum distance. This criterion eliminates 2 km² of potential habitat. The
resulting lambing habitat is only 3 km² in size and, there is < 1 km² of thermal habitat.

The analysis of roads revealed no significant impact of human development
where areas of lambing habitat are believed to exist. The only areas of significant human
activity are the towns of Chadron and Crawford, both of which are a substantial distance
from any lambing habitat. Possible remoteness values could range from 0 to 1, where 1
is the most remote. Observed remoteness values for the lambing habitat in the Pine
Ridge only ranged from 0.77 to 1, indicating that most of the lambing habitat is
sufficiently remote. Van Dyke et al. (1983) suggested that minimum patch size for ewes
during the lambing season might be less important in remote areas. However, there is no
clear definition on how remote an area must be for ewes to be less selective with regard
to the size of areas they choose for rearing lambs. Further, there is no clear indication on
what factors comprise a measure of remoteness. Therefore, the model’s indication that
road density is low for the areas of suitable lambing habitat does not indicate that
minimum patch size is not an issue during the lambing season.

It is not clear whether road density provides a confident measure of human
disturbance for bighorn sheep in the Pine Ridge, and it may be the case that ranches and
agricultural practices in the area provide a much stronger measure. Given that Van Dyke
et al. (1983) discussed the fact that bighorn sheep often flee when sighting a vehicle at a
distance of several kilometers, road density is a plausible measure for disturbance of bighorn sheep habitat. A study of elk reintroduction in southern Illinois used road density as a measurement of human disturbance and negative influence on potential elk sites, believing that a newly established elk herd is likely to attract tourists, considered harassment to elk. In that study road density was used similar to my study of bighorn sheep to provide a "map of potential habitat modified by human harassment (Van Deelen et al. 1997, p. 890)."

Ultimately the model's analysis of road density as it relates to lambing habitat provides biologists with a different perspective on habitat suitability, a perspective that considers how we, as humans, influence habitat suitability. There is no standard approach to measuring remoteness, so there is no way to say that the lambing habitat in the Pine Ridge is, or is not, remote. However, the model does indicate that, in the whole of the study area, lambing habitat resides in the areas that are less disturbed by road density. Since bighorn sheep are affected by road networks (Bleich et al. 1996), it is very important to view areas of suitable lambing habitat in relation to any major roads that are relatively nearby. Though road density near lambing habitat appears to be relatively less, this does not indicate that a single, major highway is not passing within a few km of a lambing site. This single feature could completely disturb the lambing site, though overall road density is relatively low.

4.2 Analysis of Focus Areas

Focus area (FA) 3 contains the most habitat (84 km²) of the three, followed closely by FA 1 (81 km²) and finally FA 2 (51 km²) (Table 10). However, in the 0.81 – 1.0 and 0.61 – 0.80 suitability classes, FA 1 contained more suitable habitat (a total of 41
had lower MNN values, the actual difference of distance (approximately 12 m less for FAs 1 and 2 than for FA 3) between FAs 1 and 2 and FA 3 is very small. Bighorn sheep view an area in terms of kilometer distances rather than meters, so the MNN metric is mostly valuable for spotting areas with MNN values relatively high in comparison to other areas. For the three focus areas, FA 2 rated most favorably for MNN, indicating that bighorn sheep in this focus area would have less distance to travel between neighboring habitat patches. It is unknown whether MNN is an important factor in quantifying the landscape structure for bighorn sheep. Since bighorns are vulnerable to predators and are limited to survival in areas meeting requirements for habitat suitability, they are subject to the rules of traversing distances at a cost. If a bighorn sheep must traverse an area of unsuitable habitat to reach another, known area of suitable habitat, it may fall prey to a predator. If a bighorn sheep were to seek out new areas of suitable habitat for any given reason, it may not find any suitable habitat before perishing for any number of reasons. Thus, MNN, which quantifies the distances between habitat patches, seems to be a very important statistic. It is unclear how to apply this statistic to bighorn sheep, and perhaps more research should be done in this area to properly correlate landscape metrics to areas of successful and failing bighorn herds.

General suitable habitat was abundant throughout much of the Pine Ridge (Figure 9), often occurring in extensive, contiguous patches. Suitable forage habitat (Figure 10) occurred in less abundance, though possessing a similar distribution to General habitat. Due to the small amount of habitat for the lambing and thermal habitats, maps for these categories are not shown, as these areas contain only a few pixels scattered across the
Suitable General Habitat for Bighorn Sheep in the Pine Ridge

Figure 9. Distribution of suitable general habitat for bighorn sheep in the Pine Ridge of Nebraska.
Suitable Forage Habitat for Bighorn Sheep in the Pine Ridge

Figure 10. Distribution of suitable forage habitat for bighorn sheep in the Pine Ridge of Nebraska.
study area. Gilbert-Baker, Fort Robinson, Roundtop, and Beaver-Wall were areas of distinct patch contiguity for both General and Forage habitat categories.

Bighorn sheep are known to associate strongly with the Fort Robinson area, typically on the northern border of the park. The model accurately portrayed the distribution of General habitat in that region with a relatively large amount of suitable habitat ranging from just west of Crawford, along the border of the park to the northwest (Figure 11). The model indicated that the Ponderosa Wildlife Management Area (WMA), characterized by a framework of federal and state management areas, contained a large and geographically extensive amount of suitable general and forage habitat. The model also indicated that patches of suitable bighorn habitat are scattered throughout the Pine Ridge, though often isolated from other suitable patches. This fragmentation is especially evident near Whiteclay, where patches of habitat are scattered throughout the region, but are each very isolated from the others.

Figure 11. Distribution of suitable General bighorn sheep habitat in Fort Robinson State Park, Nebraska
Suitable forage habitat very closely follows the distribution of the general habitat, though it is expectedly less abundant. The Pine Ridge is characterized by grasslands intermixed in some areas with stands of Ponderosa pine. It is rare when a large area of land in the Pine Ridge does not contain some small grassland or forage area for bighorn sheep. Thus, it is not surprising that the forage habitat distribution does not differ greatly from that of the general habitat.

FA 3 was much more spread out from west to east than FA 1 and FA 2 and contained a large area of General habitat near the Ponderosa Wildlife Management Area (WMA) and Beaver-Wall. FA 1 contained a large, contiguous area of General habitat covering the Gilbert-Baker WMA and some contiguous portions near the Roundtop area. FA 2 contained a substantial amount of General habitat that was more evenly distributed throughout the area. Though a large area of suitable habitat occurred near Beaver-Wall, this region is very isolated from the rest of the suitable habitat in all focus areas.

4.3 MVP Assessment

Various densities of bighorn sheep have been documented. Van Dyke et al. (1983) suggested a maximum density of 1.9 bighorns/km² over an entire range. However, Demarchi (1965) reported over 27 bighorns/km², which is far greater than the previous recommendation. Smith et al. (1991) suggested that a study area (including unsuitable areas) should not be expected to support densities greater than 3.9 bighorns/km². After deducting unsuitable portions of the study area, densities of 7.7 bighorns/km² may be expected. These densities, however, may vary with geographic location. For example, the current Fort Robinson herd is believed to support approximately 70 individuals in an area 23.5 km². This calculates to a density of 2.6
bighorns/km², but it is possible that this herd has not yet reached its full potential with regard to density; and the use of this number is questionable. The stocking level suggested by Smith et al. (1991) will therefore be used here.

Assuming a maximum density of 7.7 bighorns/km² and a required MVP of 125 individuals (Van Dyke et al. 1983), 16.2 km² of optimally suitable habitat are required to support an MVP of bighorn sheep in the Pine Ridge. Smith et al. (1991) also reported that approximately 8.4 – 9.7 km² of lambing habitat would be required to support 60 ewes (about half of the MVP) during the lambing season. Holl (1982) reported that approximately 60 ha of escape terrain are required for each 10 ewes. To support 60 ewes, therefore, the Pine Ridge should contain approximately 360 ha of escape terrain. The Pine Ridge, and each of the focus areas separately, contains sufficient general (and likely forage) habitat to support a minimum viable population. The model indicated, however, that insufficient lambing habitat exists to support a MVP.

There is no indication in the literature as to the quantity of habitat in each category (General, Forage, Lambing, Thermal) that must exist to support a MVP of bighorn sheep. The categories were generated by my perspective on the literature about the basic habitat requirements of bighorn sheep. Only the General and Lambing categories have a direct connection to documented densities and quantity requirements. However, Forage and Thermal habitat are discussed throughout the literature as important habitat types to bighorn sheep. This is the basis for my four-category model. Given that there are no documented quantity requirements for the Forage and Thermal categories, a discussion of MVP with regard to these two categories is difficult. It should be noted, however, that General habitat encompasses all other habitat types and more. This is not
true between the three specific use categories (Forage, Lambing, Thermal), in that Forage habitat may not encompass Lambing or Thermal habitat. It is possible that there is overlap between suitable habitat in the specific use categories, but this is not by the design of the model such as with General habitat. Therefore, determining the ability of the Pine Ridge to support a MVP of bighorn sheep is a matter of quantifying suitable General and Lambing habitat in the study area. For these two categories, documented densities are present in the literature.

4.4 Model Review

Based on existing knowledge of bighorn sheep distribution in the Pine Ridge, the model appears to be properly portraying the known suitable habitat in the region. Through discussions with the state and federal biologists, confidence in the model was established to the extent possible. Questions exist, however, regarding the accuracy of the model, validity of input variables, and methods used. Data error can be introduced at any processing stage during image/layer processing (mosaicking, reprojection, and any alteration of data) (Lunetta et al. 1991, Congalton 1997, Welch and Homsey 1997). In this study attention was given to this issue, and a strong effort was made to minimize the amount of data alteration necessary, but it is typically unavoidable. The end result of error introduction is unknown and difficult to quantify.

From the perspective of modeling bighorn sheep habitat, confidence in the input parameters is a question that could be addressed further. Except in the case of habitat use as a function of distance from escape terrain, all input parameters were given suitability coefficients in a linear fashion. As a function of distance from water, areas were assigned values of 0.0, 0.3, 0.6, or 1.0. A similar approach was used for land cover suitability. I
used my best judgement, based on a literature review of bighorn sheep requirements, to assign values of 0.0, 0.3, 0.5, and 1.0 to areas characteristic of a specific land cover type. It is unknown to what extent this approach is valid since very little quantification exists in the literature about bighorn sheep. It is this lack of quantification that makes a logistic model (used often in wildlife modeling) impossible in this study. Coefficients of association between the species of interest and the input parameters must be known. Since they are not known for bighorn sheep, logistic modeling was not possible in my research, and the assignment of parameter coefficients was purely based on my assessment of information found in the literature.

According to the model, sufficient General habitat (thirteen times the required amount) exists throughout the study area to support a MVP of bighorn sheep. It is interesting to look at the model in the area of Lambing habitat, in which case the model indicates that an insufficient amount of habitat exists for a MVP. Only 3 km² of Lambing habitat exists according to the model, but I am not certain that the model is properly quantifying the suitable Lambing habitat in the study area. A conflict exists between what the model is saying and what is happening in the Pine Ridge with bighorn sheep. Smith et al. (1991) said that lambing habitat is ultimately the controlling factor for bighorn sheep, so the model indicates that insufficient habitat exists to support a breeding population of bighorns in the Pine Ridge. Bighorns are currently breeding the Pine Ridge, and the population currently seems to be increasing in size.

If it is true that bighorn sheep are successfully breeding the in the Pine Ridge, there are two possibilities: 1) the model (or input data) are not appropriately quantifying the lambing habitat in the Pine Ridge or 2) bighorn sheep are using non-traditional habitat
in the Pine Ridge for lambing purposes. In the first possibility, bighorn sheep are using traditional lambing habitat during the lambing season, but the model has failed to appropriately "detect" the lambing habitat in the Pine Ridge. This might indicate a problem with data resolution (30 m DEMs might not appropriately characterize the slopes in the Pine Ridge), inappropriate initial selection of suitable land cover types, inappropriate application of escape terrain requirements, or inappropriate application of minimum patch size. Since the application of the escape terrain requirement (lambing habitat must reside within escape terrain), this rule might be inappropriately strict. Initial results from the escape terrain analysis indicated that the range of slopes, selected as suitable escape terrain, was too stringent. This analysis led me to finally use the range previously employed by Sweanor et al. (1994). It is possible that my requirement for lambing habitat to reside within escape terrain is also too stringent. A habitat suitability model nearly identical to that of this thesis research was employed to assess the quantity of suitable bighorn sheep habitat in the Wildcat Hills of Nebraska, a region similar to the Pine Ridge (Forbes 1999). The Wildcat Hills assessment indicated a sufficient quantity (8.3 km$^2$) of lambing habitat existed to support a MVP in that region. However, the habitat was scattered across a large study area, raising the question of whether enough contiguous lambing habitat truly existed to support a MVP.

In the second possibility, bighorn sheep have changed their behavior to fit the habitat available in the Pine Ridge. It is true that the Pine Ridge is not characteristic of the native habitat for Rocky Mountain bighorn sheep, which typically consists of mountain-like areas with extensive slopes. The Pine Ridge has very little elevation change, and slopes are limited to the sides of rocky outcroppings, which are sometimes
connected to each other to form more extensive areas of steep slopes. Many of the slopes extending upward from grasslands to the top of the rocky buttes are extremely steep, and in some cases sheer rock faces. I have witnessed sheep traversing some of these slopes, but I question whether they use them for anything but fleeing from danger. Geist (1971) stated that ewes have given birth to lambs in shrubby and other seemingly unsuitable habitat. The choice of rocky cliffs as lambing habitat may be a function of predator-prey interaction and conditioned behavior, rather than an actual requirement of the species. Van Dyke et al. (1983) said that ewes prefer remote ledges of a minimum size (2 ha) on steep slopes (escape terrain) for lambing. It is not clear that the slopes in the Pine Ridge meet these requirements because the slopes in the Pine Ridge rarely have any open ledges that are of any notable size. Regions of the required minimum size and vegetation type for lambing are more likely to be the sparse Ponderosa pine forests that are situated in between the rocky outcrops. More research needs to be conducted in this area to quantify the distribution of bighorn sheep by gender, season, and habitat use in the Pine Ridge.

A habitat assessment for bighorn sheep in the Greater Colorado National Monument Area found sufficient overall habitat in combination with sufficient, contiguous lambing habitat to support a MVP. Little information was given about the structure of the lambing habitat, but suggestions for release-site evaluation included, “verify the presence of contiguous (> 2 ha) slopes > 27° (Gudorf et al. 1995, p. 40).” That study was based primarily on habitat requirements documented by Van Dyke et al. (1983) and Smith et al. (1991). A study conducted in the Greater Theodore Roosevelt National Park Area by the same group of researchers found insufficient lambing habitat to support a MVP (Sweanor et al. 1994). Further, the researchers indicated that lambing
habitat was found to be “discontinuous” and distributed in small patches throughout the study area. They indicated that detecting lambing habitat proved difficult using GIS methodologies because GIS analysis is based on planimetric mapping, which cannot measure land on a vertical plane. Given the structure of escape terrain in the Pine Ridge of Nebraska, which consists of short, steep slopes, the inability of the GIS to capably detect slopes for lambing habitat may be a contributor to the low quantity of lambing habitat resulting from the GIS model.

4.5 Population Locale Ranking Results

The Ponderosa WMA zone is ranked as the best potential locale for a population of bighorn sheep in the Pine Ridge, based on contagion, MNN, and quantity of General habitat (Table 12). The Roundtop site came in last, primarily due to its low quantity of overall suitable habitat and low contagion value, indicating relatively little, but highly fragmented, habitat. Fort Robinson, the site of an already existing herd of sheep ranked 4th, primarily because of its high MNN value. Although it had a favorable contagion value, its MNN value was substantially higher than that of all other population locales. This may indicate that suitable bighorn habitat in Fort Robinson exists in contiguous zones that are highly separated geographically. As the existing herd of bighorn sheep continues to grow, individual bighorns may find it difficult to successfully locate other patches of suitable habitat.

Beaver-Wall, where a large portion of contiguous habitat occurred, ranked 5th overall, primarily due to its low quantity of suitable habitat. The suitable habitat that does exist in the region is highly contiguous (contagion 0.75), though patches are
relatively more separated (MNN 68.0 m) than in other locales. This site is interesting because it is so isolated from the rest of the suitable habitat in the Pine Ridge. If a population of bighorn sheep were to colonize this area, it may be effectively isolated from other populations in the Pine Ridge and may not contribute to the overall metapopulation. In this case Beaver-Wall would need to contain enough suitable, contiguous habitat to support an isolated population of bighorn sheep. The minimum General habitat for a MVP is 16.2 km², which Beaver-Wall does not have.

Table 12. Ranking of six population sites in the Pine Ridge study area. Rank is determined by (Rank = 1.1Q + 1.0C + 0.9N), where Q (quantity), C (contagion), and N (mean nearest-neighbor) are replaced by the 1-6 rank of each site with regard to that parameter.

<table>
<thead>
<tr>
<th>Site</th>
<th>Quantity (km²)</th>
<th>Contagion</th>
<th>Mean Nearest Neighbor (m)</th>
<th>Overall Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ponderosa</td>
<td>48</td>
<td>0.80</td>
<td>35.9</td>
<td>1</td>
</tr>
<tr>
<td>Gilbert-Baker</td>
<td>32</td>
<td>0.67</td>
<td>33.4</td>
<td>2</td>
</tr>
<tr>
<td>South</td>
<td>52</td>
<td>0.59</td>
<td>37.5</td>
<td>3</td>
</tr>
<tr>
<td>Fort Robinson</td>
<td>24</td>
<td>0.70</td>
<td>264.4</td>
<td>4</td>
</tr>
<tr>
<td>Beaver-Wall</td>
<td>9</td>
<td>0.75</td>
<td>68.0</td>
<td>5</td>
</tr>
<tr>
<td>Roundtop</td>
<td>22</td>
<td>0.60</td>
<td>36.0</td>
<td>6</td>
</tr>
</tbody>
</table>

4.6 Review of Landscape Approach

The study area was divided into three FAs because existing literature and discussions with state and federal biologists indicated that sheep would have difficulty either crossing the highway that divided FA 1 and FA 2 or would be reluctant to venture
across the matrix of unsuitable habitat found at the intersection of all FAs in an effort to populate FA 3. Rams have been reported in all FAs, indicating that males may not be adhering to these movement barrier assumptions. However, it may not be the case that ewes are undertaking this same sort of migration since reports of ewes outside the Fort Robinson area are fewer. Therefore, the assumptions about the delineation of the FAs may hold true and the results from this study may help to assess each FA with regard to its potential of supporting a population of bighorn sheep.

The ranking of the six population locales indicates that the current herd site (Fort Robinson) may not be the optimal location for bighorn sheep in the Pine Ridge. This indication is difficult to conclude, however, given the intricate and complex nature of wildlife and the basic abilities of models to adequately analyze habitat. It is not surprising that the existing herd of bighorn sheep is primarily located around the Fort Robinson area, since this was the site of the original translocation. Assuming that quantity of General habitat, contagion, and nearest-neighbor do play a significant role in the population locale's ability to support a herd; the model indicated that the Ponderosa WMA is the most suitable site for a population of bighorn sheep. Suitable lambing habitat is scattered across the study area. Thus, it is difficult to truly assess each locale's suitability knowing that lambing habitat is not abundant within any of them. Because much of this area is under public ownership, management agencies may be able to work together to establish a population.

My analysis of locales, however, does not take into consideration the spatial structure of all types of bighorn sheep habitat because little information is available about the importance of thermal and forage habitat and whether spatial structure of this habitat
is important to begin with. The model also does not take into account the spatial configuration of general, forage, lambing, and thermal habitat relative to each other. Again, little is known about the importance of habitat type relative to all other habitat types. General habitat was used in all landscape analyses to provide a landscape view of the study area. If more quantitative information were available about the importance each type of bighorn sheep habitat from in a spatial sense, a more thorough and descriptive landscape analysis could have been undertaken. To accomplish such a thorough analysis without any knowledge of how the results should be interpreted might be a futile exercise.

Although the Pine Ridge at one time supported Audubon bighorn sheep, it is not what one would consider a mountain type of terrain. Steep slopes are limited to those areas surrounding rocky buttes or confined to other narrow, rocky ridges. Traditional habitat for Rocky Mountain bighorn sheep consists of rocky terrain with an abundance of cliffs and precipitous terrain. These types of areas are found in limited quantities within the Pine Ridge and this raises some concern about the ability of this region to support a full population of bighorn sheep. It is not currently known whether ewes are substituting what the model deems “unsuitable lambing habitat” for suitable lambing habitat and what types of habitat individual bighorns may be using for “thermoregulation habitat” during cold and hot seasons. For these reasons wildlife biologists in the state are encouraged to undertake radio telemetry studies to determine seasonal habitat use patterns of bighorn sheep in the Pine Ridge.

Results from this study were presented to NGPC and USFS biologists in an iterative process of model review and refinement, which ultimately resulted in a high
level of confidence in the habitat suitability maps. These biologists indicated that the resulting habitat suitability maps produced by the model accurately reflected bighorn sheep usage in the Pine Ridge.
CHAPTER V: CONCLUSIONS

The empirical model used in this study was developed empirically, based primarily on the findings of Fairbanks et al. (1987) and of other studies. In Fairbanks’ study, the sheep were enclosed and access to habitat was restricted. However, data from Fairbanks’ study are the only available regarding the use of habitat by bighorn sheep in the Pine Ridge, and one of the few studies to provide quantitative information about the distribution of bighorn sheep as a function of various factors. Thus, many of the parameter coefficients in my model are based on that research. While the results of this study suggest that the Pine Ridge is capable of supporting a MVP, biologists are strongly encouraged to engage in additional studies of the current herd to find out more about the behavior of bighorn sheep in the Pine Ridge. The use of radio-tracking and in-situ data collection is recommended to learn more about habitat use by bighorn sheep within the Pine Ridge.

My research demonstrated that the combined use of GIS and remote sensing techniques was effective in performing a habitat analysis over a broad geographic region. Nevertheless, it is important to recognize the potential for errors in data and other phases of the project. One area of concern resides within the land cover classification derived from the Landsat imagery. Due to time, funding, and access constraints it was not possible to perform as detailed an accuracy assessment as is normally desired. Ground truthing work in the Pine Ridge to collect in situ data was used to develop the land cover classification, using only satellite imagery. The level of vegetative classification was very general, since land cover requirements for bighorn sheep are very general.
Therefore, this level of land cover classification may not have caused problems. However, for a habitat analysis of a species that requires very specific land cover types, certainly a more detailed land cover classification would be necessary.

An objective of this project was to use GIS to analyze the configuration of bighorn sheep habitat at both the localized and landscape level. The ability to perform these analyses was demonstrated and provided much more information that would be available using traditional habitat suitability models. By applying the model of spatial juxtaposition to the escape terrain component of the model, the description of the suitable habitat in the study area was extended to include a spatial context. Summarizing suitable habitat at the landscape level provided information about if and where future sub-populations of bighorn sheep could be established.

The bighorn habitat suitability model indicated that the Pine Ridge of Nebraska may be capable of supporting a MVP of 125 bighorn sheep. The habitat model indicated that very little lambing habitat exists, however, and this may be a limiting factor. Too little information about habitat use by bighorn sheep in the Pine Ridge exists to substantiate these conclusions. Validation of the model was accomplished through a series of peer review sessions with state and federal biologists working with bighorn sheep in the region. Concerns presented by the biologists were addressed and incorporated into the model. Results from this study should be compared to future results from radio-telemetry work to provide a further level of validation.

While this project can provide much insight into the available bighorn sheep habitat in the Pine Ridge of Nebraska, biologists for the NGPC and USFS are encouraged to use these findings as support for other research being conducted with bighorn sheep. If
nothing else, these findings are a starting point for understanding the distribution of bighorn sheep habitat within the Pine Ridge and areas of key importance. This model was specifically developed for the Pine Ridge and may not be applicable in other regions without some modifications, primarily concerning the land cover classification and land cover coefficients. Assumptions about habitat associations by bighorn sheep were made based on known information about sheep in this region. Comments from state and federal biologists about the results of the model were favorable, and results from the research were incorporated into management plans for bighorn sheep in the state of Nebraska.

Applications of results from this project are many but will naturally lead to a thorough discussion of how the current herd of sheep can be increased to the MVP level, almost twice the current herd size. A discussion of bighorn sheep management in the Pine Ridge should rely upon the habitat maps provided to account for the spatial distribution of suitable habitat. Six potential sites for future herds were analyzed, and it was determined that the Ponderosa WMA is the most suitable site for a new herd. Based on a substantial amount of land under public ownership in this area, biologists may consider establishing a herd at this site.
LITERATURE CITED


