EVALUATING BIGHORN HABITAT: A LANDSCAPE APPROACH

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Abstract

This technical note describes a method that incorporates a landscape approach with the use of Geographic Information Systems (GIS) to measure habitat and impacts for Rocky Mountain and desert bighorn sheep and to rank potential transplant sites. A landscape approach, in which habitat is viewed from a large-scale perspective as an assemblage of patches, is used because: (1) bighorn habitat is naturally patchy due to the affinity of bighorn for terrain that is both open and mountainous; (2) fragmentation (i.e., increased patchiness) often is the most severe consequence of human disturbance; and (3) the proximity and distribution of neighboring bighorn ranges may be critical factors in determining genetic and demographic support for small bighorn populations. Potential suitability (the inherent capability to support bighorn sheep) and current suitability (the effect of impacts) is determined for each study area. Habitat components measured in alpine habitat include total habitat, escape terrain, and escape terrain contiguity in both summer and winter ranges. Habitat components measured in low-elevation habitat include total habitat, escape terrain, escape terrain contiguity, and water availability.

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Introduction

Bighorn sheep were extirpated from much of the West during the late 1800s. Since the 1930s, transplants have been used to return bighorn to their former ranges (Bleich et al. 1990), although some transplanted populations have become extinct or have not grown much larger than the number transplanted (Smith et al. 1988). One reason for unsuccessful transplants may be inadequate habitat assessment, especially the failure to identify and mitigate impacts prior to release of bighorn.

Using Geographic Information Systems (GIS) and a landscape approach in evaluating habitat can increase the potential for successful transplants. Sophisticated analyses of large sets of spatial data are possible with GIS. With a landscape approach, habitat is viewed from a large-scale perspective as an assemblage of patches in which the spatial pattern of patches is an important facet (Forman and Godron 1981). This is a logical approach to evaluation of bighorn habitat because (1) bighorn habitat is naturally patchy due to the affinity of bighorn for terrain that is both open and mountainous; (2) fragmentation (i.e., increased patchiness) often is the most severe consequence of human disturbance; and (3) the proximity and distribution of neighboring bighorn ranges may be critical factors in determining genetic and demographic support for small bighorn populations (Bailey 1992).

In this technical note, a method originally developed and used in New Mexico is described that incorporates GIS and a landscape approach in evaluation of Rocky Mountain (*Ovis canadensis candensis*) and desert (*O. c. mexicana*) bighorn habitat. Two objectives are accomplished using this method: (1) habitat and impacts are measured, not simply rated; and (2) study areas are objectively ranked.

Habitat Requirements

Vegetative Cover and Topography

Bighorn sheep rely on keen vision to detect predators and rapid mobility on steep terrain to escape from them. Thus, open, steep terrain is the defining component of bighorn habitat (McQuivey 1978, Risenhoover et al. 1988) (Figure 1). Because of the need for open habitat, bighorn distribution is limited mostly to areas above (i.e., alpine Rocky Mountain bighorn habitat) or below (i.e., low-elevation Rocky Mountain or desert bighorn habitat, hereafter referred to as low-elevation habitat) forests and woodlands.[1] Tilton and Willard (1982) and Holl and Bleich (1983:61) found vegetation with canopy cover ≤25-30% open enough to be regularly used by bighorn. Slopes ≥60% generally are considered steep enough to be classified as escape terrain (Hansen 1980, Holl 1982, Armentrout and Brigham 1988, McCarty and Bailey 1994:1). Slopes <60% serve as foraging areas and as corridors between patches of escape terrain (Berger 1991, Bleich 1993). Escape terrain is especially important for ewe-lamb groups because of the high vulnerability of lambs to predation (Sandoval 1979:118, Holl and Bleich 1983:61, Gionfriddo and Krausman 1986, Berger 1991, Bleich 1993:57). Based on the affinity of ewe-lamb groups to escape terrain, it is reasonable to assume that the value of escape terrain in providing protection from predators is positively

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[1] Some desert bighorn (*O. c. nelsoni*) populations in northern Nevada also occur above timberline.
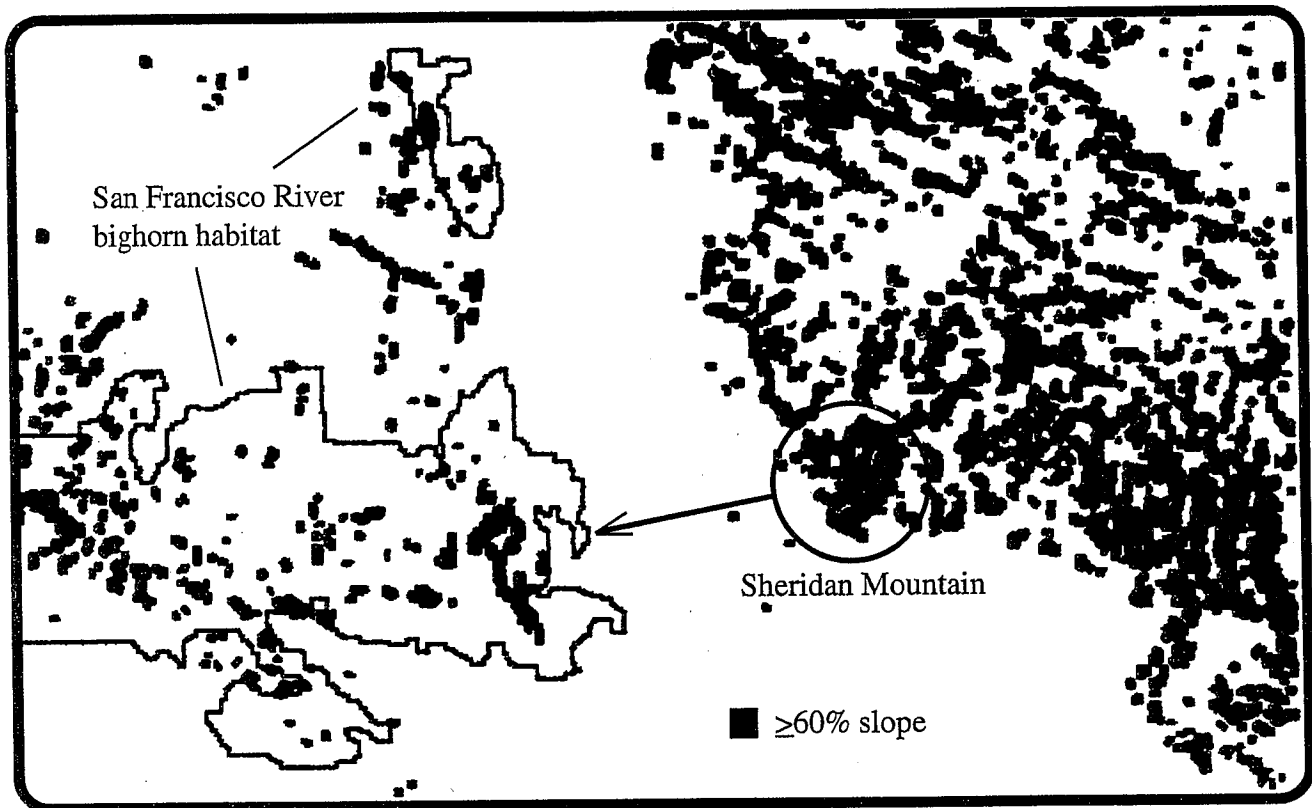
Figure 1. The importance of open habitat. If bighorn only required steep slopes for security, the forested slopes of the Mogollon Mountains, of which Sheridan Mountain is a part, would be excellent bighorn habitat. In 1964, rams from the Turkey Creek population of southwestern New Mexico traveled 30 km (18.5 mi) north to Sheridan Mountain. Eighteen more bighorn subsequently were transplanted to Sheridan Mountain. Within a year, the entire population moved to habitat along the San Francisco River (outlined area) which had less steep terrain, but was covered with open desert grass and shrub vegetation types. Currently, the San Francisco River population contains approximately 100 animals.

related to sizes of escape terrain patches and inversely related to distances between escape terrain patches (Berger 1991, Bleich 1993:87).

Seasonal Ranges

During winter, habitat use by alpine populations is restricted by deep snows. Many alpine populations migrate to low elevation winter ranges (Geist 1971:69, Festa-Bianchet 1986), but in New Mexico, bighorn remain on windswept, snow-free slopes within alpine habitat (Smith and Johnson 1979:40).

Unlike alpine populations, low-elevation bighorn populations generally do not have distinct seasonal ranges (McCarty and Bailey 1994:11).

However, low-elevation populations may restrict their ranges to areas near water during hot, dry weather when water requirements are high. During this period, ewes with lambs generally remain ≤3.2 km (2 mi) from water sources that are in open habitat and close to escape terrain (Leslie 1978, Leslie and Douglas 1979:46, Sandoval 1979:192, Bleich 1993:49).

Population Size

The survival of a population is never guaranteed no matter how large it is (Thomas 1990). The minimum size for a population to be considered viable and self-sustaining for more than a few decades generally is about 100, although several

hundred is recommended (Soule 1980, Soule and Simberloff 1986, Berger 1990, Thomas 1990). Populations with fewer than 100 animals are susceptible to extinction from catastrophic events such as disease outbreaks (Thomas 1990) and may not have enough genetic diversity for long-term persistence (Franklin 1980:147). Some bighorn populations smaller than 100 animals have survived for more than 50 years, but most of these (1) were at low levels but had enough habitat to increase to more than 100 bighorn (Krausman et al. 1993, Goodson 1994), (2) had been augmented with additional animals (Goodson 1994), or (3) were part of an interbreeding group of populations known as a metapopulation (Lande and Barrowclough 1987, Wehausen 1996). The potential for interbreeding among neighboring populations is positively related to population size and proximity to neighboring populations (Gilpin 1987). Intermountain movements of 15 km (9 mi) by ewes and 25-50 km (15-30 mi) by rams have been well documented for Rocky Mountain (Festa-Bianchet 1986, Dunn 1993:29) and desert bighorn (Elenowitz 1983, Cochran and Smith 1983, Ough and deVos 1984, Schwartz et al. 1986, Ramey 1993:118). Thus, populations within 25 km (15 mi) of each other would have a high probability of forming a metapopulation unless physical barriers prevented interchange of individuals.

Impacts

Range Conditions

Bighorn are foraging generalists and their diets vary seasonally and throughout their geographic range (Todd 1975, Johnson and Smith 1980, Cooperrider and Hansen 1982, Whitfield and Keller 1984, Miller and Gaud 1989). However, like all ruminants, bighorn do best with highly nutritious forage (Hanley 1982) and therefore can be adversely affected by poor range conditions where the quality, quantity, and diversity of forage are low (Stoddart et al. 1975:267-271, Dodd and Brady 1986).

Human Disturbance

Reaction of bighorn to human disturbance varies greatly and may be affected by the type and frequency of disturbance, season of occurrence, amount of habitat affected, position of the disturbance to the sheep, proximity of the sheep to escape terrain, and degree of habituation (Berger 1978, Wehausen 1980:192, 1983:74, Miller and Smith 1985). Impacts that can disturb sheep include:

- *Mines and Construction Sites.* Noise and vehicle traffic may cause abandonment of habitat (Leslie and Douglas 1980, Campbell and Remington 1981, DeForge and Scott 1982).

- *Recreation Use.* Bighorn may react to hikers or cross-country skiers that approach within 200 m (220 yds), especially if escape terrain is unavailable (Wehausen 1980:194, 1983:75, Holl and Bleich 1983:81, Miller and Smith 1985, Stanger et al. 1986). Harmful interactions, such as bighorn being chased by dogs and physically restrained by recreationists, have been observed in the Pecos Wilderness of northern New Mexico (Hass 1990, 1991). Trails and campsites within bighorn habitat increase the potential for harmful interactions.

- *Housing Developments.* Noise, vehicle traffic, and harassment from dogs and humans may cause bighorn to abandon habitat near housing developments (DeForge and Scott 1982, MacArthur et al. 1982).

- *Roads.* Vehicle traffic on two-lane highways generally does not disturb sheep (MacArthur et al. 1982, Miller and Smith 1985), but significant mortality from vehicles can occur (Cunningham

and deVos 1992). Bighorn movements can be impeded by highway right-of-way fences and guard rails (Witham and Smith 1979). Primitive roads provide access into otherwise undisturbed areas, which may result in habitat abandonment and increased illegal harvest.

- *Fences.* Mortality from entanglement in fences has been documented (Welsh 1971, Elenowitz 1983).

- *Aircraft.* Bighorn are not visibly disturbed by single-engine airplanes flying >100 m (110 yds) above ground (Krausman and Hervert 1983, Miller and Smith 1985) and desert bighorn apparently habituate to repeated jet overflights on military reserva-tions (Weisenberger et al. 1996). However, helicopters flying <450 m (500 yds) above ewes have been linked to increased heart rates (MacArthur et al. 1982) and decreased foraging efficiency (Stockwell et al. 1991).

Domestic Sheep

Domestic sheep carry diseases such as bronchopneumonia and scabies that can cause significant mortality in bighorn populations (Foreyt and Jessup 1982, Goodson 1982, Jessup 1985, Sandoval 1988). Therefore, the Technical Staff of the Desert Bighorn Council (1990) recommends $\geq$ 13.5 km (8 mi) separation between bighorn and domestic sheep unless topographic features or physical barriers prevent interaction.

Methods

Field Surveys

Field surveys of each study area were conducted to (1) examine perennial water sources in low-elevation habitats, (2) map range conditions and human impacts, and (3) ground-truth GIS data. Water sources were evaluated for livestock use, persistence (ephemeral or perennial), and distance to escape terrain[2]. Sources that were ephemeral, surrounded by fences higher than 1.1 m (3.6 ft) or lower than 0.5 m (1.5 ft) (Helvie 1971), or in dense vegetation were not included in the analysis. Poor range conditions were visually identified by soil erosion, recent gully formation, scarce ground litter, grasses with few seedheads, browse plants with abundant dead dance of *Aristida spp., Gutierrezia spp., or Opun-tia spp.* (Oosting, 1956:396-97, Stoddart et al., 1975:267-271). Human impacts evaluated included mines, roads, hiking trails, recreation sites, fences, and military impacts (i.e., areas affected by bombing, shelling, or ground operations).

GIS Analysis

Overview

The BLM's automated digitizing system (ADS), vector-based Map Overlay and Statistical System (MOSS), and raster-based Map Analysis Program System (MAPS) were used to create and analyze spatial databases (hereafter referred to as coverages) with a variety of operations such as buffering of geographic features, measurement

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[2] Local residents and land management agency personnel provided important information in determining livestock use and persistence of water.

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of slope, and merging or intersecting several coverages. Proficiency with eight GIS commands was needed to accomplish this method (Appendices A and B). Biologists not familiar with GIS should refer to Webster (1988), Keating (1993), or Scott et al. (1993) for introductory information and should consult with GIS specialists for assistance in using the method described in this technical note.

Study areas were categorized as alpine (i.e., above treeline) or low-elevation habitat (i.e., below forested areas). Potential suitability (the inherent capability of an area to support bighorn) and current suitability (the effect of impacts) were measured for each study area (Appendices C, D, E, and F). All habitat was included in the measure of potential suitability, whereas only habitat not affected by poor range conditions or human disturbances was included in the measure of current suitability. Six habitat components were used to evaluate alpine habitat; total habitat, escape terrain, and escape terrain contiguity were measured for both summer and winter ranges (Table 1). Four habitat components were measured to evaluate low-elevation habitat: total habitat, escape terrain, escape terrain contiguity, and water availability (Table 2).

Study Area Boundaries

Only study areas ≥15 km^2 (6 mi^2) were analyzed. Study area boundaries were defined as all patches of habitat with $\leq25\%$ canopy cover and $\geq20\%$ slope[3] that were separated by ≤5 km (3 mi) of flat terrain ($\leq20\%$ slope) or dense vegetation ($>25\%$ canopy cover). Tree and shrub canopy cover was estimated from 1:24,000 aerial photographs by using a 1.5-4x stereoscope and a canopy cover template (U.S. Forest Service North Cen-

tral Forest and Range Experiment Station, St. Paul, MN) (Figure 2). Areas with $\leq25\%$ canopy cover were outlined on 7.5' topographic maps and digitized to create a coverage of open vegetation.

Digital Elevation Model Preparation

Digital Elevation Models (DEM) comprised of 100x100 m cells (1:250,000 scale) were used for topographic analysis (U.S. Geological Survey 1987)[4]. The portion of the DEM that encompassed each study area was extracted and converted to Universal Transverse Mercator (UTM) projection. Slope was measured from the DEM with neighborhood analysis (Webster 1988:139) (Figure 3). In this operation, elevation of the central, or target, cell within a 3x3 cell window was compared by GIS to the elevation of and distance to the surrounding cells in the window. The maximum slope measured was assigned by GIS to the target cell and stored in an initial slope coverage that contained percent slope for each cell of the study area.

Potential Suitability

A coverage of slopes $\geq20\%$ was extracted from the initial slope coverage. The coverage of slopes $\geq20\%$ was intersected with the coverage of open vegetation to identify total habitat[5]. Cells with slopes $\geq60\%$ were extracted from the total habitat coverage to create a coverage of escape terrain. A coverage of escape terrain patches was created by combining (clumping) cells of escape terrain that were ≤200 m (220 yds) apart. Location (UTM coordinates) of the center of each escape terrain patch was determined using a cursor.

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[3] Chosen because the base of most desert ranges analyzed occurred where slopes were 20%.

[4] Higher resolution DEMs are also available for many areas: (1) two arc-second (60x60 m cells) DEMs with vertical accuracy of ±25 m, and (2) 7.5' DEMs (30x30 m cells) with vertical accuracy of ±15 m (Keating, Jr. 1993).

[5] Called suitable habitat in Dunn (1993, 1994).

Table 1. GIS Measurements for Analyzing Alpine Bighorn Sheep Habitat

A. **Potential Suitability** (All habitat that could be used by bighorn sheep)

1. *Potential Total Habitat (summer)*: All patches ≤5 km (3 mi) apart that have canopy cover ≤25% and slopes ≥20%.

2. *Potential Escape Terrain (summer)*: All patches that have canopy cover ≤25% and slopes ≥60%.

3. *Potential Escape Terrain Contiguity (summer)*: Measure of size and proximity of escape terrain patches.

4. *Potential Total Habitat (winter)*: Snow-free patches with canopy cover ≤25% and slopes ≥60%.

5. *Potential Escape Terrain (winter)*: Snow-free patches with canopy cover ≤25% and slopes ≥60%.

6. *Potential Escape Terrain Contiguity (winter)*: Measure of size and proximity of snow-free patches of escape terrain.

B. **Current Suitability** (Habitat not affected by impacts)

1. *Current Total Habitat (summer)*: Potential total Habitat (summer) - impacted areas.

2. *Current Escape Terrain (summer)*: Potential escape terrain (summer) - impacted areas.

3. *Current Escape Terrain Contiguity (summer)*: Measure of size and proximity of patches of escape terrain not affected by impacts.

4. *Current Winter Habitat*: Potential total habitat - impacted areas.

5. *Current Winter Escape Terrain*: Potential escape terrain - impacted areas.

6. *Current Escape Terrain Contiguity*: Measure of size and proximity of snow-free patches of escape terrain not affected by impacts.

Table 2. GIS Measurements for Analyzing Low-Elevation Bighorn Sheep Habitat

A. **Potential Suitability** (All habitat that could be used by bighorn sheep)

1. *Potential Total Habitat*: All patches ≤5 km (3 mi) apart with canopy cover ≤25% and slopes ≥20%.

2. *Potential Escape Terrain*: All patches of total habitat with slopes ≥60%.

3. *Potential Escape Terrain Contiguity*: Measure of size and proximity of escape terrain patches.

4. *Potential Water Availability*: Potential Total Habitat ≤3.2 km (2 mi) from perennial water sources that are ≤200 m (220 yds) from escape terrain.

B. **Current Suitability** (Habitat not affected by impacts)

1. *Current Total Habitat*: Potential Total Habitat - impacted areas.

2. *Current Escape Terrain*: Potential Escape Terrain - impacted areas.

3. *Current Escape Terrain Contiguity*: Measure of size and proximity of escape terrain patches not affected by human impacts.

4. *Current Water Availability*: Current total habitat <3.2 km (2 mi) from perennial water sources that are <200 m (220 yds) from escape terrain and not within impacted areas.
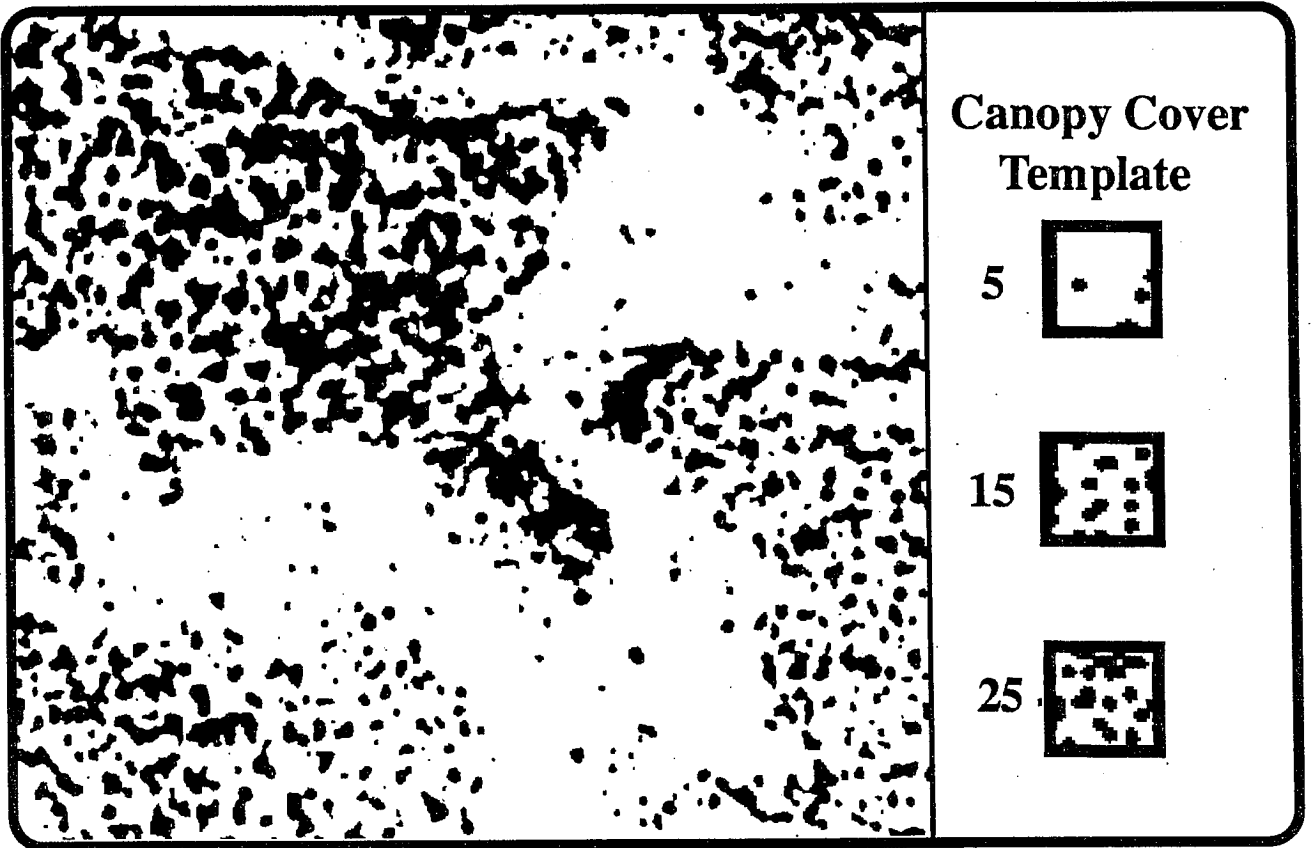
Figure 2. Estimating canopy cover from aerial photographs. Canopy cover was estimated from 1:24,000 aerial photographs by using a 1.5-4x stereoscope and a canopy cover template (U.S. Forest Service North Central Forest and Range Experiment Station, St. Paul, MN). Areas with ≤25% canopy cover were outlined on 7.5' topographic maps and digitized to create a coverage of open vegetation. The canopy of a pinyon-juniper woodland and the canopy cover template are shown above.

Figure 3. Using neighborhood analysis to calculate slope from Digital Elevation Models (DEM). Within a 3x3 cell window, elevation of the central (or target) cell was compared by GIS to the elevation of and distance to surrounding cells. The maximum slope determined in the window was assigned by GIS to the target cell (50%) and stored in an initial slope coverage.

Figure 4. Measuring escape terrain contiguity. Each patch of escape terrain within the study area became a "focal" patch and was measured against each neighboring escape terrain patch that was within 2 km (1.2 mi). For each one-to-one comparison, the areas of the focal and neighboring patch were multiplied and the product was then divided by the distance between the patches squared. The sum of all values calculated in these one-to-one comparisons was the contiguity value for the focal patch. The contiguity index for the study area was the mean of the values calculated for all escape terrain patches within the study area.

Contiguity of escape terrain was measured using a modification of the formula for calculating gravitation attraction between two objects (Zill 1992:357) (Figure 4):

$$CI = \left(\frac{1}{1000n}\right) \sum_{i=1}^{n} \sum_{j=1}^{c} \frac{(A_i)(A_j)}{d_{ij}^2}$$

where:

CI = contiguity index

n = total number of escape terrain patches within the study area

c = number of escape terrain patches ≤ 2 km (1.2 mi) of the focal escape terrain patch

A_i = area (km²) of the focal escape terrain patch

A_j = area (km²) of the neighboring escape terrain patch

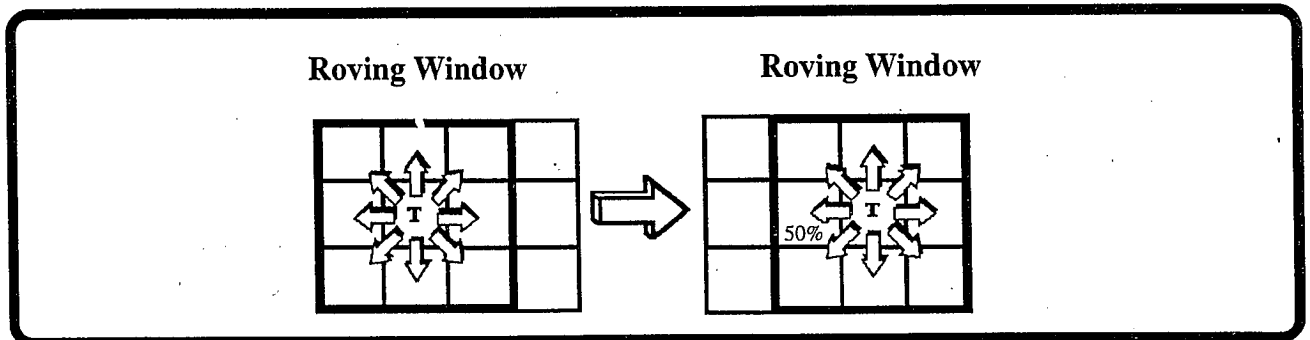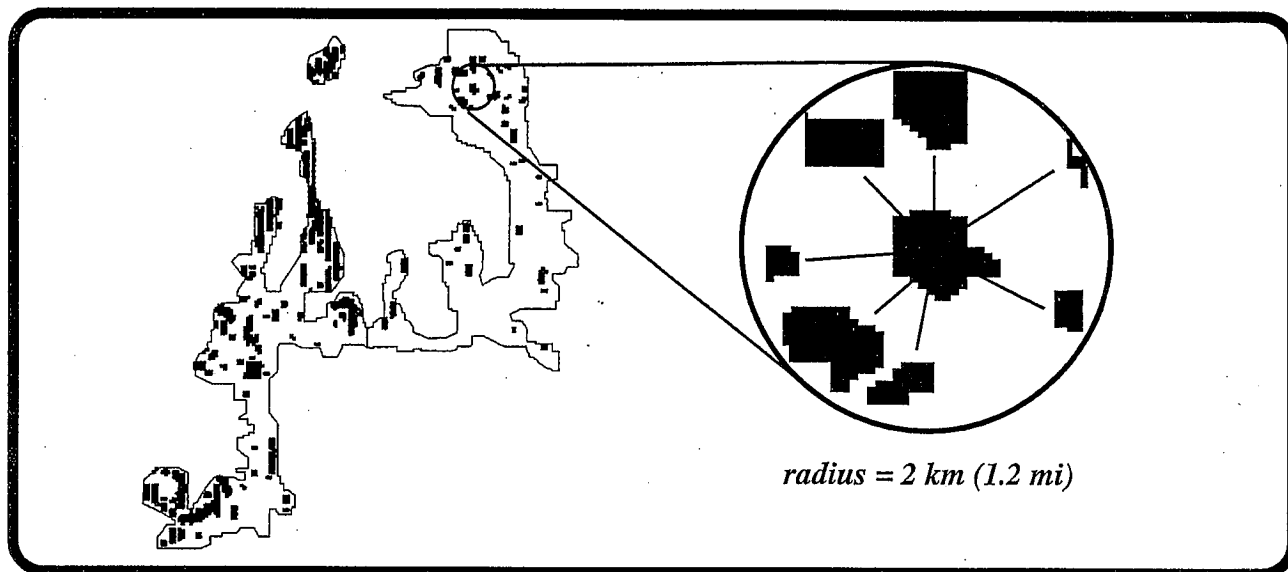d_{ij} = distance (km) between the focal and neighboring escape terrain patch

To measure contiguity in a study area, each patch of escape terrain became a "focal" patch and was compared to each neighboring escape terrain patch that was within 2 km (1.2 mi). For these one-to-one comparisons, the areas of the focal and neighboring patch were multiplied and the product was divided by the distance between the patches squared. The sum of all values calculated in the one-to-one comparisons was the contiguity value for the focal patch. The contiguity index for the study area was the mean of the values calculated for all escape terrain patches within the study area. Appendix G contains a computer program for calculating the escape terrain contiguity index of each study area using UTM coordinates and sizes of escape terrain patches.

Winter ranges of alpine study areas in New Mexico were identified from photographs taken during a mid-February, fixed-wing flight that occurred when snowpack was 120% of normal, so winter range estimates were conservative. Snow-

free slopes identified in the photographs were outlined on 7.5' maps and digitized to create a GIS coverage. This coverage was intersected with the coverages of total habitat and escape terrain to identify total habitat and escape terrain available during winter. Escape terrain contiguity was measured from the resulting winter escape terrain coverage.

For low-elevation habitat, water availability was measured as the amount of total habitat ≤ 3.2 km (2 mi) from perennial water sources that were within 200 m (220 yds) of escape terrain[6]. A coverage of perennial water sources was intersected with a coverage of escape terrain patches that had been buffered to 200 m (220 yds) to create a coverage of perennial water sources near escape terrain. A 3.2 km (2 mi) buffer was then created around these water sources and this coverage was intersected with the coverage of total habitat to measure water availability.

Current Suitability

Current suitability was measured with the same components used to measure potential suitability, but only habitat not affected by impacts was used. A coverage of impacts was created that included: (1) range in poor condition; (2) military impacts (i.e., areas where bombing, shelling, or ground operations occurred); (3) 200 m (220 yd) buffers around hiking trails (based on flight distance of bighorn) and improved roads; and (4) 500 m (550 yd) buffers around primitive roads (the probable maximum distance from which bighorn would be shot by poachers), recreation sites, and housing developments[7]. Current total habitat and escape terrain were determined by eliminating impacted areas from potential total habitat and potential escape terrain, respectively. Current escape terrain contiguity was measured from the

coverage of current escape terrain. Current water availability was measured as the amount of current total habitat ≤ 3.2 km (2 mi) from perennial water sources that were ≤ 200 m (220 yd) from escape terrain and not in areas affected by impacts.

Ranking Study Areas

To rank study areas, data were normalized for each habitat component by dividing the component value of the study area by the maximum value of that habitat component found among all study areas. Thus, component values ranged from 0 to 1. At least one range where the bighorn population size was known and at carrying capacity was included in the analysis to serve as a standard of comparison.

For alpine areas, potential (using all habitat) and current suitability (using only unimpacted habitat) scores were calculated with the formula:

$$SS = \frac{\left[\left(\frac{STH_i}{STH_{max}} \right) + \left(\frac{SET_i}{SET_{max}} \right) + \left(\frac{SETC_i}{SETC_{max}} \right) + \left(\frac{WTH_i}{WTH_{max}} \right) + \left(\frac{WET_i}{WET_{max}} \right) + \left(\frac{WETC_i}{WETC_{max}} \right) \right]}{6}$$

where:

SS	= suitability score (potential or current)
STH	= amount (km^2) of total habitat during summer
SET	= amount (km^2) of escape terrain during summer
SETC	= escape terrain contiguity during summer
WTH	= amount (km^2) of total habitat during winter
WET	= amount (km^2) of escape terrain during winter
WETC	= escape terrain contiguity during winter
i	= value of the component for the study area

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[6] Occasionally, perennial water sources >200 m (220 yds) from escape terrain were included in measurement of water availability because they were in terrain judged to be rugged enough to be regularly used by ewe-lamb groups.

[7] Improved roads included paved and gravel roads that were regularly traveled. Primitive roads included unmaintained dirt roads and jeep trails.

max = maximum value of that component for all study areas.

For low-elevation study areas, potential (using all habitat) and current (using only unimpacted habitat) suitability scores were calculated with the formula:

$$SS = \frac{\left[\left(\dfrac{TH_i}{TH_{max}} \right) + \left(\dfrac{ET_i}{ET_{max}} \right) + \left(\dfrac{ETC_i}{ETC_{max}} \right) + \left(\dfrac{WA_i}{WA_{max}} \right) \right]}{4}$$

where:

SS = suitability score (potential or current)
TH = amount (km^2) of total habitat
ET = amount (km^2) of escape terrain
ETC = escape terrain contiguity
WA = water availability (km^2)
i = value for the study area
max = maximum value of that component for all study areas.

The rank of each study area was based on the Habitat Suitability Score, the average of its potential and current suitability scores. Study areas ≤ 15 km (9 mi) from domestic sheep were included in the rankings but were not considered for transplants until the domestic sheep were permanently removed.

Calculating Carrying Capacity

Carrying capacity, the number of animals that a range can support on a sustained basis (Boyd et al. 1986:524), was calculated using the ratio of the Habitat Suitability Score to the Population Size of an occupied range containing a population at carrying capacity:

$$\frac{HSS_o}{CC_o} = \frac{HSS_i}{CC_i}$$

where:

HSS_o = the Habitat Suitability Score of the occupied range
CC_o = the carrying capacity (number of animals) of the occupied range
HSS_i = the Habitat Suitability Score of study area i
CC_i = the carrying capacity (number of animals) calculated for study area i

Results

Alpine Habitat

In New Mexico, alpine habitat occurs only in small, widely-scattered patches above 3500 m (11,500 ft) elevation. Because of a relatively mild climate, forests grow to the tops of most mountains, so alpine habitat is much more limited than in the more northerly latitudes (Arno and Hammerly 1984:16). Five alpine study areas were evaluated with this methodology.

Most bighorn habitat was found in the Pecos and Wheeler Peak Wilderness Areas, where bighorn persisted until the late 1800s and where the only alpine populations in New Mexico currently reside. Bighorn were transplanted to the Pecos Wilderness in 1964 and to Wheeler Peak in 1993. The Pecos Wilderness has approximately 320 bighorn; carrying capacity was estimated to be 175-330 (Smith and Johnson 1979:102). Wheeler Peak has 60 bighorn and the population is increasing. These two areas contain 65% of the total habitat and 77% of the escape terrain of the five alpine areas (Figures 5 and 6).
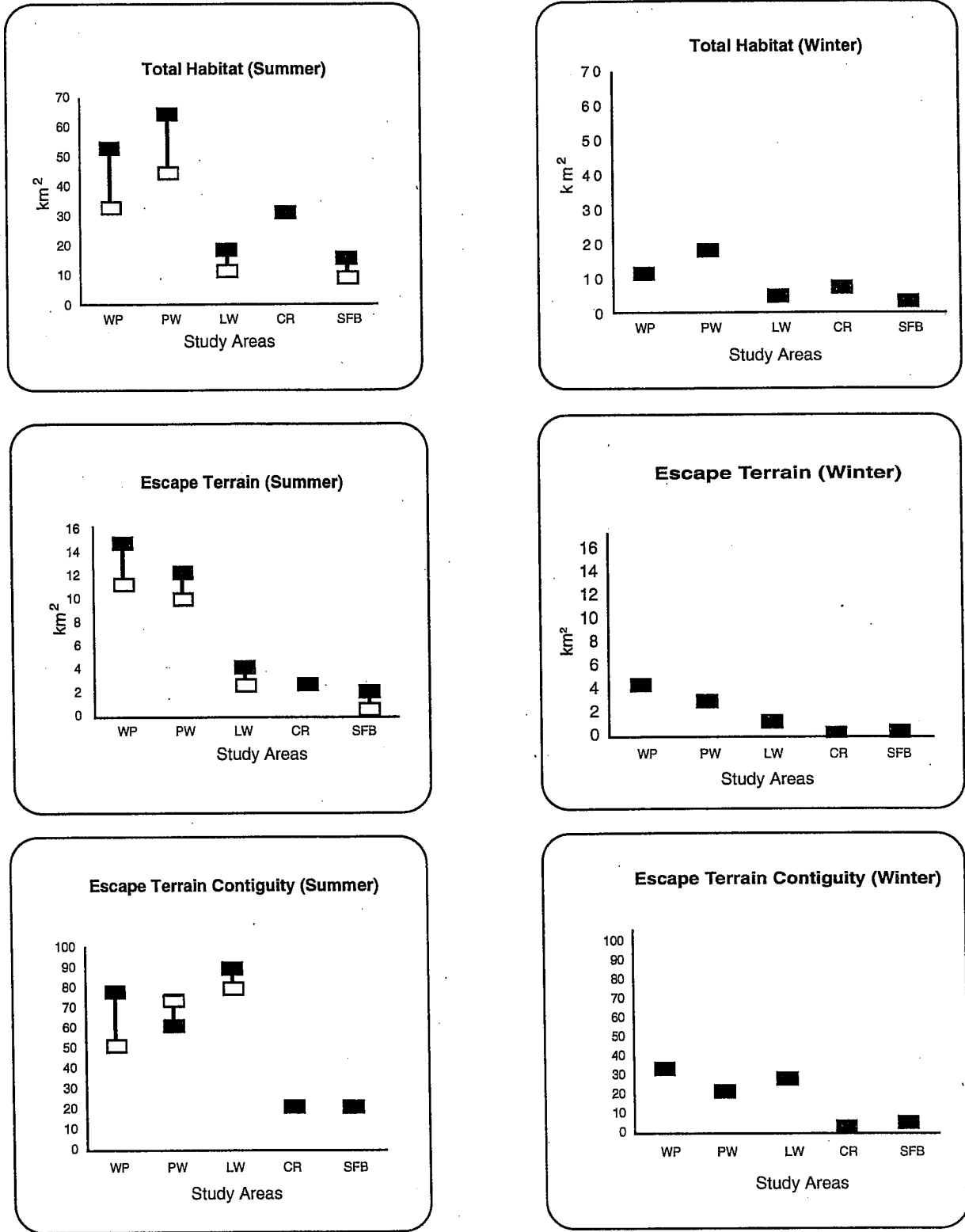
Figure 5. Values of six habitat components used to measure potential and current suitability in alpine Rocky Mountain bighorn sheep study areas in New Mexico. Potential values are shown as black boxes; current values, if different, are shown as white boxes. WP = Wheeler Peak, PW = Pecos Wilderness, LW = Latir Wilderness, CR = Culebra Range, SFB = Santa Fe Baldy.
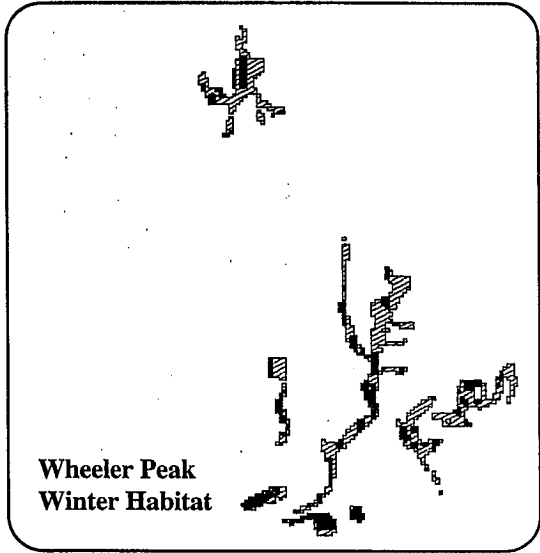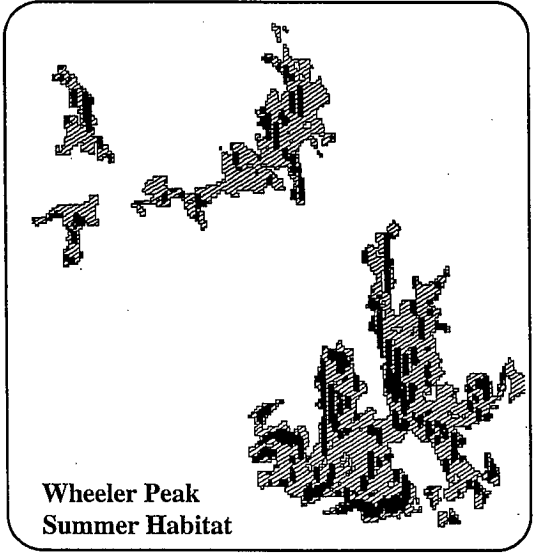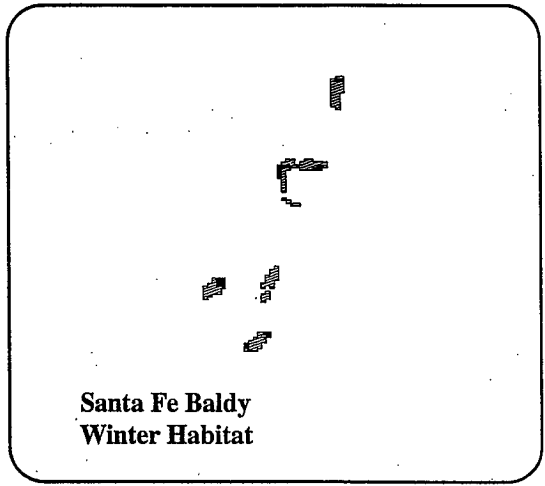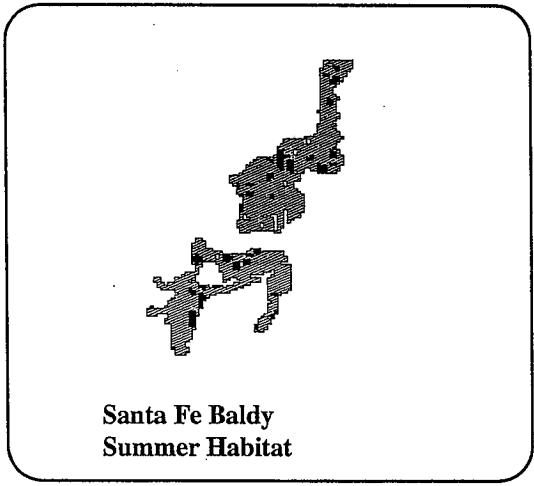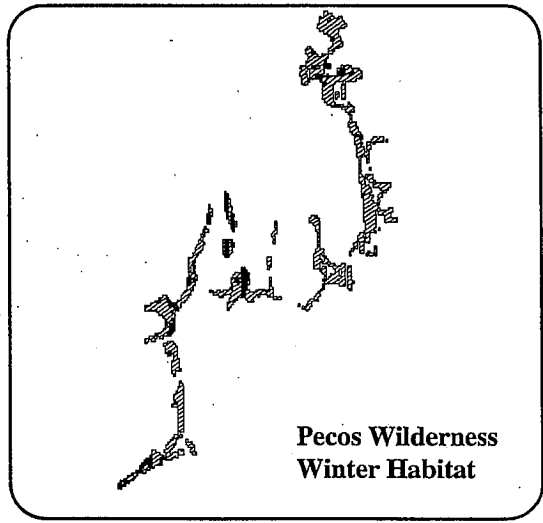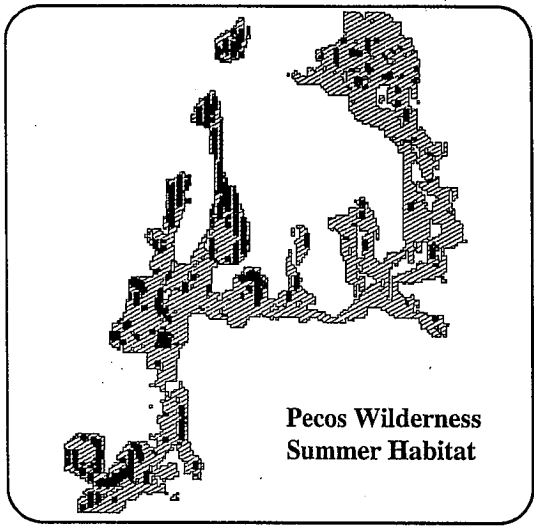
Figure 6. Potential summer and winter habitat for Rocky Mountain bighorn sheep in three alpine study areas in New Mexico. Escape terrain patches are black; open slopes 20-59% are hatched. Study areas are not shown to scale.

During winter, only 18% (range = 10-25%) of potential total habitat and 16% (range = 0-24%) of potential escape terrain occurred on snow-free slopes (Figure 6). Escape terrain contiguity averaged 54.4 (range = 20.5-88.2) in summer, but only 15.3 (range = 0-30.3) in winter, indicating that winter habitat was much more fragmented.

Summer habitat was impacted by campsites and trails in all areas (Figure 7) except the Culebra Range, which was closed to public access . On average, 22% of total habitat (range = 0-33.8%) and 14.3% (range = 0-26.7%) of escape terrain

were impacted. Little decrease in escape terrain contiguity occurred except on Wheeler Peak (Figure 5). Escape terrain contiguity in the Pecos Wilderness study area actually increased because some small scattered patches were eliminated by impacts. Winter habitat was not affected by impacts.

Wheeler Peak and Pecos Wilderness had the highest Habitat Suitability Scores because they contained the most total habitat and escape terrain (Table 3). Wheeler Peak ranked higher than the Pecos Wilderness because it had more escape terrain and higher escape terrain contiguity

**Table 3.** Calculations used to determine potential and current suitability for five alpine Rocky Mountain bighorn sheep study areas in New Mexico.

$$SS = \frac{\left[(\frac{STH_i}{STH_{max}}) + (\frac{SET_i}{SET_{max}}) + (\frac{SETC_i}{SETC_{max}}) + (\frac{WTH_i}{WTH_{max}}) + (\frac{WET_i}{WET_{max}}) + (\frac{WETC_i}{WETC_{max}}) \right]}{6}$$

where:

SS   = suitability score (potential or current)
STH = amount (km^2) of total habitat during summer
SET = amount (km^2) of escape terrain during summer
SETC = escape terrain contiguity during summer
WTH = amount (km^2) of total habitat during winter
WET = amount (km^2) of escape terrain during winter
WETC= escape terrain contiguity during winter.
i   = value of the component for the study area
max = maximum value of that component for all study areas.

POTENTIAL SUITABILITY

Study Areas	Calculations	Scores
Wheeler Peak	$\dfrac{(52.5/64.4)+(14.3/14.3)+(76.8/88.2)+(9.5/16.4)+(3.2/3.2)+(30.3/30.3)}{6}$	0.9
Pecos Wilderness	$\dfrac{(64.4/64.4)+(11.8/14.3)+(66.2/88.2)+(16.4/16.4)+(2.2/3.2)+(18.3/30.3)}{6}$	0.81
Latir Wilderness	$\dfrac{(18/64.4)+(3.7/14.3)+(88.2/88.2)+(3.3/16.4)+(0.9/3.2)+(24.4/30.3)}{6}$	0.50
Culebra Range	$\dfrac{(30.3/64.4)+(2.4/14.3)(+20.7/88.2)(+5.6/16.4)+(0/3.2)+(0/30.3)}{6}$	0.21
Santa Fe Baldy	$\dfrac{(14.8/64.4)+(1.5/14.3)+(20.5/88.2)+(1.5/16.4)+(.22/3.2)+(3.5/30.3)}{6}$	0.15

Table 3. Continued

CURRENT SUITABILITY

Study Areas	Calculations	Scores
Wheeler Peak	$\dfrac{(39.2/48.0)+(11.8/11.8)+(56/83.5)+(9.5/16.4)+(3.2/3.2)+(30.3/30.3)}{6}$	0.84
Pecos Wilderness	$\dfrac{(48/48)+(10.5/11.8)+(72.2/83.5)+(16.4/16.4)+(2.2/3.2)+(18.3/30.3)}{6}$	0.84
Latir Wilderness	$\dfrac{(13.4/48)+(3.1/11.8)+(83.5/83.5)+(3.3/16.4)+(.9/3.2)+(24.4/30.3)}{6}$	0.47
Culebra Range	$\dfrac{(30.3/48)+(2.4/11.8)+(20.7/83.5)+(5.6/16.4)+(0/3.2)+(0/30.3)}{6}$	0.24
Santa Fe Baldy	$\dfrac{(9.8/48)+(1.1/11.8)+(20.5/83.5)+(1.5/16.4)+(0.22/3.2)+(3.5/30.3)}{6}$	0.12

HABITAT SUITABILITY
(average of potential and current suitability scores)

Study Areas	Calculations	Scores
Wheeler Peak	(0.90 + 0.84)/2	0.870
Pecos Wilderness	(0.81 + 0.84)/2	0.825
Latir Wilderness	(0.50 + 0.47)/2	0.485
Culebra Range	(0.21 + 0.24)/2	0.225
Santa Fe Baldy	(0.15 + 0.12)/2	0.135

during both summer and winter. High escape terrain contiguity contributed greatly to the Habitat Suitability Score of Latir Wilderness. The Culebra Range contained more total habitat than Latir Wilderness, but ranked lower because of a lack of escape terrain. Santa Fe Baldy was lacking in all habitat components.

The midpoint value (250) of Smith and Johnson's (1979:102) carrying capacity estimates for Pecos Wilderness were used to calculate carrying capacity (Table 4). Wheeler Peak, Pecos Wilderness and Latir Wilderness had adequate habitat to support self-sustaining bighorn populations (>100 animals), but the Culebra Range and Santa Fe Baldy did not.
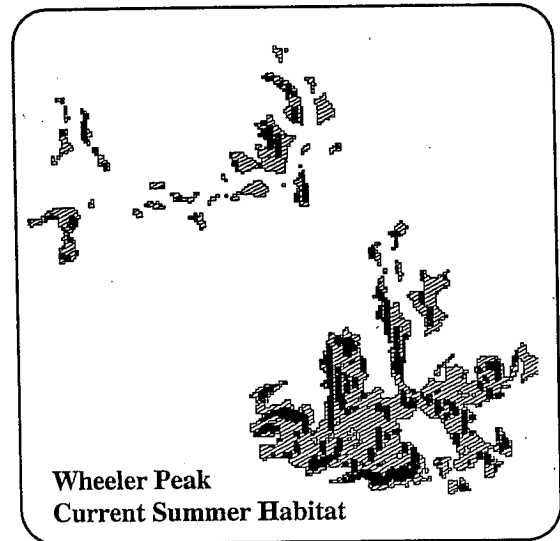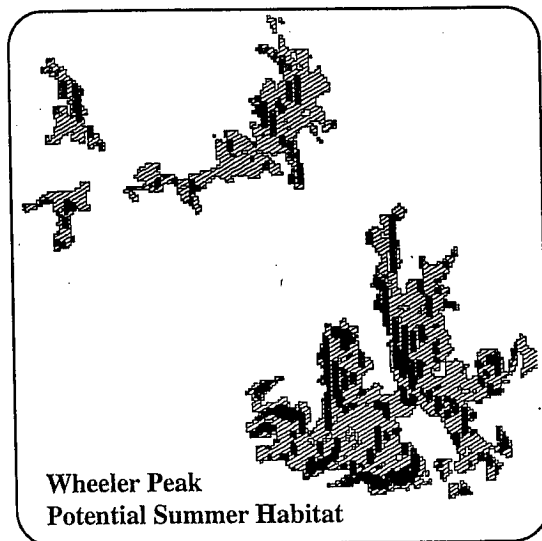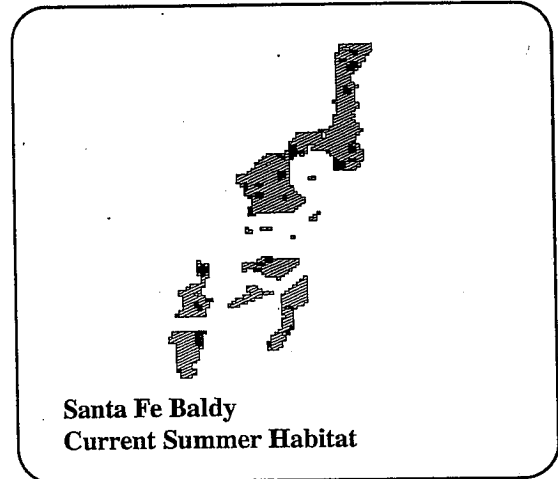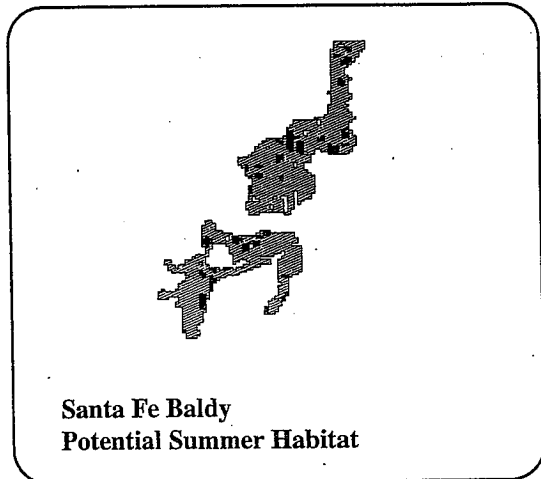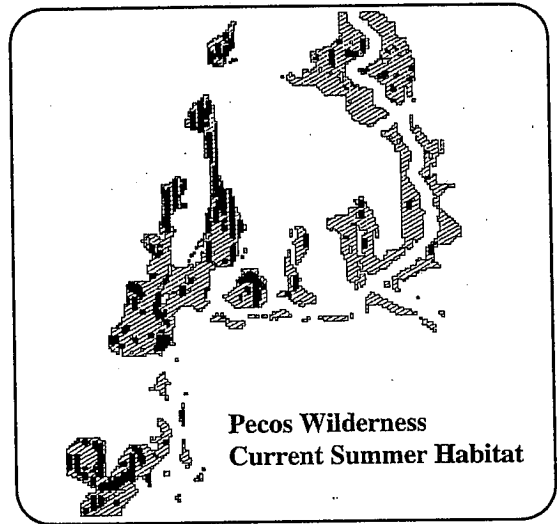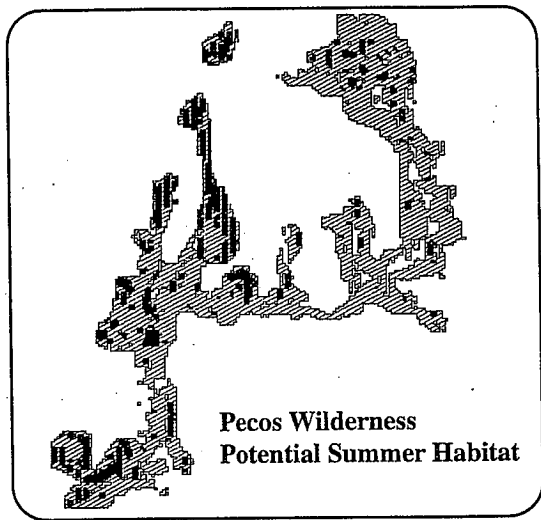
Figure 7. The effect of impacts on summer habitat in three Rocky Mountain bighorn sheep study areas in New Mexico. Potential habitat includes the total area that could be inhabited by bighorn. Current habitat includes only those areas not affected by impacts. Escape terrain patches are black; open slopes 20-59% are hatched. Study areas are not shown to scale.

Table 4. Carrying capacity calculations for five alpine Rocky Mountain bighorn sheep study areas in New Mexico. The Habitat Suitability Score (0.825) and midpoint value (250) for carrying capacity of the Pecos Wilderness population are the values for the occupied range in the calculations.

where:

$$\frac{HSS_o}{CC_o} = \frac{HSS_i}{CC_i}$$

HSS_o = the Habitat Suitability Score of the occupied range
CC_o = the carrying capacity (number of animals) of the occupied range
HSS_i = the Habitat Suitability Score of study area i
CC_i = the carrying capacity (number of animals) calculated for study area i

Study Areas	Calculations	Carrying Capacity
Wheeler Peak	(250 x 0.87) /0.825	264 bighorn
Pecos Wilderness	(250 x 0.825)/0.825	250 bighorn
Latir Wilderness	(250 x 0.47) /0.825	142 bighorn
Culebra Range	(250 x 0.225)/0.825	68 bighorn
Santa Fe Baldy	(250 x 0.135)/0.825	40 bighorn

Low-Elevation Habitat

Thirteen desert bighorn and six low-elevation Rocky Mountain bighorn study areas in New Mexico were evaluated with this methodology. Habitat components of five study areas (hereafter referred to as historic ranges) that supported indigenous desert bighorn populations at least until 1900 (Dunn 1994) were compared to components of eight other study areas that did not historically support desert bighorn (hereafter referred to as non-historic ranges).

Historic ranges contained an average of 204 km² (79 mi²) (range = 72-421 km²) of potential total habitat and 20 km² (7.7 mi²) (range = 5.4-33 km²) of escape terrain, whereas non-historic ranges contained an average of 66 km² (25.5 mi) (range = 42-127 km²) of potential total habitat and 5 km² (2 mi²) (range = 2-7.3 km²) of escape terrain (Figure 8). Escape terrain in historic ranges was more contiguous ($\bar{x}$ = 61.4; range = 43-80) than in non-historic ranges ($\bar{x}$ = 38.8; range 14-95). Water also was more available in historic ranges than non-historic ranges. Twenty-six of 33 springs $\leq$200 m (220 yds) from escape terrain were in historic ranges. Six non-historic ranges had no water sources $\leq$200 m (220 yds) from escape terrain. On average, 30.4% (range = 0-63%) of total habitat in historic ranges was $\leq$3.2 km (2 mi) from perennial water, whereas only 5.5% (range = 0-16%) of total habitat in non-historic ranges was $\leq$3.2 km (2 mi) from perennial water.

Impacts that affected desert bighorn study areas included poor range conditions, military activities, mines, recreation sites, primitive roads, trails, and fences (Figure 9). For all 13 study areas, an average of 32.4% (range = 0-38%) of total habitat and 20.2% (range = 0-28%) of escape terrain were impacted. Contiguity did not change for 6 of the 13 study areas. Water was available to 20% less total habitat because of impacts. Impacts did not affect water availability in two study areas, but in two other study areas all perennial water <200 m (220 yds) from escape terrain were affected by human impacts.
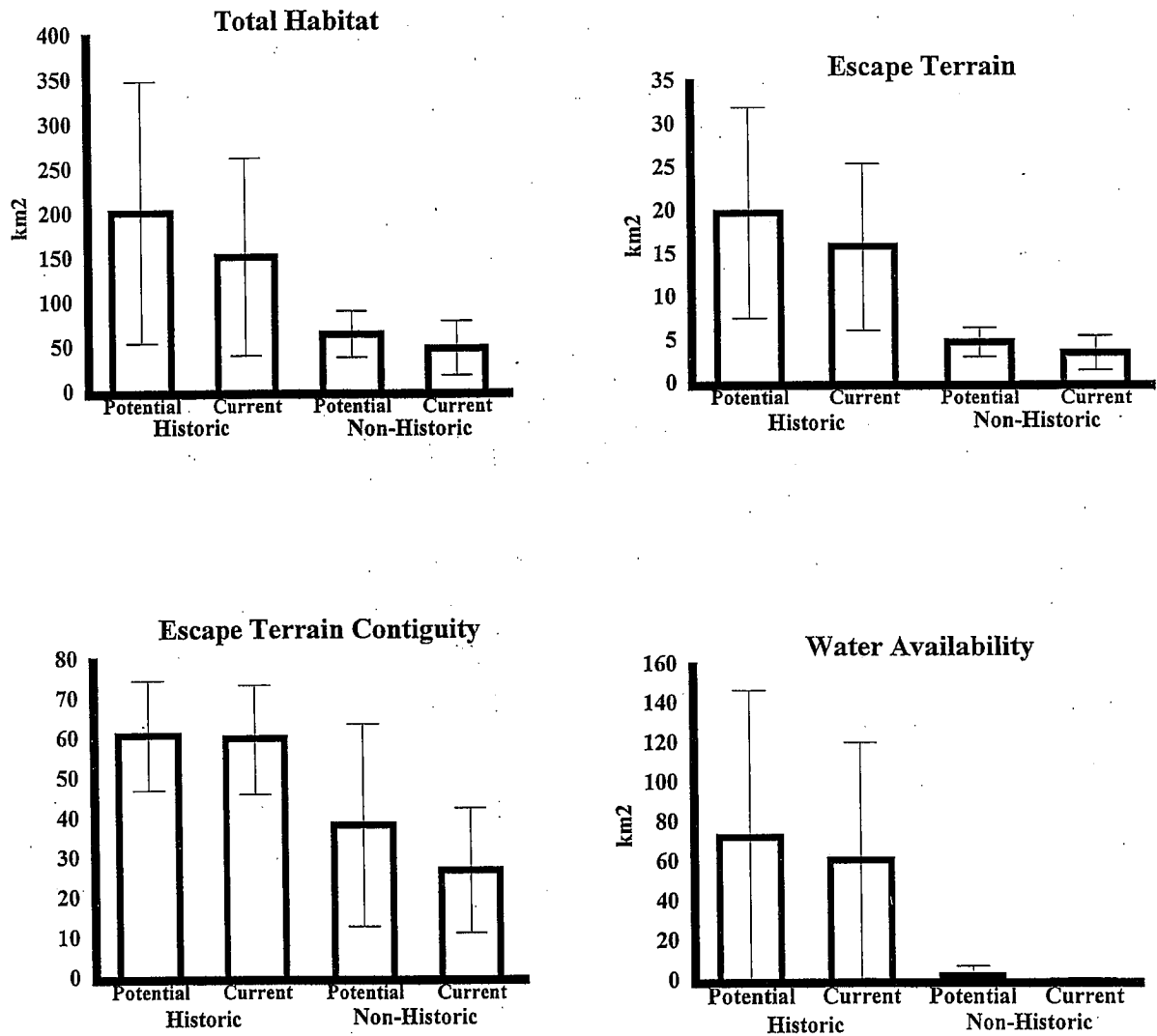
Figure 8. Values of four habitat components used to measure potential and current suitability in five historic and eight non-historic desert bighorn sheep ranges in New Mexico. Mean values are shown as bars; I-beams equal 1 standard deviation.
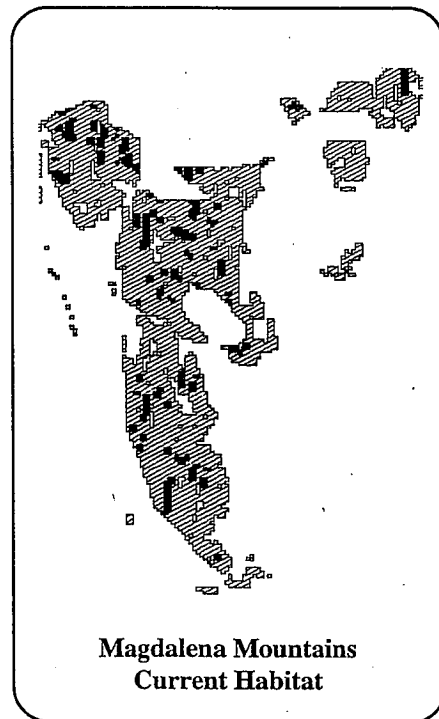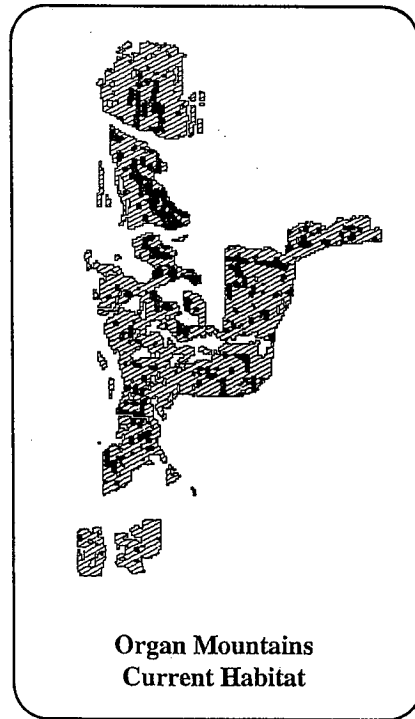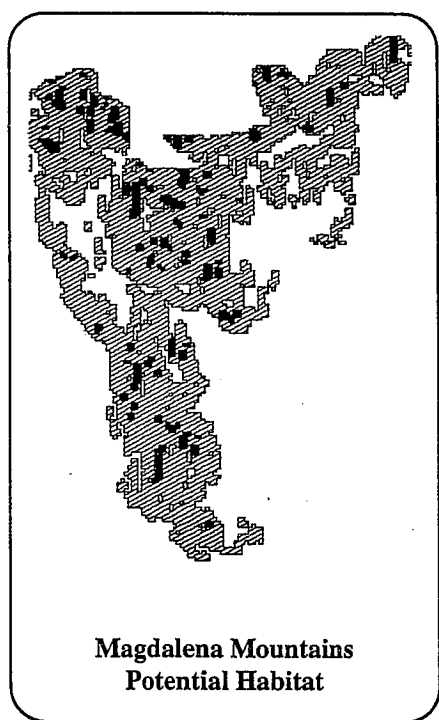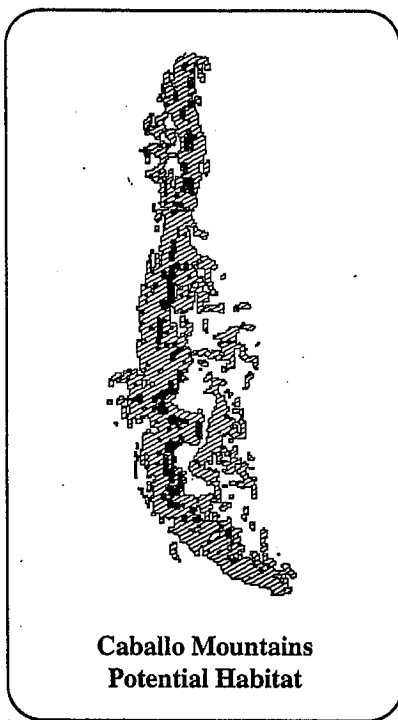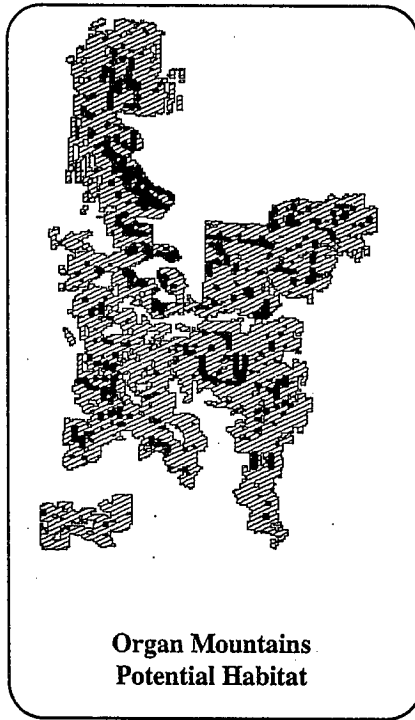
Figure 9. The effect of impacts on three desert bighorn sheep study areas in New Mexico. Potential habitat includes the total area that could be inhabited by bighorn. Current habitat includes only those areas not affected by impacts. Escape terrain patches are black; open slopes 20-59% are hatched. Study areas are not shown to scale.

Discussion

Prior to the advent of GIS, bighorn habitat was evaluated using one of two methods: (1) the conceptual method in which habitat was considered suitable if it visually appeared to contain the needed components (see Cooperrider 1986:766), or (2) a numerical scoring system (Hansen 1980, Armentrout and Brigham 1986). Hansen's (1980) method has been the most commonly used for numerical scoring. With this method, each square mile of a study area was numerically scored for quality (based on written descriptions) of each of seven habitat parameters. Based on the total score, each section was categorized as excellent, good, fair, or poor habitat. Thus, a qualitative rating was obtained, not a true measure of habitat.

Two problems can reduce the accuracy of habitat analyses when numerical scoring systems are used. First, sample units large enough to easily rate an entire mountain range may be too coarse-grained. Few mountainous areas contain homogeneous habitat throughout an entire square mile, the sample unit used by Hansen (1980:321). This problem can be rectified by having the entire section represented by the dominant habitat type (i.e., if 400 acres are steep and 240 acres are rolling hills, the section is rated as steep) or by selecting a compromise rating (i.e., moderately steep). Either strategy could result in substantial error over an entire study area.

Second, written descriptions upon which scores are based can be subjective and will compromise repeatability. Ratings of the same habitat type may vary as the attentiveness or the perceptions of evaluators vary. For example, areas rated as containing high human use by one evaluator may be rated as having medium human use by another. Subjectivity may be reduced and repeatability increased with more exact written descriptions, but not as well as when habitat is actually measured.

Use of GIS and a landscape approach is an effective and efficient means of evaluating and comparing many areas of bighorn habitat because it provides (1) consistent measurements across all study areas, so bias towards any one study area is reduced, (2) measurement of the amount and patchiness of bighorn habitat, (3) a final score and ranking derived directly from the values of the habitat components, (4) evaluation of large areas with much less effort than if they were entirely analyzed in the field, (5) both potential and current suitability, so benefits of mitigation can be more accurately analyzed, and (6) a graphic display of the amount and distribution of bighorn habitat. High scores of historic alpine bighorn ranges and differences found between historic and non-historic desert bighorn ranges in New Mexico are evidence that this method is effective for determining where bighorn can persist.

However, carrying capacities derived from the formula in this method are crude estimates and their use is best limited to separating areas that can support $\geq$100 bighorn from those that cannot. A multitude of factors, such as population structure, food habits, and patterns of habitat use, affect how many animals a range can support (Boyd et al. 1986:524). Precise estimates of carrying capacity are difficult, if not impossible, to achieve (Strickland et al., 1994:451).

Measurement of impacts provided a quantitative database from which mitigation alternatives could be analyzed, but it was the most subjective part of this methodology. Written descriptions were used for identifying range condition and road type, buffers were placed around some impacts, and temporal variation of impacts was not measured. Errors potentially introduced by written descriptions for range condition and road type should be minimal because of the conservative criteria used. Also, poor range conditions generally represented a small percentage of total impacts because of infrequent use of steep slopes by cattle (Dodd and Brady 1986).

Different-sized buffers around impacts represented a form of data weighting. Weighting has been used to discriminate among the importance of components in habitat analyses (Cooperrider 1986:766), but often it is subjective and not necessarily a true reflection of the importance of each component in determining habitat quality. Buffers were necessary in this method to provide an adequate spatial measure of point and linear impacts.

Temporal variation of impacts (e.g., number of hikers and time of day trails were used) was not measured because data on amount and period of disturbance were not available for most study areas. These data could be important in accurately measuring the effects of impacts on bighorn. For example, Hamilton et al. (1982) determined that bighorn could be more adversely affected by a high frequency of recreation use than by a high number of recreationists.

Several measures of habitat used in other studies were not included in this method. Horizontal visibility was not measured using visual estimation of vegetative obstruction (Risenhoover and Bailey 1985, Armentrout and Brigham 1986). Using canopy cover as a surrogate measure of horizontal visibility is a much more rapid means of analyzing large areas and has been shown to be effective in identifying open vegetation by Tilton and Willard (1982) and Holl and Bleich (1983:61). However, field verification of the results is important, especially in moderately dense shrub types where horizontal visibility may be greatly reduced by the amount of foliage at the eye level of bighorn (3 ft).

Aspect and elevation were not used as surrogate measures of open vegetation (M. Gudorf, Natl. Park Serv., Denver, CO, pers. commun.), thermal cover (Gionfriddo and Krausman 1986), or limits of usable habitat (Smith et al. 1991). Southerly aspects and low elevations generally are xeric and support more open vegetation but not all vegetation in these areas is necessarily open enough for bighorn. Thermal cover has not been shown to be a major factor in determining more

than temporal distribution of bighorn (McCarty and Bailey 1994:10). Elevations <2211 m (7250 ft) were used by Smith et al. (1991) to define the boundary of usable habitat, but the relationship was unique to their study area.

Escape terrain may have been overestimated in this method because vertical slopes (i.e., slickrock (Smith and Flinders 1992)) were not eliminated and rockiness was not measured (Hansen 1980:325, Armentrout and Brigham 1986, Holl 1982). Vertical slopes (>80°) comprised <2% of the total escape terrain in the study areas because of the relatively course grain (100x100 m) of 1:250,000 DEMs. Rockiness was not used because most slopes $\geq$60% contain at least some rocky areas and the amount of rockiness needed for an area to provide adequate escape terrain has not been quantified.

Escape terrain patches $\geq$2 ha (5 ac) were not defined as lambing areas (Armentrout and Brigham 1986, Smith et al. 1991) because this measure has not been empirically demonstrated as a minimum requirement for lambing (Van Dyke et al. 1983:6) and some desert bighorn populations do not consistently lamb in specific areas (Leslie and Douglas 1979:40). Open, steep terrain is the important habitat component for lambing, so measure of the amount and contiguity of escape terrain should be an adequate indicator of the sufficiency of each study area for lambing.

Forage diversity and abundance were not measured because bighorn can survive on wide varieties (Todd 1975, Cooperrider and Hanson 1982) and low densities of forage (Leslie and Douglas 1979:10), so the contribution of forage data in determining adequacy of habitat may not be worth the amount of effort needed to collect it.

Finally, the potential for movement between neighboring bighorn ranges was not measured because of the difficulty in quantifying the effect of barriers on intermountain movements. However, the contiguity index (Appendix G) could be used as a measure of the potential for establishing a metapopulation. Distance between ranges and amount of escape terrain within each range would be variables.

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Appendix A

Glossary of MOSS and MAPS Commands
Used in GIS Analysis of Bighorn Habitat

CLUMP - A command to combine cells that have a common value (i.e., ≥60% slope) and are within a specified distance from one another. Options: AT (distance) specifies the maximum distance (measured in grid spaces between cell centers) separating cells that are to be combined together. The value was 2 (i.e. 200 m (220 yd) real distance) for this analysis. DIAGONALLY specifies that the otherwise circular neighborhood defined by AT (distance) is to be extended diagonally to encompass a square.

Command Line: **CLUMP** (old coverage) AT (distance) DIAGONALLY FOR (new coverage)
Example: CLUMP *mtn*.PET AT 2 DIAGONALLY FOR *mtn*.PETCLP

EXTRACT - A command to create a new coverage only of cells with certain values (i.e., ≥60% slopes).

Command Line: **EXTRACT** (old coverage) FOR (new coverage) , ASSIGNING (new value) TO (old value)
Example: **EXTRACT** *mtn*.PTH for *mtn*.PET , ASSIGNING 1 TO 60 through 1000

MATH (intersect) - A command to create a new coverage by multiplying the values of one coverage with those of another coverage on a cell-by-cell basis. Note: EXTRACT is then used to create a discrete coverage[8].

Command Line: **MATH** (old coverage) * (old coverage) FOR (new coverage)
Example: **MATH** *mtn*.OPEN * *mtn*.DEM FOR *mtn*.BASE

MATH (subtract) - A command to create a new coverage by subtracting the values of one coverage from those of another coverage on a cell-by-cell basis. Note: EXTRACT is used to create a discrete coverage.

Command Line: **MATH** (old coverage) - (old coverage) FOR (new coverage)
Example: **MATH** *mtn*.PTH - *mtn*.HUMIMP FOR *mtn*.CTH

LOCATION - A data description command in which the coordinate of any point on a map is determined.

Command Line: **LOCATE** (cross hair input)

PROJECT - A command to change the map projection of an existing coverage or Digital Elevation Model.

Command Line: **PROJECT** *mtn*.DEM

What is the projection for the input map? UTM
What is the projection for the out put map? UTM
What is the ellipsoid for the output map? Clarke 1866
Longitude of any point with the UTM zone? -106
Latitude of any point within the UTM zone? 34
Cell Width of output map? 100
Cell Height of output map? 100

---

[8] Continuous coverages are comprised of essentially uninterrupted data sets. Discrete coverages are comprised of data grouped into distinct categories (i.e., slopes ≥20%, slopes ≥60%).

SLOPE - A neighborhood analysis command in which a new coverage of percent slope is created from a Digital Elevation Model. Within a 3x3 cell window, elevation of the central, or target cell, is compared to the elevation of and distance to surrounding cells. The maximum slope determined in the window is assigned to the target cell. Options: MATRIX specifies window size (in number of cells per side). MAXIMUM specifies that the maximum slope calculated is to be assigned to the target cell. MASK 0 specifies if any cell in the window has an elevation of 0, the target cell will be assigned a slope of 0.

Command Line: **SLOPE** (old coverage) MAXIMUM MATRIX (#) MASK 0 FOR (new coverage)
Example: **SLOPE** *mtn*.BASE MAXIMUM MATRIX 3 MASK 0 FOR *mtn*.SLOPE

ZONE (buffer) - A raster distance analysis command in which a buffer or zone of user-specified distance is created around any geographic data identified in the coverage.

Command Line: **ZONE** (old coverage) TO (distance in meters) FOR (new coverage).
Example: **ZONE** *mtn*.WATPRIM TO 3200 FOR *mtn*.WATZONE

Appendix B

Coverage Names Used in GIS Analysis of Bighorn Habitat.

Data Base Preparation

mtn.DEM[9] - DEM that has been projected to UTM projection.

mtn.OPEN - areas with $\leq$25% canopy cover. (Note: *mtn*. OPEN has a value of 1 for all cells that are within areas where canopy cover is $\leq$25%.)

mtn.BASE - *mtn*.DEM intersected with *mtn*.OPEN.

mtn. SLOPE - initial slope coverage generated from *mtn*.BASE using neighborhood analysis.

Potential Suitability

mtn.PTH - Potential Total Habitat. Slopes $\geq$20% extracted from *mtn*.SLOPE.

mtn.PET - Potential Escape Terrain. Slopes $\geq$60% extracted from *mtn*.PTH.

mtn.PETCLP - *mtn*.PET after cells have been clumped into patches.

mtn.PETLOC - locations of center of escape terrain patches in *mtn*.PETCLP.

Low Elevation Habitat Only

mtn.PERWAT - All perennial water sources.

mtn.PETBUF - *mtn*.PET with a 200 m (220 yd) buffer around escape terrain.

mtn.PWATPRIM - Primary water sources, i.e. perennial water $\leq$200m (220 yds) from escape terrain. Created by intersecting *mtn*.PERWAT with *mtn*.PETBUF.

mtn.PWATPRIMB - *mtn*.PWATPRIM buffered to 3.2 km (2 mi).

mtn.PWATAVAIL - *mtn*.WATPRIMB intersected with *mtn*.PTH to determine how much total habitat is $\leq$3.2 km (2 mi) from primary water sources.

Alpine Habitat Only

mtn.SFS - snow-free slopes available as alpine winter range.

mtn.WINPTH - Potential Total Habitat available during winter. Created by intersecting *mtn*.SFS with *mtn*.PTH.

mtn.WINPET - Potential Escape Terrain available during winter. Created by intersecting *mtn*.SFS with *mtn*.PET.

mtn.WINPETCLP - *mtn*.WINPET after cells have been clumped into patches.

mtn.WINPETLOC - locations of centers of escape terrain patches in *mtn*.WINPETLOC.

Current Suitability

mtn.IMPACTS - all impacts with their appropriate buffers merged into one coverage. Data may be stored separately in the following coverages:

  mtn.PRC - coverage of areas in poor range condition

  mtn.MINES - mines with 500 m buffers.

  mtn.RD - coverage of improved and primitive roads with 200 and 500 m buffers, respectively.

  mtn.REC - recreation sites (picnic and campgrounds, scenic viewpoints, visitor centers) with 500 m buffers.

  mtn.TRL - hiking trails with 200 m buffers.

  mtn.MILZONE - area affected by military operations.

mtn.CTH - Current Total Habitat. Created by subtracting *mtn*.IMPACTS from *mtn*.PTH.

mtn.CET - Current Escape Terrain. Created by subtracting *mtn*.IMPACTS from *mtn*.PET.

---

[9] *mtn* - location to insert study area acronym, i.e., WP.PTH = Wheeler Peak Potential Total Habitat

mtn.CETCLP - *mtn*.CET after cells have been clumped into patches.
mtn.CETLOC - locations of centers of escape terrain patches in *mtn*.CETCLP.

Low-Elevation Habitat Only

mtn.CWATPRIM - Primary water sources not affected by human impacts. Created by intersecting *mtn*.PWATPRIM with *mtn*.CTH.
mtn.CETBUF - *mtn*.CET with a 200 m (220 yd) buffer around escape terrain.
mtn.CWATPRIMB - *mtn*.CWATPRIM buffered to 3.2 km (2 mi).
mtn.CWATAVAIL - *mtn*.CWATPRIMB intersected with *mtn*.CTH to determine how much total habitat is ≤3.2. km (2 mi) from primary water sources.

Alpine Habitat Only

mtn.WINCTH - Total Habitat available during winter that is not affected by human impacts. Created by intersecting *mtn*.WR with *mtn*.CTH.
mtn.WINCET - Escape Terrain available during winter that is not affected by human impacts. Created by intersecting *mtn*.WR with *mtn*.CET.
mtn.WINCETCLP - *mtn*.WINCET after cells of escape terrain have been clumped into patches.
mtn.WINCETLOC - locations of the centers of escape terrain patches in *mtn*.WINCETCLP.
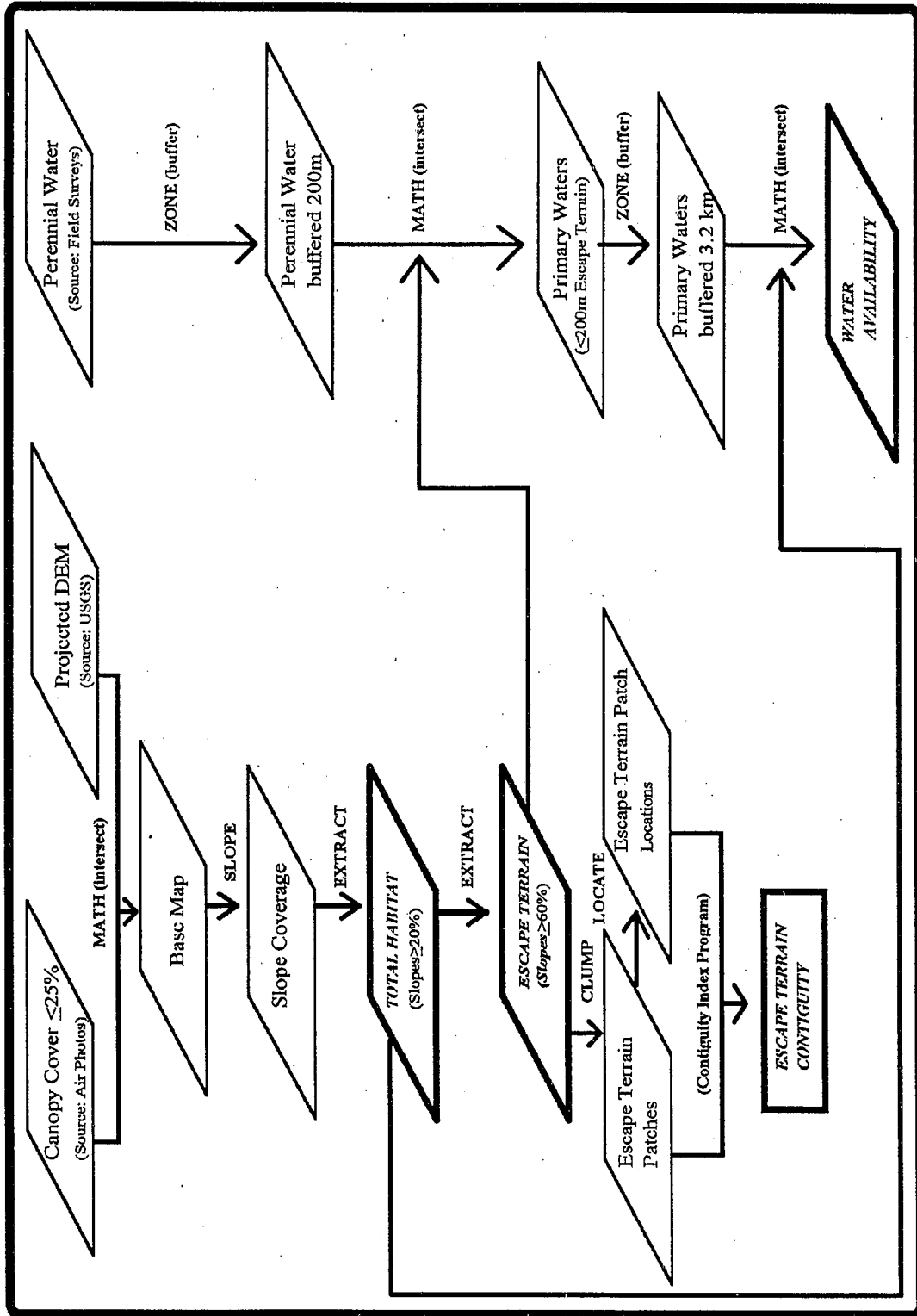
Appendix C
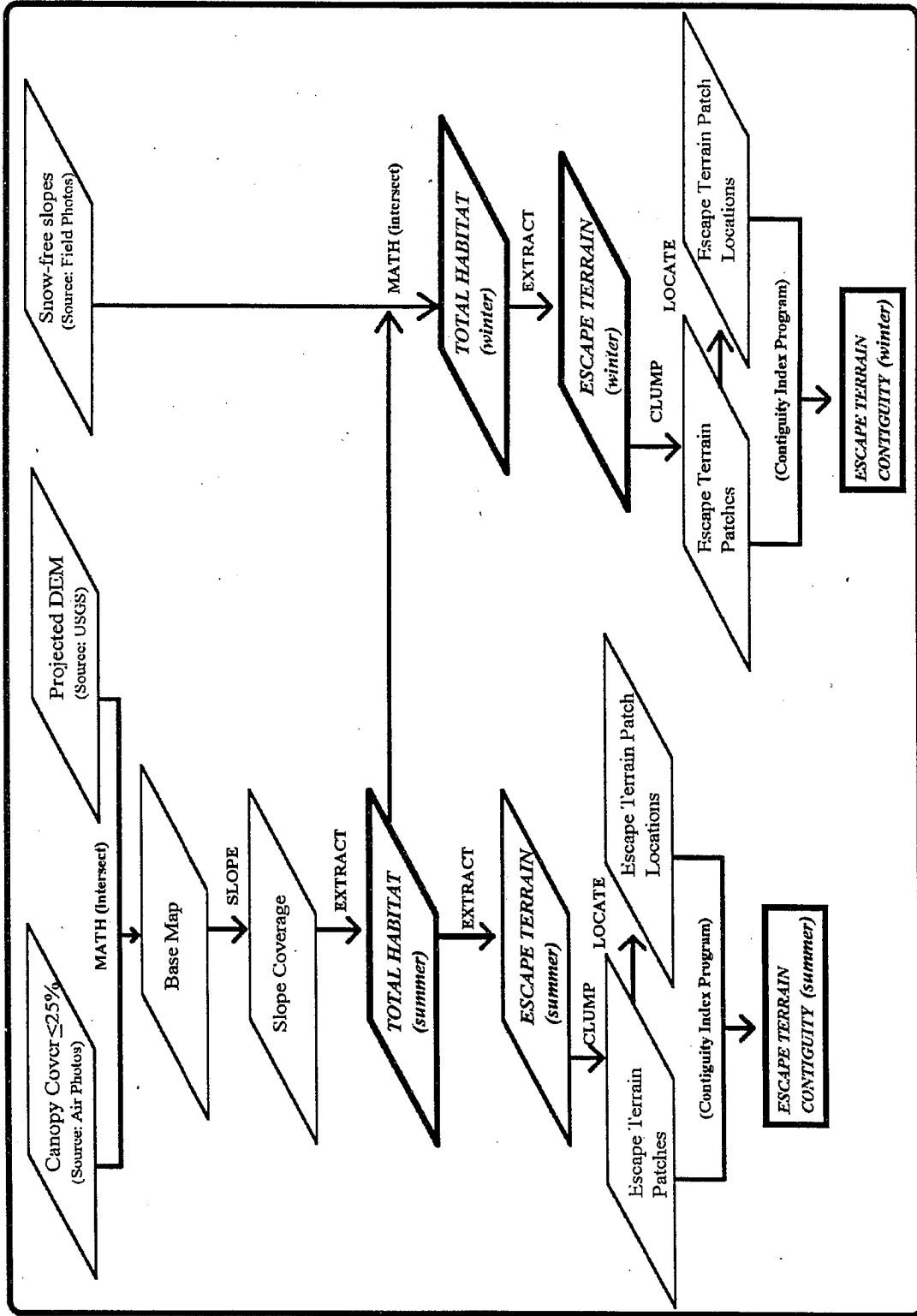
Appendix C. Flow diagram of the steps for measuring potential alpine bighorn sheep habitat. Coverages used in calculating potential suitability are in bold outlines. GIS commands are in bold print between coverages.
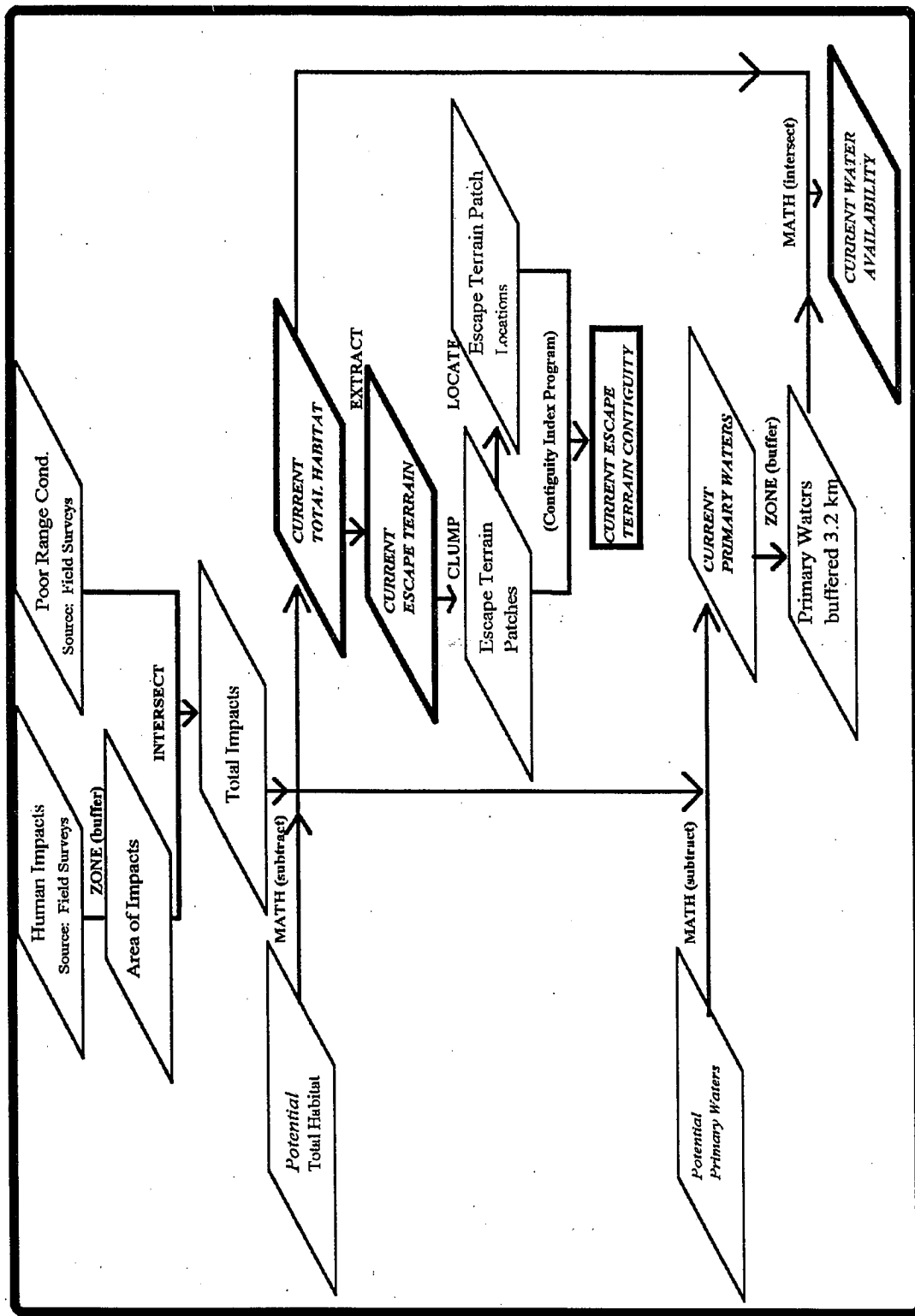
Appendix D
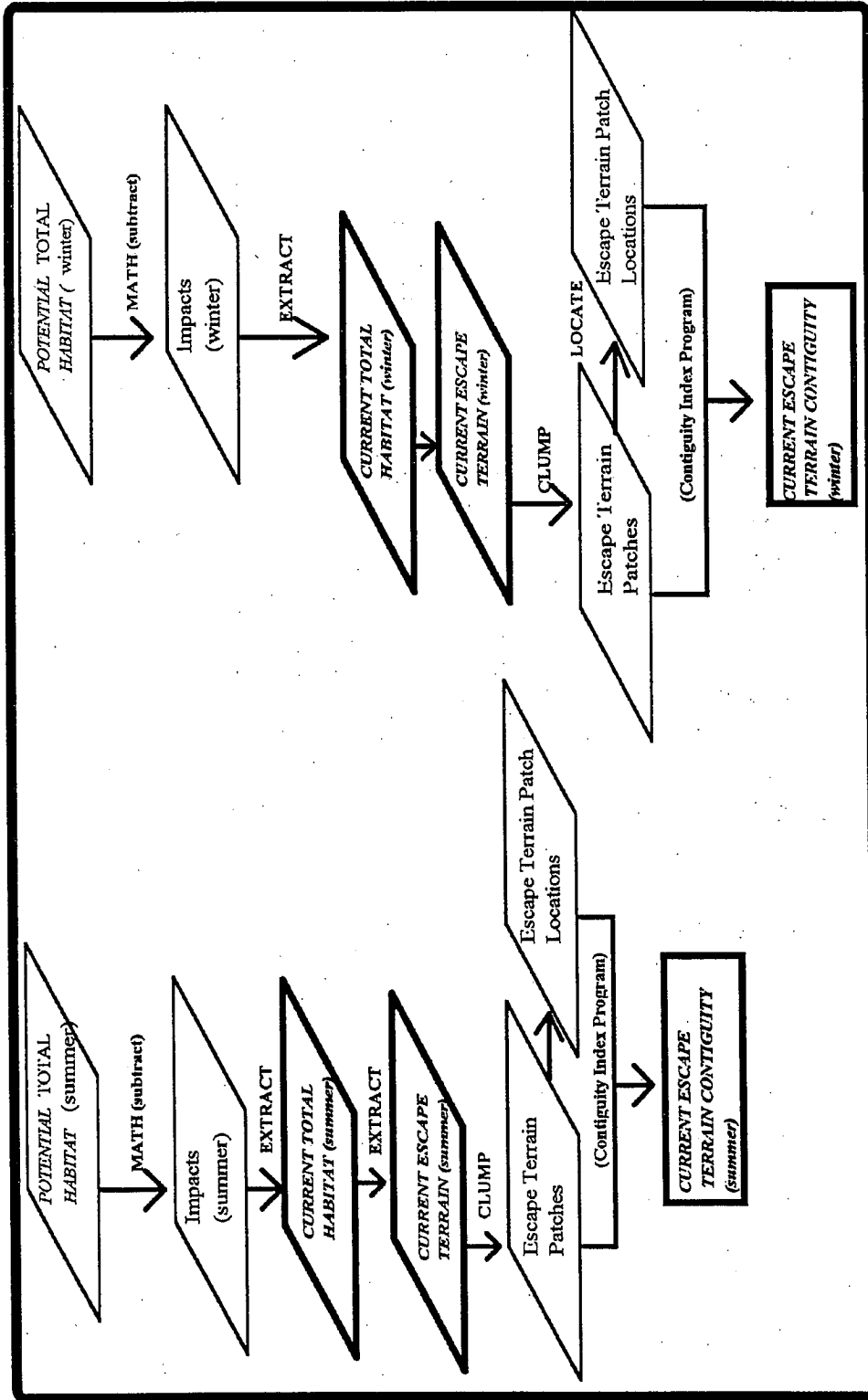
Appendix D. Flow diagram of the steps for measuring current alpine bighorn sheep habitat. Coverages used in calculating current suitability are in bold outlines. GIS commands are in bold print between coverages.

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Appendix E

Perennial Water (Source: Field Surveys) → ZONE (buffer) → **Perennial Water buffered 200m** → MATH (intersect)

Primary Waters (≤200m Escape Terrain) → ZONE (buffer) → **Primary Waters buffered 3.2 km** → MATH (intersect) → *WATER AVAILABILITY*

Projected DEM (Source: USGS)

Canopy Cover ≤25% (Source: Air Photos) → MATH (Intersect) → **Base Map** → SLOPE → **Slope Coverage** → EXTRACT → *TOTAL HABITAT* (Slopes≥20%) → EXTRACT → *ESCAPE TERRAIN* (Slopes ≥60%) → CLUMP → **Escape Terrain Patches** → LOCATE → **Escape Terrain Patch Locations** → (Contiguity Index Program) → *ESCAPE TERRAIN CONTIGUITY*

Appendix E. Flow diagram of the steps for measuring potential low-elevation bighorn sheep habitat. Coverages used in calculating potential suitability are in bold outlines. GIS commands are in bold print between coverages.

Appendix F

Appendix F. Flow diagram of the steps for measuring current low-elevation sheep habitat. Coverages used in calculating current suitability are in bold outlines. GIS commands are in bold print between coverages.

Appendix G

BASIC Program for Calculating Contiguity Indices

This program will calculate an escape terrain contiguity index from a file (see line 200) of northing ("Y") and easting ("X") UTM coordinates (both in meters) and sizes (also in meters) of escape terrain patches.

```
10 ' Program CONTIGUITY
20 ' By: Bruce T. Milne
30 ' University of New Mexico
40 ' Albuquerque, NM 87131
50 ' 4 Feb 93
60 ' (505)277-5356  bmilne@golondrinas.unm.edu
70 '
80 ' Modifications by: Gregory A. Baird
90 ' New Mexico Dept. of Game and Fish
100 ' Santa Fe, NM 87504
110 ' 20 May 93
120 ' (505)827-9927
130 '
140  DIM XY(110,3),T(110),D(110,2),N(108,2),G(108,2),S(108)
150 ' d(a,b)   d(a,1) = neighbor patch id number
160 '          d(a,2) = distance to neighbor from target
170 ' g()      x,y graphing coordinates of patches
180 '
190 FILES"*.dat
200 INPUT"Enter name of data file to read ",Z$
210 OPEN Z$ FOR INPUT AS#1
220 '
230 INPUT#1,X,Y,MASS
240    C=C+1     'count patches
250    XY(C,1)=X   'put x coordinate in array
260    XY(C,2)=Y   'put y coordinate in array
270    XY(C,3)=MASS   'put mass in array
280    IF EOF(1)=0 GOTO 230  'test for end of file
290 '
300    CLS:SCREEN 2
310 '
320    PRINT"There are ";C;" patches."
330    PRINT
340    PRINT "Enter the radius distance to be used "
350    INPUT "in forming the index (in meters): ",RADDIST
```

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```
360 '
370 FOR K = 1 TO C
380 '
390 ' get distances from target to all other sites
400 '
410   FOR I=1 TO C
420    D(I,1)=0:D(I,2)=0
430    D(I,1)=I
440    D(I,2)=((XY(K,1)-XY(I,1))^2 + (XY(K,2)-XY(I,2))^2)^.5
450       PSET(G(I,1),150-G(I,2))
460    NEXT I
470 '
480 'Sort the distances to find neighbors
490 GOSUB 770
500 '
510 ' distances have been sorted.  Now, use the RADDIST to find
520 ' neighbors within that radius.
530 '
540   DISTX=0:DISTY=0:AREAXY=0
550   NUSED=0  'counter of legal neighbors used so far
560   CC = 2   'pointer to closest patch in distance array
570 '
580     DISTX=XY(D(CC,1),1)
590     DISTY=XY(D(CC,1),2)
600     AREAXY=XY(D(CC,1),3)
610     R2=(XY(K,1)-DISTX)^2 + (XY(K,2)-DISTY)^2
620     DIST = SQR(R2)
630 '
640 IF DIST > RADDIST GOTO 720
650 '    Force between target and center of recipient.
660     FORCE = ((XY(K,3)) * AREAXY)/R2
670     CONTIND = CONTIND+FORCE
680        NUSED=NUSED+1
690        CC=CC+1
700       GOTO 570
710 '
720 NEXT K
730 CONTIND = CONTIND/C
740 PRINT"Average force = ",CONTIND
750 PRINT" for ";C;" patches with radius of ";RADDIST;" meters."
760 END
770 ' sort
780 '
790 FLAG=0
800 FOR I=1 TO C-1
```

```
810   IF D(I,2)>D(I+1,2) THEN
HOLD(1)=D(I+1,1):HOLD(2)=D(I+1,2):D(I+1,1)=D(I,1):D(I+1,2)=D(I,2)
:D(I,1)=HOLD(1):D(I,2)=HOLD(2):FLAG=1
820   NEXT I
830   IF FLAG=1 THEN GOTO 790
840 '
850 RETURN
-->
```

13. ABSTRACT (Maximum 200 words)

This technical note describes a method that incorporates a landscape approach with the use of Geographic Information Systems (GIS) to measure habitat and impacts for Rocky Mountain and desert bighorn sheep and to rank potential transplant sites. Potential suitability (the inherent capability to support bighorn sheep) and current suitability (the effect of impacts) is determined for each study area.