Quantifying Landscape Ruggedness for Animal Habitat Analysis: A Case Study Using Bighorn Sheep in the Mojave Desert

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ABSTRACT Terrain ruggedness is often an important variable in wildlife habitat models. Most methods used to quantify ruggedness are indices derived from measures of slope and, as a result, are strongly correlated with slope. Using a Geographic Information System, we developed a vector ruggedness measure (VRM) of terrain based on a geomorphological method for measuring vector dispersion that is less correlated with slope. We examined the relationship of VRM to slope and to 2 commonly used indices of ruggedness in 3 physiographically different mountain ranges within the Mojave Desert of the southwestern United States. We used VRM, slope, distance to water, and springtime bighorn sheep (*Ovis canadensis nelsoni*) adult female locations to model sheep habitat in the 3 ranges. Using logistic regression, we determined that the importance of ruggedness in habitat selection remained consistent across mountain ranges, whereas the relative importance of slope varied according to the characteristic physiography of each range. Our results indicate that the VRM quantifies local variation in terrain more independently of slope than other methods tested, and that VRM and slope distinguish 2 different components of bighorn sheep habitat.
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Rugged terrain has been variously defined as topographically uneven, broken, or rocky and steep. Measurement of terrain ruggedness is important for a number of scientific disciplines, and complex methods of quantifying surface characteristics have been evolving within fields such as geomorphology and wind engineering. For biologists and ecologists, however, methods to measure ruggedness in a less complex but biologically meaningful way have been more elusive.

Desert bighorn sheep (*Ovis canadensis nelsoni*) occupy mountain ranges in the American Southwest. One of the most important determinants of sheep habitat within these ranges is the presence of cliffs or steep, rocky slopes where sheep can outdistance or outmaneuver predators (Hanson 1980, Elenowitz 1984, Gionfriddo and Krausman 1986). Researchers have attempted to quantify this habitat component, termed escape terrain, using various measures of slope (Holl and Bleich 1983, Smith et al. 1991, Dunn 1996, Turner et al. 2004), indices of ruggedness (Ebert 1993, Bleich et al. 1997, Andrew et al. 1999, Divine et al. 2000), or a combination of both (McKinney et al. 2003). Although little consensus exists on how to measure escape terrain and no measure of terrain ruggedness has been widely accepted among biologists, a quantitative measure for escape terrain would provide an important tool for biologists to determine availability of existing habitat, locations of movement corridors, or suitability of potential translocation sites (McKinney et al. 2003).

The first widely recognized method for quantifying ruggedness among biologists was the land surface ruggedness index (LSRI) developed by Beasom et al. (1983). This index was based on the assumption that ruggedness is a function of total length of topographic contour lines in a given area (Fig. 1, left panel). The LSRI, or variations of it, has been used in a wide variety of habitat analyses (Cunningham 1989, Ebert 1993, Nellemann and Fry 1995, Bleich et al. 1997, and others). More recently, Riley et al. (1999) used digital terrain data and a Geographic Information System (GIS) to create a terrain ruggedness index (TRI), which quantifies the total elevation change across a given area (Fig. 1, middle panel). Unfortunately, neither of these indices directly measures the variability in topographic aspect and gradient, and both indices may be strongly correlated with slope. Therefore, these indices may not clearly distinguish steep, even terrain (high slope and low ruggedness) from steep terrain that is uneven and broken (high slope and high ruggedness).

An ideal measure of ruggedness should incorporate variability in both the aspect and gradient component of slope and should contribute to a multivariate representation of topography. Quantifying ruggedness independently of slope is important because bighorn sheep may perceive these characteristics differently when assessing escape terrain. In addition, the relative importance of slope and ruggedness to

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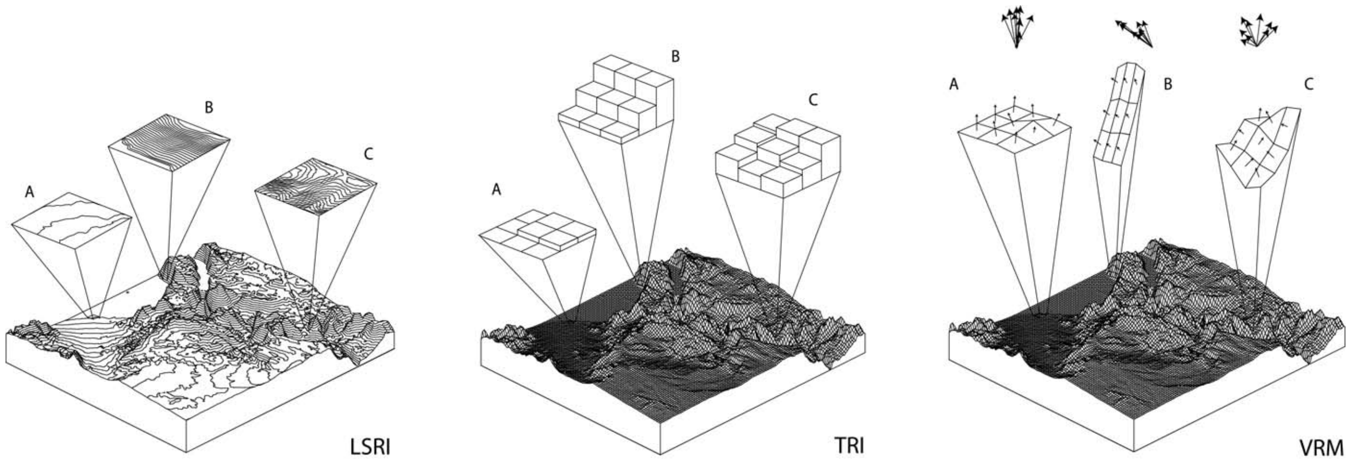

Figure 1. Graphical representation of the ability of each of 3 methods for computing terrain ruggedness to measure ruggedness independently of slope using terrain from the Eldorado Mountains in Nevada, USA. Land surface ruggedness index (LSRI; left panel) uses the density of contour lines within a given area as an index of terrain ruggedness. Index values are low in flatter areas (A), whereas index values are high in steep areas (B) and in steep, rugged areas (C). Terrain ruggedness index (TRI; middle panel) uses the sum of changes in elevation within an area as an index of terrain ruggedness. Similar to LSRI, TRI index values are low in flatter areas (A) but high in both steep areas (B) and in steep, rugged areas (C). Vector ruggedness measure (VRM; right panel) quantifies terrain ruggedness by measuring the dispersion of vectors orthogonal to the terrain surface. The VRM values are low both in flat areas (A) and in steep areas (B), but values are high in areas that are both steep and rugged (C).

a sheep's perception of escape terrain may vary as a function of the physiography of the mountain range. Based on a method developed for measuring surface roughness in geomorphology (Hobson 1972), we created a vector ruggedness measure (VRM) for use in a GIS that incorporates the heterogeneity of both slope and aspect. This measure of ruggedness uses 3-dimensional dispersion of vectors normal (orthogonal) to planar facets on a landscape (Fig. 1, right panel). By measuring vector dispersion in 3 dimensions, Hobson's technique, which combines variation in slope and aspect into a single measure, can give a better picture of heterogeneity of terrain than indices based only on slope or elevation. We tested the correlation between VRM, slope, and 2 ruggedness indices (LSRI and TRI) in 3 mountain ranges within the Mojave Desert of the southwestern United States. We then used VRM, slope, and springtime bighorn sheep adult female locations to model sheep habitat selection in these 3 ranges and examined the relative importance of slope and ruggedness in determining sheep habitat.

STUDY AREA

The Eldorado Mountains (35.95°N, 114.75°W) are located within Lake Mead National Recreation Area in southern Clark County, Nevada, USA. The range parallels the Colorado River for approximately 60 km, forming its western bank and covering nearly 930 km^2. A series of north–south running bluffs divide the range, with topography to the west of the bluffs consisting of wide, rolling hills and wide, gentle washes. On the eastern side, the bluffs end abruptly in an area of maze-like ridges and narrow, steep-sided washes that continue until the terrain drops off steeply to the banks of the Colorado River. Elevation ranges from 197 m along the Colorado River to 973 m at the highest point (Ebert 1993).

The Black Mountains (36.15°N, 116.69°W) form the southern half of the Armagosa Range in the southeastern part of Death Valley National Park in Inyo County, California, USA. The range extends approximately 70 km, tapers in width from 20 km at its southern end to 8 km at the northern end, and encompasses approximately 700 km^2. A wedge-shaped fault block that rose unevenly between 2 fault zones formed the mountain range. This resulted in a steep escarpment on the western side, with slopes averaging 89% that are dissected by washes and canyons. On the eastern side, the range slopes more gently into the alluvial-filled Greenwater Valley. Elevation ranges from −81 m at Badwater to 1,946 m at the top of Funeral Peak (Schramm 1982).

The Eagle Mountains (33.80°N, 115.60°W) are located along the southeastern border of Joshua Tree National Park in Riverside County, California, and encompass approximately 550 km^2. A large wash divides the range into northern and southern parts. Elevation ranges from 350 m in the northern portion of the range to 1,631 m at Eagle Peak in the south. Along the northern edge, steep ridges give way to rolling hills. Steep, rocky escarpments characterize the southern part. An abandoned iron ore open-pit mine was located in the northern part of the range (Divine 1998).

METHODS

GIS Base Data

We performed GIS analyses using ArcView 3.2 and ArcView Spatial Analyst 1.1. We derived topographic information from 30-m digital elevation models (United States Geological Survey 1993) and created a boundary for each range using 1:500,000 scale geologic data (Mojave Desert Ecosystem Program 1998) to delineate mountainous terrain, characterized by intrusive and metamorphic rock, from alluvial or depositional formations that form the

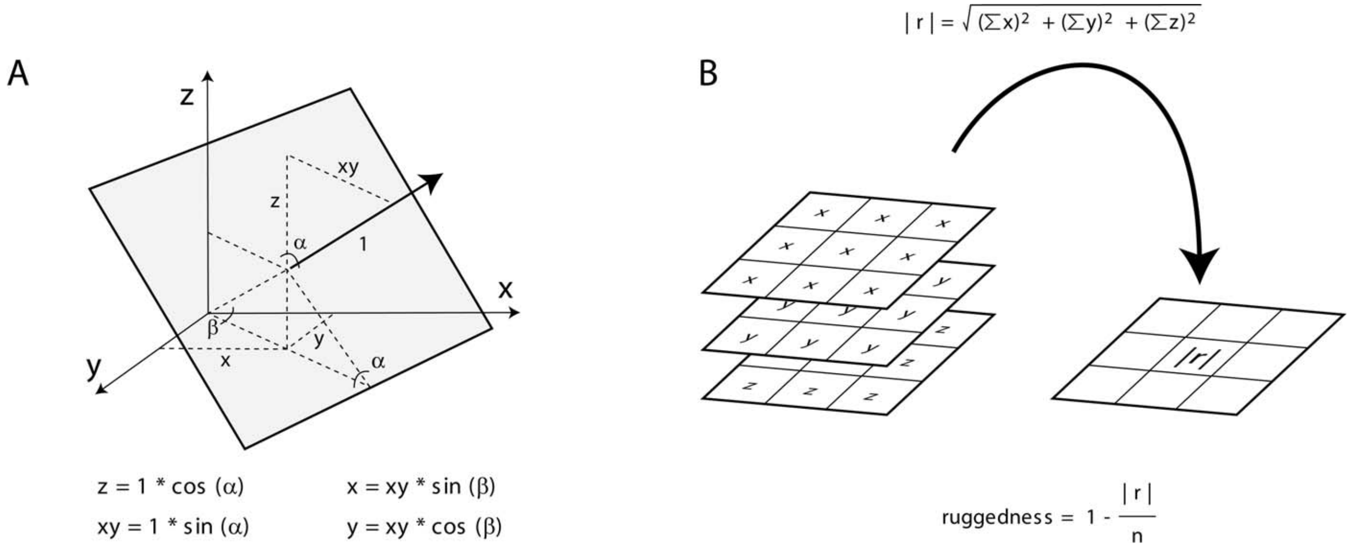

Figure 2. Calculation of vector ruggedness measure within a geographic information system using vector analysis and a raster-based digital elevation model (DEM). (A) Unit vectors orthogonal to each grid cell in the DEM are decomposed into their *x*, *y*, and *z* components using standard trigonometric operators and the slope (α) and aspect (β) of the cell. (B) We used a moving-window routine to calculate the magnitude of a resultant vector ($|\mathbf{r}|$) for a given neighborhood size centered on each grid cell. The magnitude of the resultant vector in standardized form (vector strength divided by the no. of cells in the neighborhood) is a measure of the ruggedness of the landscape for the selected scale. Subtracting this magnitude in standardized form from 1 results in a dimensionless ruggedness number that ranges from 0 (flat) to 1 (most rugged).

valleys. We generated slope, aspect, and contour (12.1-m [40-ft] intervals) layers within the boundaries of each range from elevation data using standard ArcView functions.

Quantifying Landscape Ruggedness

We created a layer of VRM values using an ArcView script to calculate the 3-dimensional dispersion of vectors normal to grid cells composing each landscape (script available online from the Environmental Systems Research Institute ArcScripts website: <www.esri.com/arcscripts>). We decomposed unit vectors normal (orthogonal) to each grid cell into their *x*, *y*, and *z* components using standard trigonometric operators and the slope and aspect of the cell (Pincus 1956, Durrant 1996; Fig. 2). We then calculated a resultant vector over a 3 × 3 neighborhood (approx. 8,100 m^2) centered on each cell, using a moving-window routine. The magnitude of the resultant vector in standardized form (vector strength divided by the number of cells in the neighborhood) is a measure of the ruggedness of the landscape for the selected scale (Hobson 1972). Subtracting this magnitude in standardized form from 1 results in a dimensionless ruggedness number that ranges from 0 (flat) to 1 (most rugged). Although VRM values can be computed using larger neighborhood sizes to measure ruggedness across larger landscape scales, we used a 3 × 3 neighborhood for our analysis to provide a measure of ruggedness over a geographic area comparable to that used for the 2 ruggedness indices. Also, we found that computing VRM with larger neighborhoods caused a smoothing effect on the landscape. We believed that by using the 3 × 3 neighborhood, we were able to capture the complexity of the landscape at a biologically meaningful scale for bighorn sheep.

We calculated a layer of TRI values within a 3 × 3 neighborhood using an ArcView script and the elevation base layer for each range. Using the map algebra methods detailed in Riley et al. (1999), we computed TRI as the sum of the absolute values of the elevation differences between a central grid cell and its 8 neighboring cells. To obtain point measurements of terrain parameters, we generated random points within the boundary of each mountain range at a density of one point per square kilometer. Using nearest neighbor analysis (Hooge and Eichenlaub 1997), we tested each set of random points for complete spatial randomness, and points were randomly distributed (Black Mountains: $n = 691$, $|z| = 1.54$, $R = 1.03$; Eagle Mountains: $n = 515$, $|z| = 0.801$, $R = 1.02$; Eldorado Mountains: $n = 111$, $|z| = 1.71$, $R = 1.09$). We measured values of slope, TRI, and VRM for random points in each range by assigning to each point the value of the underlying grid cell of the respective data layer. We calculated LSRI for each point using an ArcView script to measure the total length of contour lines within a 90 × 90-m box centered on each random point.

We used Spearman rank correlations to determine relationships between point measurements of slope, LSRI, TRI, and VRM in each of the ranges. To examine their distributions within each range, we generated histograms of slope and VRM and calculated descriptive statistics ($\bar{x}$, SD, skewness, and kurtosis) to characterize the distributions. We performed statistical analyses using SPSS 9.0 (SPSS Inc., Chicago, IL).

Ruggedness and Sheep Habitat

To examine the relative importance of slope and ruggedness in determining bighorn sheep habitat, we used logistic regression with sheep-location data and random points to model relative probabilities of habitat use by sheep as a function of environmental variables in each of the 3 ranges.

We used sheep-location data from previous studies carried out in the Eldorado Mountains (Ebert 1993), Black Mountains (Longshore and Douglas 1995), and Eagle Mountains (Divine 1998). The Animal Care and Use Committee, University of Nevada, Las Vegas, approved animal-use protocols for each of these studies. Although many of the sheep could not be visually located during aerial telemetry flights in these 3 studies, Ebert (1993) determined that the error resulting from nonvisual aerial telemetry locations in the Eldorado Mountains averaged 67.5 m ($n = 4$, SD = 29). Aerial telemetry flights were conducted $\geq$24 hours apart in each of the studies to allow independence of the observations (Ebert 1993).

To maximize our ability to discriminate between habitat choices of slope and ruggedness and to reduce the potential number of variables that might influence habitat choice, we focused our analysis on only a selected part of these data sets. Although both adult males and adult females were captured and radiotracked in each of these studies, we used only adult female locations for our analysis because bighorn females more consistently use steeper, more rugged terrain than males (Bleich et al. 1997). Data analysis was also confined to springtime locations (Jan through May) to reduce the influence of water availability during hotter months on habitat choice (Ebert 1993). However, we still included distance to available water as a variable in our analysis because of its importance to sheep. Water sources for sheep within each range were identified during the original studies (Ebert 1993, Longshore and Douglas 1995, Divine 1998). These water sources included perennial spring locations within each of the 3 ranges and the Colorado River within the Eldorado Mountains. Springs were visited during each of the original studies to ensure water availability for sheep, and sheep were frequently seen drinking along the shores of the Colorado River. We created data on distance to water in the GIS using standard ArcView functions and water source location information within each range.

For our analysis, we also pooled locations among individuals in each mountain range. Desert bighorn sheep adult female groups, unlike demes of adult females, are not stable entities through time and group structure tends to be ephemeral. Additionally, these groups are often not closely spatially associated since individuals moving across mountainous terrain may only be in visual contact. A visual inspection of the data points showed little daily association of sheep locations in each range.

We used 771 relocations from 19 adult females in the Eldorado Mountains, 412 relocations from 22 adult females in Eagle Mountains, and 159 relocations from 8 adult females in the Black Mountains. We generated random points, each set equal in number to the number of adult female locations, within the boundary of each mountain range and tested for complete spatial randomness (Black Mountains: $n = 159$, $|z| = -0.15$, $R = 0.99$; Eagle Mountains: $n = 412$, $|z| = -1.60$, $R = 0.96$; Eldorado Mountains: $n = 771$, $|z| = 1.44$, $R = 1.03$). We measured ruggedness, slope, and distance to water for random and adult female location points by assigning the value of the underlying grid cell of the respective data layer to each point.

We created binary logistic regression models following Manly et al. (1993), using sheep locations (used habitat) and an equal number of random points (available habitat) within each range. Using "design I" and "sampling protocol A" (Manley et al. 1993:125–136), the resulting resource selection functions model the relative probability of habitat use as a function of environmental and topographical variables. We tested the fit of each logistic regression model with goodness-of-fit tests of deviance. We tested the variation in adult female occurrence explained by each habitat variable by comparing the model fit with and without the variable (χ^2 test of difference in model deviance), and we computed odds ratio estimates for all variables in the model. The odds ratio is comparable to a partial regression coefficient and can be interpreted as the amount of change in the likelihood of observing an adult female given a 1-standard-deviation–unit change in the independent variable. An odds ratio estimate of 1 indicates no change in the likelihood of observing an adult female, and an estimate $<$1 indicates the likelihood decreases with respect to the standardized habitat variable. We performed statistical analyses using SAS 8.02 (SAS Institute Inc., Cary, NC).

RESULTS

Quantifying Landscape Ruggedness

We examined the correlation of slope with VRM and the 2 ruggedness indices to determine their independence from measures of slope (Fig. 3). Point measurements of LSRI and TRI were highly correlated with slope in all 3 mountain ranges ($r_s > 0.9$; $P < 0.001$ for all ranges). In contrast, the correlation between VRM and slope was much lower in the Eldorado Mountains ($r_s = 0.713$; $P < 0.001$), and was even less in the Eagle Mountains ($r_s = 0.418$; $P < 0.001$) and the Black Mountains ($r_s = 0.312$; $P < 0.001$). In addition to being intercorrelated with slope, LSRI and TRI were apparently linked to slope such that low values for these indices were not possible when slope was high (Fig. 3).

Differences in the distributions of ruggedness, measured by VRM, and slope reflected the characteristic physiography of each mountain range in our study (Fig. 4). Although values for VRM can range between 0 (flat) and 1 (most rugged), values on natural terrains were rarely $>$0.2. Experimenting with artificial terrains and different neighborhood sizes, we were able to generate values $>$0.8. Ruggedness was highest in the Black Mountains ($\bar{x} = 0.0112$, SD = 0.0166), followed by the Eagle Mountains ($\bar{x} = 0.0108$, SD = 0.0136) and the Eldorado Mountains ($\bar{x} = 0.0077$, SD = 0.0108). The distributions of ruggedness values (VRM) for all 3 mountain ranges were highly skewed to the right with the highest proportion of VRM values at the mean ($\bar{x} = 0.01$, for each mountain range) and a wide distribution of VRM values $>$0.01 (Fig. 4). Although there were differences in the skew and kurtosis of ruggedness among mountain ranges, these differences were small and

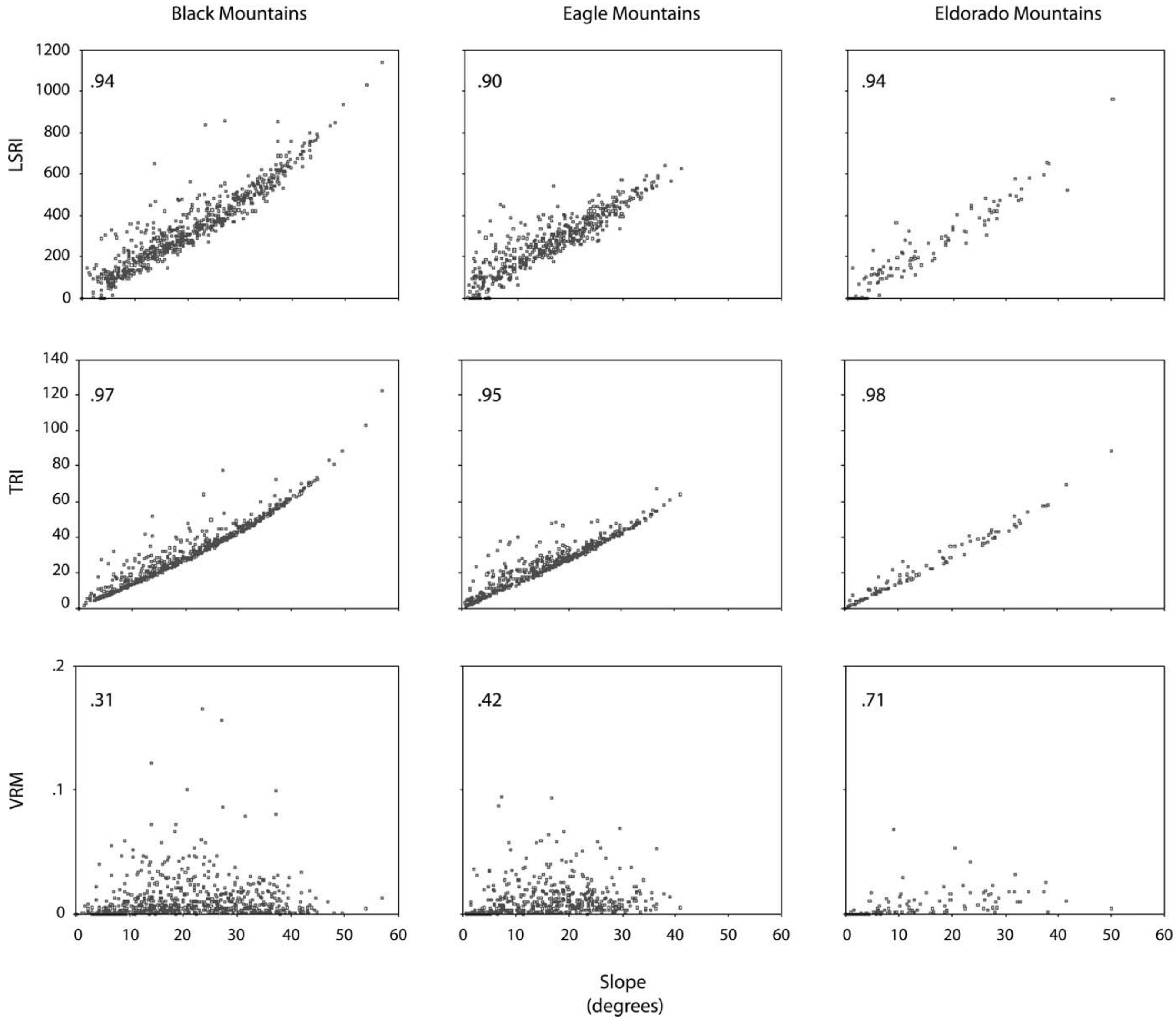

Figure 3. Spearman nonparametric correlation coefficients among random point measurements of slope, land surface ruggedness index (LSRI), terrain ruggedness index (TRI), and vector ruggedness measure (VRM) within the Eldorado Mountains in southern Nevada, Eagle Mountains in southern California, and Black Mountains in eastern California, USA. Sample sizes were proportional to the area of each range (1 point/km^2). All correlations were significant at the 0.01 level.

the distribution of ruggedness among ranges was remarkably consistent.

The major differences in physiography among mountain ranges were illustrated by differences in the mean and distribution of slope values (Fig. 4). The Black Mountains, formed by uplift along a thrust fault, had the highest mean slope ($\bar{x} = 20.1$, SD = 11.0). The steepness of the western slope was reflected by a high proportion of random points with slope values at or above 40 degrees (Fig. 4). The Eldorado Mountains, a series of rolling hills and steep rocky escarpments overlooking the Colorado River, are characterized by a large proportion of slope values at or below 10 degrees, as well as the most extreme slope values of the mountain ranges in our study. The Eagle Mountains, a series of rolling hills with steep ridges, had a more even distribution of points with low to moderate slope values (10–30 degrees) than the other mountain ranges. Despite differences in the distribution of slope values, the mean slope of the Eagle Mountains ($\bar{x} = 15.9$, SD = 9.4) was similar to that of the Eldorado Mountains ($\bar{x} = 14.4$, SD = 11.3).

Ruggedness and Sheep Habitat

In the logistic regression models, distance to water and VRM were significant predictors of adult female location in all 3 mountain ranges (Table 1). In addition, slope was a significant predictor of adult female location in the Eagle and Black Mountains, but it was not significant in the Eldorado Mountains ($P = 0.07$).

The relative importance of distance to water, ruggedness,

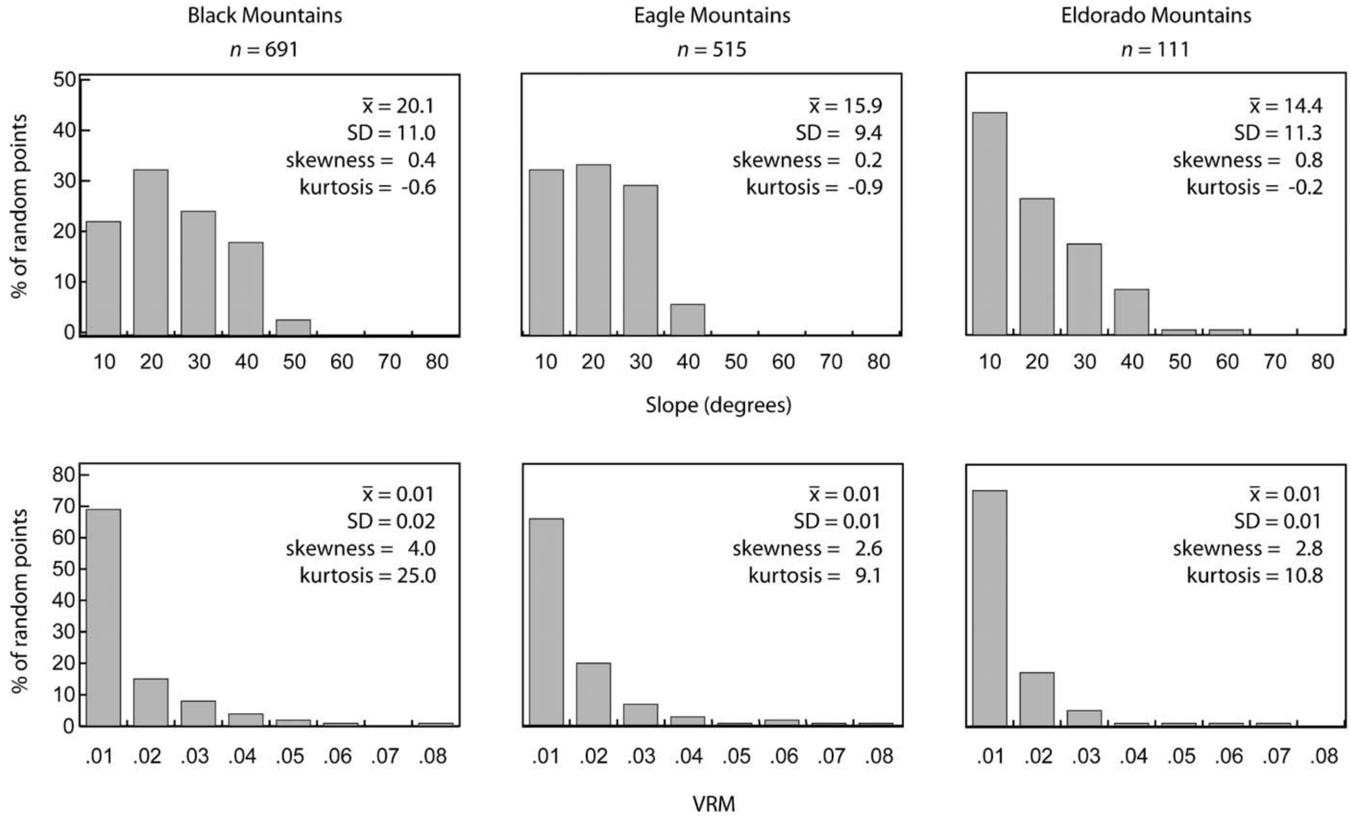

Figure 4. Distributions of slope (upper panels) and ruggedness (lower panels) within the Black Mountains in eastern California, Eagle Mountains in southern California, and Eldorado Mountains in southern Nevada, USA. We took point measurements of slope and ruggedness at a density of 1 point/km^2 in each range and calculated descriptive statistics ($\bar{x}$, SD, skewness, and kurtosis) for each distribution.

and slope in explaining variance in adult female locations differed among mountain ranges. In the Black Mountains, slope was the greatest predictor of adult female locations, followed by distance to water and ruggedness. The likelihood of observing an adult female increased 2.9-fold, with an increase of 1-standard-deviation unit of slope. In the Eagle Mountains, distance to water was the greatest predictor of adult female locations; slope and ruggedness contributed equally. The likelihood of observing an adult female increased 1.7-fold, with an increase of 1-standard-deviation unit of both slope and ruggedness. In the Eldorado Mountains, distance to water was the greatest predictor of adult female locations, followed by ruggedness. Slope was not significant. Despite differences among mountain ranges in the habitat variables selected by adult females, all of the regression models correctly classified 82–89% of actual locations.

Table 1. Maximum likelihood estimate (MLE), partial odds ratios, 95% confidence intervals, and *P*-values derived from Wald's statistics for habitat variables used in logistic regression models of desert bighorn adult female habitat use. Data were from studies conducted in the Black Mountains, California (1995), Eagle Mountains, California (1998), and Eldorado Mountains, Nevada (1993), USA.

Variable	MLE	Odds ratio	Wald 95% CI	*P*
Black Mountains				
Ruggedness	0.48	1.62	1.18–2.21	0.003
Slope	1.05	2.88	2.12–3.92	≤0.001
Distance to water	−0.55	0.58	0.42–0.79	0.001
Eagle Mountains				
Ruggedness	0.56	1.75	1.42–2.15	≤0.001
Slope	0.56	1.76	1.43–2.12	≤0.001
Distance to water	−1.52	0.22	0.17–0.28	≤0.001
Eldorado Mountains				
Ruggedness	0.33	1.39	0.29–0.41	≤0.001
Slope	0.11	1.12	1.22–1.59	0.07
Distance to water	−1.06	0.35	0.99–1.27	≤0.001

DISCUSSION

Our results showed that VRM directly measured heterogeneity of terrain more independently of slope than did either TRI or LSRI. Both TRI and LSRI showed very strong positive correlations with slope across 3 physiographically different mountain ranges, and both indices exhibited a pattern of bias in that the minimum value of ruggedness increased with increasing slope (Fig. 3). Conversely, VRM was much less correlated with slope in all 3 ranges, and patterns of correlation differed among the ranges. These results indicated that neither TRI nor LSRI quantified terrain any differently than simple measures of slope and that VRM measured a different component of terrain than slope. By decoupling ruggedness from slope, VRM allows for the treatment of these terrain components as separate variables when quantifying landscapes for habitat analysis and avoids problems of multicollinearity in regression models.

Unlike the 2 ruggedness indices, VRM differentiated smooth, steep hillsides from irregular terrain that varied in gradient and aspect. This distinction was most evident along an escarpment formed by uplift along a thrust fault on the western side of the Black Mountains. At the scale of our data, random points on the escarpment exhibited very low values of VRM but revealed high values for slope and high values for LSRI and TRI (data not shown). Because VRM measures the variation in terrain independent of its overall gradient, VRM is able to differentiate among terrain types. Another recent method proposed to quantify ruggedness, the ratio of 3-dimensional surface area to planar surface area (Jenness 2004), likely suffers from the same inability to distinguish among these different types of terrain.

Our results indicated that perception of escape terrain by bighorn adult females appeared to incorporate both ruggedness and slope, but the relative importance of the 2 variables seemed to shift in response to the availability of steep slopes. During spring, when escape terrain is important for adult females with lambs (Hanson 1980, Bleich et al. 1997, Bangs et al. 2005*b*), adult females consistently selected for rugged terrain in all 3 mountain ranges. In contrast, the importance of slope in habitat models varied among mountain ranges. In the Black Mountains, which had the greatest availability of steep slopes (Fig. 4), slope was the most important factor in habitat selection. Conversely, in the Eldorado Mountains, which had the lowest availability of steep slopes, slope was not a significant factor in habitat selection. Both slope and ruggedness were equally important in the Eagle Mountains, which had a more even distribution of slope values than the other 2 ranges.

Other recent studies of bighorn adult females have incorporated our VRM measure (Bangs et al. 2005*a*, *b*). These studies have shown both slope and ruggedness to be important factors in seasonal habitat selection and in habitat shifts during parturition. In the Fra Cristobal Mountains in southern New Mexico, USA, bighorn adult females selected habitat with higher slope and greater ruggedness in the spring, but with only higher slope in the autumn (Bangs et al. 2005*a*). Parturition sites were more rugged than preparturition sites, possibly indicating selection of areas where predators would be less likely to detect newborn lambs. Postparturition sites were both steeper and more rugged than preparturition sites, suggesting that adult females selected escape terrain offering maturing lambs the greatest ability to evade predators (Bangs et al. 2005*b*).

Ruggedness and slope appear to distinguish 2 different, but biologically meaningful, components of bighorn sheep escape terrain. Although past studies of bighorn sheep habitat have used discrete components to define escape terrain (e.g., slopes >60%), our results suggest that both slope and ruggedness should be treated as dynamic components, the importance of each based on the physiography of each specific mountain range.

MANAGEMENT IMPLICATIONS

The VRM provides a quantitative measure of terrain ruggedness that managers can use for habitat analyses where topography affects the distribution of vegetation or wildlife. For bighorn sheep, managers should use VRM in conjunction with measures of slope to provide more quantitative and accurate habitat assessments when determining patch size and configuration of escape terrain and thus prevent problems with collinearity that may result in an underestimation of available terrain. Because patch size and configuration of escape terrain may be major correlates of population size (McKinney et al. 2003), this information could enhance the success of habitat management plans and reintroduction programs. Based on our results, quantitative analysis of terrain ruggedness appears to be important in understanding behavior and distribution of bighorn sheep. Additional research is needed to further explore the perception of escape terrain as an integration of ruggedness and slope across different landscapes and at different scales.

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