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Erratum

The DOCELL code as seen in the manuscript squares the final sum rather than taking the square root. This was an error.

Here's the corrected code (below), as it should appear in the manuscript.

```
DOCELL

tri = sqrt((sqr(ell1(0,0) - ell1(-1,-1))) + (sqr(ell1(0,0) - ell1(0,-1))) +
(sqr(ell1(0,0) - ell1(1,-1))) + (sqr(ell1(0,0) - ell1(1,0))) + (sqr(ell1(0,0) -
ell1(1,1))) + (sqr(ell1(0,0) - ell1(0,1))) + (sqr(ell1(0,0) - ell1(-1,1))) +
(sqr(ell1(0,0) - ell1(-1,0))))

end
```

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Abstract

Terrain is an important feature of the structural niche occupied by terrestrial species. However, most researchers refer to terrain only in qualitative terms that precludes testing hypotheses about the actual importance of terrain. We present an easily calculated terrain ruggedness index (TRI) that provides an objective quantitative measure of topographic heterogeneity. Our model computes TRI values for each grid cell of a digital elevation model using a "DOCELL" command in an Arc/Info geographical information system that calculates the sum change in elevation between a grid cell and its eight neighbor grid cells. The concept and algorithm we present can be used at any scale relevant to the species of concern and question being asked for which elevation data exist.

Key Words: Habitat, terrain, ruggedness, geographical information systems, Montana

Terrain heterogeneity is an important variable for predicting which habitats are used by species and the density at which species occur across a variety of environments (Koehler and Hornocker 1989, Fabricius and Coetzee 1992), and is often an important component of a species' niche (Whittaker *et al.* 1973). Terrain functions as concealment cover for prey (Riley and Dood 1984, Canon and Bryant 1997), stalking cover for predators (Kruuk 1986), and affects the form and function of species (Geist and Bayer 1988). Terrain also affects the behavior of some species to disturbance from humans (Edge and Marcum 1991). Yet, most researchers describe terrain only in qualitative terms such as undulating, broken, rugged, or dissected. Estimates of terrain heterogeneity have been mostly calculated using labor-intensive techniques or techniques designed for specific areas (Beasom *et al.* 1983, Fabricius and Coetzee 1992, Nellemann and Fry 1995). An easy-to-use, quantitative measure of terrain heterogeneity is needed to test hypotheses regarding terrain as a component of habitat and provide for more informative comparisons between areas.

Beasom *et al.* (1983) presented a technique for assessing land surface ruggedness that was based on the intersection of contour lines on US Geological Survey (USGS) topographic maps and dots from a clear transparency. The technique is useful, but laborious if the area of concern is large. Technological advances in personal computers, the Internet, and software to analyze spatial data have provided easier access to geographical databases and permitted many new uses of spatial data (Koeln *et al.* 1996). As

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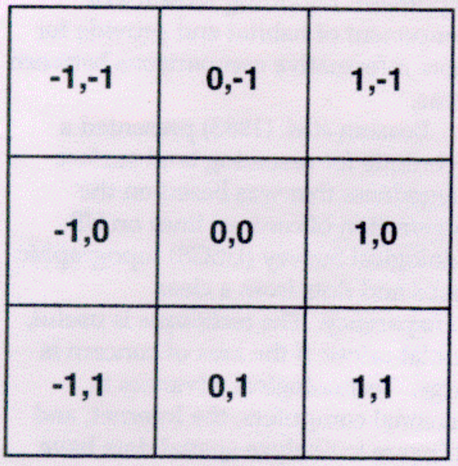
part of a study on the effect of terrain on abundance of mountain lions *(Puma concolor)* (Riley 1998:12-34), we developed a terrain ruggedness index (TRI) that is derived from USGS digital elevation models (DEM) using a terrain analysis function implemented in a geographical information system (GIS). This TRI provides a rapid, objective measure of terrain heterogeneity.

Our model computes TRI values for each grid cell of a DEM using a "DOCELL" command in Arc/Info that calculates the sum change in elevation between a grid cell and its eight neighbor grid cells (Fig. 1). We used a square grid network with 1 km^2 grid cells (Collins and Moon 1981). Grid cell-level TRI values were then averaged across any given area such as a county or hunting district for a total TRI. The TRI values also can be displayed in the form of maps that clearly reveal the distribution of terrain heterogeneity (Fig. 2). In our example, we used an "equal area" classification method to group continuous ranges of TRI values into seven classes of unequal range, but equal area. The range in TRI values for each grouping are as follows: level = 0 - 80 m; nearly level = 81-116 m; slightly rugged = 117 - 161 m; intermediately rugged = 162 - 239 m; moderately rugged = 240 - 497 m; highly rugged = 498 -958 m, and; extremely rugged = 959 - 4367 m. The classification scheme can be easy changed in Arc/Info to meet the particular needs of the map.

Several examples may help clarify the calculations used in our TRI model (Fig. 3). Figure 3a is a simulated peak with an elevation in the center grid cell much greater than in surrounding grid cells. The bowl or pit terrain depicted in Figure 3b is an inverse of Figure 3a and has an equal TRI value. The two types of terrain are viewed equally rugged by the model. A more gentle, undulating landscape is depicted in Figure 3c where the range in elevation is only 25 units and no grid cell has a greatly different elevation than the center.

Digital elevation data are now readily available on the Internet from a variety of sources. We obtained our data electronically from USGS databases (http://www.nmd.usgs.gov/www/products/1product.html). Digital elevation models depict elevations across a specified landscape and may be discrete measurements of elevation or a mean value for a specified portion of the



If each square represents a grid cell on a digital elevation model, then
TRI = Y [$\Sigma(x_{ij} - x_{00})^2$ $]^{1/2}$ where x_{ij} = elevation of each neighbor cell to cell (0,0).

The docell command is:

DOCELL ssdiff = ((sqr(el(0,0) - el(-1,-1))) + (sqr(el(0,0) - el(0,-1))) + ... (sqr(el(0,0) - el(1,1))).

TRI = sqr(ssdiff)

end

Where: ssdiff = temprorary scalar, square feet, and el = name of elevation grid.

Figure 1. *A terrain ruggedness model that uses digital elevation model data and an Arc/Info geographical information system.*

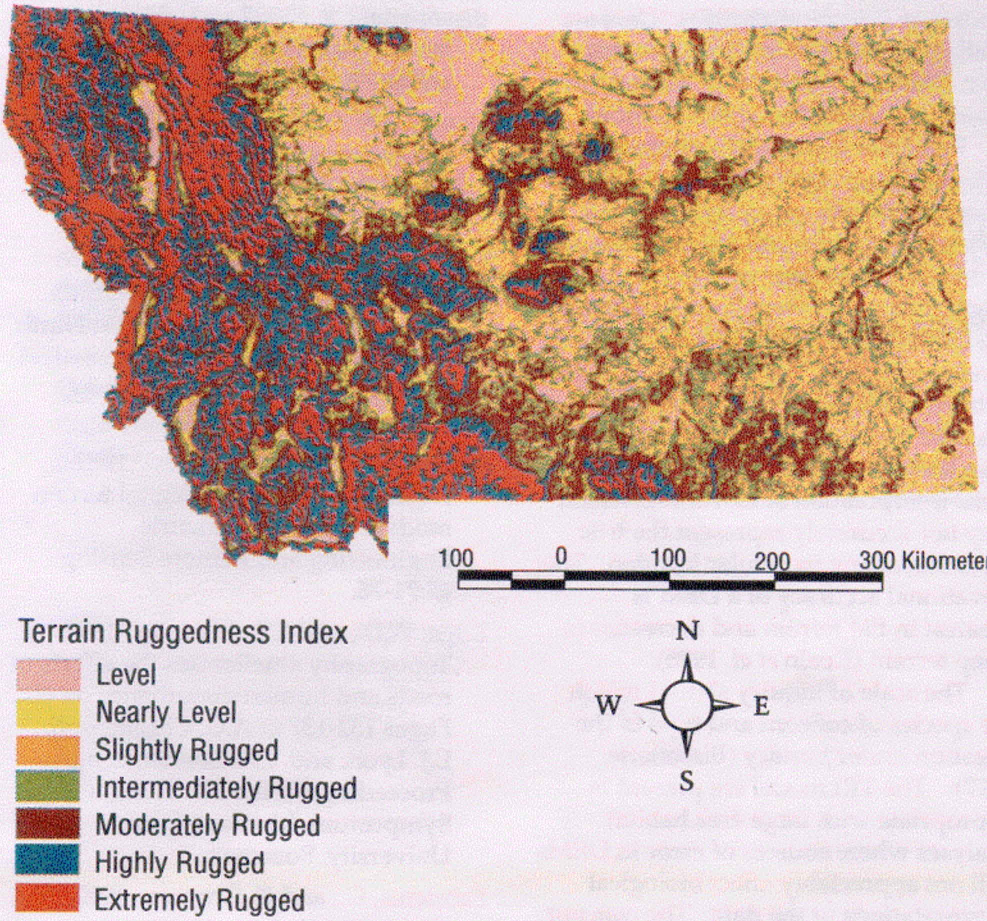


Figure 2. *A terrain ruggedness map for the state of Montana.*

(a)

100	125	100
125	200	125
100	125	100

TRI = 700

(b)

200	175	200
175	100	175
200	175	200

TRI = 700

(c)

200	210	220
210	225	225
205	210	220

TRI = 100

Figure 3. *Hypothetical square grid digital elevation data from a) a peak type topography, b) a pit type topography, and c) a gentle undulating topography and respective terrain ruggedness index (TRI) values.*

landscape (Moore *et al.* 1991). Data are available for the entire United States from USGS 3 arc-second (1° latitude by 1° longitude) DEM of North America.

Researchers must be aware of potential biases that originate in DEMs when TRI values are interpreted. All DEMs contain inherent inaccuracies due to underlying sources of error in original data that were used to generate the DEM (Carter 1989). Whereas a DEM is referenced to a "true" elevation from published maps, there is no way to evaluate the accuracy of the original map data. In addition, most DEMs have some interpolation of elevations which may not accurately represent the true elevation at any particular location. The elevational accuracy of a DEM is greatest in flat terrain and decreases in steep terrain (Koeln *et al.* 1996).

The scale of inquiry should match the species of concern and type of the question under inquiry (Bissonette 1997). The TRI model we present is appropriate with large area habitat analyses where sources of error in DEMs will not appreciably affect biological interpretations of the data. The concept and algorithm we present could be used for smaller areas with higher quality data or corrected DEMs.

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