Geomorphometric and Gradient Metrics Toolbox

INTRODUCTION

Analysis of landscape pattern and process are moving towards a continuum or gradient approach (Cushman et al., 2010). Additionally, we are seeing more and more utilization of metrics, representing steady state landform process (Pike et al., 2009), in modeling efforts describing species distribution, abundance and multiscale process. Aside from programs like FRAGSTATS, intended to describe discrete process, there are few applications that provide access to geomorphometric indices or gradient models to assist in this type of modeling. To this end, we developed a toolbox in the ArcGIS environment that provides many models and utilities that we hope, support ecological modeling.

DIRECTIONALITY

Classify Aspect - Classifies aspect into discrete classes.

Linear Aspect - Transforms circular aspect to a linear variable.

Mean Slope - Mean of slope within a defined window.

STATISTICS

Correlation (Pearson, 1895) – calculates local (focal) Pearson's product-moment correlation or covariance between two [x,y] rasters. Please note that the Person's is not robust to non-normal distributional effects or outliers. The "population" correlation coefficient is defined as:

$$p(x,y) = \frac{cov(x,y)}{\sigma_x \sigma_y}$$

Deviation from trend (Cressie 1993) – Indicates the local (window) deviation from a specified N^{th} order Lagrange polynomial trend. A 1st through 12th order trend can be specified to capture 1st (global) or 2nd (nonstationarity) order spatial effects in *y*. The "trend" option subtracts the observed values (*y*) from the trend (*x*) and the "detrend" option subtracts the trend (*x*) from the observed (*y*) thus, partialling-out the N^{th} order trend of *x* from *y*. The polynomial is $P(x)$ if degree ≤ (n-1) passing through the *n* points and is given by: $P(x) = \sum_{j=1}^{n} P_j(x),\ where;\ p_j(x) = y_j \prod_{k=1}^{n} \frac{x-x_k}{x_j-x_k}$

Gaussian smoothing (Davies 1990) – Applies an NxN Gaussian convolution kernel to a raster. This is a 2D convolution smoothing function that is useful for spatial smoothing and scale decomposition. A 2D approximation of the isotropic Gaussian kernel assumes the form:

$$G(x, y) = \frac{1}{2\pi\sigma^2} e - \frac{x^2+y^2}{2\sigma^2}$$

Invert - Inverts (flips) the values of a float raster using the following formula: ((x – max(x) * -1) + min(x).

Local deviation from global – Indicates the local (window) deviation from the specified global statistic (mean or median).

Moments - Calculates statistical moments of a distribution within a specified window with options for: "mean", "median", "mad" (median absolute deviation from median), "variance", "standard deviation", "skewness", "kurtosis", and "coefficient of variation" (in a 0-100 scale).

Normal – Creates a random Gaussian distributed raster with a specified mean and standard deviation (default mean is 0 and standard deviation is 1).

Slope Impedance – A sigmoidal function for an impedance slope function.

Sobel Gradient (Davies 1990) – Applies a Sobel Isotropic Gradient kernel. Returns either an "intensity" or "gradient" raster. This index represents a discrete differentiation operator, based on an approximation of the gradient of the image intensity function. The operator utilizes 3x3 convolution kernels to calculate approximations of the derivatives - one for horizontal changes, and one for vertical.

$$G_y \begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{bmatrix} * \alpha \text{ and } G_x \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix} * \alpha$$

Where; α is the source raster, and G_x and G_y are 3x3 kernels representing the horizontal and vertical derivative approximations.

The resulting gradient approximations can be combined to give the gradient intensity, f and direction, θ using:

$$\acute{f} = \sqrt{G_x^2 + G_y^2} \text{ and } \theta = atan2(G_y, G_x)$$

Transformations – Applies statistical transformations. Includes; "standardize" - standardizes values to a mean of 0 and standard deviation of 1; "stretch" – stretches data to specified range; "normalize: - normalizes to a scale 0-1 while retaining distribution shape: Natural logarithmic; and Square-root.

standardize = (*y* – $\bar{x}$(*y*)) / δ(*y*)

normalize (row standardize) = IF min(y) positive, (*y* / max(*y*)) ELSE (*y* – min(*y*)) / (max(*y*) – min(*y*))

stretch = (y – (min(y)) * new.max / (max(y) – min(y)) + new. min

TEXTURE AND CONFIGURATION

Dissection (Evans 1972) - Dissection describes dissection in a continuous raster surface within rectangular or circular window. Martonne's modified dissection is calculated as:

$$dissection = \frac{z(s) - z(s)_{min}}{z(s)_{max} - z(s)_{min}}$$

Hierarchical Slope Position (Murphy et al., 2010) – Identifies exposure (ridge, slope, toe slope, etc) at various spatial scales and hierarchically integrate these features into a single grid (Murphy et. al., 2010). Topographic position can be calculated using a hierarchically nested approach. Moving windows with increasing radii are applied to a DEM, and the difference between the average elevation of the window and the center cell of the window is calculated. The resulting grids are interpreted as relative topographic exposure at different spatial scales. The exposure can be interpreted as a ridge or peak if the center cell in the mowing window has a higher elevation than the average elevation of the cells in the window. Contrarily if the center cell is of lower elevation than the average elevation of the window, then the center pixel can be interpreted as "toe slope" or "valley bottom". A hierarchical integration into a single grid is achieved by starting with the standardized exposure values of the largest window, then adding standardized values from smaller windows where the (absolute) values of the smaller (search) scale grids exceed the values of the larger scale map. There is no distinction between plains and homogenous slopes, since both topographic positions reveal no concave or convex deviation from the surrounding terrain. However, it is possible to distinguish plains from slopes based on the average slope angle (as calculated in the same search window).

Landform Curvature (McNab 1993; Bolstad & Lillesand 1992; McNab 1989) - Surface curvature (concavity/convexity) index (Bolstad's variant). The index is based on features that confine the view from the center of a 3x3 window. Edge correction is addressed be dividing by the radius distance to the outermost cell (36.2m).

$$lf = \frac{\left(\sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \left(z(s)_i - z(s)_j\right)\right)/(9 * 100)}{36.2}$$

Roughness (Riley et al., 1999; Blaszczynski 1997) - represents the roughness in a continuous raster within a specified window. The Riley et al., 1999 specification can be expressed as unscaled variance. To make the index more flexible and scalable we calculate it as the focal sqrt(δ').

Slope Position (De Reu 2013; Guisan et al., 1999) - calculates scalable slope position by subtracting the average neighbor values from the focal value. Positive values indicate that the central point is located higher than its average surroundings, while negative indicates a position lower than the average. The range of the metric depends not only on differences but also on the defined neighborhood. This metric is also referred to as Topographic Position Index (TPI). Deviation measures the topographic position as a fraction of local relief, normalized to local surface roughness, and is derived as: [slope position / δ(*y*)].

Surface/Area Ratio (Berry 2002) - surface/area ratio of raster.

Surface Relief Ratio (Pike 1971) - Describes rugosity in an continuous raster surface within a specified window. The implementation of SRR can be shown as:

$$srr = \frac{\left(\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\left(z(s)_j\right)/n\right) - z(s)_{min}}{z(s)_{max} - z(s)_{min}}$$

TEMPERATURE AND MOISTURE

2nd Derivate of slope - Calculates 2nd derivate of slope.

Compound Topographic Index (Gessler et al., 1995; Moore et al., 1993) - Steady state wetness index. The CTI is a function of both the slope and the upstream contributing area per unit width orthogonal to the flow direction and is a quantification of catenary topographic convergence. The implementation of CTI can be shown as:

$$cti = ln\left(\frac{\alpha}{\tan(\theta)}\right)$$

where; α = Catchment area [(flow accumulation + 1) * (pixel area in m^2)], and θ is the slope angle in radians.

Heat load index (McCune & Keon 2002) - A southwest facing slope should have warmer temperatures than a southeast facing slope, even though the amount of solar radiation they receive is equivalent. The McCune and Keon (2002) method accounts for this by "folding" the aspect so that the highest values are southwest and the lowest values are northeast. Additionally, this method account for steepness of slope, which is not addressed in most other aspect rescaling equations. HLI values range from 0 (coolest) to 1 (hottest).

$$f(\alpha) = \left|\pi - \left|\alpha - \frac{5\pi}{4}\right|\right|$$

$$hli = 0.039 + [0.808 * \cos(l) * \cos(\theta)] - [0.196 * \sin(\theta)] - \left[0.482 * \cos\left(f(\alpha)\right) * \sin\left(f(\alpha)\right)\right]$$

where; α=slope(radians) *l* = latitude, Θ=slope(radians), and *f*(α)=folded slope.

Integrated Moisture Index (Iverson et al., 2997) – An estimate of soil moisture in topographically heterogeneous landscapes

imi = [hillshade * 0.5] + [curvature(θ) * 0.15] + [Flow Accumulation * 0.35]

Site Exposure Index (Balice et al., 2000) – The SEI rescales aspect to a north/south axis and weights it by steepness of the slope. The metric represents relative exposure ranging from -100 to 100 (coolest to warmest0 and is defined as:

$$sei = \acute{\theta}\cos\left(\pi\frac{\alpha - 180}{180}\right)$$

Slope/Aspect Transformations - Options are Stage's (1976) COS, SIN; or Roberts & Cooper (1989) TRASP (topographic radiation aspect index).

COS AND SIN - An a priori assumption of a maximum in the NW quadrant (45 azimuth) and a minimum in the SW quadrant can be replaced by an empirically determined location of the optimum (Stage, 1976). For slopes from 0% - 100%, the functions are linearized and bounded from -1 to 1. Greater than 100% slopes are treated out of the -1 to 1 range and the model sets all values greater than 100% to 101% and flat areas (-1) to nodata. The metric is defined as:

$$sca = \theta\cos(\alpha)\ or\ ssa = \theta\cos(\alpha)$$

Example values for 50% slope across 10 aspects.

Aspect	cosine	sine
N	0.500	0.000
N30E	0.433	0.250
N45E	0.345	0.345
N60E	0.250	0.433
E	0.000	0.500
ESE	-0.354	0.354
S	-0.500	0.000
SSW	-0.354	-0.354
W	0.000	-0.500

TRASP - Circular aspect is transformed to assign a value of zero to land oriented in a north-northeast direction, (typically the coolest and wettest orientation), and a value of one on the hotter, dryer south-southwesterly slopes. The result is a continuous variable between 0 - 1 (Roberts and Cooper 1989). The metric is defined as:

$$trasp = \frac{1 - \cos(\left(\frac{\pi}{180}\right)(\alpha - 30))}{2}$$

UTILITIES

Angle conversion - converts between degrees and radians.

Class Percent - Calculates the percent of a class in an integer raster within a specified window.

No Data Fill - Fills in NoData gaps using a specified FocalMedian, FocalMean (for float data) or FocalMajority (for integer data) window.

Sieve - Applies a minimum-mapping-unit (MMU) to discrete data using a sieve approach. User defines minimal number of cells to be retained. This approach is much more controllable and stable then FocalMajority. The sieve model is very effective in "de-speckling" discrete data.

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