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Research Paper

Measuring landscape pattern in three dimensional space

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ABSTRACT

General landscape metrics are mainly conducted in two dimensional space, while the terrain undulation is usually not considered. Terrain fluctuation affects a landscape's spatial heterogeneity and its spatial-temporal dynamics by diversifying the spatial distribution of soil, vegetation and animals. This article proposed three methods to measure the landscape pattern in three dimensional space, including the 3D derivation of 2D landscape metrics, 3D surface roughness parameters, 3D power spectral analysis and 3D correlation analysis. 3D surface data were designed and validated using the proposed 3D landscape pattern analyzing metrics, and the results indicated that these measurements can effectively evaluate the 3D composition, spatial configuration and texture direction of 3D landscape.

1. Introduction

Landscape ecology investigates the interactive relationships between landscape patterns and ecological processes, scale, and hierarchy (Forman, 1983; Forman & Godron, 1986; Risser, Karr, & Forman, 1984; Turner, Gardner, & O' Neill, 2001; Wu & Hobbs, 2007). The development of methods to quantify landscape pattern is particularly important not only for the understanding of interactions of pattern and process, but also for the recording of spatial-temporal changes of landscapes (Jjumba & Dragićević, 2016; Turner et al., 2001; Wu & Hobbs, 2007). These methods are usually applied in landscape pattern analysis, which is mainly focused on characteristics and spatial configuration of elements constituting landscape structure and its spatial-temporal dynamics (Turner et al., 2001; Wu & Hobbs, 2007). The past three decades have seen a large number of studies interested in landscape pattern analysis including effects of landscape pattern to ecological processes (Cousins & Eriksson, 2002; Verheyen, Bossuyt, Hermy, & Tack, 1999), landscape pattern changes (Burgess & Sharpe, 1981; Noss & Cooperrider, 1994; Rogers, Cooper, McKenzie, & McCann, 2012; Terborgh, Feeley, Silman, Nunez, & Balukjian 2006), and driving forces of landscape pattern change (Turner et al., 2001).

Landscape metrics are extensively used for the analysis of spatial pattern (Listopad, Masters, Drake, Weishampel, & Branquinho, 2015; O'Neill, Gardner, Milne, Turner, & Jackson, 1991; Turner et al., 2001). Spatial statistical methods including autocorrelation (Goodchild, 1986; Goodchild, Parks, & Steyaert, 1993), power spectrum (Turner, O'Neill, Conley, Conley, & Humphries, 1991), wavelet methods (Rosenberg, 2004) are also widely applied in the pattern analysis. Nearly all of the landscape metrics and spatial statistical methods are based on a 2D landscape with a vector or raster data format, while the 3D terrain surface is scarcely considered (Blaschke, Tiede, & Heurich, 2004; McGarigal & Cushman, 2005; Petras, Newcomb, & Mitasova, 2017). The 2D landscape map is the projection of the 3D terrain surface topography, and the landscape pattern metrics based on this compressed information cannot fully express the continuous fluctuation of the 3D form of the landscape (Hoechstetter, Thinh, & Walz, 2006). In the last decade, some spatial statistics and new spatial indices were proposed to analyze the 3D landscape pattern. Rogers et al. (2012) calculated 3D habitat area by overlaying habitat map with a digital elevation model, and founded that the habitat with a high 3D surface to 2D plane area ratio may exist relatively abundant species diversity, which indicated the high impact of 3D habitat area change on assessing the area-based biodiversity especially in marginal upland. Petras et al. (2017) proposed some methods for converting a 3D raster into 2D series and redefined the 3D fragmentation index to describe the 3D vegetation structure based on LiDAR point clouds, which can be taken as an example about how a 2D landscape metric extend to 3D space. Jjumba and Dragićević (2016) proposed some 3D landscape metrics to quantify the statistic and dynamic properties of bloxel in a voxel-based space, and analyzed the 3D landscape patterns sufficiently affected by the vegetation heights over an undulated terrain using LiDAR point clouds. As the basic physical geographical elements, 3D terrain undulation also influences a wide range of landscape patterns, processes and dynamics (Parrott, Proulx, & Thibert-Plante, 2008; Schauber, Edge, & Wolff, 1995; Swanson, Kratz, Caine, & Woodmansee, 1988), such as spatial distribution of soil, vegetation, animals, temperature and moisture (Bailey,

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1996; Blaschke et al., 2004; Neilson, 1995; Schauber et al., 1995; Swanson et al., 1988); frequency and spatial distribution of fire, wind and nibble intensities (Boose, Foster, & Fluet, 1994); etc. The development of 3D landscape pattern measures will be helpful in the impacts of terrain undulation on landscape patterns or processes (McGarigal & Cushman, 2005).

This article discusses 3D landscape measures and the corresponding arithmetic methods based on raster data. Three methods determining these 3D landscape measures were proposed: 1) derivations of 2D landscape metrics to 3D space, the main concept was to substitute the 3D spatial area or curve length for the area or length value in 2D plane; 2) application of 3D surface roughness parameters, the main concept was to introduce and modify the roughness parameters in the mechanical manufacturing science to evaluate the 3D landscape complexity; 3) 3D spatial statistics (autocorrelation function and spectrum analysis), the main concept was to derive the 2D spatial statistical analysis to 3D space and to correlate the 3D surface with landscape patterns.

2. Methods

2.1. Derivation of 2D landscape metrics to 3D space

Two types of indices comprise 2D landscape metrics, one is the composition metrics quantifying the landscape diversity and richness, the other is the spatial configuration metrics quantifying the arrangement, location and orientation of patches (McGarigal & Cushman, 2005). Some studies have been conducted to reveal the relationship between the 2D landscape pattern metrics and the 3D landscape pattern metrics. Hoechstetter et al. (2006) calculated patch area, patch perimeter, perimeter-area ratio, fractal dimension and landscape shape index in 3D space based on the DEM data, and then compared the results with the same metrics in 2D space. The results showed that area and landscape shape index had little differences between 2D and 3D space, which may be caused by the lower undulation of the DEM data. Because the difference between 2D and 3D metrics may increase due to the more intensive fluctuation of the DEM, some metrics such as patch area, perimeter, mean patch area and the mean Euclidean nearest distance may change significantly in higher terrain undulation mountain landscapes. Thus, the 2D landscape metrics combined with the 3D terrain surface need to be developed to evaluate 3D landscape patterns.

The derivation of the 2D landscape metrics to 3D space in this paper were fulfilled in three ways:

- The plane area based on the sum of the numbers of pixels was substituted by 3D surface area, which can be calculated by the average of the two sets of diagonal triangle areas (Jenness, 2004; Stout & Blunt, 2000);
- The projected 2D length of plane curve line based on the sum of the size of pixel was substituted by spatial curve length in the 3D surface, which can be calculated by summarizing the spatial distance between adjacent two pixels;
- The weight can be calculated by the ratio of 3D surface area to 2D projected area.

Significance and methods that the 2D metrics extended to 3D space are summarized in Table 1, and the algorithms of some frequently used metrics are summarized in Table 2. Given most of the metrics can be applied in patch, class and landscape level rested with the input data, metrics of different levels was not discussed respectively, and other metrics can be treated with the similar way.

2.2. Application of surface roughness parameters

The derivation of 2D metrics cannot describe some of the characterizations of the 3D surface topography, such as surface slope, surface kurtosis and surface texture, which have an important influence on many ecological processes, including wildlife migration, hydrological cycle, geochemical processes and the spatial distribution of flora and fauna (Boose et al., 1994; Kratz, Benson, Blood, Cunningham, & Dahlgren, 1991; Swanson et al., 1988). Roughness parameters are applied to evaluate the machining quality of mechanical parts or to establish corresponding machining quality standards based on the surface micro topography measured by surface measurement instruments. In the past, surface topography measurement was usually applied for the measurement of a two-dimensional section of the microcosmic surface (Stout & Blunt, 2000; Thomas, 1999; Whitehouse, 1994). With the machining technical progress and the improvement of machining management requirement, 3D surface measurement technique and the corresponding assessment technique (Stout & Blunt, 2000; Thomas, 1999) have been gradually developed based on the development of computer technology and high precision and resolution surface measurement instruments.

3D surface measurement technology are used to generate surface micro topography of mechanical parts with certain sampling density decided by the instruments' performance or the parts' property (Stout & Blunt, 2000; Thomas, 1999). According to different frequency ranges, surface topography data is classified into two types of components (Stout & Blunt, 2000; Thomas, 1999). One is surface roughness (including texture) within a less undulated area, the other is form errors within a greater undulated area. The surface micro topography needs to be filtered to reject the form errors before the evaluation of its roughness (Stout & Blunt, 2000; Thomas, 1999), and similar methods can also be introduced to the process of topography landscape data (Du Preez, 2015). 3D surface roughness is not only applied in mechanical manufacturing field, but also widely used in medical (Lagarde, Rouvrais, Black, Diridollou, & Gall, 2001; Rosen, Blunt, & Thomas, 2005), bioengineering (Derbyshire, Fisher, Dowson, Hardaker, & Brummitt, 1994; Tandon & Rakesh, 1981; Wennerberg, 1996) and other fields.

The 3D surface roughness parameters can be classified into four types (Stout & Blunt, 2000):

- amplitude parameters, mainly including the root-mean-square deviation, the kurtosis of surface height distribution, the skewness of surface height distribution and ten-point height of a surface;
- hybrid parameters, mainly including the root-mean-square slope of a surface, developed interfacial area ratio and the mean summit curvature of a surface;
- spatial parameters, mainly including the density of summits, the texture direction of a surface, the surface texture aspect ratio and the fastest decay autocorrelation length;
- functional parameters, mainly including the surface bearing index, the core fluid retention index and the valley fluid retention index.

The main 3D surface roughness parameters and the corresponding ecological significance in view of characteristics of 3D landscape analysis are summarized in Table 3. Altitude parameters describe 3D surface height distribution. Spatial parameters describe 3D surface spatial shape changes. Hybrid parameters combine altitude parameters and spatial parameters to evaluate surface characteristics. Functional parameters are used to describe 3D surface bearing capability.

2.3. Three-dimensional statistical analysis

Spatial statistical analysis describes the statistical dependence of spatial data (Tobler, 1970). The organisms naturally distribute neither uniformly nor randomly by some kind of spatial structure (Legendre & Legendre, 2012; Tobler, 1970), which can be analyzed using spatial statistics. Autocorrelation and power spectrum density have been widely applied to analyze the texture of 3D surface (Bakolas, 2003; Manesh, Ramamoorthy, & Singaperumal, 2010; Roylance, Williams, & Dwyer-Joyce, 2000; Stout & Blunt, 2000; Thomas, 1999).