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Global inventory of landscape patterns and latent variables of landscape spatial configuration

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A R T I C L E I N F O

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A B S T R A C T

We present a regionalization of the entire Earth's landmass into land units of homogeneous landscape patterns. The input to the regionalization is a high resolution Global Land Cover (GLC) dataset. The GLC is first divided into local landscapes – small non-overlapping square blocks of GLC cells. These blocks are agglomerated into much larger land units using a pattern-based segmentation algorithm. These units are tracts encompassing cohesive patterns of land cover and the procedure divides the entire landmass into tracts of land with discernibly different patterns. We characterize a pattern in each unit by a set of 39 landscape metrics. The resulting spatial database of land units is the major product of this study. We make this database freely available to the community in order to provide foundational information for studies aiming at explaining relationships between landscape pattern and ecological process and between the process and patterns and their controlling factors. The procedure of obtaining the database is described, the quality assessment of units delineation is given, and the statistics of the major properties of the units are presented. To showcase the utility of the new database we use it to demonstrate that a variability of geometric configurations of landscape patterns worldwide can be captured in terms of only two variables – complexity and aggregation – as they explain 70% of the variability. This allows for a meaningful, two-dimensional classification and mapping of landscape patterns on the basis of their geometry. Such mapping reveals that the majority of terrestrial landscapes are characterized by a simple, frequently monothematic, pattern of land cover. Thus, landscapes on Earth are mostly segregated by the land cover type and complex landscapes with a diverse mix of different land cover types are rare exceptions from the prevailing monothematic cover.

1. Introduction

Global land cover (GLC) maps are obtained by classifying pixels in a global mosaic of Earth observation (EO) images into several categories of Earth's surface properties. The spatial resolution of GLC maps ranges from 30 m to 1 km (Chen et al., 2014; Pfeifer et al., 2012; Tuanmu and Jetz, 2014; Tsendbazar et al., 2015) while their thematic resolution (number of categories) ranges from 10 to 27. The importance of land cover maps for global ecology stems from the fact that they could be used to provide the first-order information about geographical distribution of biodiversity and ecological processes (Siriwardena et al., 2000; Eyre et al., 2004; Heikkinen et al., 2004; Fuller et al., 2005; Luoto et al., 2006).

However, frequently it is a spatial pattern of land cover categories rather than a category itself that is of environmental or ecological interest. This is because grid cells of GLC maps are too small units of an area to be used for analysis on regional, continental or global scale. At such coarse scales a landscape pattern (LP) – an area having discernibly cohesive spatial arrangement (mosaic) of land cover categories – is a more natural unit of analysis (Wickham and Norton, 1994; Riitters et al., 2000; Riitters, 2011; Omernik and Griffith, 2014). A regionalization of GLC into LPs would delineate naturally occurring land units which are likely to be environmentally homogeneous and may serve as the first order approximation to global ecoregions (Bailey, 1989; Olson et al., 2001).

Regionalization of a land cover map into LPs was first proposed by Wickham and Norton (1994). However, because at that time the process of pattern-based regionalization could only be performed manually, the concept was not widely used until algorithmic methods of regionalization become available. Pattern-based units are sometimes easy to see on a land cover map but they are always difficult to delineate by manual means (especially over large spatial extent) as no two analysts are likely to arrive at the same partitioning. Only algorithmic regionalization can assure reproductivity of partitioning and it is the only practical means for partitioning large (continental, global) land cover maps.

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At first, algorithmic regionalization of land cover maps was applied only to delineate different forest patterns (Long et al., 2010; Kupfer et al., 2012), but later it was also applied to delineate multi-categorical patterns (Niesterowicz and Stepinski, 2013; Partington and Cardille, 2013; Niesterowicz et al., 2016). All regionalization algorithms delineate LPs by agglomerating local landscapes – small blocks of land cover cells whose categories form a pattern on the scale defined by the size of the block. Approaches to algorithmic regionalization differ by how local landscapes are described, compared, and agglomerated into LPs (Niesterowicz and Stepinski, 2016). Algorithmic regionalization of GLC had not been previously attempted due to computational challenges associated with the large size of a GLC dataset.

This paper has two major contributions. (1) We algorithmically regionalize a global GLC and obtain a SQL-searchable GIS database containing the global inventory of land units of cohesive land cover patterns. Global regionalization of GLC is made possible by utilizing a segmentation technique instead of clustering technique to agglomerate local landscapes. Segmentation technique also allows the results to be in the form of the GIS database with each LP described by a list of attributes that includes landscape metrics (Haines-Young and Chopping, 1996). We make the database available to the community in hope that it can support a range of investigations pertaining to environmental conservation, planning, and ecology. (2) Using the newly created database, we demonstrated that the variance in spatial (geometric) configurations of landscape mosaics worldwide is sufficiently captured (71%) by only two variables which we call complexity and aggregation. This finding facilitates classification of LPs with respect to their geometry – the first step to a complete classification of land cover patterns.

2. Methods

In this section, we describe a GLC dataset we used as an input, a principle and a technique of our pattern-based regionalization method, our selection of landscape metrics, and PCA-based analysis of metrics variability.

2.1. Data

We use the CCI-LC 2010 dataset (http://maps.elie.ucl.ac.be/CCI/viewer/) as an input for regionalization of LPs. The CCI-LC dataset is a product of ESA Climate Change Initiative (CCI) to produce a temporal series of GLC maps which are as accurate and multi-year compatible as possible so they can be used in climate modeling. CCI-LC maps are available for several epochs; we use the 2010 map. The CCI-LC map is in the form of 64,800 × 129,600 Lat/Lon grid, thus its spatial resolution is 10 arc-sec or ~300 m at the equator. Each grid cell is classified into one of 22 categories (see Fig. 2 for a legend) based on the FAO/UNEP Land Cover Classification System (LCCS).

2.2. Regionalization of landscape patterns

Regionalization of LPs is performed using the Geospatial Pattern Analysis Toolbox (GeoPAT) (Jasiewicz et al., 2015; Jasiewicz et al., 2017) – a collection of GRASS GIS (GRASS Development Team, 2016) modules for carrying out pattern-based analysis of large categorical grids, such as the CCI-LC. The entire CCI-LC grid is first tessellated into small square blocks (of the size $k \times k$ of CCI-LC cells) to form a new, k^2 coarser, grid of blocks. A mosaic of land cover categories within each block encapsulates a local pattern, and the segmentation of the grid of blocks aggregates adjacent blocks into bigger land units while preserving the cohesion of the pattern.

Segmentation is the process of partitioning a grid (commonly a digital image but in our case a categorical raster map) into multiple segments in a way that maximizes homogeneity (of a pattern in our case) within segments and dissimilarity (of pattern) between adjacent segments (Haralick and Shapiro, 1985). The segmentation algorithm in GeoPAT is based on the principle of seeded region growing (SRG) (Adams and Bischof, 1994) but has a number of features that distinguish it from image segmentation algorithms. It segments a grid consisting not of single-category cells but of blocks having complex content (a pattern of different categories) and a non-negligible spatial extent. Because of the non-negligible size of the blocks, the spatial organization of their grid is not rectangular but instead, it consists of alternating horizontal layers of blocks with each layer shifted a half block length with respect to the previous one like in masonry. Such grid is easy to set and it is a sufficiently good approximation of a preferred isotropic hexagonal grid which is difficult to set but, because of its isotropy, minimizes segments' artifacts associated with tessellation.

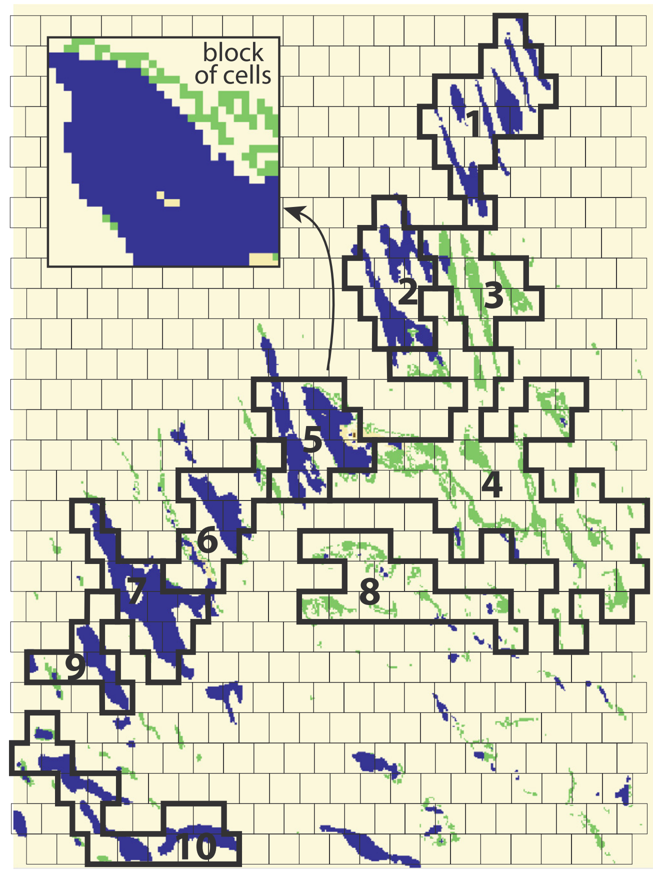

Fig. 1. Illustration of pattern-based segmentation using a site located in the Simpson Desert Regional Reserve, Australia. The CCI-LC is tessellated into 9 km-sized (30 × 30 cells) blocks shown by thin lines. The grid of blocks is segmented on the basis of pattern similarity, only 10 regions (thick lines) are shown. The inset shows a sample block in details. Land cover categories present: blue – water, green – wetlands, beige – bare lands. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 1 illustrates the concept of the grid of blocks and its segmentation. A 252 km × 180 km fragment of CCI-LC located in the Simpson Desert Regional Reserve, Australia is shown with the grid of 9 km-sized square blocks superimposed on the map. This site was selected as an illustrative example because it contains only three land cover categories (bare areas, water bodies, and wetlands) that form simple patterns. Ten examples of regions with cohesive LPs are shown as aggregated by the segmentation algorithm.

The pattern within each block is mathematically described by a normalized histogram (the sum of all its bins equals to 1) of land cover category co-occurrence pattern features (Barnsley and Barr, 1996; Chang and Krumm, 1999). Briefly, pattern features are the pairs of land cover categories assigned to two neighboring cells. Histogram counts and bins the features from eight co-occurrence matrices calculated for