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Hierarchical image segmentation based on similarity of NDVI time series

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Abstract

Although a variety of hierarchical image segmentation procedures for remote sensing imagery have been published, none of them specifically integrates remote sensing time series in spatial or hierarchical segmentation concepts. However, this integration is important for the analysis of ecosystems which are hierarchical in nature, with different ecological processes occurring at different spatial and temporal scales. Therefore, the objective of this paper is to introduce a multi-temporal hierarchical image segmentation (MTHIS) methodology to generate a hierarchical set of segments based on spatial similarity of remote sensing time series. MTHIS employs the similarity of the fast Fourier transform (FFT) components of multi-seasonal time series to group pixels with similar temporal behavior into hierarchical segments at different scales. Use of the FFT allows the distinction between noise and vegetation related signals and increases the computational efficiency. The MTHIS methodology is demonstrated on the area of South Africa in an MTHIS protocol for Normalized Difference Vegetation Index (NDVI) time series. Firstly, the FFT components that express the major spatio-temporal variation in the NDVI time series, the average and annual term, are selected and the segmentation is performed based on these components. Secondly, the results are visualized by means of a boundary stability image that confirms the accuracy of the algorithm to spatially group pixels at different scale levels. Finally, the segmentation optimum is determined based on discrepancy measures which illustrate the correspondence of the applied MTHIS output with landcover–landuse maps describing the actual vegetation. In future research, MTHIS can be used to analyze the spatial and hierarchical structure of any type of remote sensing time series and their relation to ecosystem processes.

Keywords: Hierarchical image segmentation; Fast Fourier transform; NDVI time series; Vegetation mapping

1. Introduction

The development of effective methodologies to analyze time series of satellite imagery is one of the most important issues in the understanding of temporal dynamics of vegetation cover (Bruzzone et al., 2003). The temporal component, integrated with the spectral and spatial dimensions, provides essential information on ecological systems and vegetation dynamics. However, advanced analysis methods are crucial for the proper exploration of that information; certainly with the ever increasing amount of time series data. Several methods and algorithms have already been developed based on satellite-based biophysically meaningful variables, e.g. the Normalized Difference Vegetation Index (NDVI) whose behavior follows annual cycles of vegetation growth (Running et al., 1994). These applied methods include Principal Component Analysis (PCA) (Anyamba & Eastman, 1996; Eastman & Fulk, 1993; Gurgel & Fereira, 2003), development of phenological metrics (Jönsson & Eklundh, 2004; Lee et al., 2002; Reed et al., 1994; Verbesselt et al., 2006), change detection (Coppin et al., 2004), and harmonic or Fourier analysis (Andres et al., 1994).

The fast Fourier transform (FFT) has shown to be particularly useful for NDVI time series analysis to describe and quantify fundamental temporal characteristics, since the noise-affected NDVI time series are decomposed into simpler periodic signals in the frequency domain. By performing analysis in the frequency domain, a distinction can be made between frequency

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terms with daily frequencies, related to atmospheric and cloud-contamination effects, and specific frequency terms related to vegetation in dynamic ecosystems (Evans & Geerken, 2006; Jakubauskas et al., 2001, 2002; Juarez & Liu, 2001; Olsson & Eklundh, 2001). Azzali and Menenti (2000) and Moody and Johnson (2001) have used the inter- and intra-seasonal periodic signals successfully in classification procedures to map vegetation–soil–climate units. These studies revealed typical temporal characteristics of vegetation complexes, but they are per-pixel approaches based on clustering procedures of temporal properties of individual pixels. Consequently, they do not take into account the spatial or hierarchical context of the data. As such, they ignore the information in the spatial domain and fail to aggregate the temporal information into hierarchical regions at different scales. These concepts are important since ecosystems are hierarchical in nature, with different ecological processes occurring at different spatial and temporal scales (Handcock & Csillag, 2004; Hay et al., 2003). For example, macro-ecological characteristics, e.g. climate, will have coarse spatial regional effects, while more localized characteristics, e.g. weather, create patterns of variability at finer spatial scales. In this context, ecological systems can be perceived as nested patch hierarchies, where patterns and dynamics at the focal scale are products of the potential behaviors of components at lower levels (smaller scales), and are bound within the environmental constraints imposed by higher levels (larger scales) (Woodcock & Harward, 1992; Wu & Loucks, 1995).

Image segmentation methods provide a valuable alternative to the conventional per-pixel classification methods, since they consider the spatial context. Segmentation methods partition a study area into adjoining clusters of pixels, called segments or regions, based on similarity or dissimilarity of their single or multiple-layer pixel values (Stuckens et al., 2000). Mathematically, most of these methods operate on the principle of minimizing the within-region variance, or other measures of internal homogeneity (Beaulieu & Goldberg, 1989). Different approaches are commonly used for this principle, ranging from threshold techniques, and boundary techniques, to region-based techniques and hybridized approaches (Fan et al., 2001). The advantages of the segmentation approach over classical per-pixel procedures are multiple. Firstly, they allow quantification of spatial heterogeneity within the data at various scale levels. Such measures can indicate spatial complexity, variability, and fragmentation, which can have a significant influence on the rate, character, and magnitude of ecosystem processes. Secondly, the delineation of homogeneous patches is possible and involves a certain spatial generalization. This reduces the effect of local spatial heterogeneity that often masks larger spatial patterns (Tilton & Lawrence, 2000). Thirdly, an explicit hierarchal structure can be implemented between segments at different spatial scales (Woodcock & Harward, 1992). The hierarchical structure provides insight into the functional ecology of ecosystems, since it presents the study area as a nested patch hierarchy. This means that the study area is divided into spatial sets corresponding to coarse regions. These coarse sets are subdivided into subsets corresponding to region subparts at smaller scales. This hierarchy can be represented by a tree where the segments at the lower level are joined to form segments at higher levels.

Although a number of hierarchical image segmentation procedures for remote sensing imagery have been published (e.g. Baatz & Schäpe, 2000; Tilton & Lawrence, 2000), none of them specifically incorporates similarity of temporal information in the algorithm. The objective of this paper is consequently the introduction of a multi-temporal hierarchical image segmentation (MTHIS) methodology that generates a hierarchical structure of segments based on spatial similarity of temporal profiles. MTHIS employs the similarity of FFT components to assess that similarity of temporal profiles. Application of the MTHIS consequently allows hierarchical clustering of image time series into spatio-temporal segments at numerous scales based on specific periodic patterns. This will provide insight in the hierarchical spatio-temporal structure of ecosystem processes, e.g. the relation of different landcover properties at various spatial scales, the relationship between climate-weather and vegetation phenological variability.

In this paper, the MTHIS methodology is applied on NDVI time series of South Africa to demonstrate the concept. Section 2 presents the study area and satellite data, while the MTHIS methodology is described based on its underlying theoretical concepts in Section 3. Since MTHIS is a general methodology that can be applied to any image time series, a specific MTHIS protocol for multi-temporal NDVI image series is introduced in Section 4. This protocol serves to select the relevant temporal characteristics that describe the majority of spatio-temporal variation in the original NDVI data (4.1), incorporates effective application (4.2) and visualization (4.3), and allows to extract the segmentation optima that relate to ecological processes occurring at different scales (4.4). Finally, the results of the MTHIS protocol are presented in Section 5 and the advantages and drawbacks of the methodology are discussed in Section 6.

2. Data description

2.1. Study area

The proposed methodology was tested on the area of South Africa, Swaziland and Lesotho, which approximately encompasses the geographic region between latitudes 21°S and 35°S and longitudes 33°W and 16°E. The elevation ranges from sea-level to more than 3300 m, while the rainfall varies from almost zero to more than 3000 mm in mountainous areas. Rainfall regimes are defined as winter rainfall in the west to strong summer rainfall regimes in the northeastern and northern parts of the study area. The vegetation in the study area is characterized by 68 different vegetation types (LR) as described by Low and Rebelo's Vegetation Map of South Africa, Lesotho and Swaziland (Low & Rebelo, 1996) and is illustrated in Fig. 1a. These broad vegetation types are principally identified by their vegetation structure, ecological processes and occurrence of important plant species. If the factor of human influence is also considered, 31 landcover–