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Monitoring land changes in an urban area using satellite imagery, GIS and landscape metrics

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ABSTRACT

Monitoring land changes is an important activity in landscape planning and resource management. In this study, we analyze urban land changes in Atlanta metropolitan area through the combined use of satellite imagery, geographic information systems (GIS), and landscape metrics. The study site is a fast-growing large metropolis in the United States, which contains a mosaic of complex landscape types. Our method consisted of two major components: remote sensing-based land classification and GIS-based land change analysis. Specifically, we adopted a stratified image classification strategy combined with a GIS-based spatial reclassification procedure to map land classes from Landsat Thematic Mapper (TM) scenes acquired in two different years. Then, we analyzed the spatial variation and expansion of urban land changes across the entire metropolitan area through post classification change detection and a variety of GIS-based operations. We further examined the size, pattern, and nature of land changes using landscape metrics to examine the size, pattern, and nature of land changes. This study has demonstrated the usefulness of integrating remote sensing with GIS and landscape metrics in land change analysis that allows the characterization of spatial patterns and helps reveal the underlying processes of urban land changes. Our results indicate a transition of urbanization patterns in the study site with a limited outward expansion despite the dominant suburbanization process.

Introduction

Land change science has recently emerged as a fundamental component of global environmental change and sustainability research (Gutman et al., 2004; Rindfuss, Walsh, Turner, Fox, & Mishra, 2004; Turner, Lambin, & Reenberg, 2007). Land changes (land use and/or land cover) in urban areas, especially the conversion of cropland and forest land to urban uses, is one of the most important forms of global environmental changes (Briassoulis, 2000). Since the mid-20th century, many American metropolises have experienced dramatic growth, which was dominated by a suburbanization process with new development spreading outward from the urban core towards suburbs and exurbs. While urban development has always been viewed as a sign of the regional economic prosperity, the emerged low density and leapfrog built-up land patterns in suburban and exurban areas have begun to undermine environmental sustainability. Monitoring land changes in urban areas can support decision making in urban planning and resource management (Lambin et al., 2001; Turner et al., 2007). The advances in remote sensing and geospatial information techniques offer a promising framework to monitor land changes in urban areas (Elvidge et al., 2004; Rindfuss et al., 2004; Southworth & Gibbes, 2010).

Remote sensing provides a cost-effective alternative to the ground-based survey for land use/cover mapping and change analysis. Time-series of remotely sensed data allow examining the temporal dynamics of urban attributes or processes. And post-classification comparison methods produce “from–to” change information between land classes that can help capture the nature of land changes (Jensen, 2004). Given the wide availability and long-time archive, Landsat data have been widely used in land use/cover classification and change detection at regional scales (e.g., Liu & Weng, 2013; Vogelmann et al., 2001; Yang & Liu, 2005; Yang & Lo, 2002; Yuan, Sawaya, Loeffelholz, & Bauer, 2005). However, land use/cover classification in urban areas using medium resolution remotely sensed data (e.g., Landsat Thematic Mapper) can be challenging due to the presence of heterogenous urban features and the spectral similarity between different urban land cover types (Forster, 1983; Gao & Skillcorn, 1998; Guindon, Zhang, & Dillabaugh, 2004; Herold, Gardner, & Roberts, 2003; Small, 2001;

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Welch, 1982). Sub-pixel analysis, such as spectral mixture analysis (SMA), models each pixel as the percent cover of basic land cover materials that can help preserve the heterogeneity of urban areas (Powell, Roberts, Dennison, & Hess, 2007; Small, 2001, 2003). Over the past years, a sizable number of research has demonstrated the usefulness of sub-pixel analysis in dealing with the "mixed" pixel problem associated with using medium resolution remotely sensed data in urban land mapping (e.g., Franke, Roberts, Halligan, & Menz, 2009; Liu & Yang, 2013; Myint & Okin, 2009; Powell et al., 2007; Rashed, Weeks, Roberts, Rogan, & Powell, 2003; Roberts et al., 1998; Small, 2001, 2003; Small & Lu, 2006; Song, 2005). For change analysis, the sub-pixel analysis has mostly been applied to the detection of land cover fraction change, such as percent imperviousness change (e.g., Yang, Xian, Klaver, & Deal, 2003), vegetation fraction change (e.g., Small & Miller, 1999, 2000). Some research has shown the potential of incorporating sub-pixel fraction in thematic land use/cover classification (e.g., Liu & Yang, 2013; Lu & Weng, 2006). However, using the spectral response from remote sensing alone may not be sufficient to differentiate specific land types in urban areas, which can be valuable for various applications such as driving force analyses, urban morphological studies, and land use modeling. Previous studies have identified the importance of incorporating ancillary data in image classification (e.g., Bock, Xofis, Mitchley, Rossner, & Wissen, 2005; Guindon et al., 2004; Lu & Weng, 2006).

While the post-classification change detection provides insight into the nature of land change, the integration of remote sensing and geographic information system (GIS) can be quite useful for characterizing the spatial patterns of urban land change (e.g., Aspinall & Hill, 2008; Chen, Zeng, & Xie, 2000). GIS provides a flexible environment for entering, analyzing, and displaying digital data from various sources necessary for land type identification, change detection, and database development. On the one hand, integrating GIS with remote sensing can help improve land mapping in urban areas. Examples include on-screen digitizing urban features from high resolution satellite imagery (e.g., Lathrop, 2004) and combining GIS ancillary data to improve image classification (e.g., Guindon et al., 2004; Liu & Yang, 2013; Mundia & Aniya, 2005; Shalaby & Tateishi, 2007; Yang & Liu, 2005). On the other hand, the integration of remote sensing and GIS can help generate useful information on how much, where, and what types of land changes have occurred. For example, various GIS spatial analysis functions ranging from overlay to cluster analysis has been applied to the spatial pattern analysis of land changes (e.g., Li & Yeh, 2004; Mundia & Aniya, 2005; Weng, 2002; Wu et al., 2006; Xiao et al., 2006; Yang & Lo, 2002).

Moreover, landscape metrics can be used to quantify the spatial structure of urban areas and thus add insights to the remote sensing-based change analysis (e.g., Schneider & Woodcock, 2008; Seto & Fragkias, 2005). Integrating spatial metrics with remote sensing and GIS can help examine different structural dimensions of land changes in urban areas, such as location, distribution, size, shape, and arrangement, which are important variables in quantifying urban sprawl. A variety of spatial metrics have been proposed and applied to quantify different spatial characteristics of urban areas, such as fragmentation (e.g., Kane, Connors, & Galletti, 2014; Zhang, York, Boone, & Shrestha, 2013), shape complexity (e.g., Wu, Darrel Jenerette, Buyantuyev, & Redman, 2011), and heterogeneity (e.g., Taubenboeck & Kraff, 2014). Given the complexity of the urban environment and its dynamics by nature, it is necessary to select multiple measurements in order to characterize different types of spatial patterns (Siedentop & Fina, 2010). Our literature review has also revealed a large number of spatial metrics being used in characterizing urban land patterns (e.g., Carrion-Flores & Irwin, 2004; Herold, Goldstein, & Clarke, 2003; Herold, Scepan, & Clarke, 2002; Ji, Ma, Wahab Twibell, & Underhill, 2006; Wu et al., 2011). Therefore, further research is needed to help select appropriate spatial metrics for specific urban land change studies.

In this study, we integrate satellite imagery, geographic information systems (GIS), and landscape metrics for urban land change mapping and analysis. The study site, Atlanta metropolitan area, is one of the fast-growing large metropolises in the United States, which contains a mosaic of complex land use and land cover types. Our method consisted of two major components: remote sensing-based image classification and GIS-based land change analysis. Specifically, we adopted a stratified image classification strategy combined with a GIS-based spatial reclassification procedure to map land classes from Landsat Thematic Mapper (TM) scenes acquired in two different years. Then, we employed a post-classification change detection strategy to analyze land changes through a variety of GIS-based operations. We further used landscape metrics to examine the size, pattern, and nature of land changes. The following sections will detail our research methodology and discuss the spatial characteristics and nature of land changes.

Research methods

The land change mapping and analysis used here was based on the post-classification change detection strategy (Jensen, 2004). The specific working procedural route is illustrated in Fig. 1. The sections to follow will detail each component, including the study area, data acquisition and collection, classification scheme, image processing, and landscape pattern analysis.

Study area

The study site consists of 29 counties in the Atlanta metropolitan area, Georgia, USA (Fig. 2). Specifically, it includes Hall County and the 28-county "Atlanta–Sandy Springs–Marietta" Metropolitan Statistical Area (MSA) as designated by the U.S. Office of Management and Budget (OMB) in 2010. The Hall County is included for various planning purposes by the Atlanta Regional Commission (ARC) outside the MSA. Georgia's capital and largest city, City of Atlanta, resides in the center of the region. The study area also includes many smaller cities and emerging suburbs and exurbs. The total area is approximately 23,072 km^2, which strides across three Landsat Thematic Mapper (TM) image scenes.

Physiographically, the Atlanta metropolitan area is mostly located in the low foothills of the southern Appalachian Mountains in north Georgia. The northwestern portion (approximately 7% of the total area) lies in the Appalachians and tends to be higher in elevation and significantly hillier than the southeast. The average elevation is approximately 300 m above sea level. The Atlanta metropolitan area is characterized by a humid subtropical climate with four seasons. The Chattahoochee River runs from northeast to southwest of this area.

Since the 1970s, Atlanta has experienced a rapid growth in both the population and the spatial extent. Population had increased 30–40% each decade between 1970 and 2000. The metro area expanded outward on the fringe of cities at the cost of forest and cropland. The rapid growth and suburbanization process had continued to the new century. According to the U.S. Census Bureau, the population in the 28-county Atlanta MSA had increased 24% between 2000 and 2010, which was the second-highest among the nation's largest metro areas. The entire metropolis is characterized by a complex mosaic of urban and suburban landscapes, with a combination of diverse land use and land cover types at varying spatial scales. Given its restless growth and complex patterns,