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Exurban development derived from Landsat from 1986 to 2009 surrounding the District of Columbia, USA

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ABSTRACT

People's preference for living in rural areas is converting rural landscapes into low-density residential development (i.e., exurban development). To assess the environmental impacts of exurban development (e.g., habitat fragmentation, threats to wildlife, and increased demand for natural resources), accurate maps of its spatial extent and change over time are needed. Mapping technologies that are based on remote sensing spectral data alone have generally failed to separate exurban development from the surrounding landscape and from other mixed pixels with similar spectra. Although deciduous forests in the eastern United States are thought to have experienced a significant increase in exurbanized area, a rigorous assessment of exurban trends has yet to be undertaken. The purpose of this study was to develop a novel analytic approach to map exurban development and to assess its magnitude and rate in north-central Virginia and western Maryland. We applied spectral mixture analysis to Landsat TM images from 1986 to 2009 at 4 time steps to estimate the fractional cover of vegetation, shade, substrate, and non-photosynthetic vegetation endmembers within each image. Using training data based on aerial photos, we classified the resulting endmember fraction images using a decision tree. Finally, terminal nodes from the decision tree that did not differentiate between exurban and urban areas were analyzed using morphological spatial pattern analysis to assess the shape and form of landscape elements. Scattered, isolated pixels were considered representative of exurban development. Overall classification accuracies ranged from 93 to 98%, an improvement of up to 34% over the decision tree alone. Our mapping approach effectively identified 7.3% of north-central Virginia and western Maryland as exurban development. Exurban development had a substantial expansion in the region, increasing on average 6.1% per year between 1986 and 2009. The mapping of land-cover changes beyond urban fringe provides valuable information for policymakers, planners, and land managers tasked with managing and mitigating the potential adverse consequences of this increasingly common form of landscape change.

1. Introduction

Rural landscapes in the United States have changed dramatically in recent decades due to the rapid development of private rural lands into low-density residential development (i.e., exurban development). Based on US Census data, it has been estimated that exurban areas grew more than twice as fast as metropolitan areas in the 1990s (Berube et al., 2006) and cover 25% of the contiguous US (Brown et al., 2005). The preference to live in rural areas is threatening wildlife and degrading ecosystem services (Hansen et al., 2005; Huston, 2005; Liu et al., 2003). Evaluation of exurban development growth has been done for the United States (Brown et al., 2005; Theobald, 2005), in the Midwest (Gonzalez-Abraham et al., 2007; Radeloff et al., 2005a), and in the Mountain West (e.g., Gude et al., 2006; Theobald et al., 1996). Although the eastern deciduous forest region is thought to have had a significant increase in exurbanized area from 1950 to 2000 (Brown et al., 2005; Theobald, 2005), a rigorous assessment of exurban trends has yet to be undertaken for this region of rapid population growth.

Exurban development occurs in relatively less altered landscapes, often adjacent to or nearby protected lands, and land-use activities tend to be less intensive than in urban areas (Theobald, 2005). All these characteristics make exurban development difficult to detect and map with conventional land-use mapping technologies (McCauley & Goetz, 2004; Ward et al., 2000). For example, National Land Cover Data (NLCD) is thought to underestimate the total amount of developed land use for the Mid-Atlantic region by around 5% and low-density development is not recorded at all (Jones & Jarnagin, 2009). One reason is that NLCD is based on medium-resolution sensors (i.e., Landsat 30-m data) that detect exurban areas as a mixture of different surfaces (i.e., mixed pixels). When traditional classification techniques are used, mixed pixels are misclassified

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(Small, 2003; Xian & Crane, 2005). Exurban areas, where the average cleared land area is a quarter of a pixel (Maryland Department of Planning, 2008), are usually classified as forest. To avoid the mixed pixels problem when mapping exurban development, high spatial resolution satellite sensors (e.g., IKONOS 4-m data) offer an alternative. High resolution sensors can provide reliable land-cover classification and change detection results at a local level. However, high spatial resolution imagery generally lack long-term time series and the huge amount of data required to analyze large areas present challenges of processing loads, time, and cost (Lu et al., 2004; Ward et al., 2000). Therefore, medium-resolution imagery (e.g., Landsat 30-m data) remains the standard for regional to continental assessments of land-use change (including exurbanization) despite the analytical shortcomings of using these products.

Several methods used to quantify exurban development have used human population density (Theobald, 2001, 2005) and housing density information (Radeloff et al., 2005a,b), both based on data from US Census Bureau. While these approaches have been important in estimating the extent of exurban development nationally (Brown et al., 2005; Theobald, 2001; Theobald, 2001, 2005), and regionally (e.g., Radeloff et al., 2005b; Theobald et al., 1996), there are limitations. Due to privacy issues, data from the US Census Bureau are aggregated in census block groups. Block groups change with each census, vary in shape and size, and become larger and larger beyond the urban fringe (Clark et al., 2009). The variable-sized block groups cause possible inaccuracies, but there is no easy and practical solution to these difficulties (Longley et al., 2001). In addition, population data from the US Census Bureau are tied to the primary place of residence; therefore, measures based on population underestimate exurban development because housing units in the form of vacation and second homes are not represented (Theobald, 2005). Housing density is a more complete and consistent measure of exurban development than population density (Theobald, 2005), but issues about disaggregating block groups still persist (Radeloff et al., 2005b).

Other approaches to quantify exurban development use tax property data (McCauley & Goetz, 2004), nighttime satellite imagery (Cova et al., 2004; Sutton et al., 2006; Sutton et al., 2010), and maps of impervious surface (Xian & Crane, 2005). Although tax property data provide digitized property-specific information, not all counties have this information available and different counties have different systems to store these data. Night lights are a good indicator of development and human habitation. However, the area and intensity of illumination vary significantly with density of settlement (Elvidge et al., 1997) and the spatial extent of lighted areas is consistently larger than the extent of developed land due to the blooming effect (Small et al., 2005, 2011). Impervious surface is quantified as a continuous field as opposed to discrete categories, is a well accepted indicator of urbanization (Dougherty et al., 2004; Goetz et al., 2003; Jantz et al., 2005), and has been used to estimate development in urban and suburban areas (Xian & Crane, 2005). Whereas impervious surface indicates human alteration and the amount of impervious surface increases with density of development, there is a significant overlap in the amount of impervious surface among urban, suburban, and exurban areas, which makes threshold selection problematic when mapping exurban development. In addition, estimates of impervious surface are greatly influenced by the type of imagery used, exurban development does not always include a large portion of impervious surface (Irwin et al., 2007; Yang et al., 2003), and mixed pixel spectra in exurban areas are likely to be very different from mixed pixels in suburban or urban areas (i.e., formed by a different mixture of spectra).

To enhance the understanding of exurban development in the eastern US, we developed a novel analytic approach (using spectral mixture analysis and morphological spatial pattern analysis) to map exurban development and assess its magnitude and rate in north-central Virginia and western Maryland. We used the consistent, long time series of medium-resolution Landsat imagery that is broadly, and now, freely available. This study is unique in that it describes mixed pixels containing exurban development as a combination of land covers and then uses decision trees and morphological spatial pattern analysis to further separate exurban development from other forest disturbing events. Quantifying the pervasiveness of exurban development in the eastern United States provides an important perspective on the land-use pressure facing eastern deciduous forests.

2. Methods

2.1. Study site

This study was conducted in 9 counties in north-central Virginia, US and 2 in western Maryland, US: Virginia-Clarke, Culpeper, Fauquier, Frederick, Madison, Page, Rappahannock, Shenandoah, and Warren Counties; Maryland-Washington and most of Frederick (Fig. 1). Virginia has the 12th largest population in the nation (8,001,024 people; U.S. Census Bureau, 2010) with an annual growth rate of 11% since 2000, and this growth is driven mostly by northern Virginia (Weldon Cooper Center, 2010). For example, Loudoun County alone has experienced a population increase of 78% since 2000, and accounts for one-sixth of the total population increase for the entire state. Counties included in the study area had growth rates ranging from 40% (Culpeper County) to 4% (Page County) between 2000 and 2009 (U.S. Census Bureau, 2010). Population density in the study region ranges from 10.7 persons/km^2 (Rappahannock County) to 135.9 persons/km^2 (Frederick County in Maryland) for a total population of 709,337 people (U.S. Census Bureau, 2010). One reason for the growth is the easy access and connectivity to the metropolitan Washington, DC area, which provides employment opportunities even within the current economic climate (Weldon Cooper Center, 2010).

2.2. Landsat data and preprocessing

Eight Landsat 5 Thematic Mapper images (WRS path16 row 32 and path16 row 33) were acquired from 1986 to 2009 at 4 time steps (1986, 1993, 2000, and 2009; Table 1). Image dates were selected from relatively cloud-free scenes (<10%) acquired during late spring or early summer. Georeferencing was performed at the USGS prior to downloading the data (L1T level of systematic geometric accuracy) and no further refinement was deemed necessary. Two preprocessing steps were performed on the Landsat TM data sets: atmospheric correction and topographic correction. The primary goal of atmospheric correction was to adjust the multitemporal dataset to a common radiometric scale (Song et al., 2001), therefore we employed a dark object subtraction to remove scene-by-scene variation in atmospheric scattering (Chavez, 1989; Song et al., 2001). This technique assumes the existence of dark objects (i.e., zero or small surface reflectance) throughout a scene and a horizontally homogeneous atmosphere. The minimum DN value from the entire scene is attributed to the effect of the atmosphere and is subtracted from all the pixels. This relatively simple correction method has been shown to improve classification and change detection accuracies at least as well as more complicated algorithms (Song et al., 2001). Topographic correction was performed to compensate for direction and illumination effects due to terrain and sun angle (Campbell, 2002). Because topographic shading is not only due to slope but also to shadowing of one tree crown over another, we used sun-canopy-sensor correction (SCS; Gu & Gillespie, 1998). The SCS method normalizes the sunlit area as a function of the geometry among the sun, sensor, and terrain slope. We did not apply exoatmospheric correction, which accounts for variability in irradiance due to sun radiance, sun–earth distance, and the cosine of the sun incidence angle, because the corrections we did make addressed larger sources of spectral variability between image dates. The applied sun-canopy-sensor correction, for example,