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Characterizing the magnitude, timing and duration of urban growth from time series of Landsat-based estimates of impervious cover

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ABSTRACT

Understanding the dynamics of land-change processes in urban areas requires long-term land cover and land use data at high spatial and temporal resolution. Extending an established procedure for deriving annual, fractional estimates of impervious surface cover (ISC) from per-pixel Landsat composites, here we propose a new post-classification methodology that characterizes ISC change as a continuous field in space and time. The method statistically derives the magnitude, timing and duration of ISC change at a per-pixel basis. We applied the method to a series of ISC maps of the Washington DC-Baltimore metropolitan region at an annual resolution from 1984 to 2010 to analyze the spatial, temporal and thematic patterns of urban/suburban land development. Our method was highly reliable for detecting and characterizing change, with producer's accuracy of the change-year classes (timing layer) varying between 59.4% and 97.4% and user's accuracy varying between 54.7% and 91.7%, based on a sample of independent validation points. Most misclassifications were found between neighboring years; relaxing the estimated change-year to ± 1 year increased both producer's and user's accuracy to >80%. The derived change products showed that newly developed pixels on average had a 46% increase in ISC, with the majority (80%) reaching their ISC saturation level in ≤3 years. Across the study region, annual growth in impervious surface area accelerated from ~6 km^2/year (0.7% of urban area in 1984) in the mid-1980s to ~12 km^2/year in the late-2010s, with a large inter-annual variability among municipalities and over successive years. Of these emerged urban pixels, 89% were converted from non-urban to low- and medium-density urban features, mostly suburban residential land use. However, the relative proportions of low-, medium- and high-density urban development changed dramatically over the study period, indicating that urban sprawl of the metropolis experienced major transitions in terms of land use intensity in the past three decades. Although primarily designed for change detection, our method can also be used as a temporal smoothing technique to remove noise in time-series of land cover datasets. Our results highlight the value of mapping and monitoring urban land expansion as continuous fields along the spatial-temporal-thematic dimensions for understanding the dynamics of urban land-change.

1. Introduction

Urbanization is one of the most important dimensions of contemporary global change. Today 54% of the world's population lives in urban areas, and this proportion is expected to increase to 66% by 2050 (United Nations, 2014). But as urban populations grow, urban population densities are decreasing, suggesting that urban land use is expanding faster than population growth (Angel, Parent, Civco, Blei, & Potere, 2011; Marshall, 2007; Seto, Fragkias, Güneralp, & Reilly, 2011; Seto, Sánchez-Rodríguez, & Fragkias, 2010). If these trends continue, a massive demand for built-up areas should be anticipated in the next few decades, with global urban land area tripling its 2000 coverage by 2030 (Seto, Guneralp, & Hutyra, 2012).

Urban areas play a central role in efforts to adapt to and mitigate climate and other ecosystem changes (Seto et al., 2014). Cities are responsible for 76% of global energy use and associated greenhouse gas emissions (Grubler et al., 2012). Urban population growth is also a main driver of tropical deforestation, which is the second largest anthropogenic source of carbon dioxide emissions (DeFries, Rudel, Uriarte, & Hansen, 2010; van der Werf et al., 2009). However, there are still significant uncertainties as to how cities will develop in the future (Seto et al., 2014). The mechanisms of city development are often studied with simulation models (Batty, 2009; BenDor, Westervelt, Song, & Sexton, 2013; Clarke & Gaydos, 1998; Jantz, Goetz, & Shelley, 2003; Waddell, 2002; Westervelt, BenDor, & Sexton, 2011). Urban growth models, or more generally land-change models have benefited greatly in recent years from the proliferation of modeling techniques and the increasing availability of geographic datasets (Brown, Verburg, Pontius, & Lange, 2013). An important research opportunity to advance future models and understanding is to incorporate satellite observations

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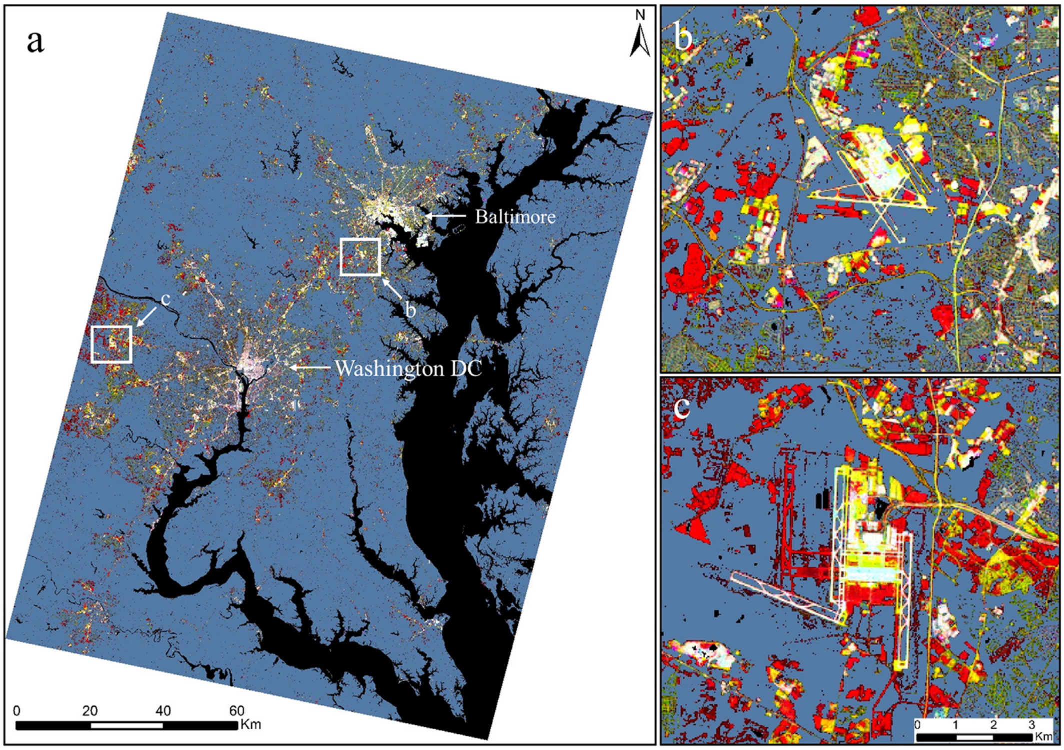

Fig. 1. Twenty-six years of annual percent impervious surface estimates over the Washington DC-Baltimore metropolitan region shown in three year composites: Red 2010, Green 1996 and Blue 1984. Overview of the study region is shown in (a). Urban development surrounding the two major international airports (Baltimore-Washington airport and Dulles airport) is shown in (b) and (c) respectively. Pixels in grey and blue are unchanged pixels with dark blue representing 0% ISC and white representing 100% ISC. Pixels in red indicate an increase in impervious surface between 1996 and 2010 and pixels in yellow indicate an increase in impervious surface between 1984 and 1996.

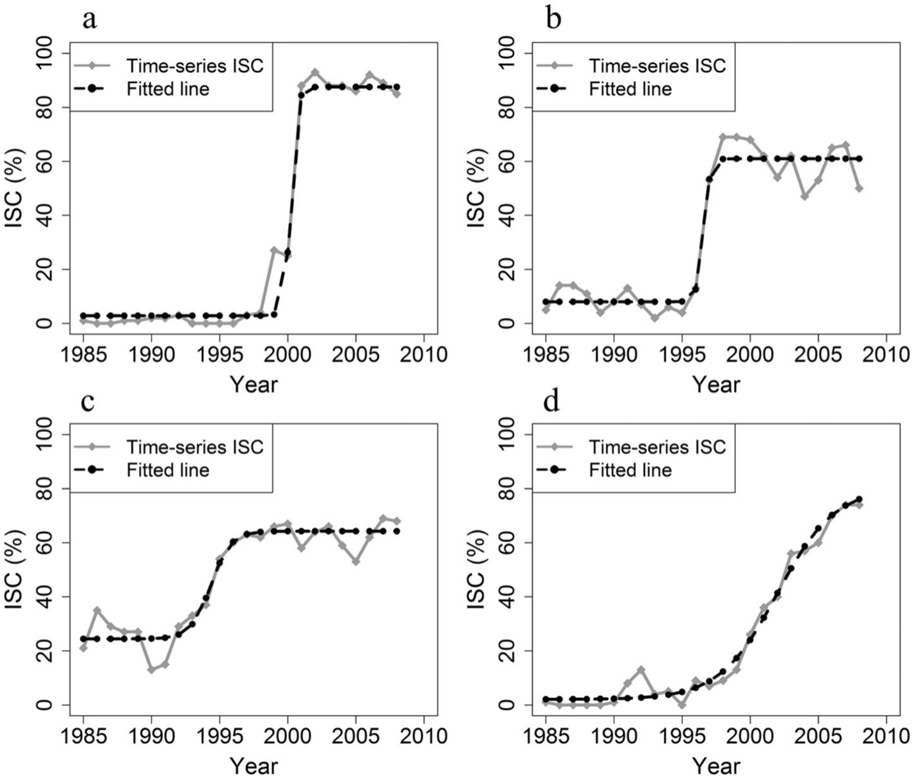

Fig. 2. Typical urban growth trajectories in terms of impervious surface cover. Solid grey lines represent annual ISC estimates and dashed black lines represent the temporally smoothed curves after logistic fitting. (a) An example of rapid development from non-urban to high-density urban. (b) Rapid development from non-urban to moderate-density urban. (c) Rapid development from low-density urban to moderate-density urban. (d) Slow development from non-urban to high-density urban. Cases (a), (b) and (c) are common but cases like (d) are rare in the study area.