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Locally optimized separability enhancement indices for urban land cover mapping: Exploring thermal environmental consequences of rapid urbanization in Addis Ababa, Ethiopia

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ABSTRACT

Landsat data were used to assess urbanization-induced dynamics in Land use/cover (LULC), surface thermal intensity, and its relationships with urban biophysical composition. The study was undertaken in Addis Ababa city, Ethiopia. Ground-based data and high resolution images were used as reference data in LULC classification. To more accurately quantify landscape patterns and their changes, we applied new locally optimized separability enhancement indices and decision rules (SEI–DR approach) to address commonly observed classification accuracy problems in urban environments. We tested the SEI–DR approach using eight Landsat images acquired between 1985 and 2010. Two approaches were applied to quantify surface heat intensity (SHIn) and to examine its spatial patterns over 25 years: thermal gradient analysis and hot spot analysis. A Simultaneous Autoregressive Spatial error model (SARerr) was used to explore relationships between surface temperature and biophysical variables describing urban surfaces. Compared to Maximum Likelihood (ML) and Support Vector Machine (SVM) classification, accuracy improvement achieved through use of the SEI–DR procedure was, respectively, 6% and 5% and the differences were statistically significant ($P < 0.05$). The Surface Heat Intensity (SHIn) analysis showed increasing contrast (1985-2010) between urban centers and the outskirt. On average, outskirts were cooler than central urban areas by up to 3.7 °C. We detected statistically significant differences in intra-urban thermal aggregation ($P < 0.01$) and the differences ranged from 4.4 °C to 5.3 °C. Increasing heat intensity was observed between 1985 and 2010. However, we observed no clear evidence of urban areas being warmer than rural. Built-up surfaces and bare soil showed similar positive relationships with surface temperature ($P < 0.01$), while vegetation showed a negative relationship ($P < 0.05$). We conclude that with rapid urbanization, thermal intensity increased but relationships with vegetation suggest that options for mitigating urban warming in tropical climates may be available. The development of a new urban classification method, use of hotspot analysis, and the investigations of the UHI for an African city fill important research gaps for studies of urban thermal variation.

1. Introduction

Currently over half of the world's population lives in urban areas and by 2050 this figure is projected to rise to 70%, with almost all of the growth occurring in developing regions (Forbes, 2011). Africa still is the least urbanized region of the world, and in particular the Eastern sub-region is characterized by low level of urbanization (The World Bank, 2012). However, currently African urban growth rates are among the highest in the world with an annual urban population growth of 3.3% between 2005 and 2010 (UN-HABITAT, 2010). Urbanization is one of the most important drivers of environmental changes in recent years (Grimm et al., 2008). Detrimental environmental consequences of urbanization are well studied and understood (Elmqvist et al., 2013; Grimm et al., 2008). Changes in ecological functioning and local warming, the phenomenon commonly described as the urban heat island (UHI) effect, are among the most noticeable environmental impacts of urbanization (Grimm et al., 2008). Thermal impacts of rapid urban expansion in Africa are given limited research attention; particularly remote sensing studies addressing urbanization-induced environmental changes in Africa are rare.

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Surface urban heat island (SUHI) is a widely studied form of environmental impacts of urbanization and associated alterations in Land use/cover (LULC) types. The SUHI is commonly studied using satellite-based thermal infrared remote sensing (RS) technologies (Weng, 2014) and recently SUHI has gained increasing scientific attention (Imhoff, Zhang, Wolfe, & Bounoua, 2010; Weng, 2014). Despite the enormous literature on remote sensing based urban thermal studies, there is still inconsistency in procedures for estimating magnitudes of SUHI and lack of information about African cities. Magnitude and patterns of SUHI vary considerably with urban-specific factors such as climatic location of cities (Lazzarini, Marpu, Molini, Ouarda, & Ghedira, 2014; Marpu, Lazzarini, Molini, & Ghedira, 2013), their sizes (Imhoff et al., 2010), seasonality and time of the day (Kato & Yamaguchi, 2005; Wang, Huang, Fu, & Atkinson, 2015), and biophysical variables characterizing the cities (Deng & Wu, 2013; Rotem-Mindali, Michael, Helman, & Lensky, 2015).

The capability of satellite thermal remote sensing in acquiring surface temperature synchronously over large areas allows rapid assessment of thermal variations in space and time. Satellite-based surface thermal information, such as from Landsat sensors, is often coupled with spectral reflectance data enabling simultaneous analysis of spatial and temporal relationships between surface temperature and LULC. However, the potentials of RS in urban LULC studies are often constrained by poor classification accuracy (Myint, Gober, Brazel, Grossman-Clarke, & Weng, 2011; Rashed & Jürgens, 2010). Urban LULC classification and change analyses are challenging due to the heterogeneity of surfaces in urban environments (Weng, 2012). In situations where data are scarce and the use of coarse spectral resolution data such as Landsat imagery is an option, and in the presence of land cover types of similar spectral characteristics, LULC classification and change analyses over long time spans are even more challenging. When inaccurate classification results are used in spatial modeling to study the effects of urban biophysical variables on thermal variations, the results could be unrealistic and biased. Hence, accurate classification is essential not only to understand the dynamics of LULC but also to model spatial relationships that depend on classification outputs.

For several years enormous efforts have been devoted to improve accuracy of urban land cover classification (Jebur, Mohd Shafri, Pradhan, & Tehrany, 2014; Liu, Skidmore, & Van Oosten, 2002; Lu & Weng, 2004; Salehi, Sahebi, & Maghsoudi, 2014; Yan, Shaker, & El-Ashmawy, 2015). The accuracy of RS of urban LULC mainly depends on spatial resolution of images used (Pu & Landry, 2012) and classification methods applied (Aguirre-Gutierrez, Seijmonsbergen, & Duivenvoorden, 2012; Weng, 2012). Depending on types of imagery data (Chen, Stow, & Gong, 2004; Myint et al., 2011; Sisodia, Tiwari, & Kumar, 2014), and size of training samples (Li, Wang, Wang, Hu, & Gong, 2014; Myburgh & van Niekerk, 2014), studies have come up with inconsistent recommendations of selection of classification methods. Methods that perform well in

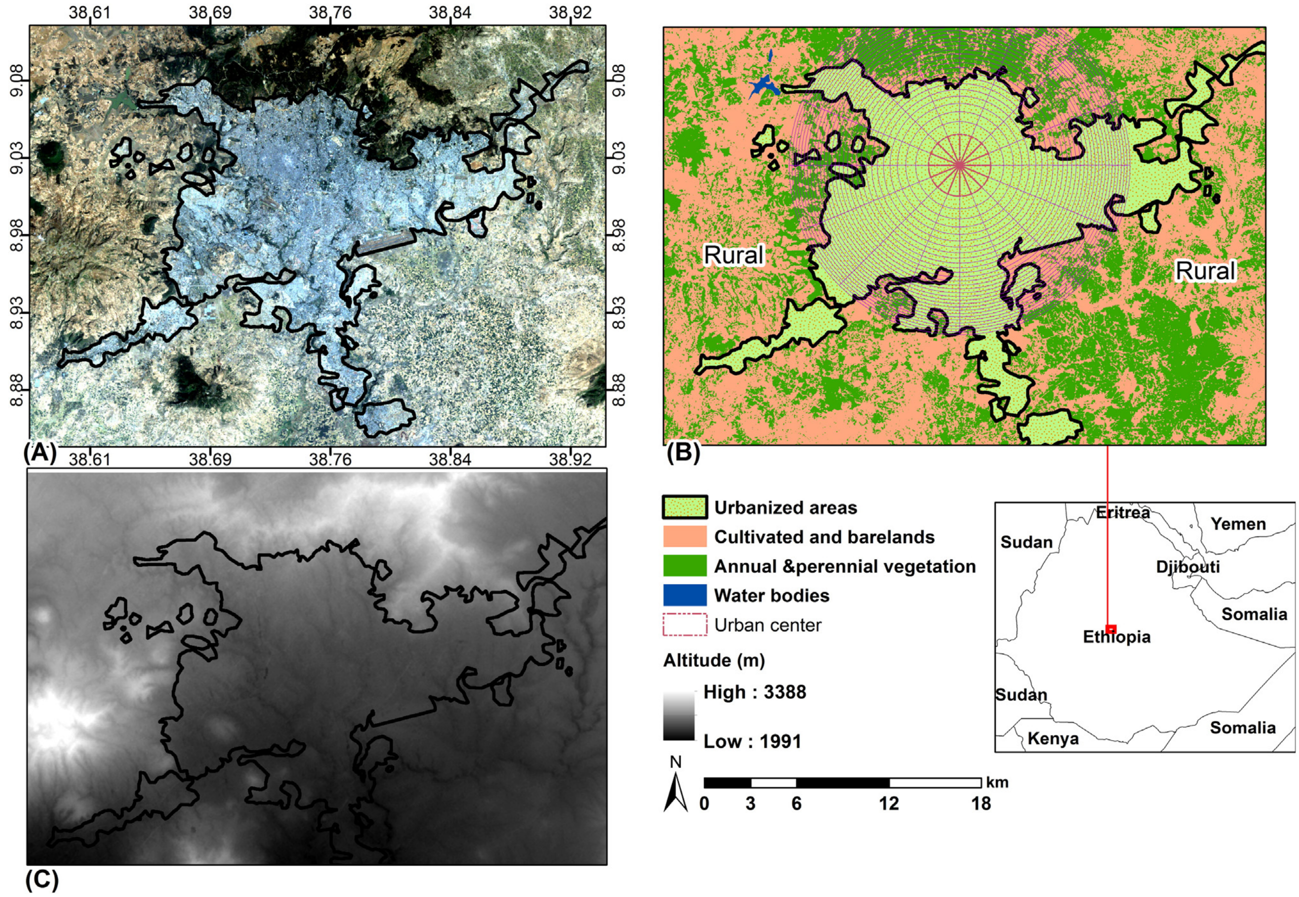

Fig. 1. Study site map showing: (A) a true color composite of Landsat reflective bands showing urbanized area extent (image acquisition date: December 9, 2010); (B) major land cover types around urbanized zone, and a spider-web pattern used in studying surface thermal behavior at increasing distance from the center and in different directions, and its relationships with urban biophysical characteristics; (C) topography of the area. Urban area within 2 km from approximate center of the city was considered as urban center and areas within 2 km from boundary of urbanized zone (inward) were considered 'outskirt'.