Mapping decades of urban growth and development with multi-temporal spectral mixture models

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Abstract. The Landsat program provides more than three decades of decameter resolution multispectral observations of the growth and evolution of human settlements and development worldwide. While these changes are often easy to observe visually, accurate repeatable quantification has proven elusive. In part, this is a consequence of the multi-scale heterogeneity and diversity of human settlements worldwide. Efforts to map urban extent are also confounded by the lack of a single, physically-based, definition of what constitutes urban, suburban, peri-urban and other types of human settlement. We attempt to resolve both of these challenges by quantifying changes in human modified environments in terms of measurable changes in their physical properties. This is accomplished using standardized spectral endmember fractions to represent combinations of the most spectrally and functionally distinct components of land cover; soil and impervious substrates, vegetation, water and shadow. The spectral similarity of soils and impervious substrates that makes thematic classifications error prone can be resolved by using multi-season composites of spectral endmembers to distinguish spectrally stable impervious substrates from temporally variable soil reflectance resulting from seasonal changes in moisture content (thus albedo) and fractional vegetation cover. By representing the diversity of anthropogenic land use as a continuous mosaic of land cover it is possible to quantify the wide variety of human settlements in a way that is physically consistent, repeatable and scalable. By dispensing with discrete classification and its inherent loss of information, it is possible to quantify the physical changes that characterize the growth and evolution of the built environment.

Keywords: urban, land cover, Landsat, multi-temporal, spectral mixture, remote sensing.

1. Introduction

Accurate, consistent mapping of human settlements with remotely sensed imagery is challenging. In part, this is a consequence of the multi-scale heterogeneity and diversity of human settlements worldwide. Efforts to map urban extent are also confounded by the lack of a single, physically-based, definition of what constitutes urban, suburban, peri-urban and other types of human settlement. We attempt to resolve both of these challenges by quantifying changes in human modified environments in terms of measurable changes in their physical properties.

The Landsat program provides more than three decades of decameter resolution multispectral observations of the growth and evolution of human settlements and development worldwide. While these changes are often easy to observe visually, accurate repeatable quantification has proven elusive . Despite the challenges described above, the Landsat program provides the longest and most geographically extensive imaging of anthropogenic land cover currently available. As such, it provides an accurate, wellcalibrated representation of the physical properties of the human habitat and how it has changed over the past three decades.

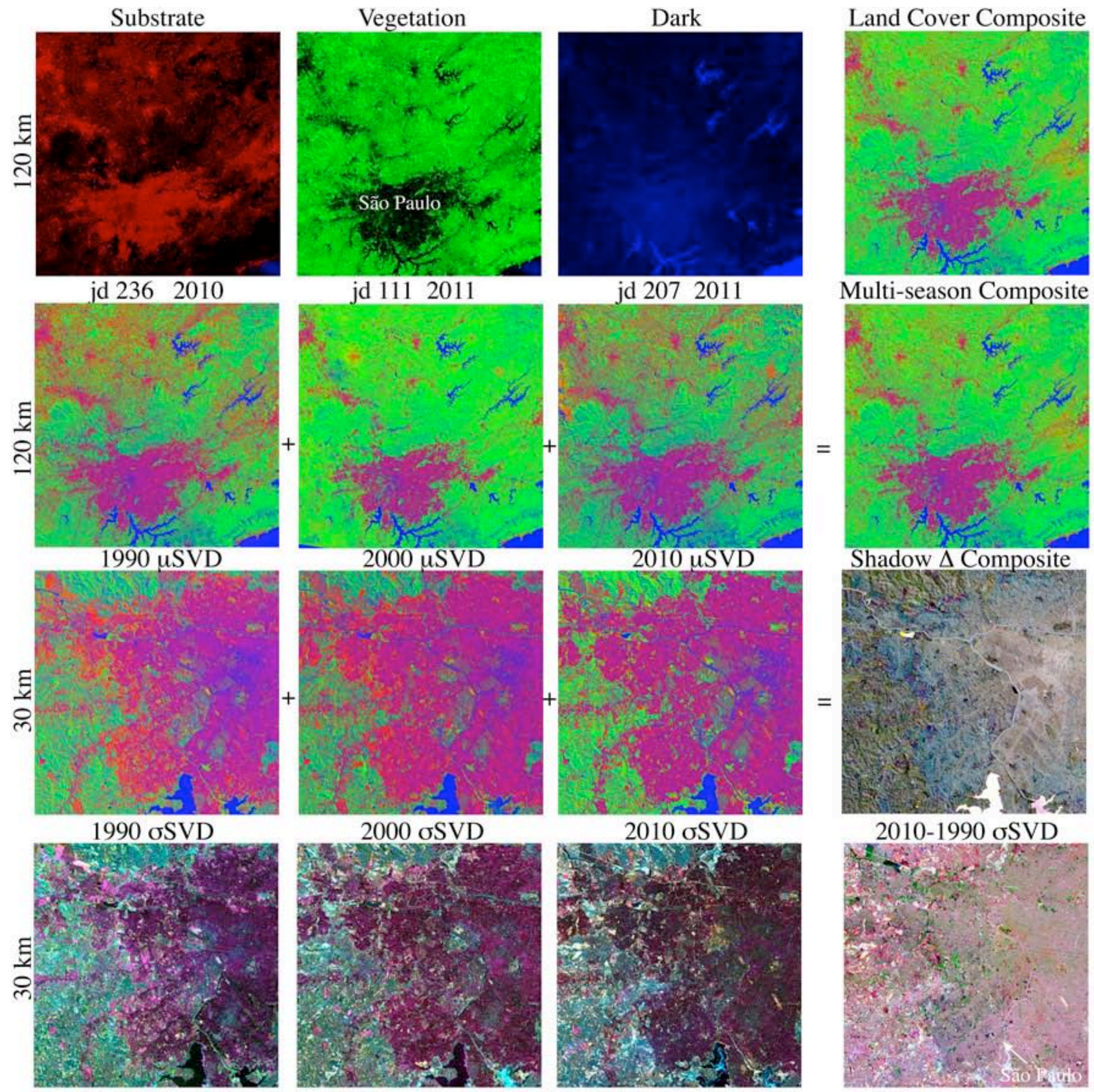

Figure 1 Urban growth and development as continuous field color composites of São Paulo. *Land Cover Composite* (top row); Diversity of land cover at subpixel scales can be represented as RGB composites of Substrates (rock, soil, impervious), Vegetation (trees, grasses, agriculture) and Darks (shadow, water). SVD endmember fractions can be estimated with Landsat multispectral imagery from the mid-1980s to present. *Multi-season Composite* (upper middle row); Seasonal variability of reflectance and illumination can highlight different types of land cover in multi-season averages of SVD fractions. Soils are distinguished from impervious substrates by greater variability resulting from seasonal variations in moisture and vegetation cover. Temporally stable impervious substrates in urban areas (red) are mixed with persistent building shadow (blue) at the scale of Landsat's 30m pixel. *Fraction Change Composite* (lower middle row); Increasing shadow fraction in peri-urban municipalities of São Paulo over the past two decades is depicted in SVD μ composites as a progressive change from red to magenta. The shadow change composite (R: D_{1990} G: D_{2000} B: D_{2010}) clearly shows a blue halo in the peri-urban areas and isolated patches of blue within the urban core where high rise construction has occured since 1990. *Stability Change Composite* (bottom row); seasonal variability (σ) of S,V and D shows pronounced difference between stable impervious reflectance and more variable soil and vegetation reflectance in surrounding areas. Differencing the σ images for S,V and D highlights decadal land cover changes as changes in spectral variability.

We present an approach to mapping human-modified landscapes (urban or otherwise) that avoids the loss of information and introduction of error inherent in discrete thematic classification by mapping the continuum of land cover in terms of the physical properties of the most spectrally and functionally distinct components of terrestrial land cover. This is accomplished using standardized spectral endmember fractions to represent combinations of the most spectrally and functionally distinct components of land cover; soil and impervious substrates, vegetation, water and shadow. The spectral similarity of soils and impervious substrates that makes thematic classifications error prone can be resolved by using multi-season composites of spectral endmembers to distinguish spectrally stable impervious substrates from temporally variable soil reflectance resulting from seasonal changes in moisture content (thus albedo) and fractional vegetation cover. We illustrate the utility of this approach by mapping land cover changes associated with the growth and evolution of São Paulo and the Southeast Corridor of Brasil between 1990 and 2010.

2. Methodology

The spectral properties of a wide range of land cover types can be accurately represented as areal fractions of spectrally distinct endmembers. The relative areal abundance of spectral endmembers present in a spectrally mixed pixel can be estimated using linear spectral mixture models (Adams et al. 1986). Linear spectral mixture models are often used with location-specific spectral end members – but they can also be used with standardized global spectral endmembers (Small and Milesi 2013). Using standardized spectral endmembers allows estimates of endmember fractions to be compared between different places and times.

In this analysis we represent the continuum of land cover as continuous fractions of rock, soil and impervious Substrate (S), Vegetation (V), and Dark (D) features like water and shadow. We use standardized SVD endmembers from (Small and Milesi 2013) to unmix intercalibrated exoatmospheric reflectance from Landsat Level 1T imagery provided by the USGS.

The spectral similarity of soils and impervious substrates that makes thematic classifications error prone can be resolved by using multi-season composites of spectral endmembers to distinguish spectrally stable impervious substrates from temporally variable soil reflectance resulting from seasonal changes in moisture content (thus albedo) and fractional vegetation cover (Small et al. 2014). We use 4 to 7 individual Landsat scenes per year to produce multi-season SVD composites for São Paulo and surrounding areas of Brasil's Southeast Corridor in 1990, 2000 and 2010. Single scene SVD composites are used to compute the temporal mean and standard deviation of S, V and D within each year. These components and their annual means and standard deviations are illustrated in Figure 1.

3. Results and Discussion

The decadal multi-season SVD fraction composites shown in Figure 1 illustrate the combined use of multi-season mean (μ) and standard deviation (σ) moments for S,V and D fractions simultaneously. The composites show decadal changes in land cover by continuous gradations in the seasonal mean land cover abundances and their seasonal variability.

One example of the kind of information that is lost by discrete thematic classifications is illustrated by the decadal changes in substrate and dark fractions with the developed area of São Paulo. The SVD fraction composites distinguish between high rise development where the extreme variability in building height results in large areas of shadow projected by tall buildings. These areas are easily distinguished on the mean SVD composites in Figure 1 by the magenta color indicative of a mixture of illuminated substrate (red) and building shadow (blue). The variability maps indicate that the reflectance of these areas is stable throughout the year. In contrast, the areas at the periphery of the city have lower dark fractions and higher substrate fractions because low rise, low intensity development results in less variability in building height and therefore less intra-building shadow. Decadal changes in building density, and therefore intra-building shadow, result in an increase in shadow fraction revealed by the blue halo around the periphery of the city as low rise vertical development continues and more buildings add individual stories. Figure 2 shows the overall change in substrate and dark fraction distributions between 1990 and 2010 for São Paulo and adjacent areas. The scatterplots show the simultaneous decrease in substrate fractions and increase in dark fractions associated with vertical growth of the city – both from high rise and low rise development.

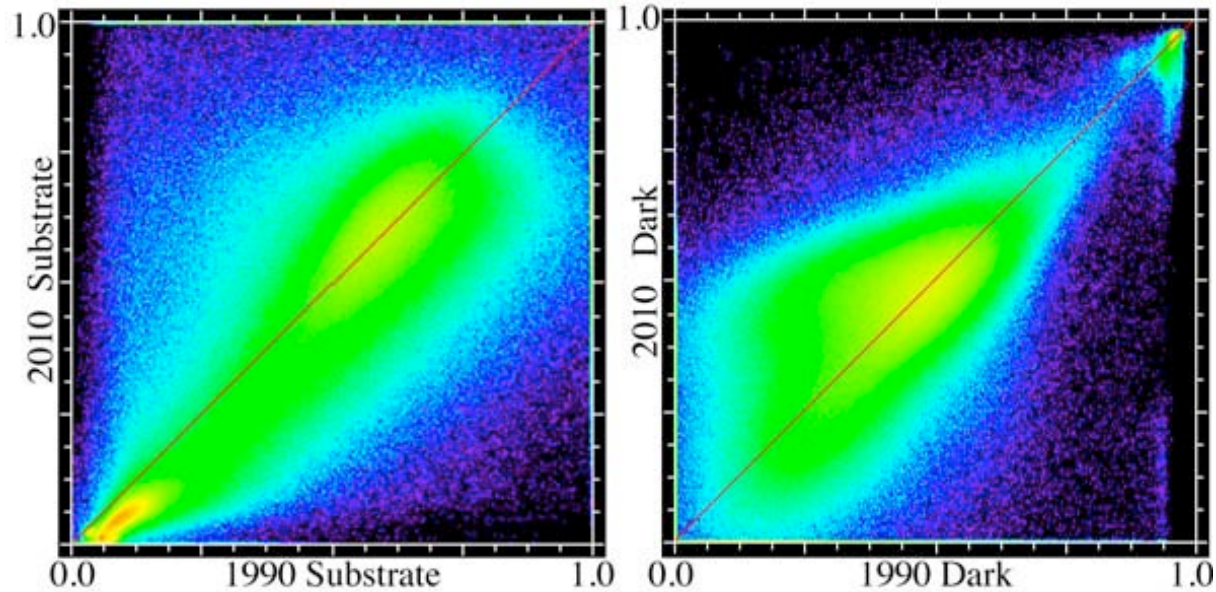

Figure 2 Change in land cover fractions between 1990 and 2010. Simultaneous decrease of substrate over full range and increase of low to medium dark fractions results from increased shadowing of impervious surfaces as both high and low rise height variability increases in developed areas.

The increase in building density and height variability inferred to cause the increase in shadow fraction can be vicariously validated by comparing high spatial resolution imagery collected under similar solar illumination conditions. Figures 3, 4 and 5 illustrate the changes in SVD fractions and the associated change in building height variability and shadow from Quickbird imagery.

By representing the diversity of anthropogenic land use as a continuous mosaic of land cover it is possible to quantify the wide variety of human settlements in a way that is physically consistent, repeatable and scalable. By dispensing with discrete classification and its inherent loss of information, it is possible to quantify the physical changes that characterize the growth and evolution of the built environment. One of the principal weaknesses inherent in discrete thematic classification is the need to make assumptions about the physical properties of developed environments. These physical properties change in time and are extremely variable – both within and between environments. By combining the spectral characteristics of land cover with its temporal variability (or stability) we are able to distinguish between spectrally similar materials (e.g. soils and impervious surfaces) on the basis of their behavior on short time scales.

Figure 3 Low rise infill development and vertical growth of Carapicuíba São Paulo between 2002 and 2010. Quickbird natural color composites (top & center) collected under similar solar illumination show narrowing and paving of streets, construction on green space and increased shadow from vertical growth. Multi-season Landsat SVD composites from 2000 and 2010 (bottom) show increase in dark fraction.

Figure 4 High rise development in and around Morumbi São Paulo between 2004 and 2014. Quickbird natural color composites (top,& center) collected under similar solar illumination show increased shadow from a large increase in the number of high rise buildings casting shadows several times their footprint. Multi-season Landsat SVD composites from 2000 and 2010 (bottom) show conspicuous increase in dark fractions.

Figure 5 Interspersed high and low rise development in and around Paraisópolis São Paulo between 2005 and 2014. Quickbird natural color composites (top,& center) collected under similar solar illumination show increased shadow from both types of development at different spatial scales. Multi-season Landsat SVD composites from 2000 and 2010 (bottom) show some increasese in dark fraction of Paraisópolis but more in the high rise southwest.

A parallel benefit of using continuous field depictions of physical properties to represent anthropogenically modified environments is the non-necessity of defining heterogeneous environments with an assumption of homogeneity or arbitrary physical properties that are not consistent from place to place. Many physical process models of land surface phenomena rely more on the physical properties of the landscape than its formal definition. These models can use spectral endmember fractions directly, or as parameterized inputs. In cases where its absolutely necessary to represent the land surface as discrete thematic classes, decision trees can be used to discretize continuous fields on the basis of clearly defined (and therefore repeatable) decision boundaries applied to the spectral endmember fractions – rather than arbitrary, and often sensitive, statistical decision boundaries (e.g. Maximum Likelihood).

4. Acknowledgements

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