Spatiotemporal Monitoring of Urban Vegetation

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Monitoring spatiotemporal changes in urban agglomorations will become increasingly important as the number and proportion of urban residents continue to increase. Intra-urban variations in vegetation abundance influence environmental conditions and energy fluxes by selective reflection and absorbtion of solar radiation, by modulation of evapotranspiration and by sequestration of pollutants. The spatiotemporal distribution of vegetation may be effectively monitored with multispectral satellite observations. This study examines spatiotemporal analysis of urban vegetation using a linear spectral mixing model to estimate vegetation abundance from Landsat TM data. The inherent dimensionality of TM imagery of the New York City area suggests that urban reflectance measurements may be described by linear mixing between high albedo, low albedo and vegetative endmembers. Quantitative validation using vegetation abundance measurements from high resolution aerial photography shows agreement to within fractional abundances of 0.1 for vegetation fractions greater than 0.2. A spatiotemporal analysis of vegetation fraction in the New York metro area in 1996 shows intra-urban gradients of several tens of percent and pronounced spatial variations in phenology.

URBAN VEGETATION

The spatiotemporal distribution of vegetation is a fundamental component of the urban/suburban environment. Vegetation influences urban environmental conditions and energy fluxes by selective reflection and absorption of solar radiation (e.g. *Goward et al, 1985; Roth et al, 1989; Gallo et al, 1993*) and by modulation of evapotranspiration (e.g. *Price, 1990; Carlson et al, 1994; Gillies et al, 1997; Owen et al, 1998*). The presence and abundance of vegetation in urban areas as long been recognised as a strong influence on energy demand and development of the urban heat island (e.g. *Harrington, 1977; Oke, 1982; Huang et. al., 1987*). Urban vegetation abundance may also influence air quality and human health (*Wagrowski and Hites, 1997*) because trees provide surface area for sequestration of particulate matter and ozone. Urban vegetation experiences both short and long term phenological changes and may itself be sensitive to subtle changes in environmental conditions. Changes in the built component of the urban environment are generally documented at various levels of detail but phenological changes in urban vegetation are not subject to direct human control and are not generally monitored over large areas.

The synoptic view of the urban mosaic provided by satellite and airborne sensors is an important complement to *in situ* measurements of physical, environmental and socioeconomic variables in urban settings (*Forster, 1983).* Compared to agricultural areas and forests, however, application of remote sensing to studies of the urban environment has been rather limited. In part, this is because accurate identification of most built components of the urban environment requires finer spatial resolution than is offered by operational satellites such as Landsat or SPOT. The spatial resolution of the Landsat TM sensor is too coarse for identification of urban infrastructure but it is sufficient to detect significant spatial and temporal variations in urban vegetation and surface temperature. The objective of this paper is to present preliminary results of a spatiotemporal analysis of urban vegetation distribution in New York City and to discuss implications for environmental monitoring of evolving urban areas.

SPECTRAL MIXING AND URBAN REFLECTANCE

The characteristic spatial scale and the spectral variability of urban landcover poses serious problems for traditional image classification algorithms. In urban areas where the reflectance spectra of the landcover vary appreciably at scales comparable to, or smaller than, the Ground Instantaneous Field Of View (GIFOV) of most satellite sensors, the spectral reflectance of a individual pixel will generally not resemble the reflectance of a single landcover class but rather a mixture of the reflectances of two or more targets present within the GIFOV. Because they are combinations of spectrally distinct landcover types, mixed pixels in urban areas are frequently misclassified as other landcover classes.

Conversely, the definition of an urban spectral class will often misclassify pixels of other non-urban landcover.

If an urban area contains significant amounts of vegetation then the reflectance spectra measured by the sensor will be influenced by the reflectance characteristics of the vegetation. Macroscopic combinations of homogeneous "endmember" materials within the GIFOV often produce a composite reflectance spectrum that can be described as a linear combination of the spectra of the endmembers (*Singer and McCord, 1979*). If mixing between the endmember spectra is predominantly linear and the endmembers are known *apriori*, it may be possible to "unmix" individual pixels by estimating the fraction of each endmember in the composite reflectance of a mixed pixel (e.g. *Adams et al, 1986; Boardman, 1989; Smith et al, 1990)*. A variety of methods have been developed to estimate the areal abundance of endmember materials within mixed pixels - particularly for use with imaging spectrometers in geologic remote sensing (e.g. *Clark and Roush, 1984; Goetz et al 1985; Kruse, 1988; Boardman, 1989*) and vegetation mapping (e.g. *Smith et. al., 1985; Pech et. al., 1986; Elvidge et al, 1993; Roberts et al, 1993; Wessman et al, 1994*).

Analysis of Landsat TM imagery suggests that the spectral reflectance of the New York metropolitan area can be described as linear mixing of three distinct spectral endmembers (*Small, 1999*). Eigenvalue distributions suggest that the majority of Landsat TM scene variance is contained within a two dimensional mixing space. The corresponding triangular distribution of reflectances in feature space bears a strong similarity to the well known Tasseled Cap distribution discovered by *Kauth and Thomas (1976).* These feature space distributions are similar in the sense that both contain a vegetation endmember which is distinct from a mixing continuum between high and low albedo endmembers.

The spectral endmembers determined for the New York area correspond to low albedo (e.g. water, shadow, roofing), high albedo (e.g. cloud, sand, roofing) and vegetation. The strong visible absorbtion and infrared reflectance that is characteristic of vegetation is sufficiently distinct from the spectrally flat reflectance of the low and high albedo endmembers to allow the three components to be "unmixed" using a simple three component linear mixing model. The result of the unmixing is a set of fraction images showing the areal percentages of each endmember present within each pixel. Analysis of Landsat imagery of the New York area shows that a three component linear mixing model provides stable, consistent estimates of vegetation fraction for both constrained and unconstrained inversions using three different endmember selection methods *(Small, 1999)*. RMS misfits of the estimated endmember fractions to observed reflectances are generally low (95% < 0.02 RMS) with consistently lower misfit for vegetated areas and larger misfits for high albedo targets.

Spectral endmembers for a single image can be determined from the image itself but a multitemporal analysis requires that the spectral endmembers be consistent from scene to scene. In order to generate self consistent estimates of vegetation fraction it is necessary to minimize the effects of differences in illumination and atmosphere so that the changes observed represent actual changes in the target reflectance. A modification of the radiometric rectification procedures proposed by *Schott et al (1988)* and *Hall et al (1991)* was used to rectify a set of six Landsat scenes of the New York metro area acquired in 1996.

VALIDATION

The Landsat-derived vegetation fraction estimates discussed here were validated by comparison with high resolution (2 m) visible color aerial photography of central Manhattan acquired nine days prior to a Landsat overpass in July 1996. Details of the validation procedure are provided by *Small (1999).* Thirty four validation sites were chosen to span the full range of vegetation fraction (0 to 1) and a wide range of spatial scales from 1 to 930 Landsat TM pixels. The vegetation fraction estimates obtained from the Landsat imagery agree with the areal vegetation fractions measured from 2 m aerial photography to within fractional abundances of 0.1 for most areas with vegetation fractions greater than 0.2 (Fig.1).

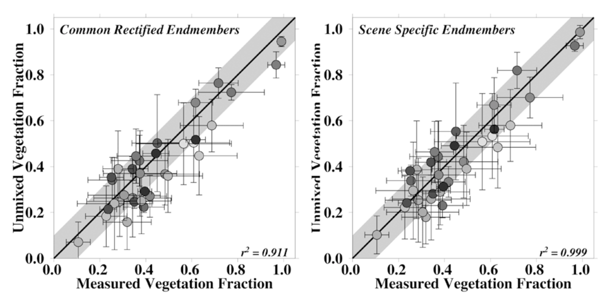

Figure 1. *Validation of vegetation fractions from Landsat imagery using both scene specific and radiometrically rectified endmembers. Mean values of unmixed vegetation fractions for sites of different sizes generally agree to within 10% of measured values (gray diagonal) for scene specific endmembers. Shading of the symbol is proportional to the area of the validation site ranging from 1 (dark) to 930 Landsat pixels. Bars show the standard deviation of the distribution of measured and unmixed vegetation fractions for each validation site.*

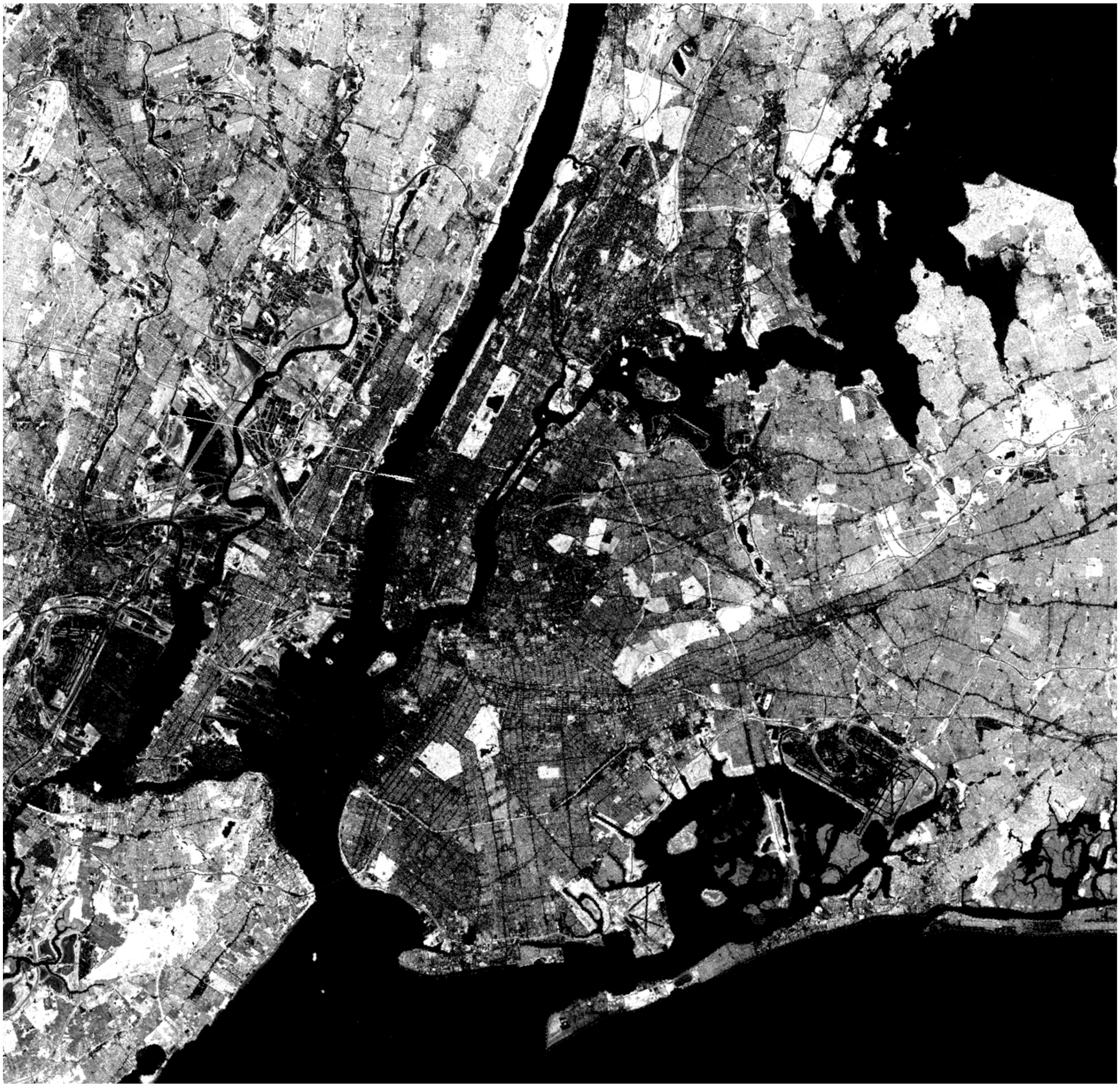

Figure 2. *Vegetation fraction image of the New York metro area derived from a Landsat TM scene acquired on 6/2/96. Gray shading shows vegetation fractions between 0 (black) and 0.7 and is saturated white for fractions greater than 0.7 to emphasize smaller intra-urban variations. Significant differences between neighborhoods result from different densities of street trees and courtyard vegetation. Color image available from http://www.LDEO.columbia.edu/~small/NYCveg.html*

SPATIOTEMPORAL ANALYSIS

Analysis of urban vegetation distribution in the New York metro area over the 1996 growing season reveals significant intra-urban variations in vegetation fraction as well as differences in phenological cycles. Fig. 2 shows the spatial variation in vegetation fraction for a representative scene acquired near the peak of the cycle and is stretched to emphasize these intra-urban differences at the expense of detail in the more densely vegetated parks and cemeteries. In Manhattan, all parks and public greenspaces are easily distinguished and real differences in street and courtyard vegetation are consistently detected. Within Central Park, varying fractions of shadow and vegetation endmembers distinguish between grass and trees and reveal variations in canopy architecture observed on high resolution airphotos. The images of the New York metro area clearly distinguish between industrial and residential areas and highlight the vegetation gradient between the city center and the suburbs.

Intra-urban vegetation fraction estimates vary by several tens of percent within the metro area with consistently higher vegetation fractions observed in the suburban areas on Long Island and in New Jersey. The absolute differences between neighborhoods are comparable to the error implied by Fig. 1 but neighborhood averages are internally self consistent suggesting that the magnitude of the differences may be accurate. Further validation is necessary to determine the accuracy of the method for different amounts of vegetation at various scales and spatial distributions. Different spatial configurations of vegetation within the GIFOV may result in different illumination conditions and multiple scattering which may influence the linearity of the spectral mixing. A systematic analysis of these factors under different atmospheric conditions should be conducted to calibrate the accuracy of the method.

Temporal analysis of the six 1996 Landsat images shows variations in the phenological cycle of deciduous vegetation in the New York metro area. The most obvious feature seen in these images is the early senesence of the wetland vegetation in Jamaica Bay and in the New Jersey Meadowlands. There is also some indication that the suburban areas had experienced greater senescence than the urban areas by the time that the October image was acquired but the magnitude of the difference is comparable to the measurement uncertainty so a more detailed analysis will be required to verify this observation. The temporal variation in the overall distribution of vegetation fraction indicates that the greatest seasonal variation occurs in areas having between 15% and 50% vegetation cover at full leaf-out.

Differences in the spatial distribution of vegetation may influence a number of environmental conditions ranging from urban heat island dynamics to air quality. Experiments to test these assertions are currently being planned. The spatial distribution and abundance of vegetation represents a boundary condition for radiation sinks and evapotranspiration sources that may be significant for the micrometeorology of the urban system. Similarly, the areal distribution of urban vegetation may act as a distributed sink for surface reactant pollutants such as particulate matter and ozone. Given adequate temporal resolution, vegetation fraction estimates may also be able to distinguish intra-urban differences in the phase of the phenological cycle related to differences in environmental conditions.

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