ESTIMATION AND VALIDATION OF URBAN VEGETATION ABUNDANCE BY SPECTRAL MIXTURE ANALYSIS

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ABSTRACT:

Moderate resolution (< 50 m) optical sensors can provide multitemporal imagery of urban vegetation distribution and abundance. Given a rigorous, repeatable and verifiable method for estimating vegetation abundance, this imagery could provide important inputs to mesoscale models of ecologic, hydrologic, climatic processes. Spectral mixture analyses produce vegetation fraction estimates that can be radiometrically rectified for change analyses and can be validated with high spatial resolution (<5 m) optical imagery. A simple three endmember linear mixture model produces stable estimates of vegetation fraction for a wide range of land use types in New York City. These estimates agree to within 10% with aggregated 2.8 m estimates derived from Quickbird imagery. The observed scatter between the 30 m Landsat estimates and the aggregated 2.8 m Quickbird estimates is generally less than 10% and cannot be explained by estimation error alone. The form of the scatter can be explained by a combination of estimation error and subpixel spatial uncertainty in the registration of the Landsat imagery. The scatter is consistent with a 6% estimation error combined with a 17 m spatial misregistration between the Landsat and Quickbird imagery

INTRODUCTION

Vegetation abundance and distribution are primary determinants of urban environmental conditions. In addition to its obvious aesthetic importance, vegetation exerts a strong influence on mass and energy fluxes through the urban environment by modulating evapotranspiration and absorption of solar radiation. Accurate mapping and monitoring of vegetation distribution and condition is central to the understanding of urban ecosystems. Urbanization is a dominant demographic trend and the resultant land use and land cover change has been identified as one of the three major global impacts of humans {Vitousek, 1994}. The growing presence and importance of cities makes these human-dominated ecosystems ideal laboratories for the study of ecological change. Resource managers also use information on the abundance, condition and spatial distribution of urban vegetation for park and natural area management and urban planning. While in situ data collection is the primary means of monitoring urban vegetation, remotely sensed observations can provide valuable complements to traditional field observations.

New York City, most famous for its skyscrapers and worldly population, is also home to an estimated 5.2 million trees {Nowak, 2002}. New York City's vegetation is comprised of a patchwork of remnant forests, inherited estates, neighborhood parks and playgrounds, green streetscapes, parkways and private backyards and roof gardens. New York City Parks & Recreation has jurisdiction for over half of the estimated 5 million total trees in the city. In 1996, Parks & Recreation mobilized over 700 volunteers to conduct a comprehensive census of all the street trees in New York City. The census counted over 498,000 street trees in New York City, comprising of approximately 70 different varieties. The vast majority of trees, however, comprise a small number of species; over 40% of the street tree population consists of just two species. New York City's street trees are relatively small, with almost 60% measuring less than 12 inches diameter at breast height {Watt, 1998}. However, many other types of vegetation in New York City, managed or impacted by Parks and at least another dozen city, state, and federal agencies and private actors, are not well characterized through on the ground inventories. Management of New York's trees by the Parks Dept. relies on the street tree census to represent the spatial distribution and health of its vegetative assets.

Quantitative estimates of vegetation abundance derived from moderate and high spatial resolution optical sensors have the potential to be used for operational monitoring of urban vegetation. Operational use of these data requires a robust methodology for converting measurements of optical radiance to accurate and verifiable estimates of vegetation abundance. A primary requirement for operational use of remotely sensed vegetation abundance estimates is that they provide physical units that can be compared directly with other measures of vegetation abundance and condition. Spectral Mixture Analysis (SMA) satisfies this requirement by providing pixel-scale estimates of areal abundance of spectral endmembers. In recent years SMA has been used for a variety of urban land cover mapping applications (e.g. [*Kressler and Steinnocher*, 1996] [*Small*, 2001] [*Rashed et al.*, 2002] [*Wu and Murray*, 2003] {Weng, 2004}). In comparison to vegetation indices (e.g. Normalized Difference Vegetation Index (NDVI)), SMA offers the advantage of providing estimates of areal vegetation abundance that can be compared directly to other measures of vegetation cover per unit area. In spite of its increasingly widespread use, most spectral mixture analyses do not validate the endmember fraction estimates they produce. [*Elmore et al.*, 2000] devised a thorough field validation methodology based on point frame transect measurement of individual plants in a semi-arid environment but the procedure is very labor intensive and not suitable for environments containing large trees. [*Small*, 2001] proposed a methodology for high spatial resolution vegetation abundance measurement from aerial photographs but the procedure relies on manual selection of specific validation sites also somewhat labor intensive. In light of the current availability of calibrated moderate (< 30 m) and high (< 5 m) resolution multispectral imagery from Landsat ETM+, Ikonos and Quickbird, the potential for quantitative validation of fractional abundance estimates has increased considerably since the time these earlier studies were conducted. High spatial resolution imagery also provide a means to examine the structural characteristics of moderate resolution (~20-40 m) targets as well.

The objectives of this study are to define operational procedures for moderate resolution vegetation fraction estimation and validation and to examine some of the factors that limit the use of vegetation fraction estimates for urban applications. In the first part of the analysis we summarize the procedure used to derive vegetation fraction estimates from Landsat and Quickbird imagery. This procedure is explained in greater detail in [*Small*, 2001] and {Small, 2003}. In the second part of the analysis we quantify the agreement between the moderate and high resolution estimates and investigate the effects of estimate error and spatial misregistration. The discussion focuses on the physical interpretation of vegetation fraction estimates and comparison to *in situ* measures of urban vegetation abundance.

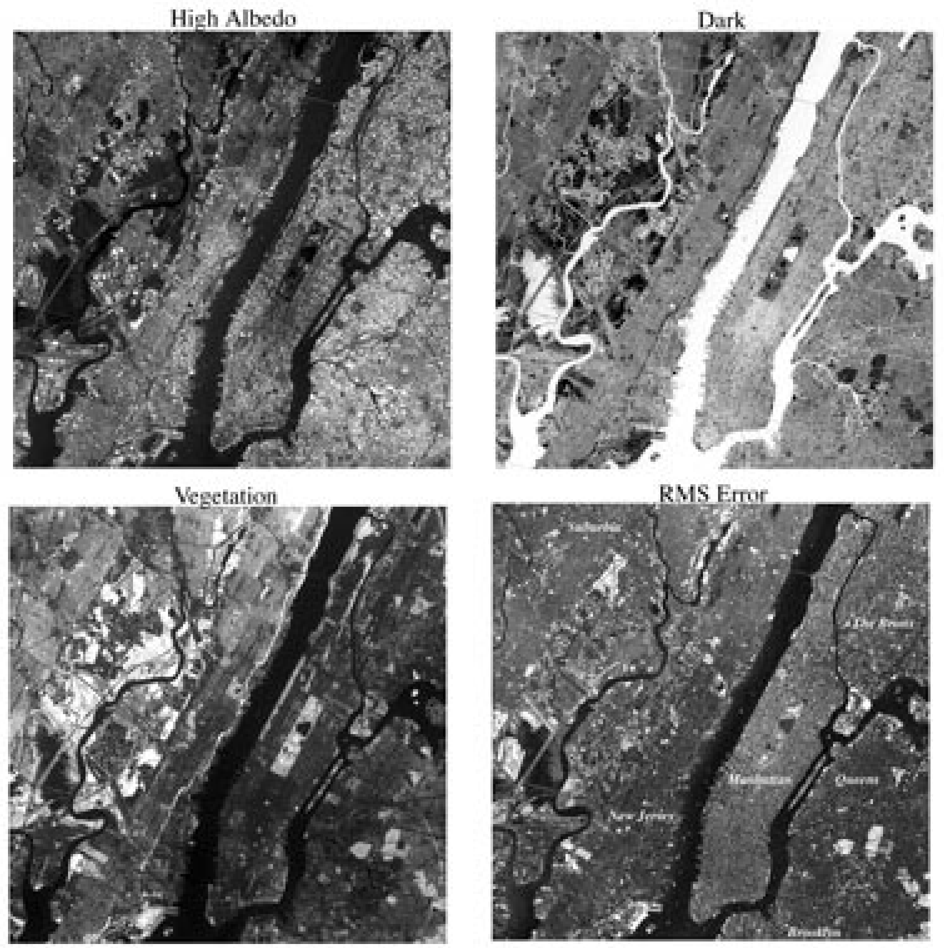

Figure 1 Endmember fractions and RMS error for the ETM+ three endmember linear mixture model for the New York metro area. Higher fractions (and error) are indicated by lighter shading. A 2% linear stretch has been applied to each image. Spatially contiguous areas of higher RMS error correspond to exposed soil that is not represented by the three endmember model. Note the neighborhood scale variations in vegetation abundance.

DATA

Both images used in this study were acquired in August 2002. At the time, the New York metro area was experiencing draught conditions following several years of below average rainfall. Although some smaller trees were experiencing premature senescence by August, the vegetation abundance within the study area was equivalent to full leaf-on conditions at the time that both images were acquired. We do not expect that the vegetation cover changed significantly between the times the images were acquired. The Landsat ETM+ image (p.14, r.32) used in this study was acquired on 14 August 2002 at 9:45 AM local time. Image Dns were converted to exoatmospheric reflectance units as described by *Markham and Barker (1986, 1987)* and in the Landsat 7 Users Handbook *(http://ltpwww.gsfc.nasa.gov/IAS/handbook/handbook_toc.html)*. No atmospheric correction was applied. The Quickbird imagery was acquired 2 August 2002 at 10:48 AM from a viewing angle of 68°. Image DNs were converted to at-sensor radiance using parameters provided by Digital Globe. Spatial accuracy of the georegistered image was verified to be within 31 meters by comparison with 48 validation sites derived from a Garmin 12 Map handheld GPS receiver.

SPECTRAL MIXTURE ANALYSIS

Spectral Mixture Analysis (SMA) is a methodology whereby an observed radiance is modeled as a linear mixture of spectrally pure endmember radiances. Linear mixture models are based on the observation that, in many situations, radiances from surfaces with different "endmember" reflectances mix linearly in proportion to area within the IFOV ([*Johnson et al.*, 1983; *Singer*, 1981; *Singer and McCord*, 1979]). This observation has made possible the development of a systematic methodology for spectral mixture analysis ([*Adams et al.*, 1993; *Adams et al.*, 1986; *Gillespie et al.*, 1990; *Sabol et al.*, 1992; *Smith et al.*, 1990]) in which land surface reflectance variations are represented by a set of endmember fraction images describing spatial variations in the areal abundance of each endmember.

Endmember fractions were estimated with a constrained least squares inversion following the procedure described in detail by [*Small*, 2001]. The resulting fraction and RMS error distributions – shown in Figure 1 - are very similar to those obtained by Small (2001). This is to be expected given the similarity in the study area and endmember spectra. As in the previous study, the largest misfits are associated with areas of exposed soil and isolated high albedo targets. This is consistent with the lack of a soil endmember in the model and the fact that the mixing space diverges near the High Albedo endmember. RMS error diminishes with increasing fractions of Dark and Vegetation endmembers. This indicates that the inverse problem is well posed with respect to vegetation fraction estimation. RMS error is generally less than 0.02 reflectance units, suggesting that the 3 endmember linear model is capable of replicating the observed mixed reflectances quite closely. This does not, however, guarantee that the fraction estimates are accurate. The accuracy must be determined through validation.

VALIDATION

We validate the ETM+ vegetation fraction estimates by quantifying their degree of correspondence to vegetation fraction estimates derived from Quickbird multispectral imagery. The 2.6 meter spatial resolution of the Quickbird sensor allows it to image the individual components of the urban mosaic at significantly higher spatial resolution than the 20 to 30 meter characteristic scale estimated for the New York urban mosaic (Small, 2003). This is why individual features like buildings, sidewalks, streets and trees can be identified in Quickbird imagery. The 2.6 meter resolution is more than adequate to image medium to large tree crowns and to detect the presence of fairly small street trees. At the 30 meter scale of the ETM+ IFOV, each 2.6 meter Quickbird pixel represents less than 1% of the area within the Full Width Half Max of the ETM+ point spread function. This is more than adequate to represent the spatial scale of the dominant targets responsible for the multiple scattering that is the primary source of nonlinear mixing within the ETM+ IFOV. Because nonlinear mixing is the primary source of error in this estimation problem, we consider the spatial oversampling provided by the Quickbird data to be well suited to address the fundamental question in the mixing problem. The validity of using high resolution vegetation fractions to validate moderate resolution fractions therefore depends on whether there is a consistent bias in the linear mixing model that corrupts both the moderate and high resolution estimates in such a way that they are mutually consistent but consistently wrong.

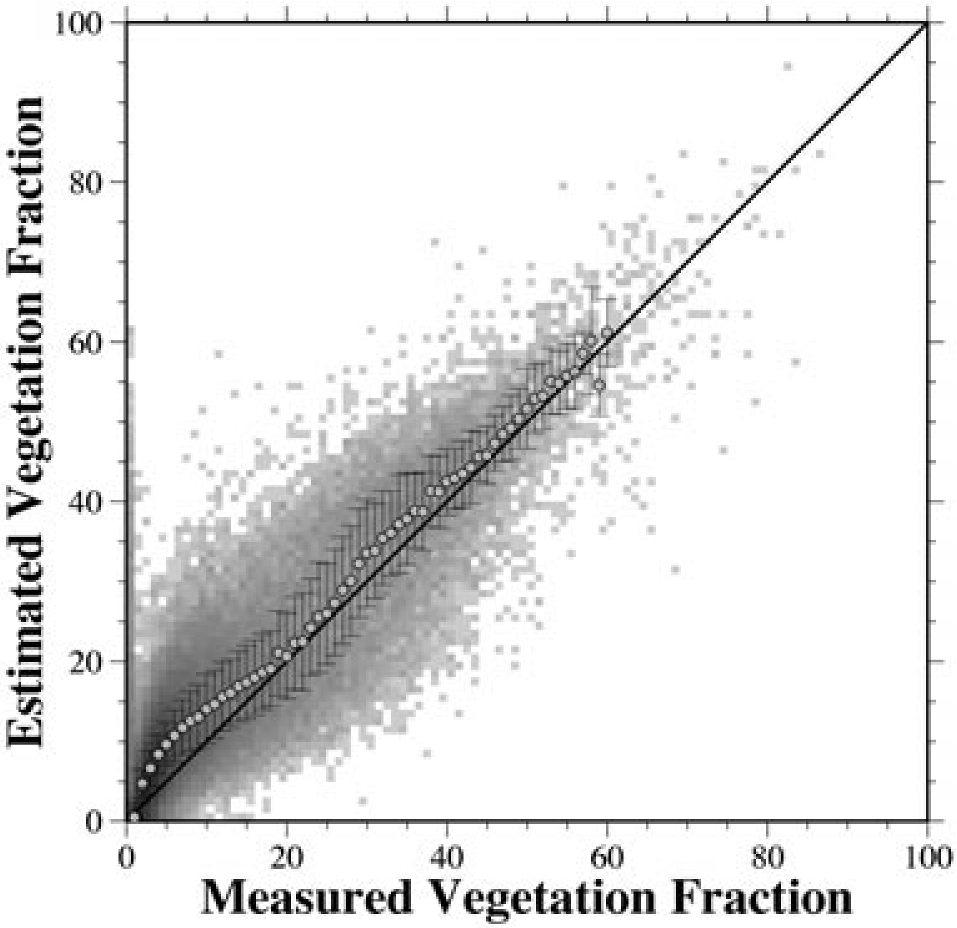

Figure 2 Measured versus estimated vegetation fractions for the New York validation site. Measured fractions are calculated from 2.8 meter Quickbird estimates resampled to 30 meters. Estimated fractions are derived from LandsatETM+ estimates coregistered to the resampled Quickbird image. Circles show median estimated fractions and bars show InterQuartile Ranges in 1% bins. Darker pixels correspond to larger numbers of 30 m samples. Medians are within 5% for fractions greater than 0.2. The observed scatter about the 1:1 line may result from estimation error and/or subpixel image misregistration.

Convolution and resampling of the 2.6 meter vegetation fractions at 30 meter resolution makes it possible to assess the geographic coregistration and to compare the moderate resolution estimates and the high resolution measurements directly. Comparison of the Quickbird image to the handheld GPS measurements showed a generally ENE displacement of 10 to 30 meters. As this is within the spatial uncertainty of GPS receiver and the expected geolocation error of both images, we did not attempt to relocate either image. Visual comparison of the interactively overlaid 30 meter images showed no evidence for systematic misregistration. A density shaded scatterplot of the 30 meter ETM+ estimates versus the 30 meter resampled Quickbird vegetation fractions is shown in Figure 2. The linear correlation coefficient for the 80850 (245x330) coregistered 30 meter pixels is 0.89. Medians and interquartile ranges calculated at 1% increments indicate that the ETM+ estimates agree with the Quickbird vegetation fractions to within 5% for fractions greater than 0.2 and that

50% of ETM+ fractions agree to within 10%. The ETM+ fractions are consistently higher than the Quickbird estimates for fractions less than 0.2 with the positive bias diminishing monotonically approaching 0.2. Scatter about the 1:1 line increases for fractions up to ~0.3 and diminishes for higher fractions. We investigate two possible causes for this scatter by simulating the effects of spatial misregistration and systematic estimation error.

The scatter about the 1:1 line could result from 1) error in the ETM+ fraction estimates or from 2) subpixel (< 30 m) spatial misregistration between the ETM+ and Quickbird images or from 3) a combination of estimate error and spatial misregistration. Spatial misregistration of the images causes the spatial correlation to diminish as the scatter increases with offset. The effect of spatial misregistration can be simulated by introducing a series of geographic offsets to identical 2.8 meter vegetation fraction images, convolving each image with the ETM+ spatial response function, resampling each to 30 meter resolution and comparing the correlation of the displaced 30 meter images.

We simulate the combined effects of spatial misregistration and estimation error by comparing scatterplots of perturbed versus unperturbed vegetation fractions. By varying the amount of misregistration and the amount of estimation error we can compare the dispersion of the resulting scatterplots with that observed in Figure 2. The effect of geolocation error combined with estimation error by adding specified amounts of normally distributed random noise to each pixel in the perturbed image. The distribution of scatter is most similar to that seen for a northeastward misregistration of 17 meters with less than 3% estimation error or an 11 meter misregistration with less than 6% estimation error.

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