DIGITAL CITIES II:
Monitoring the Urban Environment from Space

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Abstract ***Monitoring spatiotemporal changes in large urban agglomorations will become increasingly important as the number and proportion of urban residents continue to increase. The synoptic view of urban landcover provided by satellite and airborne sensors is an important complement to in situ measurements of physical, environmental and socioeconomic variables in urban settings. The 10 to 80 m spatial resolution of most operational satellites has impeded the use of remotely sensed imagery for studies of urban infrastructure but this resolution is sufficient for measurement of some important environmental parameters that would be logistically difficult or prohibitively expensive to measure directly. Intra-urban variations in vegetation abundance influence environmental conditions and mass/energy fluxes by selective reflection and absorbtion of solar radiation and by modulation of evapotranspiration. Operational satellites such as Landsat provide the ability to monitor spatiotemporal dynamics of urban vegetation and thermal emission simultaneously on seasonal to interannual time scales to better understand their relationship to the urban environment. Monitoring of spatiotemporal variations of urban vegetation abundance may also allow the effect of the urban environment on vegetation phenology to be determined. In this study, we discuss methodology for measurement of urban vegetation and compare vegetation distributions in the New York and Guangzhou metropolitan areas using Landsat TM imagery. A systematic analysis of the spatiotemporal dynamics of vegetation in the world's major evolving urban centers would facilitate comparative studies of urban environment and its role in public health and energy consumption as well as constraining the role of the urban center in the dynamics of larger metro-agro-plex system***

Importance of Urban Vegetation

One of the primary challenges to understanding the dynamics of the Earth system is an accurate assessment of the relationships between human population and the other components of the system. Recent estimates indicate that over 45% of the world's human population now lives in urban areas with over 60% projected by 2030 (***United Nations, 1997***). The global rate of urbanization is expected to continue to accelerate in the near future with the emergence of large urban agglomerations in developing countries (***Berry, 1990; United Nations, 1980***). Even if developing countries follow the course of post-industrial urban dispersion to suburbs, the continuing localization of populations from rural to urban/suburban connurbations will result in increasing numbers of people living in built environments. As the size and number of urban agglomerations increases, so does the relative importance of the urban environment to the global population. Urban areas exert influences on the Earth system far disproportionate to their geographic extent and require special consideration in the context of a Digital Earth (***Miller and Small, this volume***). Monitoring spatio-temporal changes in large urban/suburban areas will therefore become increasingly important as the number and proportion of urban residents continue to increase.

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 has long been recognised as a strong influence on energy demand and development of the urban heat island (e.g. ***Harrington, 1977; Oke, 1979; Huang et. al., 1987***). Urban vegetation abundance may also influence air quality and human health (***Wagrowski and Hites, 1997***) because trees provide abundant surface area for sequestration of particulate matter and ozone. Urban vegetation also 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 under 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)*** provides a thorough summary of the evolution of urban remote sensing and introduces a methodology with which some socioeconomic parameters may be predicted using reflectance based estimates of land cover classes. Compared to agricultural areas and sparsely populated regions, however, application of remotely sensed observations 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 30 to 50 m spatial resolution of the Landsat TM sensor (***Markham, 1985; Wilson, 1988***) is comparable to the characteristic scale of urban land cover (***Welch, 1982, Woodcock & Strahler, 1987***) and is generally too coarse for identification of individual structures. While this resolution has limited Landsat's use for studies of the built urban environment, it may be sufficient to detect significant spatial and temporal variations in urban vegetation and surface temperature. The objective of this paper is to present results of an analysis of urban vegetation distribution in New York City and to discuss implications for environmental monitoring of evolving urban areas.

Estimation of Urban Vegetation with Landsat Imagery

Urban areas are generally recognized in remotely sensed imagery by their geometric and textural characteristics. Spectral characteristics of urban landcover are less diagnostic than those of the rural periphery. Urban areas are generally characterized by

Figure 1. Vegetation fraction distribution for New York City and surrounding regions estimated from Landsat TM imagery acquired 2 June, 1996. Shading ranges from 0% (black) to 60% (white) vegetation fraction. Areas with fractions greater then 60%, such as parks, are saturated white in this image to emphasize contrast at lower fractions. Note the sharp intra-urban vegetation gradients and the gradual increase in vegetation fraction toward the suburbs

spectral heterogeneity at scales approaching the 10 to 50 m resolution of most operational satellite sensors. The characteristic spatial scale and the spectral variability of urban landcover poses serious problems for traditional image classification algorithms because these methods rely on distinctions between spectrally homogeneous landcover classes. In 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 the sensor, the spectral reflectance of an individual pixel will not generally resemble the reflectance of a single landcover class but rather a mixture of the reflectances of two or more classes present within the GIFOV. The problem of mixed pixels for urban classification is discussed extensively by ***Forster (1985)***.

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***). When mixing between the endmember spectra is predominantly linear and the endmembers are known ***apriori*** , it may be possible to "unmix" individual pixels by inverting a system of mixing equations to estimate the fraction of each endmember in the composite reflectance of the mixed pixel. This concept has been used extensively with imaging spectrometers in geologic remote sensing (e.g. ***Clark and Roush, 1984; Goetz et al 1985; Kruse, 1988; Boardman, 1989; Boardman and Kruse, 1994***) and vegetation mapping (e.g. ***Smith et. al., 1985, 1990; Pech et. al., 1986; Elvidge et al, 1993; Roberts et al, 1993; Wessman et al, 1994***).

While urban spectral heterogeneity is a confounding factor for traditional hard classification, the spectral undersampling by broadband sensors such as Landsat may act to simplify the diversity of urban reflectance. A recent analysis of urban reflectance in the New York metro area found that the inherent dimensionality of spectrally undersampled urban reflectance is low enough that the majority of scene variance could be described as linear combinations of three spectral endmembers in Landsat TM imagery (***Small, 1999***). Image dimensionality and spectral endmember determination can be accomplished using eigenvalue decomposition and convex geometry as described by ***Boardman (1993).***

The spectral endmembers determined for the New York area correspond to low albedo (water, shadow, roofing), high albedo (cloud, 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. 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. RMS misfits of the estimated endmember fractions to observed reflectances are generally low (95% < 0.02 RMS) with consistently lower misfit for the low albedo and vegetated areas and larger misfits for high albedo areas. Maximum RMS misfit diminishes monotonically with increasing vegetation fraction and is consistently low for vegetation fractions greater than 0.2. The small misfit for pixels having a significant vegetation fraction suggests that the three component linear mixing model may provide robust estimates of vegetation abundance in urban Landsat imagery. Vegetation fraction distribution estimated for imagery acquired 20 July, 1996 is shown in Figure 1.

Validation

In order to quantify the accuracy of the vegetation fraction estimates it is necessary to validate the results with independently derived groundtruth estimates of the actual vegetation fraction. Measurements of the areal vegetation fraction and distribution can be obtained from high resolution imagery in which vegetation can be unambiguously identified by texture, color and context. The Landsat-derived vegetation fraction estimates were validated by comparison with high resolution (1 m) visible color aerial photography of central Manhattan acquired nine days prior to the a Landsat overpass. Convolution of the measured distribution of vegetation and shadow fraction with the Landsat sensor Line Spread Function (***Markham, 1985***) allows forward calculation of expected detectable vegetation fraction for comparison with the fraction estimated from inversion of the mixing equations. Full details of the validation procedure are provided by ***Small (1999)***. Thirty four validation sites were chosen to span the range of vegetation fraction (0.1 to 1) and a wide range of spatial scales (from 1 to 930 Landsat TM pixels). Response weighted areal vegetation fraction calculated using the high resolution airphoto imagery was found to correspond linearly to the vegetation fraction estimated by inversion of the three component mixing model for Landsat TM imagery. The quantitative validation shows agreement to within fractional abundances of 0.1 for vegetation fractions greater than 0.2 (Figure 2).

One of the primary advantages of spectral unmixing relative to most commonly used vegetation indices is the relatively straightforward physical interpretation. The apparent first order linearity of macroscopic spectral mixing of vegetation in urban areas suggests a direct correspondence between unmixed vegetation fraction and the area within the GIFOV containing vegetation cover. In contrast, the commonly used Normalized Difference Vegetation Index (NDVI) infers the presence of vegetation on the basis of the difference between Visible and VNIR reflectance but does not provide areal estimates of the amount of vegetation. In addition to the dependence of NDVI on the spectral bandwidth of the particular sensor, the relationship between NDVI and other measures of vegetation abundance (e.g. Leaf Area Index) is notoriously nonlinear (***Asrar et al, 1984, 1989***). A comparison between NDVI and vegetation fraction for the New York City area shows the expected nonlinearity with saturation of the NDVI at vegetation fractions greater than ~0.6 (***Small, 1999***). When compared to the unmixed vegetation fraction, the NDVI cannot distinguish between open and closed canopy forest or grass covered areas in parks. NDVI also overestimates abundance of interspersed non-park vegetation relative to more densely vegetated areas in parks and densely vegetated suburbs and therefore distorts the vegetation gradient from city center to surrounding rural areas.

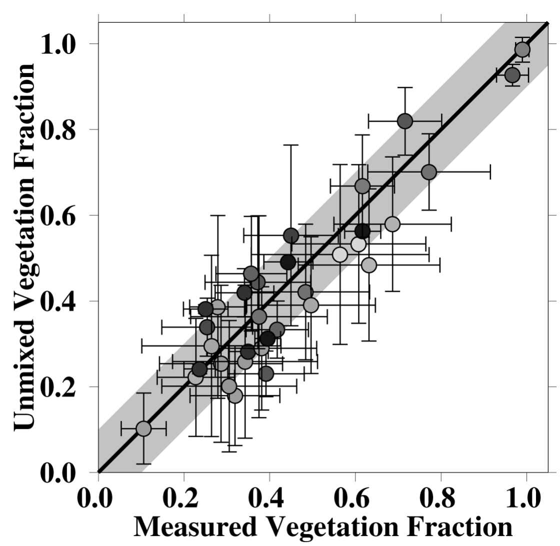

Figure 2 . Validation of vegetation fraction estimated from Landsat imagery with vegetation fraction measured from high resolution imagery. Comparison of mean values of measured and estimated vegetation fractions for sites of different sizes indicates good agreement - generally within 10% of measured values (gray diagonal). Shading of the symbol is proportional to the Log of the area of the validation site ranging from 1 (dark) to 930 Landsat pixels. Bars on the symbols show the standard deviations of the vegetation fraction distribution within each validation site.

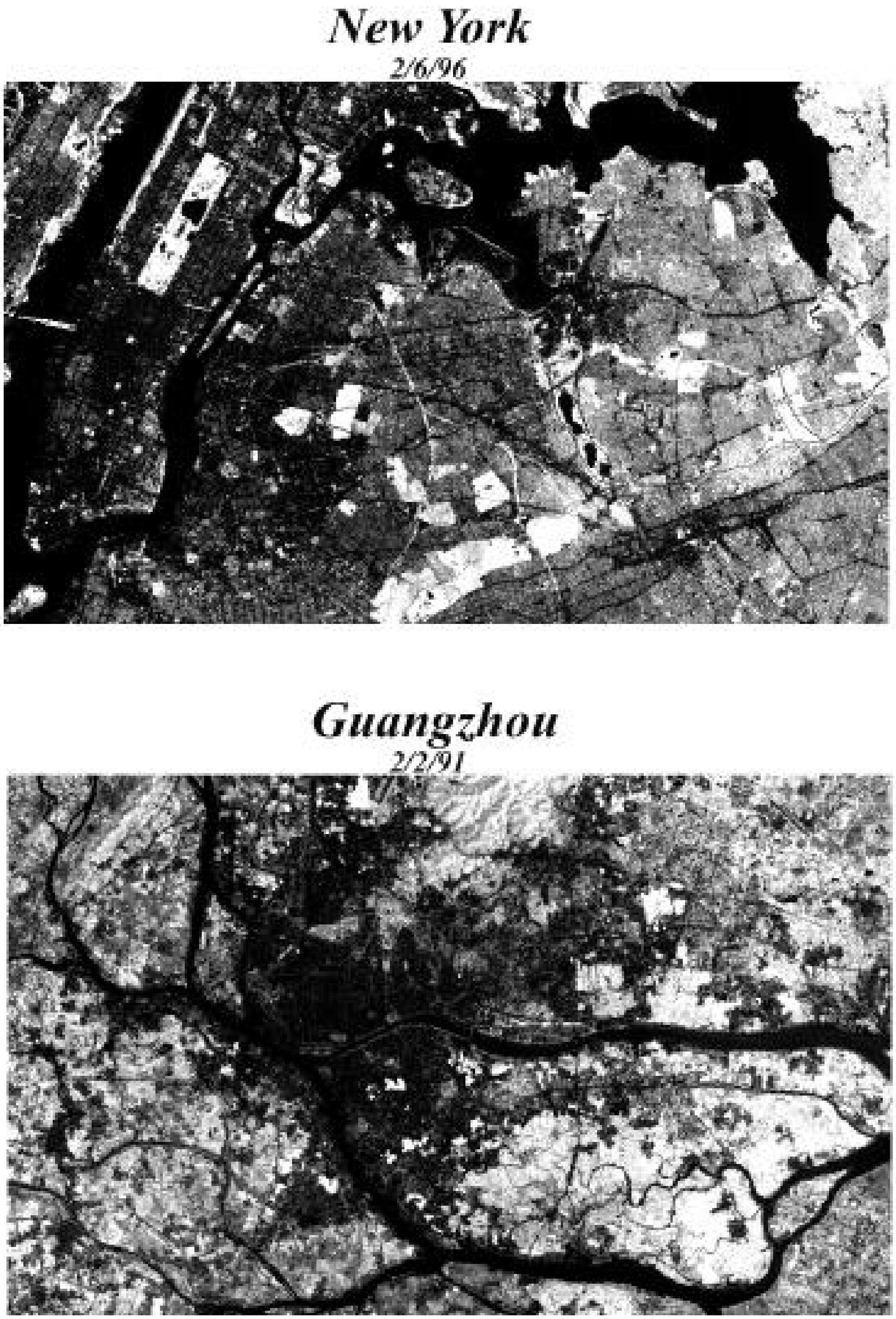

Figure 3. Comparison of vegetation fraction images for subregions of the Guangzhou and New York metropolitan areas. Both images are linearly gray shaded between 0 (black) and 60% (white) vegetation fraction. Note the gradual suburban vegetation gradient in the New York image and the abrupt transitions in vegetation fraction in the Guangzhou image. Both images are ~24 x 15 km in area

Spatial Distribution of Urban Vegetation

Preliminary 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 the phenological cycle within the metro area. Figure 1 is stretched to emphasize these intra-urban differences at the expense of detail in the more densely vegetated parks and cemetaries. These differences in vegetation distribution may influence a number of environmental factors ranging from urban heat island dynamics to air quality. Experiments to test these assertions are currently being conducted. The spatial distribution and density of vegetation imposes boundary conditions on the radiation balance and evapotranspiration that may be significant for the micrometeorology of the urban/rural system. Similarly, the areal distribution of urban vegetation may act as a distributed sink for surface reactant pollutants such as particulate matter and ozone. In spite of the widespread acknowledgement of the importance of urban vegetation, a number of fundamental questions have yet to be answered. Is the role of parks more or less significant than the role of diffuse vegetation? Is a distribution of medium size parks more or less energetically efficient than a few large parks? What is the role of urban/suburban vegetation gradient on the development of the urban canopy and boundary layers? What is the role of diffuse vegetation on net evapotranspiration and mesoscale convection? These questions may warrant consideration for rapidly expanding urban areas in the future.

The combination of moderate resolution mapping of urban vegetation and thermal infrared mapping of urban areas may answer some of the questions posed above. Recent thermal infrared mapping of urban areas in the U.S. has resulted in greater recognition of the importance of vegetation to urban energy consumption (***http://www.ghcc.msfc.nasa.gov/atlanta)***. The role of vegetation in evapotranspiration has been studied extensively using NDVI and surface temperature measurements (e.g. ***Price, 1990; Carlson et al, 1994; Gillies et. al. 1997***). The factors discussed above should make vegetation fraction more suitable than NDVI for this type of analysis and facilitate studies of the impact of vegetation on mass and energy fluxes of urban systems. Preliminary analyses of the relationship between vegetation fraction discussed here and Landsat derived surface temperature in the New York metro area show the expected inverse relationship between vegetation fraction and surface temperature and provides constraints on urban evapotranspiration. The increasing availability of Landsat imagery in combination with sensors aboard the Terra satellite may allow spatiotemporal variations in this relationship to be quantified in greater detail.

Comparative Urban Analyses

A scale comparison between vegetation distributions for New York and Guangzhou (Figure 3) reveals vastly different spatial distributions and gradients in vegetation fraction which could have significant impact on environmental conditions in and around each city. A systematic, self-consistent methodology for monitoring spatiotemporal dynamics of urban vegetation and surface temperature would allow comparitive analyses of urban environments to be conducted in all of the world's major metroplexes. Such an analysis, when coupled with ***in situ*** measurements of other environmental, epidemiological and socioeconomic parameters would facilitate systematic comparitive studies of the urban environment (***Miller and Small, this volume***). This type of study could provide valuable information for urban planning and policy in developing countries where urbanization is currently increasing most rapidly.

In a larger context, this type of analysis could play an important role in the synoptic observation of spatiotemporal dynamics of regional connurbations and the evolving continental scale metro-agro-plexes. The importance of metro-agro-plexes in the global system of production and consumption has been discussed by ***Chameides et al (1994)*** and their role in global change scenarios for Asia was considered by ***Fu et al (1998)***. Urban vegetation distribution is therefore significant not only for the urban environment itself but also for its role in modulating mass and energy flux through the urban component of this system. Higher spatial resolution observations are especially critical in urban areas where smaller changes in environmental conditions could have a disproportionately large effect on mass and energy fluxes throughout the system because of the number of people impacted. Because of the relatively condensed spatial scale of urban areas, a systematic spatiotemporal analysis of the world's major agro-metro-plexes could be accomplished with a modest amount of satellite imagery and, given sufficient groundtruth, could vastly improve our understanding of the role of urban systems in global scale processes.

Conclusions

In conclusion, the linear spectral mixing model provides a simple, physically based measure of vegetation abundance and distribution in the New York metro area. If the method proves equally effective in other urban areas it could provide an efficient means for systematic, quantitative analyses of a major determinant of urban environmental conditions. Quantitative validation of Landsat-derived vegetation estimates with high spatial resolution vegetation measurements from aerial photography shows agreement to within 0.1 for vegetation fractions greater than 0.2 across the full range of vegetation abundances for the New York area. The accuracy of estimates for smaller vegetation fraction and the limitations imposed by atmospheric scattering and illumination conditions remain to be determined. Studies in other urban areas will be necessary to assess the general applicability of a three component mixing model. Increased spectral resolution of next-generation sensors may allow a more general, multiple endmember model to be developed.

The role of urban vegetation distribution in the modulation of mass and energy flux through the urban system, as well as its impact on human health and environmental conditions, warrants further investigation into vegetation monitoring and its applications to urban systems. If the general applicability of the method can be established, a systematic comparative analysis of the world's major evolving urban centers could be undertaken at relatively modest expense. Such a study could yield substantial returns on two research fronts. Comparative analyses of the role of vegetation distribution on urban environmental conditions could result in significant improvements in health, energy efficiency and quality of life for vast numbers of people in rapidly expanding connurbations. In addition, an improved understanding of the mass and energy fluxes through urban centers would improve our understanding of the dynamics of the larger scale metro-agro-plexes within which many urban centers exist. Because of the disproportionately large impact of urban areas on their surrounding environments, such an investigation would presumably yield a relatively large return in the form of improved understanding of one of the major anthropogenic drivers of global change.

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