

URBAN LAND COVER AND SPATIAL VARIATION OBSERVATION USING ASTER AND MODIS SATELLITE IMAGE DATA

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Commission VII, WG

KEY WORDS: ASTER, landscape metrics, urban analysis, land cover

ABSTRACT:

Land cover and land use changes associated with urbanization are important drivers of local geological, hydrological, ecological, and climatic change. Quantification and monitoring of these changes in 100 global urban centres are part of the mission of the ASTER instrument on board the NASA Terra satellite, and comprise the fundamental research objective of the Urban Environmental Monitoring (UEM) Program at Arizona State University. Data have been acquired for the majority of the target urban centres and are used to compare landscape fragmentation patterns on the basis of land cover classifications at both local and global scales. The primary application of remote sensing data in this study is to provide a means for extrapolating detailed measurements at local sites to a regional context. Specifically, multi-spectral image classification, vegetation indices, and multi-kernel texture analysis are used to identify both natural and built land cover types. This information is combined with ancillary data such as land use using an expert system framework, to obtain final pixel classifications. Because modifications of the urban environment are coupled frequently with modifications of the spatial structure, the investigation of texture and shape parameters, or neighbourhood relations, out of remote sensing data apart from the spectral investigation applied so far represents an additional analysis potential. Thus, a methodological approach using and analyzing landscape metrics is presented and compared with biogeophysical variables obtained from the MODIS sensor for the Phoenix, AZ metropolitan area.

1. CURRENT RESEARCH

While characterization and monitoring of ongoing urbanization processes is important, equally important is the ability to predict the local and regional environmental effects and feedbacks associated with expanding urban centres (Grimm et al., 2000). We define six major research objectives to achieve this goal:

- Objective 1:** Tracking urban area growth and change: speed, density, direction, structures, impervious surfaces, land use consumed.
- Objective 2:** Spatial arrangement of green/open space within cities and at periphery: amount distribution, links.
- Objective 3:** Track changes in peri-urban regions: farmland conversions, wetland infringement, biodiversity threats.
- Objective 4:** Monitor land cover/land use changes that influence urban climatology and atmospheric deposition.
- Objective 5:** Monitor urban growth as it intersects areas of potential environmental hazards: earthquake, subsidence, mudslides, floods, etc.
- Objective 6:** Map environmental parameters such as micro-climate, heat island, access to open space, percent impervious surface, percent green space and assess the geographic differences within regions and

whether they correlate with social, economic, or ethnic divisions.

The Urban Environmental Monitoring program (<http://elwood.la.asu.edu/grsl/UEM/>) is using a variety of remotely sensed and GIS datasets (ASTER, Landsat, MODIS, astronaut photography, socioeconomic data, historical maps) to establish development trajectories within a pilot study for 8 urban centers located around the globe.

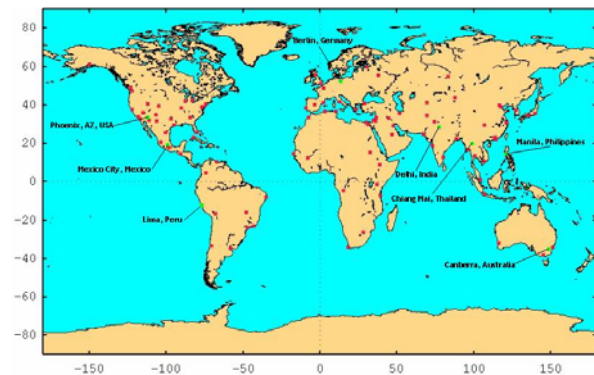


Figure 1. Location map of eight "intensive study" cities. Red squares indicate other UEM cities.

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These urban centers (Berlin, Germany; Canberra, Australia; Chiang Mai, Thailand; Delhi, India; Mexico City, Mexico; Lima, Peru; and Phoenix, Arizona, USA) are selected on the basis of urban growth projections, geologic/geographic setting, and climatic patterns. Our initial goal is to determine classes or groupings of urban development trajectories defined by several variables (land use/land cover, landscape metrics, climatic patterns, geologic hazard assessment, and development history). The understanding of how these urban centers have developed and responded to various environmental, climatic, and sociopolitical stressors will inform models of how sustainable they are given similar future stressors (Alberti and Waddell, 2000). Improvement in understanding of urban resilience and sustainability is of great importance to scientists, policy-makers, and citizens alike. The models we develop will allow policy-makers to incorporate remotely sensed data into their local and regional planning efforts.

In this contribution we focus on the complementary use of two NASA Earth Observing System (EOS)-based sensors for urban ecological analysis to assess the hypothesis “does urban landscape structure influence biogeophysical parameters at the 1 km scale?” We use the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on board the Terra satellite, and the Moderate Resolution Imaging Spectroradiometer (MODIS) sensors on board both the Terra and Aqua satellites to answer this question. The ASTER instrument was built by the Japanese Ministry of International Trade and Industry, and acquires surficial data in the visible to near-infrared (3 bands at 15 meters/pixel), shortwave infrared (6 bands at 30 meters/pixel), and thermal-infrared (5 bands at 90 meters/pixel) wavelength regions of the electromagnetic spectrum. An additional panchromatic band is included to allow for the generation of high-resolution (30 meter postings) digital elevation models from ASTER scenes (Abrams, 2000). Each ASTER scene captures a 60 km x 60 km area. The expanded wavelength range, spectral resolution, and increased spatial resolution of ASTER allow for increased characterization and investigation of urban/exurban land cover and biogeophysical parameters (biomass, albedo, spatial metrics, and surface temperature/emissivity) relative to the Landsat sensors (Ramsey et al., 1999; Stefanov et al., 2001a; Zhu and Blumberg 2002; Ramsey, 2003; Netzbund and Stefanov, 2003).

The MODIS sensors are similar to ASTER in that they obtain spectral information in the visible through mid-infrared wavelengths over 36 bands with a swath width of 2300 km. However, the spatial resolution of MODIS data is significantly lower and ranges from 250 meters/pixel (2 visible bands), 500 meters/pixel (5 visible to shortwave infrared bands), and 1000 meters/pixel (29 visible, near infrared, shortwave infrared, and mid-infrared bands; Parkinson and Greenstone, 2000). As both the Terra and Aqua satellites are equipped with MODIS sensors, repeat coverage over any given area of the Earth is acquired every 1-2 days. This makes MODIS data especially attractive for fine-scale temporal monitoring of regional land surface processes associated with urban centers (Schaaf et al., 2002; Schneider et al., 2003). In addition, the MODIS science team produces data products useful for characterization and monitoring of regional-scale biogeophysical and climatic variables in urban/peri-urban areas.

2. LANDCOVER, LANDSCAPE METRICS AND BIOGEOPHYSICAL PROPERTIES IN URBAN AREAS

Within the UEM project we will continue to produce standardized land cover classifications for 100 urban centers located around the globe using ASTER data throughout the duration of the Terra mission. In addition, we will monitor the geological and ecological status of these cities using ASTER and MODIS. Classification of urban development trajectories and spatial structure will be determined for a representative subset of 8 urban centers (see figure 1) using a coherent methodological approach to ensure comparability of the results. Ongoing research in this area includes development of detailed land cover classification models for the eight study cities (figure 2).

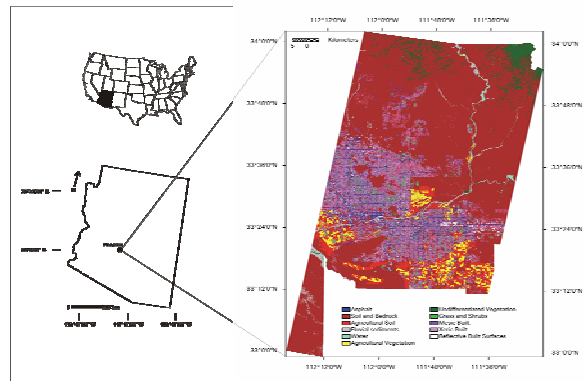


Figure 2. Land cover classification for the eastern Phoenix area.

2.1 Land Cover Classification for the Phoenix Area

We illustrate the use of ASTER and MODIS data for urban ecological analysis using the Phoenix, Arizona metropolitan area. Phoenix was selected because it is one of the fastest-growing conurbations in the United States, and is the focus of the Central Arizona–Phoenix Long-Term Ecological Research Project (CAP LTER; Grimm et al., 2000). The greater Phoenix metropolitan area is situated on an alluvial plain formed by the Salt River and alluvial fans derived from the surrounding mountain ranges at an elevation of 305 meters in an arid environment that averages less than 20 centimeters of annual precipitation. The region is quite hot, with mean monthly temperatures ranging from 12 C in January to 34 C in July. At the same time, this area contains 300,000 hectares of highly productive farmland, and 3.2 million people are concentrated in an expanding metropolitan area.

The general urban structure of Phoenix is the product of only 150 years of development. The majority of the current built-up area was constructed after 1940, and currently defines a northwest-southeast trending “figure 8” set along a regular north-south and east-west transportation grid (figure 2). This distinctive pattern is the result of physiographic constraints (mountains), availability of water delivery infrastructure, the dominance of individual automobile transport rather than mass transit, and political boundaries related to federal and Native American lands (GP2100, 2003). The Phoenix metropolitan area has a fairly well defined urban core defined by the skyscrapers of downtown Phoenix proper. This is surrounded

by a heterogeneous mixture of residential, commercial, industrial, and parkland areas of varying age and spatial extent comprising the numerous surrounding municipalities.

Older residential developments within the urban agglomeration tend to be more open and occupy larger plots of land. More expensive and exclusive developments located in desert areas and next to scenic landforms also tend to be less dense. A burst of construction of dense multi-unit residential developments that began in the 1990's defines the location of the current urban fringe together with a fragmenting halo of agricultural fields and farms undergoing land use conversion to residential/commercial uses. Most of the socially and economically weak segments of society in Phoenix are concentrated well within the urbanized region rather than along the outskirts (Gammage, 1999).

The datasets combined in the expert system framework (Stefanov et al., 2001b) include an initial minimum distance to means (MDM) land cover classification of ASTER visible to near infrared data acquired on September 19, 2000; unsupervised classifications of the NDVI and spatial variance texture data (using both 3 x 3 and 5 x 5 kernels), and a land use vector polygon dataset. The land use data were acquired from the Maricopa Association of Governments (MAG, 2000) and are contemporaneous with both the ASTER and MODIS data. The land use data are constructed from a combination of survey questionnaires, site visit, and aerial photograph data. This dataset contains 46 separate land use categories which were aggregated to seven for use in the expert system model: Open Residential, Built, Cemeteries, Open Space, Golf Courses, Water, and Agriculture. A series of decision rules were then constructed to recode misclassified pixels in the MDM classification product. The MDM classes White Rooftops and Blue Rooftops were also recoded into one class, Reflective Built Surfaces, within the expert system model. The expert classification model was run using the area of overlap of the MDM classification and the MAG land use dataset only (Figure 2).

The fifteen-class output of the expert classification model was then further aggregated to 11 classes prior to accuracy assessment. Classes were aggregated if they were functionally similar landscape elements (i.e. Canopied and Riparian Vegetation) to minimize potential confusion in the reference dataset used for accuracy assessment. The reference dataset was constructed from 3 m/pixel digital aerial orthophotos for the Phoenix metropolitan region collected in 1999. The 2000 ASTER VNIR data were also examined during the assessment process to minimize reference dataset error due to temporal change in classes such as Agricultural Vegetation. Assessment points were selected using a stratified random approach to ensure that each class had at least 50 associated reference points. Each accuracy assessment point was then examined to ensure that it did not fall within the associated class of interest's training regions; any point that did was removed from the reference dataset. If the number of reference points for a given class fell below 40, new points were selected to achieve this minimum number. The Overall Classification Accuracy was 88.06% (Stefanov and Netzbald, in review).

2.2 Grid Construction and Landscape Metrics Calculation

A grid with 1 km² elements was created from the reprojected MODIS data pixels to allow for direct comparison of calculated landscape metrics with the aggregated land cover classification. The full extent of the Phoenix urban area is not captured by the 2000 ASTER data, but we selected the location and extent of the analysis grid to capture a representative portion of both the urban and peri-urban regions of Phoenix (figure 3). Four metrics were selected for analysis: Class Area, Mean Patch Size, Edge Density, and Interspersion/Juxtaposition Index. These metrics were computed using the FRAGSTATS software package (McGarigal and Marks, 1994). This suite of metrics was selected as representing key aspects of urban landscape structure that are also easily interpreted in terms of biogeophysical variables obtained from MODIS.

Class Area (CA) equals the area (m²) of the given land cover type divided by 10,000 (to convert to hectares). Mean Patch Size (MPS) indicates the mean land cover pixel size in hectares and is a function of the total area of the landscape and the number of land cover types. Smaller values indicate a higher fragmentation of the landscape. Edge Density (ED) equals the sum of the lengths of all edge segments involving the corresponding land cover type divided by the total landscape area (converted to hectares). The Interspersion/Juxtaposition Index (IJI) describes the observed interspersion over the maximum possible interspersion for a given number of patch types within the landscape. IJI approaches 0 when the corresponding land cover type is adjacent to only 1 other land cover type. IJI equals 100 when the corresponding land cover type is equally adjacent to all other land cover types (i.e., maximally interspersed and juxtaposed to other land cover types) within the landscape.

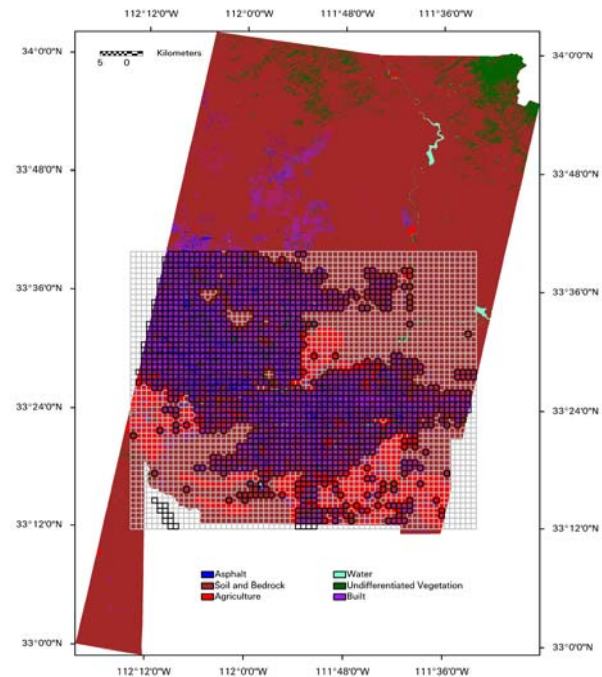


Figure 3. One kilometer grid overlain on land cover classification recoded to six classes. Black grid cells are urban, all others are nonurban.

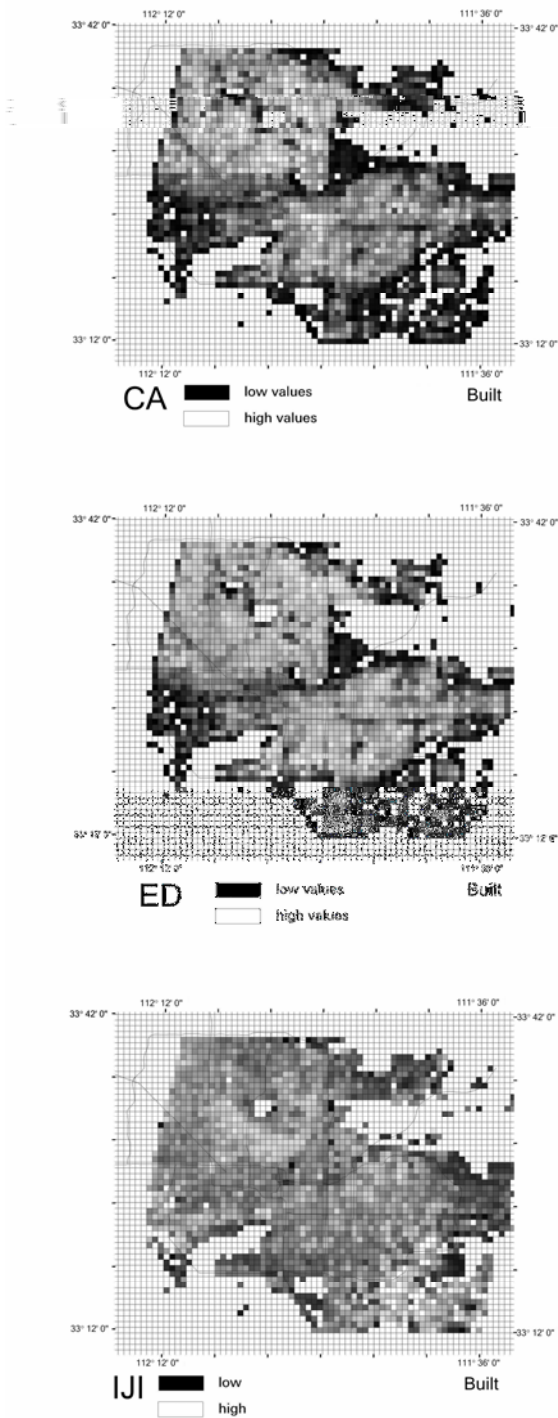


Figure 4. Class Area (CA), Edge Density (ED), and Interspersion/Juxtaposition indices for the Built aggregate land cover class. Grid corresponds to that depicted in Figure 3. Background vector data are major highways.

The majority of variance in the metric results is expressed in the urban grid cells (figures 4 and 5), as the nonurban grid cells include relatively little variation in land cover types. Representative results for the CA, ED, and IJI metrics for the

Built aggregate land cover class are presented as greyscale raster images in Figure 4. An example of the Mean Patch Size results is not included as there is little to no variation in this metric at the 1km analysis scale (leading to monotonic raster results). Raster images were generated for each aggregate land cover class (data not shown) with the exception of the Water class. This class was not included as it had minimal representation in the grid analysis area. The Asphalt class exhibits relatively low IJI values in areas associated with urban mountain parks and along the urban/peri-urban fringe area. Highest values are associated with older mesic residential areas, while significantly variable IJI is obtained for the remainder of the urbanized region. Older residential areas in the Phoenix region are generally comprised of lots with high amounts of vegetation (grass, trees) in addition to built materials and asphalt roadways (Hope et al., 2003).

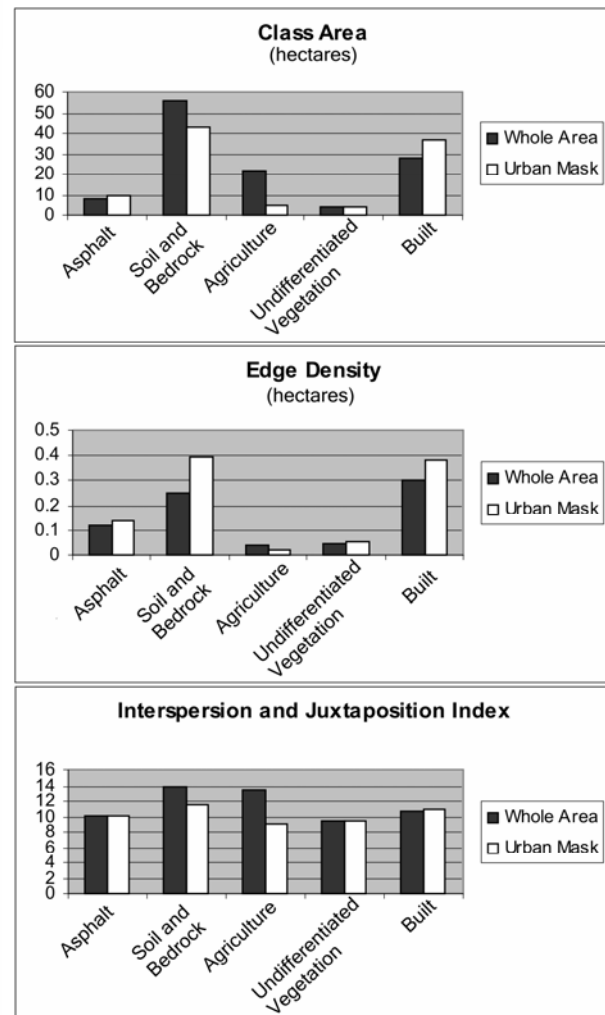


Figure 5. Class Area, Edge Density, and Interspersion and Juxtaposition Index for the aggregated land cover classes (whole investigated area and for urban masked grid cells).

The metric results for the Soil and Bedrock class suggest that while the majority of surficial soil and rock material in the urban area is not highly intermingled with other land cover

types (relatively low IJI), these areas are irregular in shape (relatively high ED). The boundaries between urban and peri-urban regions are not as sharply defined for the Soil and Bedrock class as for the other classes. This is to be expected as the majority of the peri-urban region is comprised of desert soils with low vegetation cover or exposed bedrock (GP2100, 2003). The Agriculture class has minor representation in the urban region, however it exhibits low to moderate ED in keeping with the generally rectilinear plan of agricultural fields in this region.

The Undifferentiated Vegetation class shows highest ED values along the Salt River bed and in areas of mesic residential land cover/land use. While the Salt River bed is generally dry, there is enough water released in association with an upstream impoundment of water (Tempe Town Lake) to support a sparse riparian vegetation community (Mussacchio, 2003). The IJI values for the Undifferentiated Vegetation class are similar to those for Asphalt; relatively high values are recorded in older mesic regions, while variable results are associated with the remainder of the urban area. Both ED and IJI values for the Built class are generally high throughout the urban region. This suggests that this class is evenly distributed, highly intermingled with other land cover types throughout the urbanized area, and has generally irregular boundaries with other classes at the 1 km scale of analysis. The land cover classification discussed previously (Section 2.1) and presented in Figure 2 illustrates the degree of mixing present between soil, built, and vegetation land cover types in the Phoenix region.

2.3 Comparison of Landscape Metrics with MODIS Data

We hypothesized that the landscape structure of the Phoenix urban/peri-urban area correlated with a variety of biogeophysical parameters at the 1 km scale of a MODIS pixel. The results (Stefanov and Netzbund, in review) suggest that this hypothesis is not generally correct. Table 1 presents descriptive statistics for the MODIS datasets. The MODIS datasets were selected in order to be temporally coincident with the September 19, 2000 ASTER data. Examination of the results for both the urban and nonurban grid cells indicates generally low variance in the MODIS data; standard deviations are typically an order of magnitude or more lower than the means. This suggests that at the 1 km/pixel scale of the MODIS data, the Phoenix metropolitan area appears fairly uniform. The exceptions to this general conclusion are the fPAR and LAI datasets. The observed high variance of these datasets is however the result of small sample size rather than actual variation across the metropolitan region.

Dataset (units)	Mean		$\pm 1 \sigma$	
	(U)	(NU)	(U)	(NU)
Albedo (unitless)	0.19	0.20	0.03	0.04
fPAR (%)	0.28	0.26	0.10	0.11
LAI (m^2/m^2)	0.38	0.37	0.22	0.29
Day Surface Temperature (Kelvin)	47.26	47.74	1.66	2.96
Night Surface Temperature (Kelvin)	27.55	26.82	2.08	4.48
NDVI (unitless)	0.24	0.23	0.08	0.11

Table 1. Mean and Standard Deviation for MODIS Data for Urban (U) and Nonurban (NU) Grid Cells. Abbreviations are: fPAR – fraction of photosynthetically active radiation; LAI – leaf area index; NDVI – normalized difference vegetation index.

3. CONCLUSION AND OUTLOOK

We explore the relationships between landscape structure and biogeophysical variables in Phoenix, Arizona using spatial metrics derived from ASTER data and 1 km/pixel MODIS data. Spatial metrics used include Class Area, Mean Patch Size, Edge Density, and the Interspersion and Juxtaposition Index. Biogeophysical parameters investigated include albedo, fraction of photosynthetically active radiation, leaf area index, day/night surface temperature, and the normalized difference vegetation index. Our results indicate some control of these biogeophysical parameters by urban/peri-urban landscape structure. The correlations are not strong however, and may reflect both the spatial heterogeneity of the Phoenix metropolitan region and the relatively low variance of the MODIS data over the urban/peri-urban region at the 1 km/pixel scale. Further analyses of this type performed in urban centers with different histories and geographic/climatic contexts, and using MODIS data with smaller pixel sizes, are necessary to verify this conclusion.

Over the past two years, ASU scientists from a variety of disciplines including geology, engineering, geography, ecology, and sociology have been developing a comprehensive series of metrics to characterize the spatial and socio-ecological structure of cities together with methods to validate the inferred patterns. Much of this current work focuses upon Phoenix, taking advantage of the extensive on-the-ground resources of the Central Arizona–Phoenix Long Term Ecological Research (CAP LTER) project. To further test these methods, we are now forming an expanding network of partner cities in the developed world where scientific resources are readily available, and in developing countries where there is great enthusiasm for applying this approach to pressing environmental problems. In parallel with the growth of this network, we are collaborating with government agencies (such as NASA) and the scientific community to establish an enhanced satellite system that directly serves the needs of urban areas.

Despite the promising and exciting possibilities presented by new and fast-developing sensors and technologies we still perceive a gap between the generally academic and research-focused spectrum of results offered by the urban remote sensing community and the application of these data and products by the local governmental bodies of urban cities and regions. There is no end of interesting science questions that we can ask about cities, but sometimes these questions don't match well with what the operational problems and concerns of a given city are. Our hope is that through the UEM project and collaborations with partners from other urban regions we can determine what the important questions are, and how we can use our data and scientific skills to help answer them.

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