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Monitoring Urban Growth and Its Environmental Impacts Using Remote Sensing

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The size of the world's growing urban population gives urgency to the need for accurate estimates of the location, size, and growth of existing urban areas as well as forecasts of likely regions, magnitudes, and configurations of urban growth. However, to date, there exists no global database that accurately describes and maps which portions of Earth's habitable land are urbanized, or how those portions have changed over the recent decades. Satellite remote sensing and spatial modeling offer tremendous opportunities to map historical patterns of urban growth, monitor urban areas, and forecast urban expansion.

Recent advances in remote sensing—both in satellite hardware technology and image-processing algorithm development—provide opportunities for collection and dissemination of timely information on urban form and size that can be useful for policy and planning. In spite of these developments, there are also limitations to remote sensing and its application in practice. In this paper, I will describe some of the opportunities for, and limitations on, monitoring urban growth using remote-sensing data, and I will provide examples of the environmental impacts of urban growth, as monitored with remote sensing.

<A>Satellite Remote Sensing: Opportunities and Limitations for Urban Mapping

Satellite remote sensing affords a number of unique opportunities for monitoring urban growth. The internally consistent measurements and long observational record of satellite sensor data make it an attractive source of reliable information on urban extent and form. Beginning with the launch of the first Landsat satellite in 1972 and continuing with Landsat 7, satellites have provided more than thirty years of 30–80 m multispectral imagery for much of Earth's surface. Each Landsat scene covers approximately 170 km north-south and 185 km east-west, an area that easily encompasses a metropolitan area if the city is imaged near the center of the scene.

Satellite images are digital data of reflected energy collected across portions of the electromagnetic spectrum. Because most satellite data are multispectral, they contain information from the nonvisible portions of the electromagnetic spectrum (vegetation and soils are most reflective in the nonvisible range). Among the many types of information that can be derived from remote sensing, those relevant to the discussion of urbanization include local surface temperature, wildlife habitats and biodiversity corridors, and extent of impervious surfaces. Moreover, because satellite images are simply digital arrays of information, they can be reprocessed in the future as new digital image processing methods become available.

The ability of satellite data to identify urban areas rests on the unique spectral characteristics of urban areas relative to other land covers such as vegetation, water, or soil. Because urban areas are composites of other land covers (e.g., lawns, swimming pools, rooftops, concrete sidewalks, buildings, etc.), a single "urban pixel" in an image is likely to be a mix of composite land covers. Very few urban pixels will be "pure" (i.e., entirely pavement, entirely building, entirely roads, etc.). The purity of any given pixel will be determined by the scale of the urban elements (e.g., building, road) relative to the spatial resolution in the image (Woodcock and Strahler 1987). For example, the spatial resolution of Landsat makes it useful for mapping large urban areas and indicators of urban form and land use, but it does not lend itself to street-level urban mapping or differentiating between residential and commercial urban development, or between high-density and low-density urban development, unless additional ancillary data are available. Data from the first Landsat period, from 1972 to 1983, were imaged at 79 meter resolution. Since 1984 and Landsat 5, multispectral data have been collected at 30 meter resolution. For the purposes of urban mapping, these data are relatively coarse and cannot detect small-scale urban change. For example, intercity highways, isolated patches of small urban development, or urban infilling may not be distinguishable in a Landsat image. Where urban growth is occurring in agricultural regions, Landsat data may be too coarse to differentiate among irrigation ditches, dirt paths, and other types of land use which coexist in urban agricultural areas.

High-resolution urban mapping is best achieved with aerial photographs or commercial-grade satellite data such as IKONOS or Quickbird, but these data are significantly more expensive than Landsat data and have small area coverage: a single IKONOS image covers an area of 16.5 km by 16.5 km. With 4-meter multispectral and 1-meter panchromatic spatial resolution, these data can be used for city-level urban mapping. However, IKONOS was launched only in 1999 and has an anticipated lifespan of nine years, thereby limiting its utility for historical mapping. Moreover, IKONOS images are priced between $350 and $1,800 per scene, compared to Landsat data, which are now available at no cost; this difference suggest another limit on use of IKONOS data. DigitalGlobe's Quickbird also has high resolution data (at 2.4 meters in the multispectral mode and 60 centimeters in the panchromatic mode) and is priced similarly to IKONOS. The satellite has been operational since 2001 and is fueled for seven years.

Despite their low spatial resolution, Landsat data can provide useful information for a wide range of urban applications, including analysis of historical urban growth;

modeling and forecasting future urban growth; predicting and planning for infrastructure needs; assessments of impervious surfaces and runoff in watersheds; identification of agricultural land, forests, and other places vulnerable to urban envelopment; conservation planning; and land management. Some of the most valuable information that can be extracted from remote sensing includes the size and spatial configuration of urban areas. No other information source can provide a similarly consistent dataset that can be used for inter- and intraregional comparative studies. Data on urban extent, or “built-up area,” provided by national statistics often suffer from being aspatial; information is provided in terms of total area without any reference to location, making it harder to measure urban growth patterns over time or space.

One of the biggest challenges in urban remote-sensing research is how to map urban growth dynamics. Some cities are growing rapidly and require frequent acquisition of satellite data over short time intervals. For example, mapping the growth dynamics of one of the fastest growing cities in the United States, Las Vegas, Nevada, would require the use of interannual images. Using only a few images to describe the city’s growth patterns may not adequately reflect the temporal and spatial patterns of change. Yet, most remote-sensing urban change studies utilize only two or three satellite images because a majority of image-processing algorithms are designed to analyze landscape change between two periods. Computationally, the same image-processing algorithm can be applied to more than three images, but the repeated application can introduce errors. It is widely recognized that the accuracy of a change analysis made from two separate classifications will be at best the product of the two individual classifications (Singh 1989). For example, if each individually classified map has an accuracy of 90 percent, a change map made with these two maps will have at best 81 percent accuracy if the errors are spatially correlated. Therefore, it is important to use algorithms that process all the images simultaneously rather than sequentially or in a pair-wise fashion (Kaufmann and Seto 2001; Seto and Kaufmann 2003; Boucher et al. 2006). Such algorithms do exist and more are currently being developed, but their use is limited to a small community of specialized researchers, and their widespread adoption by the larger remote-sensing community is unlikely to occur soon due to technical and human resource constraints.

With increasingly long time series images, change-detection accuracy may not just be evaluated for two time periods, but may include multiple time points. That is, one must ensure accuracy through time. Temporal accuracy becomes as important as spatial accuracy, especially when linking landscape changes with policy or socioeconomic data.

In terms of mapping and monitoring of “urban hot spots,” perhaps the most significant limiting factor is the need to do a geographic sampling of existing urban areas. It is estimated that the fastest-growing urban areas are medium-sized cities. Global-scale monitoring efforts with coarse-resolution imagery may not detect small-scale changes that occur in these cities. However, due to technical and fiscal constraints, it is impossible to do a comprehensive study using moderate- or high-resolution images. Therefore a sampling scheme is required. How should this sampling be achieved, by population size or area? Areas with large urban populations are not necessarily areas that are large in urban extent. Similarly, large urban areas do not indicate large urban populations. Currently, global estimates of urbanization are based on population size, and there are no reliable or consistent global—or even regional—estimates of urban extents.

Finally, other obstacles to the use of satellite imagery to map urban growth include the limited availability of this imagery, especially for tropical regions where presence of cloud cover in the images is prevalent; the level of technical expertise required to utilize the data beyond visual interpretation; and the costs associated with developing and maintaining extensive geospatial databases. Although the Landsat record extends back to 1972 with a repeat cycle of sixteen days, in reality, for most locations outside the United States, there exist only a handful of images for the Landsat 1 through 3 missions. The dearth of data during this period is due to a combination of poor and inconsistent archiving methods and the lack of cloud-free data for many regions of the world. In terms of technical expertise, there is a growing community of remote-sensing users, but algorithm developers and remote-sensing specialists remain in limited supply, especially outside of the industrialized countries. While remote-sensing researchers develop increasingly more specialized and technical methods, the vast majority of the remote-sensing community continues to use time-tested algorithms that are easy to implement but may not be the most advanced. Lastly, the development of geospatial databases is a costly effort, in terms of both human and financial resources. Maintaining and archiving these databases is often comparable to, if not more expensive than, their development.

<A>Urban Growth and Environmental Impacts in the Pearl River Delta, China

The Pearl River Delta in South China is one of the most economically vibrant regions in China (figure 9.1). For over a decade, we have been using remote sensing to monitor urban growth in the region and assess associated environmental impacts. In a country where an average of twenty new cities are being built each year (*People's Daily* 2000), timely monitoring of urban growth is critical for sustainable urban development. Within the Pearl River Delta, we focus on four of the fastest growing cities in the region: Guangzhou, Shenzhen, Dongguan, and Zhongshan.

<<INSERT FIGURE 9.1 HERE>>

Guangzhou (Canton), capital of Guangdong Province, is the oldest among the four cities in the study. Located at the mouth of the Pearl River, it has a long-established park system and a rich assemblage of vegetation, especially in the older districts where dense tree cover is common. Traditionally, Guangzhou has been considered the cultural, economic, and industrial focal point of southern China. It is also a transportation hub; it has an international airport, one of the most active regional seaports, and railroad connections to all regions of the country. Just a small fishing village until it was declared a Special Economic Zone in 1979, Shenzhen is located on the Hong Kong–China border and has experienced the most dramatic economic growth and landscape changes of the cities in the study. Regionally, it receives the bulk of foreign direct investment (FDI) and has a large population (estimated to be between 5 and 10 million) of temporary workers.

Located between Guangzhou and Shenzhen in the northeastern part of the Delta, Dongguan is a leader in export-oriented industries such as textiles, toys, and food processing. It has developed rapidly in part because of its proximity to Hong Kong. The soils in Dongguan are well suited for agriculture, and lychees from the region are famous throughout the country. Zhongshan is located in the low-lying western mouth of the Pearl River Delta, approximately 80 kilometers south of Guangzhou. It differs from the other three cities in that it has received relatively little foreign direct investment, and a shift from the primary to the secondary and tertiary sectors of the economy has been led by a mix of both domestic and foreign enterprises. These differences have resulted in a city that has developed more slowly and with a more domestic Chinese character than the other three cities.

We used ten Landsat Thematic Mapper (TM) images, covering the period from 1988 to 1999, to develop maps of urban extent (Seto et al. 2002). Following the remote-sensing analysis, we calculated landscape metrics for each of the maps. The characterization of landscape mosaics and patterns has a long tradition in ecological studies, where understanding habitat fragmentation, landscape heterogeneity, and the distribution of landscape disturbance is important for understanding ecological processes (Ives et al. 1998). Landscape metrics can be used to characterize how the landscape has developed. For example, they can empirically describe the shape, complexity, compactness, patchiness, linearity and squareness, and size of urban areas (Riitters et al. 1995; Schneider et al. 2005). We calculated six landscape metrics to describe the spatial and temporal patterns of urban land development and to identify common patterns in the shape, size, and growth patterns across cities at different stages of economic development. We chose metrics that describe three aspects of the urban landscape: absolute size, relative size, and complexity of urban form. Absolute size is described by two metrics: total urban area and number of urban patches. As urban growth occurs, total urban area continually increases due to the highly nonreversible nature of urbanization. The number of urban patches is a measure of discrete urban areas in the landscape and is expected to increase during periods of rapid urban nuclei development, but may decrease if urban areas expand and merge into continuous urban fabric.

Relative size is described by the mean urban patch size and urban patch size coefficient of variation. The mean urban patch size is a function of the number of urban patches and the size of each urban area and can either increase or decrease through time. Decreasing values of mean urban patch size imply that new urban centers are growing faster than existing urban areas. That is, urban growth occurs more as a process of new and multiple urban nuclei formation than of envelopment or annexation. The urban patch size coefficient of variation is a normalized metric of the urban area and can either decrease or increase through time.

Urban edge density measures the total edge of urban areas relative to the total landscape and should increase with new urban nuclei, but may decline as urban areas fuse together and boundaries dissolve. The metric for the area-weighted mean patch fractal dimension describes the degree to which the shape of an urban area is simple versus irregular or complex. The more irregular the shape of the urban area, the higher the value of the fractal dimension. Of the many shape and complexity measures available, we used the area-weighted mean patch fractal dimension because it is normalized. Values range between 1 and 2, with values closer to 1 indicating areas with relatively simple shapes such as squares or circles. Values that approach 2 represent complex and irregular shapes. The area-weighted mean patch fractal dimension is hypothesized to increase during the early periods of urban land-use change when new urban nuclei and expansion of existing urban space create irregularly shaped landscape patterns. This metric is expected to decline as urban form becomes more regular.

We calculate the six landscape metrics for each of the ten years of satellite data for three buffer zones drawn at 0–3 km, 3–10 km, and 10–20 km from the city centers.

Our rationale for a concentric ring partitioning of urban space and the selection of buffer size was based on three criteria: (1) the need for a standard buffer size to which the cities in the study could be compared through time; (2) the need for each buffer to capture variation within and among cities (drawn too close to the city center, the buffers would capture variations only within the central business district; drawn too distant from city centers, the buffers would capture variation over too large of an area); and (3) our interest in the boundaries of the urban-rural fringe and the forces that drive landscape changes at the edges of cities.

<A>Urbanization Impacts on Agricultural Land and Local Precipitation

Results from the analysis indicate that the average annual rate of urban growth for the four cities between 1988 and 1999 was 17 percent, with the largest growth of 32 percent between 1992 and 1993 (figure 9.2). Total urban land for the four cities nearly quadrupled during the study period, from 290 km^2 in 1988 to 1,122 km^2 in 1999 (figure 9.3). Most of the new urban development has been at the expense of agricultural land. Four major types of agricultural land loss have occurred. First, the construction of industrial centers, residential complexes, and factories has led to the conversion of large tracts of agricultural land. Second, on a smaller scale, improvement of houses owned by farmers and agricultural workers has also reduced the amount of land available for agriculture. Third, highway development has divided agricultural plots and removed them from cultivation. Fourth, the flooding of fields for water reservoirs and dams has also taken farmland out of production. Reservoirs and dikes have been constructed to support the booming residential and industrial sectors. Despite a 1985 moratorium in the region that limited the amount of agricultural land that could be converted for nonagricultural purposes, remote-sensing analysis reveals that the loss of agricultural land is more than 11 percent greater than the amount reported in statistical yearbooks (Seto et al. 2000).

<<INSERT FIGURES 9.2 AND 9.3 HERE>>

The higher estimates of loss of farmland may be due to the coarse resolution of the Landsat data, which cannot differentiate among irrigation ditches, dirt paths, small houses, and other land uses that coexist with agriculture. Yet even with this potential bias, there are reasons to believe that the total amount of agricultural land was systematically underreported by farmers due to institutional factors such as the tax system and historical grain quotas. Since 1958 with the Great Leap Forward, farmers have had strong incentives to underestimate their agricultural land. During this period, grain quotas were based on total farmland acreage. Therefore, underestimates of agricultural area reduced a farmer's grain quota. Although this production quota has been eliminated, the regional moratorium has also had the effect of causing farmers to underestimate the loss of farmland.

Urban growth rates are strongly related to foreign investments, politics, and policies (Seto and Kaufmann 2003). Immediately following the Tiananmen Square incident in 1989, foreign investments dropped significantly and some large-scale development projects were suspended in the delta. In January 1992, Premier Deng Xiao Peng visited the delta to reassure investors that China would continue to pursue reform. This led to the resumption of foreign investments and development projects.

The region's long history of agriculture and human settlement resulted in extensive deforestation that occurred well before the current period of economic development. Little urban growth has recently occurred in forested areas. Most of the large intact tracts of forests are located in the mountainous regions north of the delta's basin, away from the major cities and industrial zones. The conversion of natural vegetation that occurred in the delta consisted mainly of shrubs, small patches of forests, and hills. Urban development has led to the quarrying of hills and has caused widespread soil erosion. A preliminary analysis of the topography in the region shows that the region has become more leveled over the last two decades as a result of quarrying and new construction. Soil erosion has become prevalent, and the Chinese Academy of Forestry has engaged in collaborative reforestation projects with international organizations. The Chinese government's Ninth Five-Year Plan increased forest coverage by planting 1.2 million hectares of forest in the delta. Plantation efforts have focused on fast-growing species of *Eucalyptus, Acacia,* and native Chinese pine. Especially prevalent is *Acacia mangium*, which is tolerant of poor soils and has grown successfully under similar conditions in other tropical environments. The introduction of nonnative tree species and reforestation efforts are two unintended effects of urbanization in this region. Whether these efforts will abate soil erosion is unclear, especially given that large-scale land-use change and urban development continue in the region.

The results highlight a few points about the style of urban development in the region. First, urban growth in the four cities occurred through two primary processes: envelopment—the annexation of the surrounding landscape through the growth of extant urban areas—and multiple nuclei development (Seto and Fragkias 2005). In South China, most of the area surrounding urban centers is used for agriculture. Therefore, urban growth through envelopment occurs mostly at the expense of cultivated land. Multiple nuclei urban growth occurs when new urban centers are developed in areas disconnected from existing urban areas. This development occurs mainly as result of high-tech zones that are financed primarily by foreign direct investment. These clusters of industrial zones were initially constructed in rural communities distant from the urban core, usually on agricultural or unproductive land. The trend of multiple nuclei urban development has been documented in a number of other cities throughout China (Schneider et al. 2005).

The spatial pattern of development reflects land-use decision making that occurred at all levels of the Chinese administration and at different stages in the evolution of development policies. The original 1987 land administration law allowed development zones to be sanctioned by the central government's State Council. The land law also allowed various lower-level administrative units, such as municipal and local governments, to develop industrial zones. This gave rise to internal competition across multiple administrative levels to develop specialty zones, which led to a polynucleated urban space. Town and municipal governments competed directly against each other in their attempts to establish high-tech and industrial zones to attract foreign investments.

Incorporating a temporal component to landscape metrics reveals that the urban form of cities can change relatively quickly over short time periods. It is widely noted that the patterns of cities change slowly, primarily because the establishment of infrastructure such as roads limits the direction in which urban growth can occur (Henderson 1988). Once the basic form of a city is in place, it is difficult to alter the trajectory of city structure. Although there is a certain level of urban growth path dependency, however, the results show that urban form can vary greatly during the early stages of economic development.

The expansion of these cities follows a particular spatial and temporal form. Despite differences in levels of economic development and local policies, there are common patterns in shape, size, and growth across urban zones and cities in the four cities. There is also evidence that disconnected urban areas converge toward a pattern of contiguous urban fabric.

Modification of land cover through urban growth changes the biophysical attributes of the land surface and ecosystem functions. These changes then contribute to regional and global climate change by modifying surface energy and water budgets and biogeochemical cycles. Building cities on land that was previously vegetated modifies the exchange of heat, water, trace gases, aerosols, and momentum between the land surface and overlying atmosphere (Crutzen 2004). In addition, the composition of the atmosphere over urban areas differs from vegetated and nonurban areas (Pataki et al. 2003). These changes imply that converting vegetated land to urban areas can affect local, regional, and possibly global climate at diurnal, seasonal, and long-term scales (Zhou et al. 2004; Zhang et al. 2005).

Research over the last two decades has generated significant understanding of the relationship between urban areas and climate. There is now a well-established urban heat island (UHI) effect that appears stronger during the night than the day (Lo et al. 1997). The urban heat island effect is thought to be created by the interaction of many factors, including building geometry, land cover, and urban materials (Oke 1976). In terms of the relationship between urban areas and precipitation, there is general consensus that urbanization affects precipitation, but the mechanisms by which urbanization affects precipitation are not well understood (Lowry 1998). Possible mechanisms include (1) enhanced convergence due to increased surface roughness in the urban environment (Thielen et al. 2000); (2) destabilization due to UHI-thermal perturbation of the boundary layer and the resulting downstream translation of the UHI circulation or UHI-generated convective clouds (Sheppard et al. 2002); (3) enhanced aerosols in the urban environment for cloud condensation nuclei sources (Molders and Olson 2004); and (4) bifurcating or diverting precipitating systems by the urban canopy or related processes (Bornstein and Lin 2000). It is also hypothesized that urban areas serve as moisture sources needed for convective development (Dixon and Mote 2003). Even less is understood about the relationship between urban growth—or urban land conversion—and local climate. While numerous studies focus on urban climate, few examine urban growth explicitly (Tereshchenko and Filonov 2001).

Given the rate and magnitude of urban growth in the Pearl River Delta and its likely impact on local climate, we evaluated the relationship between urban growth patterns and precipitation and temperature. We coupled the satellite-generated urban growth analysis from 1988 to 1996 with monthly climate data from sixteen local meteorological stations. A statistical analysis of the relationship between climate and urban growth in concentric buffers around the meteorological stations indicates that there is a causal relationship from temporal and spatial patterns of urbanization to temporal and spatial patterns of precipitation during the dry season (Kaufmann et al. 2007). The results suggest an "urban precipitation deficit" in which urbanization reduces local precipitation during the dry months of October through April. This reduction may be caused by changes in surface hydrology that extend beyond the urban heat island effect and energy-related aerosol emissions. No causal relationship is found between urbanization and precipitation during the rainy season. The rainy season occurs from May through September, when the effects of the Asian monsoon dominate and may overwhelm local urban impacts. During the dry season, cold fronts from northern China bring rainfall to the region, but with a much smaller magnitude than during the summer months. Therefore, local urban effects may be more pronounced during the dry season. This may explain why the urban heat island is most visible in winter (Zhou et al. 2004).

<A> Urban Growth and Environmental Impacts in Bengaluru, India

The urban landscape of Bengaluru (formerly Bangalore), India, has been transformed since the central government initiated policy reforms in 1991. Reforms of industrial, trade, and agricultural policies at both the central and state levels have created an investor-friendly environment that has encouraged foreign direct investment and fostered economic and urban growth. Located in the South India state of Karnataka, Bengaluru had an estimated population of 6.5 million in 2006, making it the fourth-largest city in India (Mumbai, New Delhi, and Kolkata are larger). After liberalization of the Indian economy, foreign direct investment has increased significantly, from 200 million USD in 1987–1990 to 4.1 billion USD in 2001–2004 (UNCTAD online database). Since the mid-1990s, FDI has shifted from the agriculture and manufacturing sectors to services. Citing Bengaluru’s numerous technology institutes, learning centers, and large skilled labor pool as comparative advantages, multinational information technology (IT) and high-tech corporations such as IBM, Microsoft, and Motorola now have major operations in the city.

The development of Bengaluru's IT and associated industries has reshaped the urban environment. Industrial parks that house multiple high-tech companies to create a research campus environment are akin to those found in Silicon Valley (O'Mara 2004). These research parks represent only one dimension of the new urban fabric. Other pieces of the urban mosaic include new residential communities that house high-tech workers and upper and middle management, along with premium transportation corridors that connect different districts of the metropolitan area. The new residential communities range in style and size, with the most opulent targeting senior management nonresident Indians and expatriates. These "master-planned" developments are similar in style to those in the United States, complete with exclusive, limited-access facilities such as tennis courts, golf courses, swimming pools, and even schools. They do differ from American-style suburban developments in that their scale is vastly smaller, with pedestrian-friendly streets and homes that are designed to house multigenerational families.

Our analysis of urban growth in Greater Bengaluru uses Landsat TM imagery from 1973, 1992, 2000, 2005, and 2006. Preliminary results indicate that the period 1992 to 2000 was the most significant in terms of urban expansion, with most change occurring on the edges—most notably on the southern edges—of the city rather than through infilling in the city core. Urban growth during this period is characterized by intensive road building, especially around the city in an effort to connect Bengaluru to other major cities around the country. For the period 2000 to 2006, growth is evident in the east and south, following the development of industrial parks and residential communities (figure 9.4). New growth is also evident in the northeast near the proposed new international airport. Like that in the Pearl River Delta, most of the urban expansion in Bengaluru has been at the expense of agricultural land.

<<INSERT FIGURE 9.4 HERE>>

<A>Challenges to Mapping and Monitoring Urban Growth

Urban areas in China and India pose mapping challenges unique to their environments. In both case studies, the biggest challenge lies in identifying urban growth at small scales. Peri-urban growth takes place contiguous to as well as in agricultural areas. Agriculture occurs at small scales, which can be likened to household gardening with respect to the size of plots and the variety of crops produced. Multicrop fields, terracing, and small field sizes produce texture and tones that can be difficult to differentiate. Agricultural plots are generally small, less than an acre, but the plots of a village are usually adjacent to each other. The smaller plots, and the variety of crop types (vegetable fields, fish ponds, and fruit orchards often abut each other) within the plots, create heterogeneous surfaces which are more difficult to characterize than large-area plots of a single monocrop.

Detection of urban growth in agricultural regions in China and India is inherently difficult because significant landscape changes result from both traditional and novel practices. In both case studies, an increase in farmers' disposable incomes has permitted the refurbishing of old homes and the construction of new homes. The use of new materials often creates a change in spectral signal distinct from the surrounding agriculture. On the other hand, the cycle of planting, growth, plowing, and harvesting introduces an element of change to multidate images independent of urban growth dynamics. For instance, after rice has been harvested, rice fields are essentially bare plots of soil, which spectrally look similar to land which has been cleared for construction of new buildings. Only when rice fields maintain a high level of moisture are they spectrally distinct from bright, dry soils. Therefore, the phenological and planting cycles of rice can be confused with new urban development. Located in tropical and semitropical regions, South China’s and South India’s agricultural fields often support multiple crops per year, and the timing of crops varies among individual fields. Under these conditions, individual satellite images will include fields at all stages of the agricultural cycle, and it is easy to confuse recently plowed, planted, or fallow agricultural fields with new urban land.

Although the spatial resolution of Landsat data allows for discrimination of urban features, such as large road networks, the spatial variance of urban environments in China and India is also high. The heterogeneous nature of urban areas in these countries makes it particularly difficult to generate accurate urban maps. Moreover, magnitudinal changes, such as increases in urban density, are much more difficult to identify with remote sensing.

In terms of integrating remote sensing and socioeconomic data to understand the drivers of urban growth, work in both countries has been limited by a lack of spatially explicit socioeconomic data and reliable administrative boundaries. In China and India, new cities emerge from existing villages and towns, and city growth often occurs as small towns are enveloped by larger municipal units. As a result, administrative boundaries are frequently adjusted and redrawn. Accurate administrative boundaries are critical to urban growth forecasting because urban land-use data derived from remote sensing are linked to socioeconomic data through governmental units. Without digital representations of administrative boundaries, it is difficult to integrate satellite data with socioeconomic data. The challenge ahead is to develop analytical tools and approaches that can be applied across regions.

Our experience in China and India shows that remote sensing can contribute significantly to the understanding of the patterns of urban development and their environmental impacts. The effects of urbanization on precipitation in South China suggest that urban growth in semitropical areas could have major effects on local precipitation worldwide. Given that urban growth is rapid in many developing countries, it is critical to develop a global database of urban growth patterns. Only when we monitor the scale, pattern, and rate of urban change can we begin to understand their potential impacts on the earth's functioning as a system.

<Captions>
Figure 9.1. <AUTHOR: PLEASE SUPPLY TITLE and SOURCE>
Figure 9.2. <AUTHOR: PLEASE SUPPLY TITLE and SOURCE>
Figure 9.3. <AUTHOR: PLEASE SUPPLY TITLE and SOURCE>
Figure 9.4. Change Map for Bangalore,. November 2000–March 2006

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