The Form of Change:
Inter-Annual Analysis of Urban Expansion using Landscape Metrics

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2/18/2009
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Abstract

The past few years have witnessed a proliferation of studies using spatial metrics to examine spatial structure of land cover change. Urban analysts are no exception, applying landscape metrics to study and model patterns of urban growth. While the majority of this research examines emerging urban structures by measuring changes in their *aggregate* forms, these spatial patterns are often dominated by stable regions at the urban core. This study proposes the direct measurement of *discrete* changes across the urban landscape, testing the technique through a comparative assessment of *aggregate* and *discrete* land cover changes across seven classified Landsat images from China's Pearl River Delta. The study presents results on area and compactness metrics computed with Fragstats 3.3 software, which reveal distinct trends between two complimentary methods. Analysis of this data suggests a potential role for *discrete* pattern analysis as a compliment to aggregate change analysis, particularly suited to detecting and characterizing process dynamics involved in urban expansion.

Introduction

Land change research increasingly emphasizes the importance of spatial structure and form in addition to magnitude and direction of land conversion processes. This focus on spatial patterns has emerged as researchers recognize that aggregate measurements of converted lands cannot alone capture the complexity of terrestrial ecosystems. A more sophisticated picture of spatial patterns can therefore lead to superior models of drivers and impacts of land cover change, as well as more effective land use policy (Herold et al 2005).

Spatial metrics consists of a set of tools for measuring the composition and spatial configuration of geographic systems, initially developed within information theory and fractal geometry and extensively developed within landscape ecology under the label landscape metrics (Gustafson 1998). Landscape metrics have been utilized to examine a variety of spatial systems of interest to the satellite remote sensing community. These studies can be divided into two basic types: (1) those that utilize landscape metrics to characterize the patterns inherent within systems (in equilibrium) such as source habitat, forest structure, and urban form (Fauth et al 2000, Schneider et al 2007) and (2) those that utilize landscape metrics to characterize patterns of land cover change across time such as deforestation, urban expansion, habitat fragmentation (Herold et al 2003, Ji et al 2006, Hargis et al 1998).

Within the field of urban systems analysis, both types of studies have been utilized to investigate previously unmeasured urban phenomena. While geographers and economists have been actively generating geometric models that describe and explain the morphology of cities for over a century (see Herold et al 2005 for review), many elements of urban spatial structure have proven elusive. Newer research that combines satellite/GIS data with landscape metrics is capable of examining land cover fragmentation, diversity and richness, and compactness within and across cities. This research highlights the heterogeneous structure urban landscape, with variance often occurring as a function of distance from the city center (Luck and Wu, 2002, Seto and Fragkias, 2005). These spatial indices have been integrated into hedonic models of residential housing values in order to analyze the economic value of green-space (Geoghegan et al, 1997). Other studies demonstrate the viability of using single-date landscape analysis for distinguishing between residential and commercial/industrial land cover types (Herold et al 2002).

The application of landscape metrics to the measurement of patterns of urban change is mainly driven by questions about the drivers and impacts of expansion. Research in the Pearl River Delta indicates that the spatial structure of city growth is non-linear, alternating between periods of satellite development and infill (Seto and Fragkias 2005). Seto et al (2005) also suggest that spatial forms across cities tend to grow more similar at a greater distance from the city center, while the composition of core areas tends to remain distinct. In recognition of the importance of a city's evolving spatial structure, several researchers have called for the integration of time series spatial metrics in urban modeling (Alberti and Waddell 2000, Harold et al 2003, Herold et al 2005, Parker and Meretsky 2004).

While existing studies tend to measure the spatial structure of accumulating urban expansion, this paper investigates the use of an alternative analytical framework and measurement technique. The study proposes the application of spatial metrics to analyze patterns of discrete or marginal changes in land cover, asking the question "Will the spatial pattern of discrete urban change vary from the spatial pattern of aggregate change?" Differences between the two methods are examined in an attempt to encourage a more dynamic use of spatial metrics in the study of land cover change.

Aggregate versus Discrete Change

The majority of studies that pair spatial metrics with remotely sensed data involve the measurement of a particular land cover class as it evolves across a time series. For instance, Southworth et al (2002) compared the number of patches and mean patch size of forested land cover across three classified Landsat TM images (1987, 1991, 1996) to assess the extent of forest fragmentation in Western Honduras. This type of multi-date comparison is intuitive and lends itself to straightforward interpretation. However, while the multi-date technique characterizes nearly every current use of spatial metrics, it may not provide the most appropriate technique for analyzing questions regarding the spatial character of the change *process*.

This paper proposes a slightly different technique, which consists of the application of spatial metrics to characterize the spatial structure change class itself. This technique is based on the logic that change *processes* may possess inherent spatial structures that are not equivalent to the difference between the spatial structure of a land cover class T_1 and T_2. The analyst can therefore examine certain change process more directly by measuring the spatial structure of a change class than by making inferences based on a broad comparison across images. This variation on conventional spatial metric analysis provides an opportunity to examine the structure of change processes in addition to that of change outcomes.

Methods

This study utilizes a set of pre-classified images from the Pearl River Delta to test differences in the spatial pattern of accumulated and discrete annual land conversion within the region. Classification of raw data involved ISO unsupervised classification of 7 Landsat images[1]. Each successive classification procedure was spatially confined to a subset of non-urban pixels from the previous year and a maximum of 30 spectral classes and 40 iterations was allowed. The resulting spectral classes from each year were aggregated into 5 final land cover classes: water, natural vegetation, urban, agriculture, and mixed. The classification results should be seen as preliminary, since they have not

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[1] Images utilized were near-anniversary (December) dates for the following years: 2001, 2002, 2003, 2004, 2005, 2006, 2008

yet been subjected to formal accuracy assessment. While this does render analysis of regional dynamics speculative, analysis of the behavior of aggregate and discrete *change types* (both derived from the same classification) is quite useful.

This paper solely utilizes the results of one component of the overall land cover classification: the urban class. The seven classified images were processed to isolate all urban pixels for each year as well as each inter-annual urban change class, thus creating a pair of images for each year: (1) an image that represents the total *aggregate* urban land cover class for each year and (2) an image that represents a *discrete* class of new urban pixels for each year (see appendix 1). Classified images were subset to exclude image borders and other extraneous material. Landscape metrics were then calculated using the Fragstats 3.3 software (McGarigal et al 2002**)**. The following landscape metrics were calculated for each image:

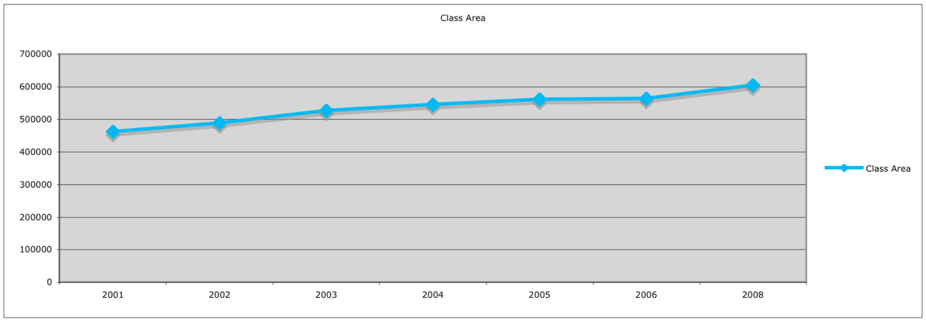
(1) **Class Area**: The total area of the (urban) land cover class.
(2) **Patch Density**: The total number of patches of a given (urban) land cover class divided by the total landscape area.
(3) **Largest Patch Index**: The percentage of the total landscape area comprised by the largest patch.
(4) **Mean Patch Size**: The sum of total (urban) class area, divided by the number of (urban) patches. The average size of an urban patch.
(5) **Normalized Shape Index**: A normalized measure of aggregation across the (urban) class.
(6) **Percent Like Adjacencies**: The rate of adjacency between pairs of like (urban) patches (shape complexity can also reduce values within this index). At the landscape level, PLA is a measure of (urban) class dispersion.
(7) Aggregation Index: The rate of adjacency between pairs of like (urban) patches (shape complexity can also reduce values within this index). Unlike the PLA index, the aggregation index counts each cell side only once and disregards landscape boundaries.

(See McGarigal et al 2002 for documentation and mathematical notation)

Results

A comparison of *Aggregate Change* and *Discrete Change* metrics suggests that these methods do in fact reveal distinct patterns of urban change in the Pearl River Delta. A baseline for interpreting these patterns is provided by the “class area” metric, which suggests that the urban territory expands at a decelerating rate across the time series.

Class Area: *Aggregate Change*

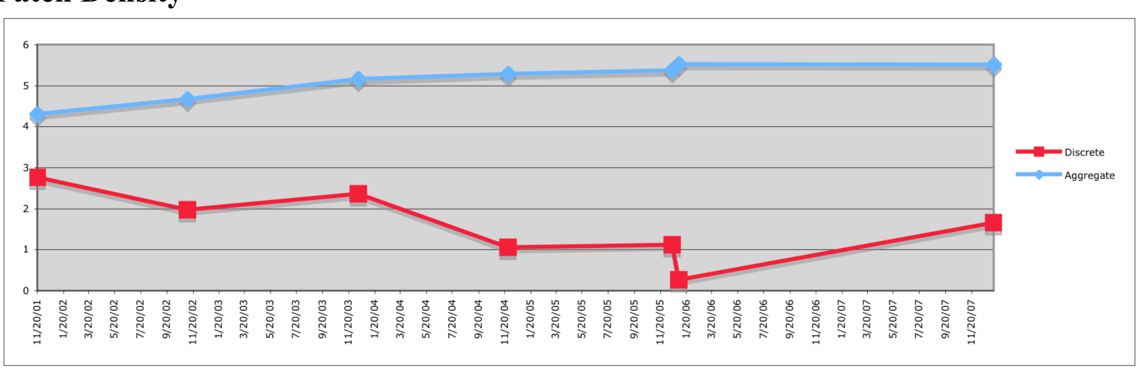


Area/Shape Metrics

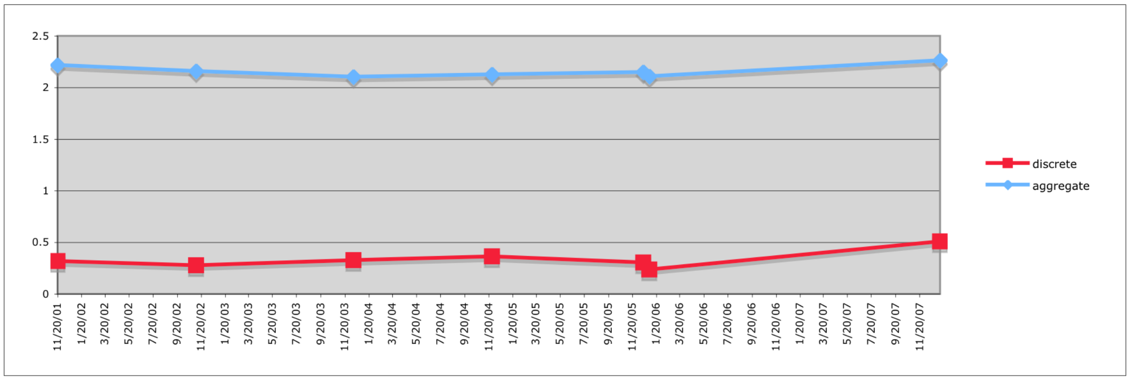
Stark differences between the measures of *aggregate change* and measures of *discrete change* become apparent in interpretation the area/shape metrics. When urban expansion is measured on aggregate, the patch density measure suggests that urban patches increase between 2001 and 2009 but begin to flatten near the end of the series. This can be interpreted either as a reflection of decelerating urban growth (fewer patches per year) or as the result of urban infill that links older patches together. The patch density of discrete change indicates a decreasing trend across the decade, whereby fewer new patches emerge each year are developed each year. It is important to note that since the discrete measure excludes patch linkages over time, this variable provides for a more precise reading of inter-annual patch formation but cannot measure relationships between new and established urban areas.

The measurement of mean patch size illustrates a similar inverse relationship between *aggregate* and *discrete* urban change. On aggregate, the average patch forms a slight u-shaped curve, diminishing in the first part of the series and then becoming larger toward the end. This may reflect a change from satellite development during the first part of the decade to infill toward the end. *Discrete* or marginal changes, which will not measure infill, suggest significant inter-annual variance in the development of large versus small new developments. While this index does not lend itself to simple analysis of decadal trends, it does provide a more precise measurement of the inter-annual process dynamics. Most importantly, the inverse and independent correlations between *aggregate* and *discrete* changes is mean patch size provide evidence that they are indeed measuring distinct phenomena.

Patch Density



Mean Patch Size

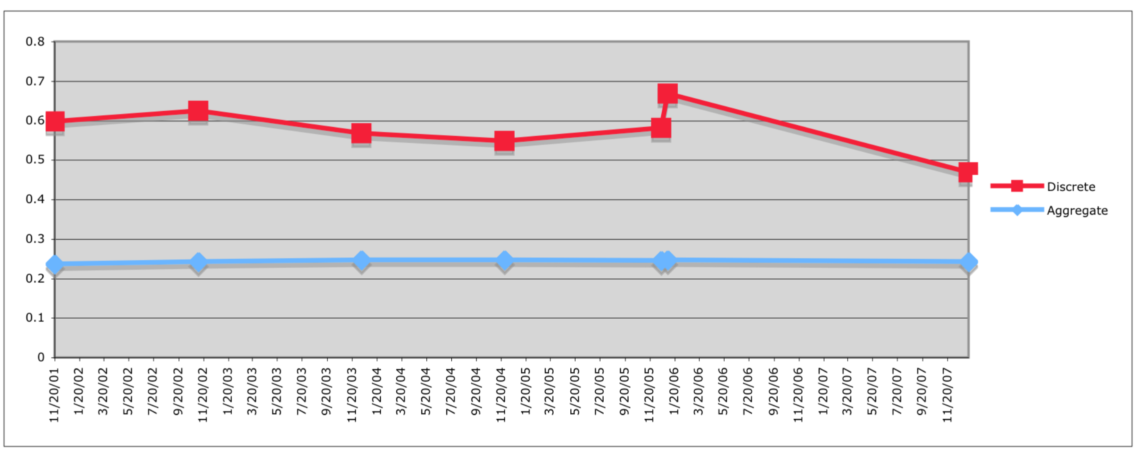


Dispersion/Compactness Metrics

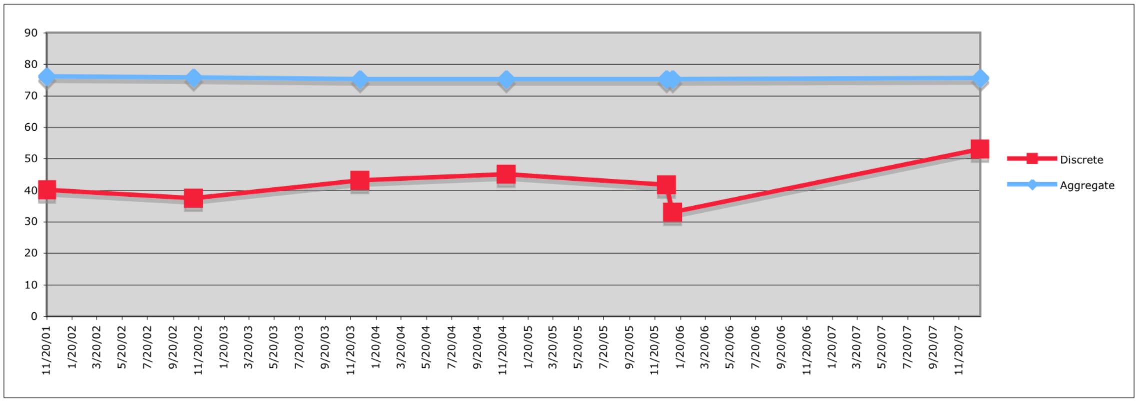
The second type of spatial metric employed to examine the differences between *aggregate* and *discrete* change in urban land conversion includes a set of tools for measuring the extent to which urban patches are disbursed/diffuse versus aggregated/compact. While the three metrics selected for this study offer highly correlated results, I have included all three to demonstrate the robust character of the trends. Across all three metrics, the *aggregate* urban class tends to become more diffuse during the first half of the decade and then more compact during the second half. On an aggregate level, these affects to the overall urban form appear slight.

The *discrete* measure of change, on the other hand, exhibits an inverse trend. This should not be interpreted as a countervailing force, however, since *discrete* measures of compactness are actually fundamentally different from *aggregate* measures. *Discrete* change is designed to measure only within-year effects while excluding relationships between new and existing urban zones. Therefore, the *discrete* measure suggests that new urban developments were increasing in concentration during most of 2001-2004 and then became increasingly diffuse in later years.

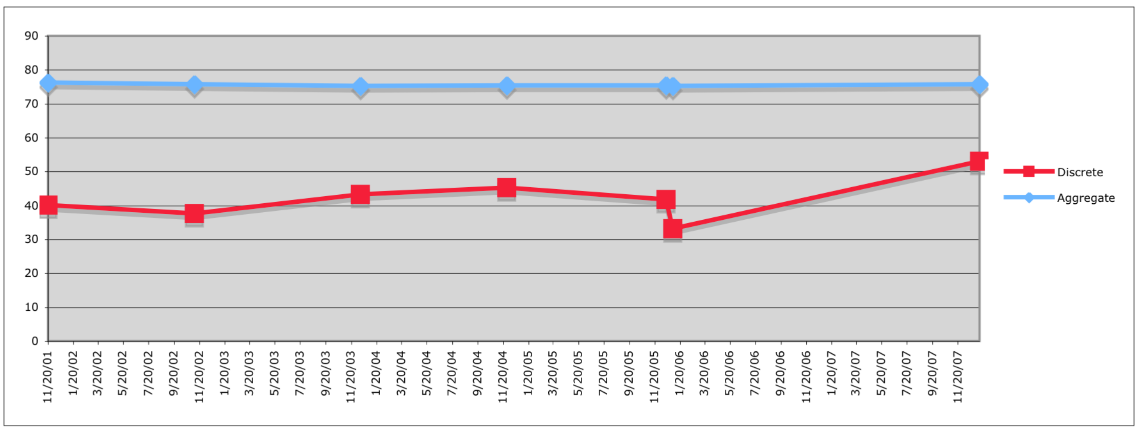
Normalized Shape Index



Percent Like Adjacencies



Aggregation Index



Discussion

Results from this paper suggest that spatial analysis of *discrete* land cover changes can reveal trends that are not apparent in research on *aggregate* classes. Not only do inter-temporal spatial dynamics become more pronounced when teased apart from the stable system – they can behave completely differently. While the spatial pattern of new development is often of intense interest to researchers, the common measurement of *aggregate* urban change can obscure these patterns due to the dominance of stable systems within a landscape. The choice of *aggregate* versus *discrete* spatial analysis of change depends entirely on the empirical questions of interest to the analyst. A comprehensive understanding of the process and overall trends of urban land cover change may be achieved through a comparison of both discrete and aggregate forms.

While this paper has introduced only a few metrics as a proof of concept, the *discrete* method may be used to examine a range of questions pertinent to land cover change. For example, the degree to which urban expansion on a given period is characterized by the development of roads could be explored through the application of a "linearity" metric to a *discrete* urban class. The extent to which new urban areas is concentrated in a single development or in multiple areas might be achieved by the "contiguity" metric. Beyond the field of urbanization, *discrete* change analysis could shed light on the spatial configuration of processes such as forest clearing processes or vegetation phenology.

While *discrete* pattern analysis offers unique opportunities to the analyst, while also possessing unique constraints. In studying the spatial configuration of change *processes*, these methods will be quite sensitive to temporal irregularities. This is evidenced in the erratic spatial pattern of each metric for the final two images in the series, which illustrate the effect of abnormally very short and long time intervals. An unbalanced time series will require normalization, as would a "rate of change" calculation, and in some cases may render results that are very difficult to interpret. In addition to temporal sensitivity, the relationship between spatial patterns of change and the spatial configuration of stable land cover classes may provide analytical challenges, since the metrics treat them as entirely distinct.[2]

Conclusion

Research on Land Use/Cover Change increasingly demands spatially explicit data and analysis of spatial structure of rapid change. Researchers have responded by exploring the use of spatial metrics to examine a range of land cover phenomena. More recently, researchers have called for the systematic integration of spatial metrics with remote sensing analysis (Herold et al 2005). While the methodological discourse on integrating change detection techniques with spatial pattern analysis remains relatively nascent, interest in spatial metrics has proliferated across various domains of LUCC.

This paper proposes a variation of the conventional use of landscape metrics to examine land use change. In addition to comparing the spatial structure of evolving systems on *aggregate*, analysts can directly measure the pattern of *discrete* change classes. By utilizing a select set of spatial metrics to characterize a time series of seven classified images from the Pearl River Delta, this study demonstrates that *discrete* and *aggregate* patterns of change are empirically distinct. Results suggest that further development of this analytical framework and its application could provide fruitful for the urban land change community.

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[2] For example, a new urban patch that adjoins an old urban patch will be treated as an isolated new urban patch.
(Note: it is possible to adapt a classification to examine these relationships with certain Fragstats metrics)

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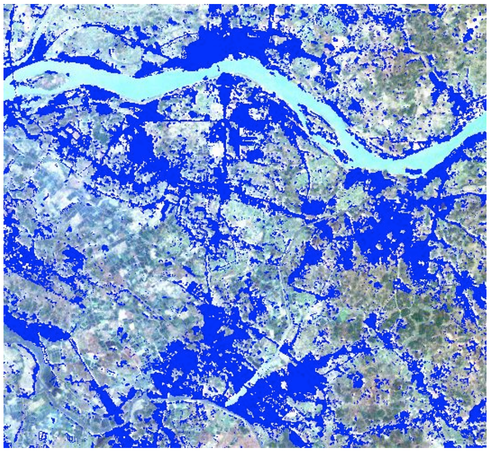
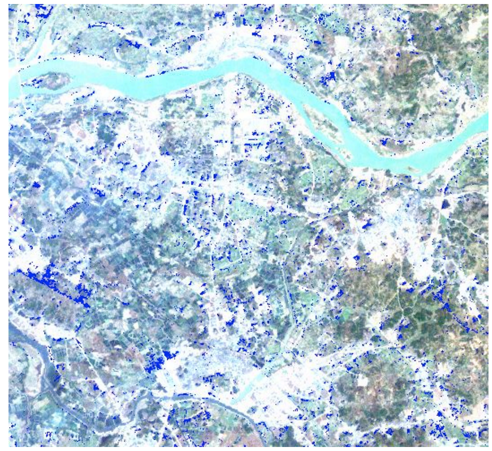
Appendix

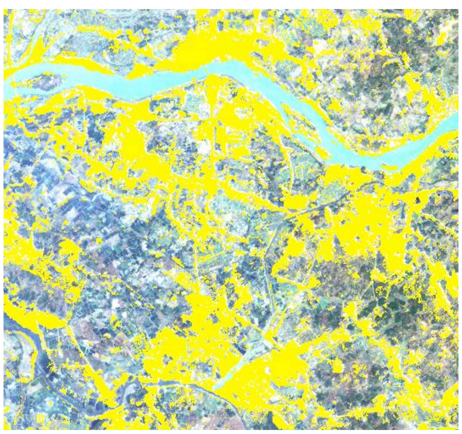
Aggregate Urban Class 2001



Discrete Change Class 2000-2001

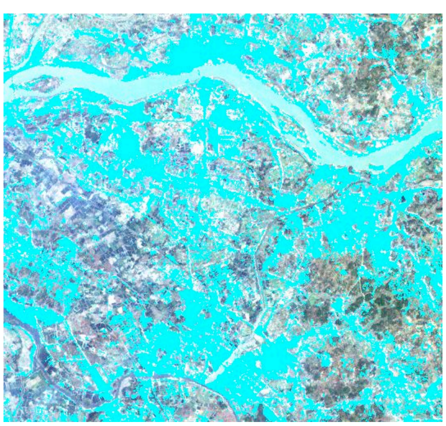


Aggregate Urban Class 2002

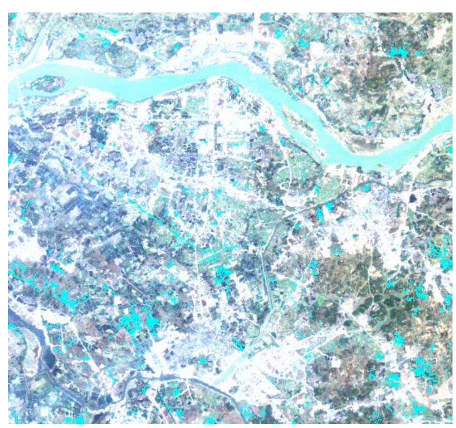


Discrete Change Class 2001-2002

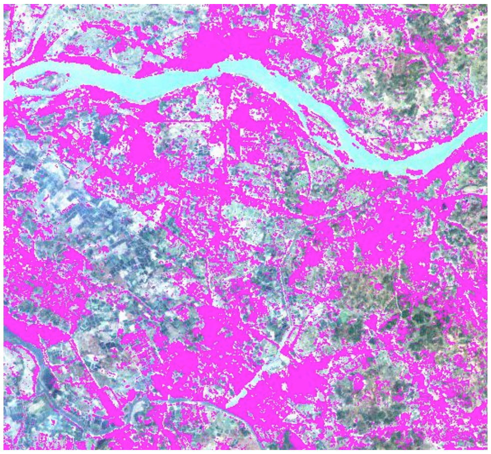
Aggregate Urban Class 2003



Discrete Change Class 2002-2003

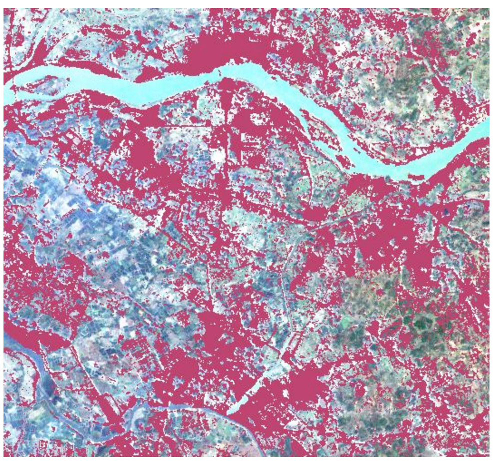


Aggregate Urban Class 2004



Discrete Change Class 2003-2004

Aggregate Urban Class 2005

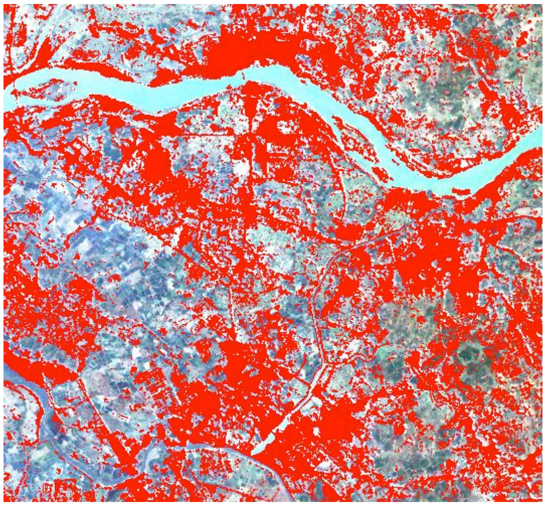


Discrete Change Class 2004-2005

Aggregate Urban Class 2006

Discrete Change Class 2005-2006

Aggregate Urban Class 2008



Discrete Change Class 2006-2008