Urban Land-Cover Change Detection through Sub-Pixel Imperviousness Mapping Using Remotely Sensed Data

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Abstract

We developed a Sub-pixel Imperviousness Change Detection (SICD) approach to detect urban land-cover changes using Landsat and high-resolution imagery. The sub-pixel percent imperviousness was mapped for two dates (09 March 1993 and 11 March 2001) over western Georgia using a regression tree algorithm. The accuracy of the predicted imperviousness was reasonable based on a comparison using independent reference data. The average absolute error between predicted and reference data was 16.4 percent for 1993 and 15.3 percent for 2001. The correlation coefficient (r) was 0.73 for 1993 and 0.78 for 2001, respectively. Areas with a significant increase (greater than 20 percent) in impervious surface from 1993 to 2001 were mostly related to known land-cover/land-use changes that occurred in this area, suggesting that the spatial change of an impervious surface is a useful indicator for identifying spatial extent, intensity, and, potentially, type of urban land-cover/land-use changes. Compared to other pixel-based change-detection methods (band differencing, rationing, change vector, post-classification), information on changes in sub-pixel percent imperviousness allow users to quantify and interpret urban land-cover/land-use changes based on their own definition. Such information is considered complementary to products generated using other change-detection methods. In addition, the procedure for mapping imperviousness is objective and repeatable, hence, can be used for monitoring urban land-cover/land-use change over a large geographic area. Potential applications and limitations of the products developed through this study in urban environmental studies are also discussed.

Introduction

Rapid urbanization and urban sprawl have significant impact on conditions of urban ecosystems. Accurate and updated information on the status and trends of urban ecosystems is needed to develop strategies for sustainable development and to improve the livelihood of cities. The ability to monitor urban land-cover/land-use changes is highly desirable by local communities and by policy decision makers alike. With increased availability and improved quality of multi-spatial and multi-temporal remote sensing data as well as new analytical techniques, it is now possible to monitor urban land-cover/land-use changes and urban sprawl in a timely and cost-effective way.

Using multi-date satellite remote sensing data to detect land-cover change goes back to the early 1970s (Singh, 1989). Many remote sensing change-detection methods have been evaluated (e.g., Kam, 1995; Jensen, 1995; Ridd and Liu, 1998; Sohl, 1999). There is no consensus as to a single method/algorithm that is universally applicable. The most commonly used change-detection methods are either spectrally based (image-to-image) or classification-based (map-to-map) method (e.g., Green *et al.*, 1994; Yang and Lo, 2002; Loveland *et al.*, 2002).

Most urban land-cover/land-use change studies utilized Landsat data due to the uniqueness of the dataset as the only long-term digital archive with a medium spatial resolution and relatively consistent spectral and radiometric resolution. Urban change studies using Landsat Multispectral Scanner (MSS) or Landsat Thematic Mapper (TM) data have been conducted either at a regional scale encompassing several urban areas (Todd, 1977; Royer *et al.*, 1988) or a single metropolitan area (Gomarasca *et al.*, 1993; Johnston and Watters, 1996). Recently, long-term urban land-cover/land-use changes (over two decades or longer) have been studied using the methodology of post-classification comparison using the Landsat archive as a baseline data source (Chen *et al.*, 2002; Yang and Lo, 2002; Loveland *et al.*, 2002).

Despite continued improvements in methodology, several limitations are recognized regarding some commonly used change-detection methods. First, existing change-detection techniques have distinct advantages and disadvantages. For example, the post-classification (map-to-map comparison) method identifies conversion from one land-cover/land-use type to another with little information on the intensity of such changes. This method often involves intensive manual interpretation and relies heavily on the skills of the interpreter. The spectrally based (image-to-image) method of change detection provides quantitative information on spectral change over time. However, interpretation of the spectral difference images with regard to the type of land-cover/land-use change is not always straightforward (Sohl, 1999). Second, the majority of urban change studies using remotely sensed data assumed homogeneity within a single pixel, resulting in no quantifiable changes at the sub-pixel level. In actuality, most Landsat pixels in urban areas are mixed and composed of several land-cover/land-use types. Ignoring the sub-pixel variation of Landsat imagery can lead to a biased estimate in urban change analysis. Finally, conventional methods allow users

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little flexibility in defining type and intensity of changes for their own application needs.

Research Objective

The primary goal of this research was to develop an alternative approach to spatially quantify urban land-cover/land-use changes using remote sensing data. Such an approach needs to be objective, repeatable, and, ideally, automated. Towards this end, we proposed to use a physical parameter, "anthropogenic impervious surface," as an indicator for identifying the spatial extent and intensity of urban development. This parameter was chosen because the amount and change of impervious surfaces are likely linked to the major urban land-cover types and their changes. Indeed, impenetrable surfaces such as rooftops, roads, and parking lots have been identified as key environmental indicators for urbanization and urban sprawl (e.g., Arnold and Gibbons, 1996). The spatial extent and changes of impervious surfaces impact urban climate by altering sensible and latent heat fluxes within the urban surface and boundary layers. Development of impervious surfaces within a drainage basin increases the frequency and intensity of downstream runoff and decreases water quality (Schueler, 1994).

Past studies have shown that it is feasible to map imperviousness with reasonable accuracy (Deguchi and Sugio, 1994; Williams and Norton, 2000; Phinn *et al.*, 2000), suggesting that "anthropogenic impervious surface" can effectively be used as a physical parameter to indicate urban change. Various methods have been used to identify urban imperviousness through multiple regression (Forster, 1980; Ridd, 1995), spectral unmixing (Ji and Jensen, 1999; Ward *et al.*, 2000), artificial neural network (Wang *et al.*, 2000; Flanagan and Civco, 2001), classification and regression trees (Yang *et al.*, 2003; Smith *et al.*, 2003), and integration of remote sensing data with geographic information systems (Prisloe *et al.*, 2001).

The primary research questions of this study were, (1) Can an objective and simple method be developed to quantify urban land-cover/land-use changes through mapping imperviousness at two points in time? and (2) What accuracy can be achieved in detecting urban land-cover/land-use changes using this method?

Study Area and Satellite Data

The study area covers the western portion of the state of Georgia, extending southwest from the Atlanta metropolitan area to the cities of Columbus and Albany. Landsat 5 TM and Landsat 7 Enhanced Thematic Mapper Plus (ETM+) data from two path/rows (about 180 km from east to west and 350 km from north to south) were obtained, including two scenes acquired from 09 March 1993 and another two from 11 March 2001 (Table 1).

All images were preprocessed by the U.S. Geological Survey (USGS) EROS Data Center using standard methods (Irish, 2000), including (1) radiometric and geometric calibration and terrain correction, (2) conversion from digital number to at-satellite reflectance in order to correct for changing illumination geometry (for six reflective bands), (3) reprojection to the Albers Equal Area Projection, and (4) resampling to a 30-meter resolution using a cubic convolution. After initial preprocessing, tasseled-cap brightness, greenness, and wetness were derived using at-satellite reflectance-based coefficients according to Huang *et al.* (2002).

TABLE 1. STUDY AREAS AND SELECTED LANDSAT TM/ETM+ IMAGES USED FOR THIS STUDY

Location	Path	Row	Date
Atlanta, Georgia	19	36	09 Mar 1993
	19	37	
Columbus, Georgia	19	36	11 Mar 2001
	19	37	

TABLE 2. COEFFICIENTS FOR CONVERSION OF LANDSAT 5 TM DN TO LANDSAT 7 ETM+ DN

Band	Slope	Intercept
1	0.9398	4.2934
2	1.7731	4.7289
3	1.5348	3.9796
4	1.4239	7.032
5	0.9828	7.0185
7	1.3017	7.6568

Another important preprocessing step for change-detection analysis is the radiometric normalization among images acquired from different dates. Although we were able to obtain cloud-free images near an anniversary date, which greatly reduces the phenology differences and changes related to sun-sensor-target geometry, some of the changes between each image pair could arise from the change of atmospheric conditions and slightly different sensor characteristics between TM and ETM+ arising from long-term degrading of the TM sensor. To correct the potential bias caused by the sensor differences and their calibration, we first converted the digital number of Landsat 5 TM (DN5) to a pseudo Landsat 7 ETM+ DN (DN7) using calibration coefficients developed by Vogelmann *et al.* (2001). The coefficients were derived based on an analysis of tandem data sets of the Landsat 7 and Landsat 5 collected over the central United States. This conversion was made to take advantage of the superior radiometric calibration of the ETM+. The conversion equation is $DN7 = DN5 * \text{slope} + \text{intercept}$. The slope and intercept values are shown in Table 2 for all six spectral bands.

After Landsat 5 data were converted to pseudo ETM+ DN (DN7), the remaining processing steps were the same as those applied to ETM+ data. Correction of atmospheric effects using absolute radiometric normalization was not possible for this study due to the lack of *in situ* measurements needed for characterizing the atmospheric conditions of optical depth, water vapor content, and aerosols. Using pseudo-invariant objects to apply a relative radiometric normalization resulted in a large reduction in the dynamic range of the digital number compared to the original data, and was not applied to the images.

Methodology

The proposed methodology for sub-pixel impervious surface mapping and related change detection includes several components: (1) training/validation data development, (2) predictive variable selection, and initial regression tree modeling and assessment, (3) final spatial modeling and mapping, and (4) imperviousness change detection and interpretations. We will refer this method as the "Sub-pixel Imperviousness Change Detection" (SICD). Figure 1 illustrates the processing flow for the method.

Regression Tree Algorithm

For this study, a machine-learning algorithm-regression tree was utilized to model sub-pixel percent imperviousness. The regression tree algorithm conducts a binary recursive partitioning and produces a set of rules and regression models to predict a target variable (percent imperviousness) based on training data. Each rule set defines the conditions under which a multivariate linear regression model is established for prediction (Breiman *et al.*, 1984). In the partitioning process, each split is made such that the model's combined residual error for

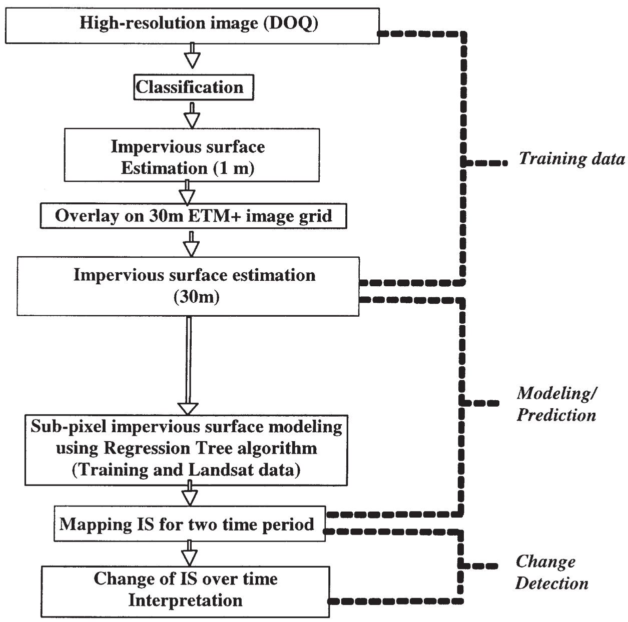

Figure 1. The proposed procedure for impervious surface mapping and change detection using remote sensing data and a regression tree model.

the two subsets is significantly lower than the residual error of the single best model (Huang and Townshend, 2003). The main advantages of the regression tree algorithm are that it can account for a non-linear relationship between predictive and target variables, and that it allows both continuous and discrete variables to be used as input (predictive) data. The Cubist[1] is the regression tree algorithm used in this study. This program has some advanced features, including pruning, committee model, and instance model. For a more formal and detailed description of the regression tree method, readers are referred to Breiman *et al.* (1984).

Reference Data Development for Sub-Pixel Imperviousness Mapping

The Digital Orthophoto Quarter Quadrangles (DOQQs) of late 1990s produced by the USGS were utilized to derive training data and test imperviousness. The DOQQs were scanned from the color-infrared photographs acquired from the National Aerial Photography Program (NAPP). Each DOQQ has three bands: green, red, and near-infrared with a nominal spatial resolution of 1 meter.

For our study area, three DOQQ images were selected for deriving the training/reference data, one within southern Atlanta, Georgia and two within Columbus, Georgia. These DOQQs were selected to capture the spectral and spatial variability of impermeable surfaces due to differences in building materials, ages, surface colors, and spatial orientation in and around the urban areas. Areas where observed land-cover changes occurred between the acquisition of the DOQQs and the TM/ETM+ images were excluded from the training dataset. All DOQQ images were reprojected to the Albers Equal Area Projection to register to the Landsat imagery. Visual inspection showed the co-registration uncertainty between the DOQQ and the TM/ETM+ images was within ten meters.

[1]Use of any trade, product, or company names is for descriptive purposes only and does not imply endorsement by the U.S. Government. Limited information on this program can be found at http://www.rulequest.com/cubist-unix.html.

Five broad land-cover classes—impervious surface, trees, grass, water, barren, and shadow—were differentiated on all DOQQ images. The classification was made through an unsupervised method. The preliminary classification was further refined by screen digitizing and recoding to achieve specified classification accuracy (greater than 85 percent). The shadow class was excluded from the following calculation of imperviousness because the class could not be unambiguously merged with any single land-cover class.

Pixels classified as impervious surface within a 30-meter grid from the DOQQ final land-cover classification were totaled to compute the impervious surface percentage. To accomplish this process, the DOQQ pixel whose coordinates matched the coordinates of the upper-left TM/ETM+ pixel was used as the starting point of the 30-meter grid. This resulted in a 30-meter-resolution raster image of percent imperviousness.

Regression Tree Model Development and Evaluation

For this study, all regression tree models were developed by Cubist using training data (percent imperviousness developed from DOQQs) as the dependent variable and TM or ETM+ spectral bands as independent variables. During the process, several regression tree models were built using various pruning, input band combinations, and other model options available from the Cubist algorithm. A single best model was selected to identify percent impervious surfaces on a pixel-by-pixel basis.

The percent of impervious surface attributed to each pixel was evaluated using independent test data. Ideally, the test data should be collected from the field work based on a statistical sampling design. Due to time and resource constraints, impervious estimates derived from the DOQQ were used for model evaluation. To ensure the validity of the assessment, all test data (pixels) were selected randomly and independently from the training data. Specifically, the quality of the constructed regression tree model was measured by an average error R of a regression tree T, expressed by

$$R(T) = \frac{1}{N}\sum_{i=1}^{n} |y_i - g(\vec{x}_i)|.$$

Function $g(\vec{x}_i)$ represents the regression plane through the example set, and N is the number of samples used to establish the tree. Cubist calculated the average error and Product-Moment correlation coefficient (r) between actual and predicted values. Both $R(T)$ and r were used in this study to assess the quality of model prediction.

Results

Final products of the research are (1) spatial estimates of sub-pixel percent imperviousness at a 30-meter resolution for two Landsat scenes, and its change at two points in time, (2) a rule set on conditions under which each regression tree model was built, and (3) error estimates of regression tree predicted imperviousness through model validation. Overall, the average absolute error of the 1993 impervious prediction (by comparing model prediction against "true" values from the test data) was 16.4 percent, and the correlation coefficient (r) was 0.73. For 2001 impervious prediction, the average absolute error was 15.3 percent and r was 0.78. Figure 2 shows a comparison between model predicted imperviousness versus the impervious estimates derived from the DOQQ using 2,000 sample pixels from the 1993 prediction.

The relative importance of predictive variables was assessed based on frequency of a variable used and the position of the variable within the multivariate linear regression equations, because the variables were ordered in decreasing relevance to the dependent variable (percent imperviousness). The most important variables in predicting the imperviousness were band 3 (VIS), band 4 (NIR), and band 5 or 7 (mid-IR). The most frequently used band in the regression tree model

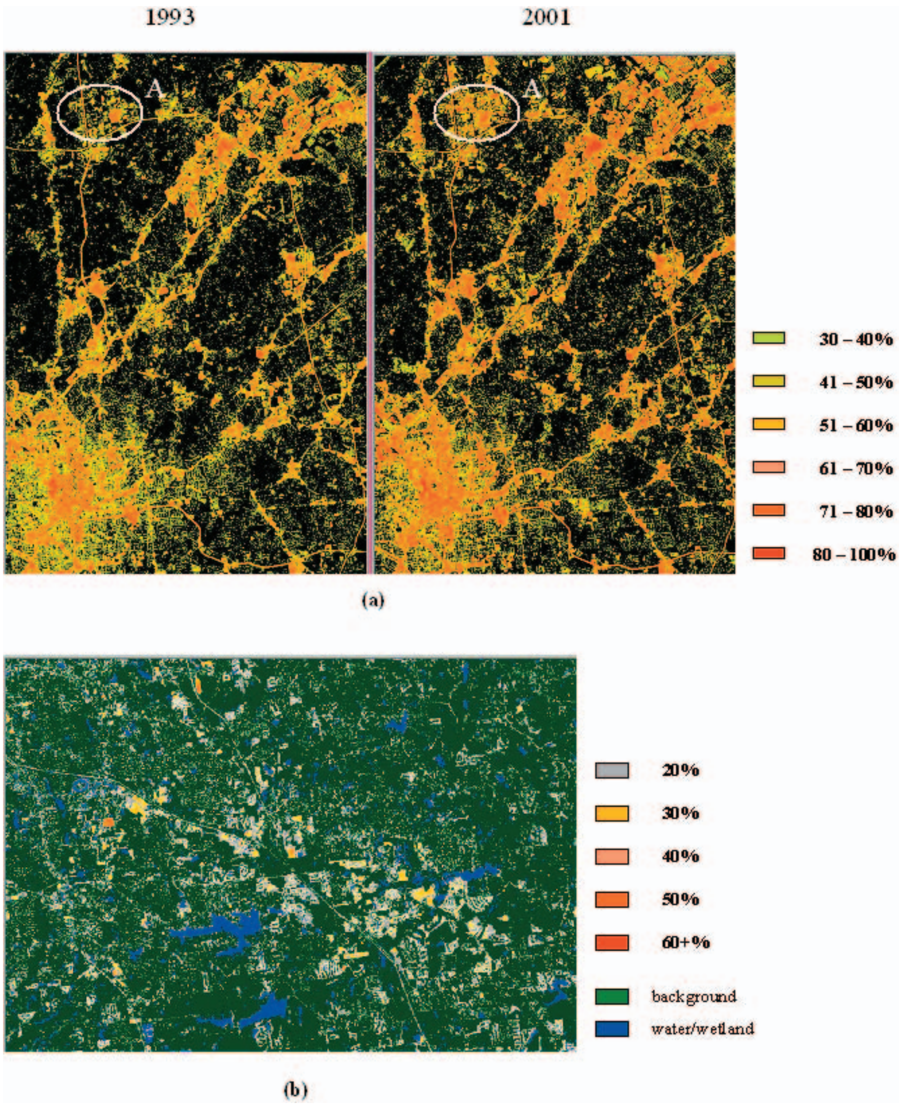

Plate 1. (a) Subpixel percent imperviousness of northern Atlanta, Georgia, 1993 and 2001. Note a notable development (Perimeter Mall) occurred at the northeastern cross-section by the highways areas along the interstate highway 285 and the U.S. highway 19 in northern Atlanta (circled and labeled in A). (b) Increase of percent imperviousness, southeastern Atlanta, Georgia, 2001–1993. Significant residential development was evident in this area.

was band 3 and the least used was band 1. The lower range of the prediction (imperviousness less than 25 percent) was the least accurate, probably due to under-sampling the range in the training data or due to the high variability in spectral response of the different types of impervious surfaces.

Western Georgia

The spatial patterns of the predicted percent imperviousness over western Georgia were reasonable. As is expected, all urban centers and the immediate surroundings located in and around the Atlanta metropolitan area were identified as the medium-to-high imperviousness. Areas of residential use around the urban-rural fringe were identified as low-medium imperviousness. The high impervious percentage change areas were in and around the city of Atlanta and other urban centers where most of the urban sprawl and suburbanization took place. However, commission errors were observed in some areas where bare ground was mapped as medium-to-high impervious surface, due to its spectral confusion with the built-up areas.

Atlanta Metropolitan Area and Vicinity

The population and developed areas in and around the city of Atlanta have grown significantly in the past 20 years (Yang and Lo, 2002). Plate 1a shows the predicted percent imperviousness in this area at two points in time, 1993 and 2001. Highly developed urban centers were mapped with the highest percent imperviousness (greater than 50 percent), whereas residential areas were predicted with a relatively low value (20 to 40 percent). Areas with distinct increases in impervious

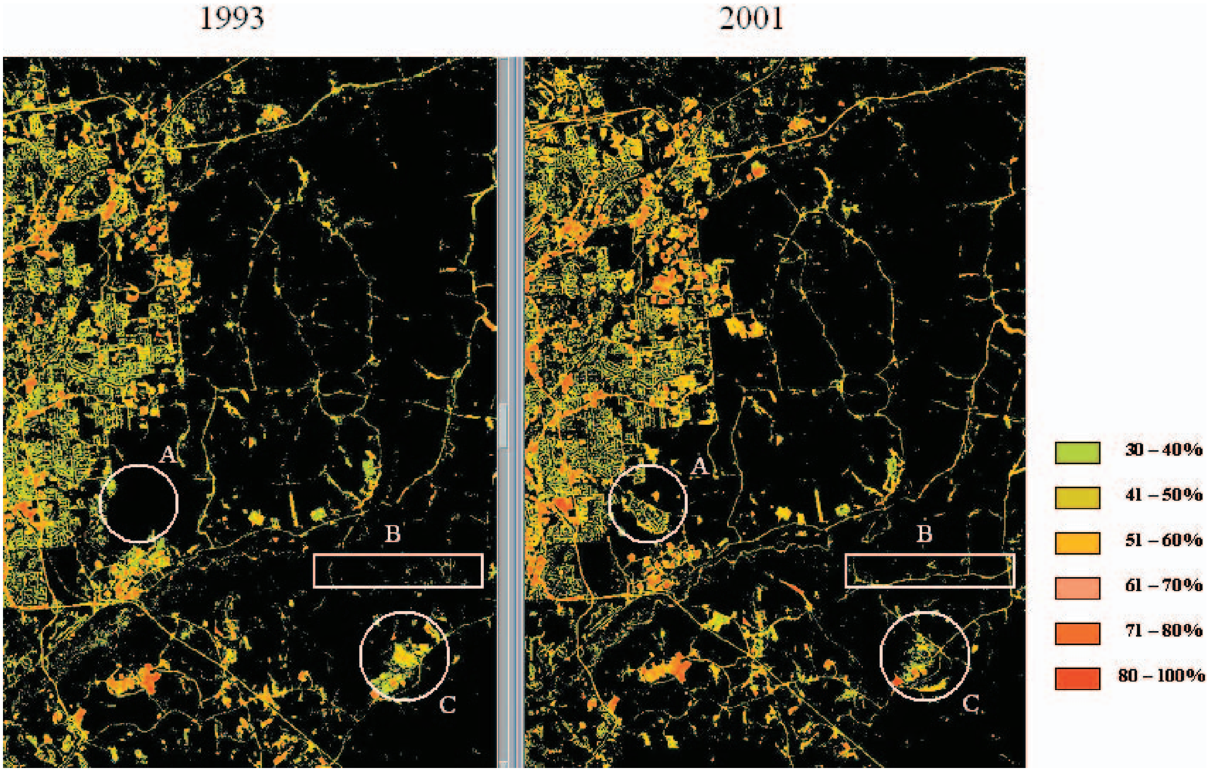

Plate 2. Subpixel percent imperviousness of Columbus, Georgia, 1993 and 2001. Note residential growth near the fringe of the Columbus (labeled in A), a newly developed road within the training base (labeled in B), and the regrowth of grass (labeled in C).

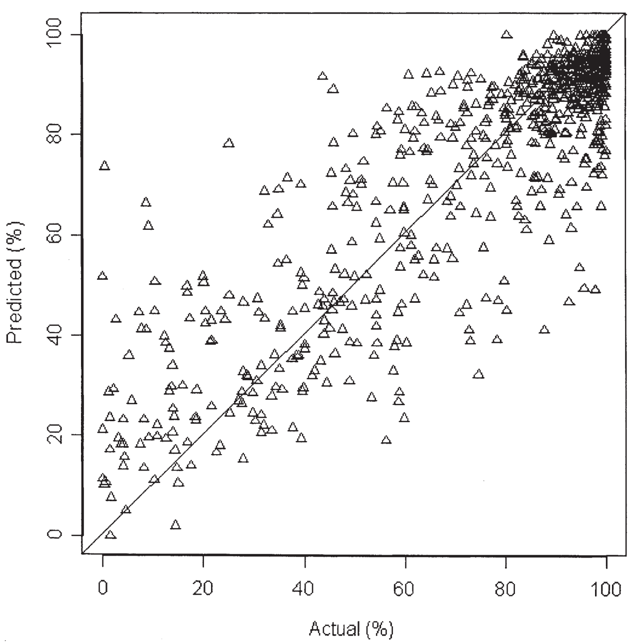

Figure 2. A scatter plot showing model predicted imperviousness versus that derived from the 1-meter DOQQs. The data are based on 2,000 random selected pixels from the 1993 prediction.

surfaces were identified. For example, a notable development (Perimeter Mall) occurred at the northeastern cross-section of interstate highway 285 and the U.S. highway 19 in northern Atlanta (A in Plate 1a). In southeastern Atlanta significant residential development was evident (Plate 1b). This area is one of the fastest growing residential areas in the city of Atlanta since 1987 (Yang and Lo, 2002).

The rate of urban land-cover change over metropolitan Atlanta (areas with an increase of percent imperviousness greater than 10 percent from 1993 to 2001) was 7.5 percent. This estimate may be a little aggressive by including all areas with 10 percent increase or higher, considering the uncertainty of the regression tree prediction was within the same order of magnitude (about 10 percent). By restricting changed areas to at least a 20 percent increase, the change rate became 4.0 percent. This is similar to a 3.5 percent increase reported by Yang and Lo (2002) based on area of increased low- and high-intensity urban land use derived from 1992 and 1997/98 Landsat data. It should be noted that our study did not cover the entire Atlanta metropolitan area but included more surrounding suburban areas than the 13 counties reported by Yang and Lo (2002).

City of Columbus and Fort Benning Area

Another area of interest for this study is in the Fort Benning military training base. The military installation is located in the lower Piedmont Region in western-central Georgia. Its immediate neighbors include Columbus, Georgia and Phoenix City, Alabama. Over time, urban development in those areas has influenced the military community's ability to maintain their mission focus. Conversely, the military installations affected the local community by alteration of land-cover/land-use and other training activities. The Sub-pixel Imperviousness Change Detection (SICD) method identified land-cover/land-use changes due to continued urban development as well as land-cover changes within and around the military installation.

Plate 2 presents the mapped percent imperviousness in 1993 and 2001, respectively. The map illustrates many land-cover/land-use changes in this area, including some residential growth near the fringe of Columbus (A in Plate 2), a newly developed road within the training base (B in Plate 2), and the regrowth of grass in previously logged over areas (C in Plate 2). The spatial extent and the magnitude of changes of the impervious surface provide useful information to assess the interactions between the military installation and nearby cities.

Discussion

Evaluation of the Method

In this study, we employed a regression tree method to map sub-pixel imperviousness at the two points in time using multi-date Landsat data and DOQQs. Results obtained from this study were used to identify urban land-cover/land-use changes that occurred from 1993 to 2001 in western Georgia. Areas with increased impervious surfaces were mostly related to known land-cover/land-use changes in this area. The accuracy of the sub-pixel percent imperviousness estimates was reasonable, the mapping procedure was repeatable, and for the most part, was automated. This method provides sub-pixel level information that recognizes the non-homogeneity of the Landsat pixels in the urban environment. In addition, the change product generated by this approach allows users to define and interpret land-cover/land-use changes based on their own definition (e.g., change above a certain percentage).

During this study, a large effort was devoted to the development of good training data from the DOQQs. Once the training data were developed, the process was straightforward to generate a regression tree model and spatially apply it to all study areas. The actual time taken to compute imperviousness for all pixels for a two-scene mosaic of each date was less than one hour using a desktop PC. For these reasons, the SICD method can be used for monitoring urban land-cover/land-use change over large geographic areas.

Usefulness of Urban Imperviousness Training Data

A high quality training data set of impervious surface is necessary for conducting sub-pixel percent imperviousness prediction with a high confidence. At a regional scale, training data can be developed from the high-resolution remote sensing image (e.g., Ikonos, DOQ), which was demonstrated by this study and our previous research (Yang *et al.*, 2003). Once the training data are established, a regression tree model can be developed for predicting sub-pixel imperviousness using medium-resolution satellite data as input (e.g., Landsat data). Because the spectral characteristics of most urban land-cover types are relatively stable compared to other natural vegetation and land-cover types, the regression tree model for imperviousness prediction can be used repeatedly to detect urban land-cover/land-use change using the most recent satellite data. This approach should work to the extent that the multi-temporal images to be used are acquired near their anniversary dates and are calibrated to a common physical unit (such as surface reflectance) through either absolute or relative radiometric calibration.

Information Content of the Sub-Pixel Impervious Estimates

Compared to conventional urban change detection methods (band differencing, ratioing, change vector, post-classification, and others), change detection through sub-pixel percent imperviousness mapping provides useful information on the spatial extent and the intensity of urban land-cover/land-use change. The additional information of intensity of urban land-cover/land-use change may help to infer the type of land-cover/land-use changes. For instance, when the imperviousness change over two time periods is above 80 percent, it is likely that the area has undergone a significant change from rural land use (e.g., forest, agricultural, grassland) to a high-intensity urban land use (e.g., commercial and industrial development), whereas a much lower amount of change (less than 20 percent) near an urban-rural fringe is likely related to changes due to developed residential land use. Figure 3 presents a conceptual framework illustrating how the magnitude of change in percent imperviousness over time could be correlated to type and intensity of the urban-rural land-cover/land-use changes. In figure 3, the relationship between amount of change in the impervious land surface and the possible urban land-cover/land-use changes was based solely on analysis from this study. Further research is needed in other urban areas to corroborate this relationship for all urban areas.

Applications of the Method and the Impervious Surface Data

There are many potential applications for the method and products developed from this study. The most direct application is to use this technique to identify changes over time in urban and suburban areas. In addition, timely and spatially explicit imperviousness estimates and their trends provide urban-land managers with useful data to assist in their decision making and implementation of strategies for today's complex urban growth issues. Another potential application of this type of data set is in the field of urban ecological modeling. It has been recognized that development of impervious surfaces increases the frequency and intensity of downstream runoff and decreases water quality within watershed areas. Geospatial data of impervious surfaces and its change can be used not only as an indicator for water quality assessment but also as a critical input for urban hydrological modeling. Because the change of the spatial extent of impervious surfaces alters the partitioning of sensible and latent heat fluxes within urban surface and boundary layers, change-detection data derived through sub-pixel percent imperviousness are useful to quantify the land-atmosphere interaction within urban climate systems. Finally, quantification of urban development through mapping change of impervious surfaces provides useful data for urban dynamic simulation through model calibration and validation (Jantz *et al.*, 2003).

Conclusions

We developed an approach to detect urban land-cover/land-use changes by quantifying sub-pixel percent imperviousness using Landsat and high-resolution imagery. The percent impervious surface and its change (30-meter resolution) were mapped for two points in time over western Georgia using a regression tree algorithm. The method was found to be satisfactory based on a comparison using independent reference data. The average absolute errors between predicted imperviousness and reference data were 16.4 percent (1993) and 15.3 percent (2001), and the correlation coefficients (r) were 0.73 (1993) and 0.78 (2001), respectively. The change-detection procedure developed through this exercise is repeatable and efficient provided that good training data cover the whole range of spectral variability of all impervious surfaces.

Change in percent imperviousness over time appears to be a useful indicator for identification of the spatial extent, intensity, and, potentially, type of urban land-cover/land-use changes. The magnitude of impervious surface change often relates to a particular type of urban land-cover/land-use

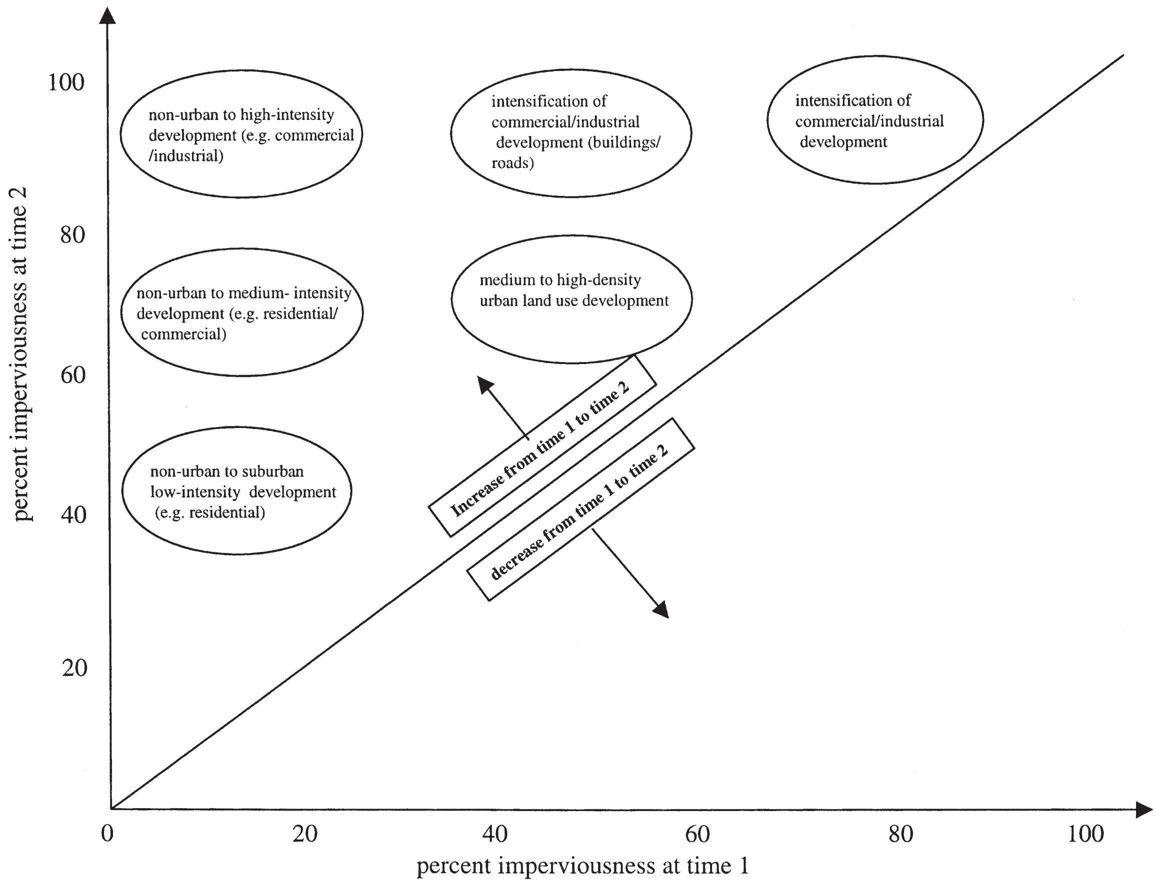

Figure 3. Generalized relationship between change of percent imperviousness and the possible urban land-cover/land-use changes based on this study.

change. Such information is complementary to change products generated from other methods (e.g., post-classification, spectral differencing). In addition, information on sub-pixel imperviousness allows the data user to quantify urban land-cover/land-use changes based on their own threshold.

It should be noted that the change product generated by this study has some limitations. Due to the uncertainty of the predicted imperviousness (around 10 to 15 percent), a 15 percent or less increase in imperviousness may or may not reflect actual changes within the study area. In addition, all accuracy information reported here was based on evaluation of imperviousness estimates for each individual time period. No direct assessment was made to evaluate the quality of the change product due to the lack of ground-truth data for both time periods. For that reason, the quality of the change product has to be inferred indirectly from the accuracy estimates of each individual time period.

Although not quantified, the absolute accuracy of the change products generated through this study is likely to be limited by several factors, including a lack of absolute image normalization among all images, use of a single-date image for predicting imperviousness, and the uncertainty/error in the training data (such as shadow class). Nevertheless, these limiting factors can be potentially mitigated with improved remote sensing data calibration and image interpretation techniques. Therefore, we remain optimistic that the Sub-pixel Imperviousness Change Detection (SICD) method developed by this study for urban land-cover/land-use change detection is a useful addition to the existing methods. The change-detection products generated using this method can be improved in future.

Acknowledgments

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