Estimating Landscape Imperviousness Index From Satellite Imagery

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***Abstract*—This letter presents a practical method for landscape imperviousness estimation through the synergistic use of Landsat Enhanced Thematic Mapper Plus (ETM+) and high-resolution imagery. A 1-m resolution color-infrared digital orthophoto was used to calibrate a stepwise multivariate statistical model for continuous landscape imperviousness estimation from medium-resolution ETM+ data. A variety of predictive variables were initially considered, but only brightness and greenness images were retained because they were account for most of the imperviousness variation measured from the calibration data. The performance of this method was assessed, both visually and statistically. Operationally, this method is promising because it does not involve any more sophisticated algorithms, such as classification tree or neural networks, but offers comparable mapping accuracy. Further improvements are also discussed.**

***Index Terms*—Accuracy, digital orthophoto, imperviousness index, satellite imagery, spatial statistical analysis.**

I. Introduction

LANDSCAPE imperviousness is defined as a sum of impermeable features that include buildings, roads, parking lots, sidewalks, and other built surfaces. It has recently emerged as a key indicator being used to address a variety of urban environmental issues such as water quality, biodiversity of aquatic systems, habitat structure, and watershed health [1], [2].

Extensive research has been conducted with an attempt to map impervious surfaces accurately through remote sensing. Earlier works were largely based on manual interpretation of aerial photographs in connection to watershed analysis [3]. These works, although quite accurate, are labor intensive and costly. Later on, Landsat Thematic Mapper (TM) and SPOT High Resolution Visible imagery were used to map impervious surfaces over large areas, mainly through automated or semi-automated approaches [4]–[6].

Many of the existing studies generally estimated the presence or absence of impervious surfaces at the pixel level. Recent technological advancements in the field of digital image processing allow the derivation of imperviousness information at the subpixel level. Several advanced technologies have been adopted for landscape imperviousness estimation, including spectral mixing modeling [5]–[7], artificial neural networks [8], and classification trees [9], [10]. These methods are quite impressive given their technological sophistication and soundness. However, these methods are not always easy to implement for landscape managers because of inadequate technical resources. On the other hand, these methods can vary greatly in their performance with the changes in image characteristics and the circumstances for specific studies. Clearly, further efforts will need to consolidate the absolute and comparative applicability of remote sensing for landscape imperviousness estimation.

This letter presents a practical method for continuous imperviousness estimation through the synergistic use of Landsat Enhanced TM Plus (ETM+) and high-resolution imagery. The fundamental promise made here is that the relationship between remotely sensed signals and landscape imperviousness can be modeled through statistical analysis. This is in line with the basic principles of quantitative remote sensing [11]. The following sections document the major procedures including: 1) Landsat ETM+ data acquisition and preprocessing; 2) high-resolution calibration data processing; 3) continuous imperviousness index estimation; and (4) performance assessment. The entire procedural route is illustrated in Fig. 1.

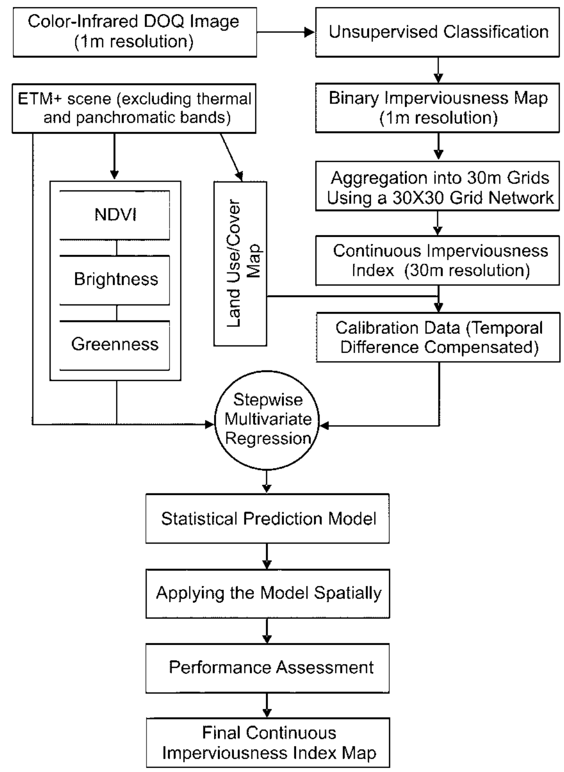

Fig. 1. Working procedural route for continuous imperviousness index estimation.

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II. Landsat ETM+ Data Acquisition and Preprocessing

A predominantly cloud-free Landsat ETM+ image covering Pensacola, FL was acquired from U.S. Geological Survey (USGS) Earth Resources Observation System Data Center for May 20, 2002, which was used as the primary data for continuous imperviousness index estimation. With a 1 : 24 000 digital topographic map covering the same area as the reference, this image was rectified to the Universal Transverse Mercator (UTM) map projection, North American Datum 1983 (NAD83) horizontal datum, and Geodetic Reference System 1984 (GRS 84) ellipsoid.

III. High-Resolution Calibration Data Processing

Ideally, *in situ* measurements are most desired for statistical model calibration so that the relationship between image signals and landscape imperviousness can be established. Given the cost-effectiveness, however, a high-resolution digital orthophoto quadrangle (DOQ) image covering part of the ETM+ scene was used for calibration purpose. The DOQ image is a standard product created by the National Digital Orthophoto Program (NDOP) from the color-infrared photograph dated November 27, 1999 which was acquired by the National Aerial Photography Program (NAPP). We could not acquire a 2002 DOQ scene for the study area. With the ground coverage of approximately 44 km^2, the DOQ image is 1 : 1200-scale, quarter-quadrangle centered. Its spatial resolution is 1 m. It can be decomposed into three bands, corresponding to the green, red, and near-infrared portions of the electromagnetic spectrum. More details about the DOQ data standard can be found from the USGS (http://rmmcweb.cr.usgs.gov/public/nmpstds/doqstds.html).

An automated method was used to extract impervious surfaces from the DOQ image. In doing so, the iterative self-organizing data analysis technique (ISODATA) algorithm was initially applied to identify 60 spectral clusters from the DOQ image. The resultant spectral clusters were meaningful because the radiometry of the DOQ image was mostly intact despite some possible minor modifications in the original brightness values during the aerial photograph scanning and rectification processes. Then, each spectral cluster was interpreted interactively and labeled as either impervious surface or other covers. In this way, a binary map was created with impervious surfaces as 1 and the rest as 0. A standard accuracy assessment described by Congalton [12] was conducted for this binary map, and the overall error was found to be approximately 10%.

With the 1-m grid binary map, one more step was proceeded in order to generate continuous imperiousness estimation from the calibration data. In doing so, a 30 $\times$ 30 m grid network was constructed to match the ETM+ image's grid system. Then, this grid network was used to aggregate the impervious surface measures from the high-resolution binary image. Within each 30-m grid, all 1-m pixels classified as impervious surfaces in the binary image were enumerated, and thus, the percent imperviousness was determined. In this way, a 30-m grid continuous imperviousness map was generated.

The 30-m grid map was slightly modified to compensate the changes in impervious surfaces because of the three-year temporal difference between the 1999 DOQ image and the 2002 ETM+ scene. This modification could be avoided if a 2002 DOQ scene would be used. Because of the continued urban growth in the study area after 1999, it is expected that some more impervious surfaces should be found in 2002. Therefore, a small number of pixels that were at the low extreme in the 1999 DOQ-derived map but were classified as urban in the land use/cover map derived from the 2002 ETM+ image were reclassified into 100 in their imperviousness index. It should be noted that the 2002 land use/cover map was created through the combined use of layered classification and spatial reclassification techniques [13]. The layered classification was based on the procedure that divides the image into urban and rural regions early in the classification with a "mask" defined by road intersection density slices and road buffers. Each part was classified independently in its most effective context, and later, both were merged to form a complete map. In spatial reclassification, image interpretation procedures, auxiliary vector data, and a variety of geographic information system (GIS) functions were synthesized to resolve spectral confusion and improve mapping accuracy. The overall accuracy for the land use/cover map was at 93%.

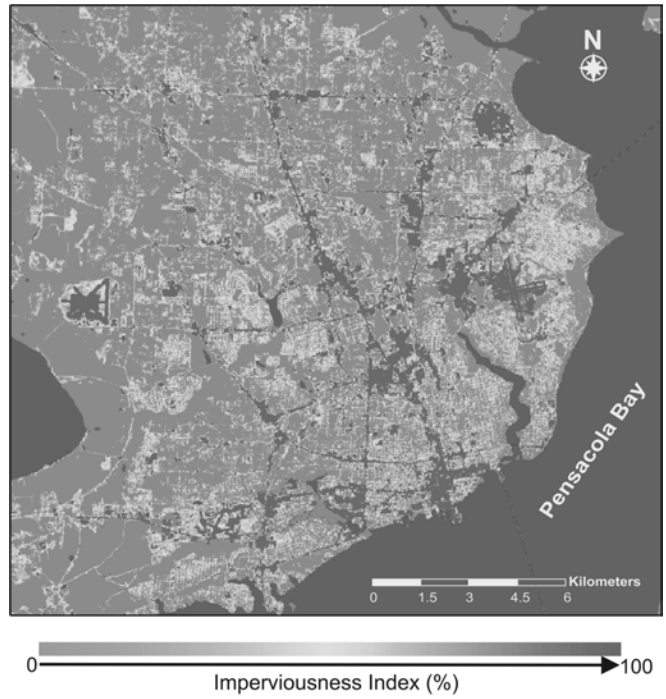

Fig. 2. Imperviousness estimation for part of the Pensacola metropolitan area (the original figure was in color).

IV. Continuous Imperviousness Index Estimation

The major purpose of this research was to demonstrate that an continuous imperviousness index can be accurately estimated by using a linear combination of image bands or ratios. Critical to this research effort was the use of the DOQ-derived imperviousness map as the dependent variable to calibrate a multivariate regression model that can be used to estimate continuous imperviousness index from the ETM+ image. The independent variables were derived from six ETM+ bands and three image ratios. The thermal and panchromatic bands were not included because

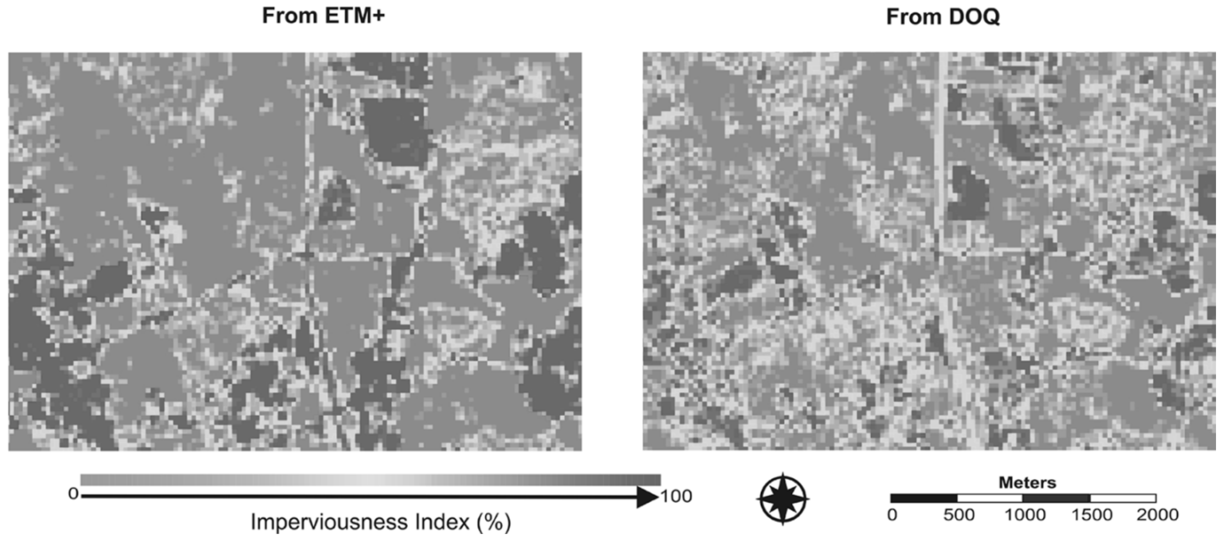

Fig. 3. Comparison of the imperviousness index map estimated from (left) the ETM+ image versus (right) that derived from high-resolution DOQ data (the original figure was in color).

the thermal portion of the electromagnetic spectrum is seldom used for landscape characterization except surface temperature estimation and the panchromatic band virtually overlays with the blue, green, and red bands in spectral resolution that were already included. The three image ratios are NDVI, brightness, and greenness. NDVI was computed by using a standard algorithm [11]. Brightness and greenness were computed with the tasseled-cap transformation equation developed by Huang *et al.* [14] for ETM+ data. A total of 12 224 sample points were randomly selected from the layers of dependent and independent variables. Then, a statistical model was built by using a stepwise multivariate regression

$$IS = 1.285\boldsymbol{B} - 0.189\boldsymbol{G} - 231.757$$

where IS is the imperviousness index (in percent), and $\boldsymbol{B}$ and $\boldsymbol{G}$ are the brightness and greenness derived from tasseled-cap transformation of the ETM+ image. The adjusted $\boldsymbol{R}$ square value for this model is 0.91, and the standard error of the estimate is 8.5%. It should be noted that the final model is actually a simple model in which only the brightness and the greenness were retained because they survived the test of "stepping criteria." In other words, these two ratios account for most of the variance of the calibration data.

The last step for imperviousness estimation was to apply the above model spatially to an area of approximately 484 km^2, and therefore, a continuous imperviousness index map was created (Fig. 2). The imperviousness index is represented continuously with a diverging sequential color scheme. Green color represents low extreme (0%) and red for high extreme (100%).

V. Performance Assessment

For performance assessment, the imperviousness index map derived from the 1999 DOQ image and modified with the 2002 land use and land cover data was used as the reference. Note that the reference data were primarily an aggregated derivative from the 1-m impervious surface map with accuracy at 90%.

Once the reference data were identified, the performance of the above method for continuous imperviousness index estimation was assessed, both visually and statistically. Visual comparison of the continuous imperviousness estimation from the ETM+ image with the reference map is probably the most straightforward way for a qualitative assessment. It was found that an overwhelming similarity exists in the general pattern of impervious features estimated by using ETM+ image and by using calibration data. This can be clearly visualized from Fig. 3.

The imperviousness index map produced from the ETM+ image in this study belongs to continuous data. Therefore, the accuracy assessment method based on error matrix and kappa index [12] cannot be used here because it is designed for categorical data only [15]. Instead, correlation analysis was used for the quantitative comparison between the ETM+-derived imperviousness map and the reference data. This method has been used by Civco *et al.* [8] and Wu and Murray [7] in the accuracy assessment of their imperviousness mapping products.

For correlation analysis, approximately 8233 sample points were selected randomly from both the ETM+-derived imperviousness map and the reference data. Note that these points do not include those used for statistical model development. Then, Pearson's coefficient was computed for this sample set, which was at 0.96, thus indicating that the ETM+-derived imperviousness map was strongly correlated with the reference data. The overall estimate error is 8.37% (Fig. 4), which is comparable to the accuracies of several studies conducted by other investigators such as Deguchi and Sugio [4], Wu and Murray [7], and Yang *et al.* [10].

On the other hand, the statistical analysis suggests this model slightly overestimate the imperviousness percent in less developed areas (0% to 20%) and slightly underestimate in highly developed area (80% to 100%) (Fig. 4). A similar problem has been reported by Wu and Murray whose method was based on spectral mixing modeling [7]. The problem in the highly developed area may be due to the occurrence of barren soils that show

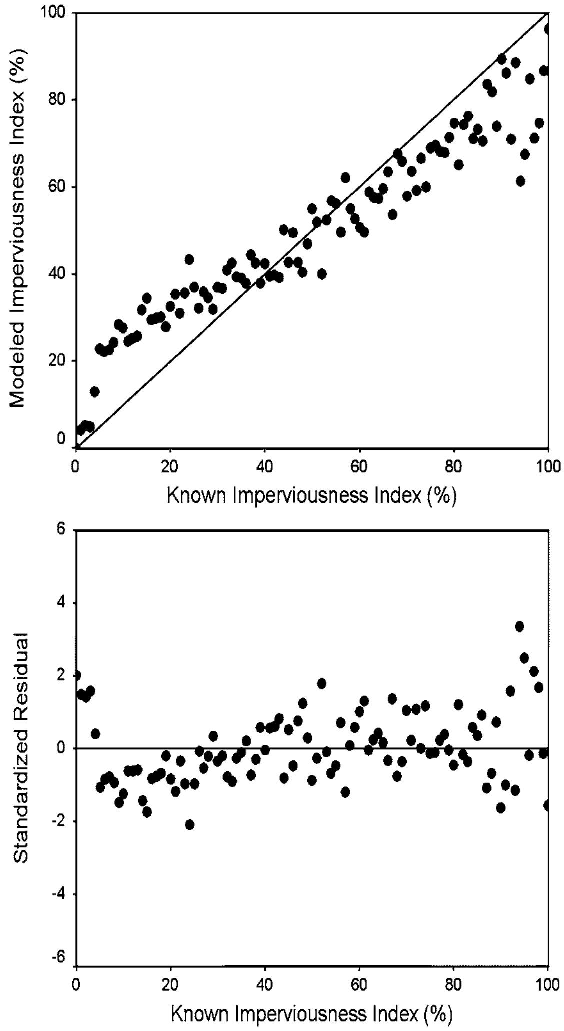

Fig. 4. Accuracy assessment for the ETM+-derived imperviousness map.

similar spectral reflectance to urban impervious surfaces such as parking lots.

VI. Conclusion

This study identified a practical method for continuous landscape imperviousness mapping, which was based on the synergistic use of medium-resolution ETM+ and high-resolution imagery through multivariate regression analysis. The high-resolution DOQ image was used as calibration data to help develop a statistical model for landscape imperviousness estimation from the ETM+ image. The development of calibration data and the choice of initial predictive variables were critical for this method. The final prediction model was a linear combination of two image ratios.

This method can be implemented by landscape managers without much difficulty when calibration data, either high-resolution imagery or *in situ* measurements, are available. The independent variables are image bands or ratios that can be derived from the ETM+ image. The multivariate linear regression algorithm is available from most of statistics or image processing software packages. This method does not use much complex algorithms, such as classification trees or neural networks, which would require the acquisition of some specialized software packages or additional programming work. Given the relatively simple procedures and the good mapping accuracy, the method seems to be promising from an operational perspective.

Nevertheless, it should be noted that like many practical methods, the one we developed for continuous imperviousness index estimation can have certain limitations. The linear assumption made in this study may be a little bit simplistic, which could lead to the difficulty of estimating imperviousness index in less developed areas (0% to 20%) and highly developed areas (80% to 100%). Further research is needed to adopt more complex models that can help develop more realistic solutions. In addition, more image indices and some GIS data (e.g., road density) should be incorporated, which may help improve landscape imperviousness mapping in areas where barren soils exit.

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