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Use of satellite-derived landscape imperviousness index to characterize urban spatial growth

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Abstract

Urban change analysis has traditionally been supported through land use/cover classification and map-to-map comparison. In this research, we investigate the usefulness of satellite-derived imperviousness index as an alternative for urban spatial growth characterization. The study area, Pensacola, FL, has witnessed considerable growth in population and regional economies during the past decade. The research consists of a number of procedures. First, we identify a method for landscape imperviousness estimation by synergistic use of medium-resolution satellite imagery and high-resolution color orthophoto through multivariate statistical analysis. We apply this method to map landscape imperviousness index for the years of 1989 and 2002, respectively. We assess the maps' accuracy with the imperviousness estimation from high-resolution DOQQ imagery as the reference. The overall error is estimated to be less than 10%. Then, we analyze the spatio-temporal changing trend of landscape imperviousness index with the emphasis upon some 'hot' spots of development areas. We find that this trend is compatible with the urban land use/cover changing trend detected through image interpretation. We conclude that satellite-derived landscape imperviousness index is able to serve as an invaluable alternative for quick and objective assessment of urban spatial growth, particularly over large areas.

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1. Introduction and research objectives

Several decades of population explosion and accelerating urban growth have had profound environmental and socioeconomic impacts felt in both developing and developed countries alike (Longley, 2002). Urbanization has often been viewed as a sign of the vitality of regional economies, but it has rarely been well planned, thus provoking concerns over the degradation of our environmental and ecological health. Monitoring growth and change brought on by urbanization has been a critical concern both to those who study urban dynamics and those who must manage resources and provide services in these rapidly changing environments.

Remote sensing, given its cost effectiveness and technological soundness, has been increasingly used for characterizing urban areas and analyzing urban spatial growth (de Sherbinin et al., 2002; Yang, 2003). For nearly three decades, extensive research efforts have been directed for urban change detections by using remotely sensed imagery (e.g. Green, Kempka, & Lackey, 1994; Gomarasca, Brivio, Pagnoni, & Galli, 1993; Lo & Shipman, 1990; Royer, Charbonneau, & Bonn, 1988; Todd, 1977; Toll, Royal, & Davis, 1980; Toll, 1985; Yang, 2002; Yeh & Li, 1996). These studies have been supported through either an image-to-image comparison or a map-to-map comparison. The image-based comparison is generally accurate, but it suffers from the inability to provide detailed information of how various urban land use/cover categories change (Kam, 1995; Ridd & Liu, 1998; Singh, 1989). In contrast, the map-to-map comparison, or post-classification comparison, has the potentiality to detect the nature of urban land use/cover changes (Jensen, 1995). With the availability of higher resolution imagery and the development of improved image classification methods, more details of urban land use/cover changes can be mapped with reasonable accuracy (Jensen & Cowen, 1999).

Although the map-to-map comparison has been taken for granted as the major change detection method for many years, it is not without problem. First, urban landscape changes can be conceptualized as two major forms: urban land use/cover conversion, a change from one class to another; and urban land use/cover modification or intensification, a change of condition within a category (Turner & Meyer, 1994). Change detection based on image classifications, no matter how detailed they could be, can only quantify inter-class conversion but not intra-class modification or intensification, thus providing an incomplete trajectory of urban landscape dynamics. Second, although there are a variety of urban land use/cover classification schemes, the actual definition and image interpretation for specific urban classes are not always consistent with respect to different applications. This inconsistency has made difficult to analyze urban changes with land use/cover maps produced independently by different teams. Last, conventional methods do not permit users with any flexibility in defining type and intensity of changes for their own applications (Yang, Xian, Klaver, & Deal, 2003b).

Remote sensing community has recently shown an increasing interest in developing alternatives, such as Chi square transformation (Ridd & Liu, 1998), normalized difference built-up index (Zha, Gao, & Ni, 2002), and urban imperviousness (Civco, Hurd, Arnold, & Prisloe, 2002; Smith, 2000; Yang, Huang, Homer, Wylie, & Coan, 2003a), for urban change characterization. Among these documented alternatives, urban imperviousness is probably the most promising. Urban imperviousness is defined as a sum of impermeable landscape 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 (Arnold & Gibbons, 1996). Imperviousness as a useful alternative to assess urban growth has an indispensable linkage with the Vegetation (V)–Imperviousness (I)–Soil (S) model proposed by Ridd (1995). In this model, urban land use/cover can be the fraction of vegetation, impervious surface, and soil. The VIS model offers a conceptual framework for standardization, comparison, and change detection in urban ecosystems (Ridd, 1995). Yang et al. (2003a) developed an approach to detect urban land use/cover changes by quantifying imperviousness from remotely sensed imagery. Their research indicates that the spatial change of impervious surfaces may be used as an indicator for identifying spatial extent, intensity, and type of urban land use/cover changes. Despite these efforts, further research is needed in other urban areas in order to reinforce the absolute and comparative relationship between the magnitude of change in landscape imperviousness and the type and intensity of urban land use/cover change.

In this research, we investigate the usefulness of satellite-derived imperviousness index as an alternative for urban spatial growth characterization with the city of Pensacola, FL as a case (Fig. 1). The study area, well known as a coastal tourism resort, has witnessed considerable population and economic growth during the past decade. Population increased 19.7% between 1990 and 2000 but the urbanized area has almost doubled in size and thus, Pensacola was listed as one of 30 most sprawl-threatened cities in the United States (Sierra Club, 1998). This fast growing and sprawling pattern is not only changing the life style for people living in Florida's Panhandle area but also threatening the ecosystem. Starting from 2000, the authors have been involved in various projects focusing on the understanding of the dynamics of change in Florida's coasts through the use of geographic information technologies. This article examines urban spatial growth in Pensacola by quantifying imperviousness index change over time. The specific research objectives are: (1) to identify a method for estimating imperviousness index using Landsat TM/ETM+ and high resolution imagery; (2) to apply this method to map imperviousness for two different years; (3) to analyze the spatio-temporal changing trend in landscape imperviousness as related to urban land use/cover changes; and (4) to establish a relationship between imperviousness index change magnitude and urban land use/cover change detected through image interpretation.

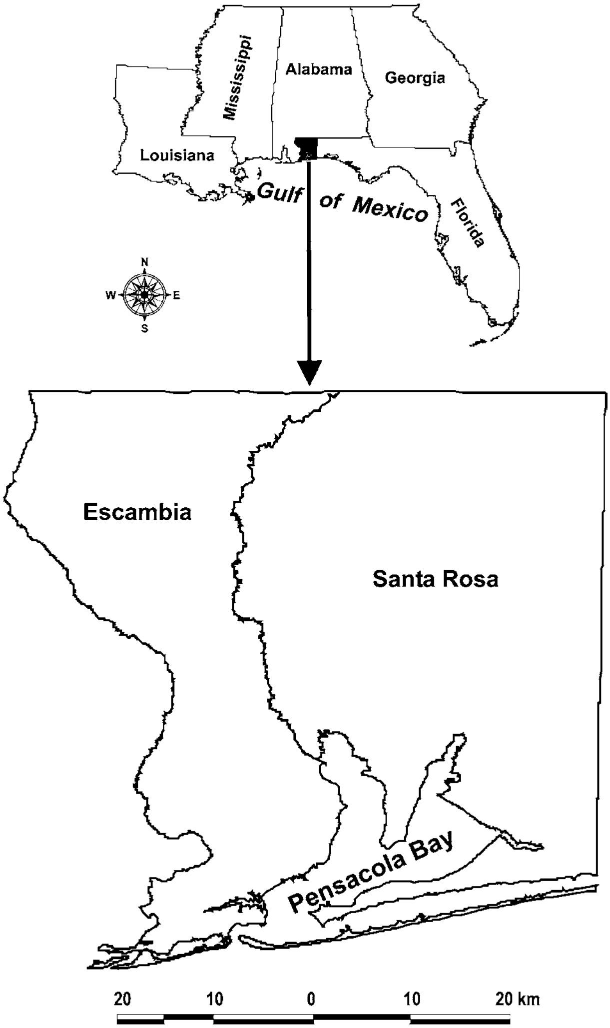

Fig. 1. Location of the study area. It covers the Pensacola Metropolitan Statistical Area (PMSA) which consists of two counties: Escambia and Santa Rosa.

2. Remote sensing of impervious surfaces

Extensive research has been conducted to map impervious surfaces accurately by using remote sensing. Earlier works were largely based on manual interpretation of aerial photographs in connection to watershed analysis (Lee, 1987). These works, although quite accurate, were labor intensive and costly. Later on, Landsat and SPOT imagery were used to map impervious surfaces over large areas, mainly through automated or semi-automated approaches (e.g. Deguchi & Sugio, 1994; Ji & Jensen, 1999; Phinn, Stanford, Scarth, Murray, & Shyy, 2002; Smith, 2000).

Many of the existing studies generally estimated the presence or absence of impervious surfaces at per pixel level. These investigations were largely based on supervised or unsupervised classification, clustering, thresholding, or rule-based algorithm. Deguchi and Sugio (1994) used a clustering algorithm to estimate impervious covers from SPOT HRV imagery. Hodgson, Jesen, Tullis, Riordan, and Archer (2003) compared the performance of three classification algorithms, namely maximum-likelihood classification, spectral clustering, and expert system, for mapping imperviousness from digital orthophoto and LIDAR data. These methods yield standard error ranging from 5.85% to 7.15%. Another method to estimate imperviousness is through the combined use of land use/cover information interpreted from satellite imagery and impervious surface coefficients derived from other sources such as large-scale planimetric data (Prisloe, Lei, & Hurd, 2001).

Recent technological advancements in the field of digital image processing allow the derivation of imperviousness information at the sub-pixel level. Among the new methods used for urban imperviousness estimations, spectral mixing modeling, artificial neural networks, and classification trees are probably the most noteworthy. Ji and Jensen (1999) used a linear mixture modeling to produce layered classification of impervious surface fraction with overall accuracy at 83%. Phinn et al. (2002) estimated urban imperviousness with a constrained spectral mixing modeling and their user's accuracy was 57.46%. Wu and Murray (2003) used a fully constrained linear spectral mixture model to estimate imperviousness from Landsat EMT+ data and their overall root mean square error was 10%. Civco et al. (2002) used an artificial neural network approach for mapping sub-pixel imperviousness from Landsat data and the correlation between actual and predicted impervious surfaces ranged from 0.78 to 0.83. Smith (2000) employed a decision tree classification for urban imperviousness estimation from TM imagery and the overall accuracy was above 65%. Yang et al. (2003a) used a decision tree algorithm for mapping large-area impervious surfaces from ETM+ imagery and the average error ranged from 8.8% to 11.4%.

From the above review, it is clear that substantial research efforts have been made to improve the accuracy of urban imperviousness mapping through the use of multisensor data and advanced algorithms. However, these technologies and methods can vary greatly with the change in image characteristics and the circumstance for targeted studies. For a specific application, an analyst must identify an appropriate method in order to produce satisfactory result with acceptable accuracy. Therefore, further efforts will need in order to consolidate the applicability of remote sensing for landscape imperviousness mapping.

3. Research methodology

The research methodology can be divided into the following major components: (1) Landsat data acquisition and preprocessing, (2) high-resolution calibration image selection and processing, (3) imperviousness index estimation, (4) accuracy assessment, and (5) urban spatial growth analysis. Collectively, the first four parts were to map landscape imperviousness through statistical analysis of the relationship

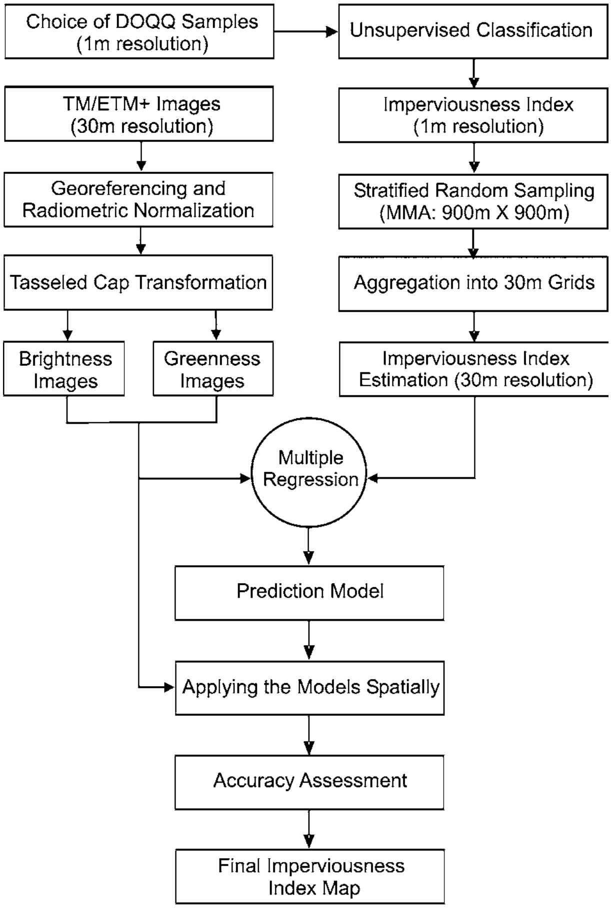

Fig. 2. Working procedural route followed in imperviousness index mapping.

between sample estimation and satellite imagery. The detailed mapping procedures are illustrated in Fig. 2. This section will describe the technical details for the first four components. Part 5 will be discussed in the next section.

3.1. Landsat data acquisition and preprocessing

Ideally, high resolution imagery (such as IKONOS and QuickBird) are the most desirable for urban landscape imperviousness mapping. But they are costly for a large area and demand more processing time and computational resources. Given the budget constraint and the time availability, this study used Landsat TM and ETM+ imagery as the primary data for imperviousness mapping and urban spatial growth analysis. A predominantly cloud-free scene of Landsat imagery covering the Pensacola metropolitan area were acquired for 1989 and 2002, respectively. The

Table 1
Summary of the satellite imagery used

Date	Type of image	Landsat no.	Spatial resolution (m)	No. of bands	Sun elevation (degree)	Sun azimuth (degree)	RMSE (GCP no.)	Radiometric normalization[a]
06 April 1989	TM	5	30	7	52.73	124.03	0.089 (16)	Yes
20 May 2002	ETM+	7	15[b], 30, 60[c]	8	66.00	109.30	Reference	Yes

[a] Radiometric normalization was conducted by using a method proposed by Hall, Strebel, Nickeson, and Goetz (1991). The reference scene was the TM image acquired on 9 April 1996. This image is not listed here because it was not actually used in the landscape imperviousness mapping.

[b] The panchromatic band has a resolution of 15 m.

[c] The thermal band has a resolution of 60 m.

specific dates, types of imagery, Landsat satellite series number, nominal spatial resolution, number of bands, and other environmental parameters are summarized in Table 1.

Both geometric rectification and radiometric normalization were conducted in the phase of preprocessing. The georeferencing strategy adopted here was actually an image-to-image registration. First, the 2002 ETM+ image was rectified by using 1:24,000 digital topographic map. The ETM+ image was georeferenced to the UTM map projection (Zone 16), NAD83 horizontal datum, and GRS84 ellipsoid. Then, this image was used as the reference to rectify the 1989 TM image. In total, 16 good ground control points were used and the root mean square error was 0.089 pixel or 2.67 m in ground distance, given the grid size of 30 m. This indicates an excellent rectification.

Radiometric normalization was used to suppress the spectral differences that were caused because of factors such as atmospheric absorption and scattering, sensor-target-illustration geometry, sensor calibration, and image data processing procedures, which tend to change over time. This is a critical procedure for any change analysis (Jensen, 1995). There are a variety of radiometric normalization methods and their performance can alter according to the variations in the pattern of land use/cover distribution, water–land distribution, topographic relief, similarity between the reference and subject scenes, and sample size (Yang & Lo, 2000). After a careful examination over the Pensacola image scenes, the radiometric normalization method developed by Hall et al. (1991) was adopted because this method is particularly suitable for scenes characterized by relatively even terrain with some deep water bodies and highly reflective urban built-up land (Yang & Lo, 2000). The 1989 and 2002 scenes were radiometrically rectified to the reference image acquired on 9 April 1996. The 1996 image was used for the purpose of radiometric rectification only.

3.2. High-resolution calibration data selection and processing

Calibration data are needed to help develop statistical models for landscape imperviousness estimation. Ideally, calibration data should have higher spatial resolution than the primary imagery. Given the 30-m pixel size of the primary imagery, calibration data should have at least 4 times higher spatial resolution, which is 7.5 m. Besides aerial photos, there are some types of commercial satellite imagery, such as IKONOS and Quick Bird, which reach that high level of spatial resolution. However, these commercial satellite products are costly. Given the budget constraint, a color-IR quarter-quadrangle digital orthophoto (DOQQ) was selected as the calibration image. The orthophoto was produced by the USGS from 1999 perspective aerial photos. It has 1-m nominal ground resolution, covering an area of 81 km^2. Geographically, it covers a part of the city of Pensacola.

An unsupervised classification approach was adopted to map impervious surfaces. This work consisted of two steps. First, the ISODATA (Iterative Self-Organizing DATa Analysis) algorithm was used to identify spectral clusters from the DOQQ image. Then, each cluster was interpreted interactively and labeled as one of the five land cover classes: water, vegetated areas, bare soil, impervious surfaces, or shadow. In this way, a land use/cover classification map was created. A binary map was further generated by recoding the impervious surfaces on the land use/cover map as 1 and the rest as 0. The binary map has 1-m grid size. The classification accuracy was assessed with a standard procedure described by Congalton (1991) and the overall accuracy was found to be 90%.

A grid-network file with the identical grid system as the Landsat TM/ETM+ imagery was created. Each grid cell covers a ground area of 900 m^2 (30 m $\times$ 30 m). The total area of the calibration image is 81 km^2 and therefore, the entire scene contains 90,000 grid cells. Within a 30 m $\times$ 30 m grid, all 1-m pixels classified as impervious surface in the binary map were enumerated to determine the percent imperviousness for each grid. In this way, a calibration map with continuous imperviousness estimation (in %) was generated. It has a 30-m grid size.

It should be noted that the above calibration map derived from the 1999 DOQQ scene was not actually used for statistical model development. For the purpose of statistical analysis, two maps were created by modifying the 1999 map slightly according to the land use/cover distributions for 1989 and 2002, respectively. The land use/cover information was derived through automated classification of Landsat imagery.

For modifications, attentions were paid on the change in urban impervious surfaces. These modifications are necessary because of the temporal difference between the 1999 calibration image and the Landsat TM/ETM+ imagery. The 1989 Landsat TM image contains some non-impervious pixels which are classified as impervious surfaces in the 1999 DOQQ image because of land use/cover conversion. For the 2002 ETM+ image, the situation is on the contrary. These differences have been addressed in the modifications. The modified maps represent percent imperviousness estimations for 1989 and 2002, respectively. These calibration imperviousness maps have a 30-m grid size.

3.3. Imperviousness index estimation

Statistical models were developed to estimate imperviousness index from Landsat TM/ETM+ imagery. In doing so, a number of predictive variables were identified, which are considered to be critical for establishing meaningful statistical models (Smith, 2000; Yang et al., 2003a). This work consisted of two steps. First, a set of variables were initially selected, which included NDVI, brightness, greenness, and 6 bands of the Landsat image data. Note that the thermal band and ETM+'s panchromatic band were not included. Brightness and greenness were computed with the Tasseled-Cap transformation equations developed by Crist and Kauth (1986) and Huang, Wylie, Yang, Homer, and Zylstra (2002) for TM and ETM+ data, respectively. After some trials, only brightness and greenness were retained because they appeared to be more significant in explaining the percent imperviousness variation measured from the calibration data. For statistical soundness, a total of 12,224 sample grids were randomly selected. Multiple regression analysis was conducted to develop imperviousness prediction models.

The final model used to estimate 1989 imperviousness index is

$$\boldsymbol{IS}_{89} = 0.360\boldsymbol{B}_{89} - 1.794\boldsymbol{G}_{89} - 46.179 \tag{1}$$

where $\boldsymbol{IS}$ is the imperviousness index pixel (in percent); $\boldsymbol{B}$ is the brightness value derived from tasseled-cap transformation; $\boldsymbol{G}$ is the greenness value from tasseled-cap transformation; and the subscript 89 indicates the 1989 Landsat TM image. The adjusted $\boldsymbol{R}$ square value for this model is 0.97, with standard error of the estimate of 5.2%.

The final model used to estimate 2002 imperviousness index is

$$\boldsymbol{IS}_{02} = 1.285\boldsymbol{B}_{02} - 0.189\boldsymbol{G}_{02} - 231.757 \tag{2}$$

where $\boldsymbol{IS}$ is the imperviousness index pixel (in %); $\boldsymbol{B}$ is the brightness value derived from tasseled-cap transformation; $\boldsymbol{G}$ is the greenness value from tasseled-cap transformation; and the subscript 02 indicates the 2002 Landsat TM image. The adjusted $\boldsymbol{R}$ square value for this model is 0.91, with standard error of the estimate of 8.5%.

The last step for imperviousness estimation was to apply the above models spatially. An imperviousness index map was created for 1989 and 2002, respectively.

3.4. Accuracy assessment

The accuracy of imperviousness index maps was assessed through an approach combining visual inspection and statistical analysis with the 1989 and 2002 calibration maps as the 'reference'. Visual comparison of the imperviousness map estimated from the Landsat imagery with a calibration map is probably the most straightforward way for a qualitative accuracy assessment. A substantial similarity exists in the general pattern of impervious features identified by using Landsat imagery and by using calibration data. However, because the calibration image has much higher spatial resolution, the imperviousness map estimated from this image shows much more details when comparing to the map derived from the Landsat imagery.

Quantitative accuracy assessment was conducted for the 2002 map only. Because the 1989 map was produced with similar procedures, it is believed that the accuracy assessment for the 2002 map should be sufficient to shed light on the level of overall efficiency of the method identified for imperviousness index estimation in this study.

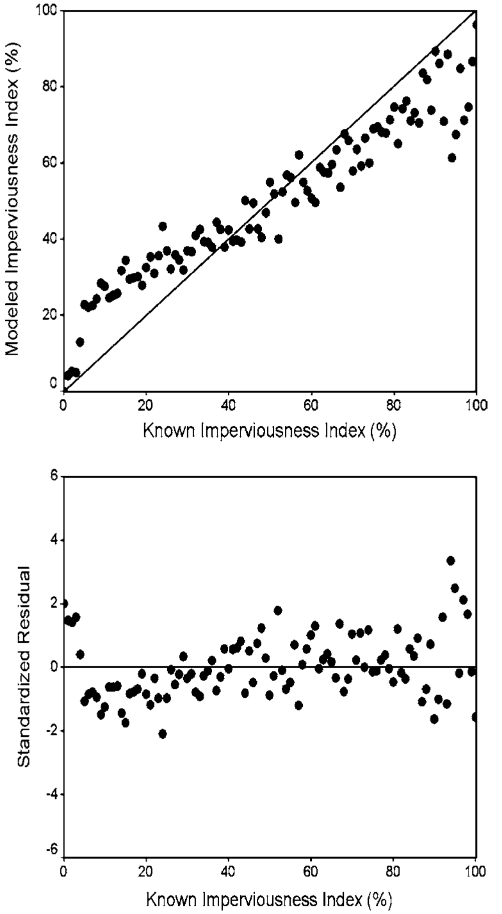

Fig. 3. Imperviousness index estimation accuracy assessment. The upper figure is the result of the accuracy assessment and the lower is the result of the residual error analysis.

Approximately 8233 sample points were randomly selected from both the 2002 imperviousness index map and the 2002 calibration map. These points do not include those used in the phase of statistical model development. The correlation between the modeled and actual (calibration) imperviousness index is 0.96. The overall estimation error is 8.37% (Fig. 4), which is comparable to the accuracies of several studies conducted by other investigators such as Deguchi and Sugio (1994), Wu and Murray (2003), and Yang et al. (2003a). The residual analysis reveals that slightly larger estimation errors exit for highly developed area with imperviousness index of 90–100% (Fig. 3). Similar problem has also been reported by Wu and Murray (2003). The statistical analysis suggests this model overestimate slightly the imperviousness percent in less developed areas (0–20%) while underestimating slightly in highly developed area (80–100%).

4. Result and discussion

The final imperviousness index maps for 1989 and 2002 are partly illustrated in Fig. 4. The imperviousness index is represented continuously with a diverging sequential color scheme. Green color represents low extreme and red for high extreme. Visual inspection indicates that the spatial pattern of imperviousness estimations has been quite reasonable for both maps. Urban centers, shopping centers, commercial/industrial corridors oriented along major highways, military facilities, and large transportation facilities (such as interstate highways, airports, parking lots, etc.) were predicted with the highest imperviousness index (in red). Residential areas show medium-high imperviousness index (in orange). With the use of land use/cover mapping data, the average imperviousness index for different land use/cover categories can be computed. For high-density urban (industrial, commercial, and large transportation facilities), the average imperviousness index is 88%. For low-density urban (residential and local road networks), the average is 59%.

By comparing both maps, the spatial distribution of Pensacola's urbanization between 1989 and 2002 can be well perceived (Fig. 4). It is clear that the commercial/industrial corridors along the major highways, particularly the Palafox/US29 Corridor (Fig. 4(1)) and the Davis Highway Corridor (Fig. 4(2)), have experienced significant development between 1989 and 2002. These corridors are Pensacola's most

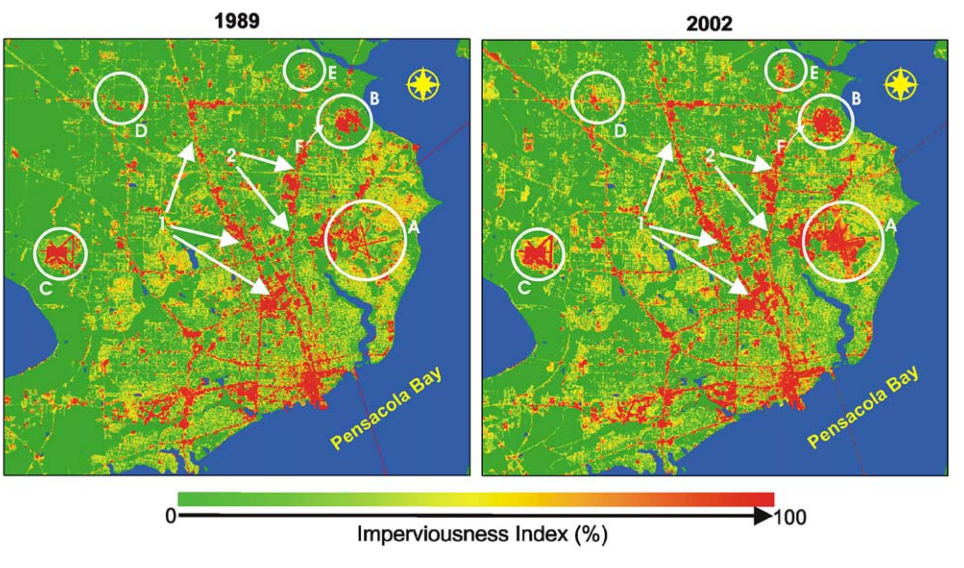

Fig. 4. Imperviousness estimations for a part of the Pensacola metropolitan area at two different years. The dimension for each map is approximately 20 km × 22 km. Blue area is water body. (1) Parafox/US29 commercial and industrial corridor; (2) Davis highway commercial and industrial corridor; A: Pensacola Regional Airport; B: West Florida Regional Medical Center; C: Saufley Field (US Naval flight training base); D: US naval reservation; E: University of West Florida, main campus; and F: Housing subdivision.

Table 2
Change in landscape imperviousness index between 1989 and 2002

Imperviousness index (%)	1989		2002		Percent of change
	Area (ha)	Percent	Area (ha)	Percent	
1–10	57,686	13.15	53,490	12.19	−7
11–20	42,444	9.67	51,725	11.79	22
21–30	31,303	7.13	41,558	9.47	33
31–40	22,766	5.19	28,019	6.39	23
41–50	15,997	3.65	18,337	4.18	15
51–60	11,011	2.51	12,667	2.89	15
61–70	8308	1.89	9768	2.23	18
71–80	7769	1.77	8278	1.89	7
81–90	5918	1.35	8381	1.91	42
91–100	14,926	3.40	26,547	6.05	78

Note. The statistics for 0% of imperviousness index is not included here.

important service and manufacturing industrial bases. Although manufacturing industry shrank, the services industry has grown momentously during the past decade. From 1990 to 1995 alone, the number of service related employees increased 250%. This explosive business growth has prompted considerable land use/cover dynamics, along with substantial increase in landscape imperviousness index (Table 2).

Pensacola regional airport is another 'hot' spot of growth, as shown with a substantial increase of highly developed area (Figs. 4A and 5A). The 1980s and 1990s witnessed a variety of construction activities that transformed the Pensacola Municipal Airport into Pensacola Regional Airport in accommodation with the rocketed growth of aviation industry. Passenger traffic has shown an average of double-digit growth rate over the past few years. Dramatic changes occurred in nearly every corner of the airport. Some major new additions during the late 1990s include a new control tower, extended runways, and a large parking garage complex. These changes dramatically increased the amount of impervious surfaces within the airport area (Figs. 4A and 5A).

The considerable increase of impervious surfaces is found around several major military bases (e.g. Figs. 4C, D and 5C, D). Although generally declining, military industry has been an important sector in regional economy. In 2002 along, the economic impact of military industry in Pensacola metropolitan is estimated at $3890 million (Cushing & Harper, 2003). Fig. 5C is the Saufley Field, which became US Naval Education and Training Professional Development and Technology Center (NETPDTC) in 1986. Fig. 5D is another military base. The development land has intensified within both sites (Fig. 4C and D).

The emergent health care industry during the 1980s and 1990s was characterized by the establishment of a few major medical centers in Pensacola, which increased the amount of impervious surfaces (e.g. Figs. 4B and 5B). In 2002, the employment in health care and social assistance sector represented 12% of the total working population. Fig. 5B is the West Florida Regional Medical Center, a huge development

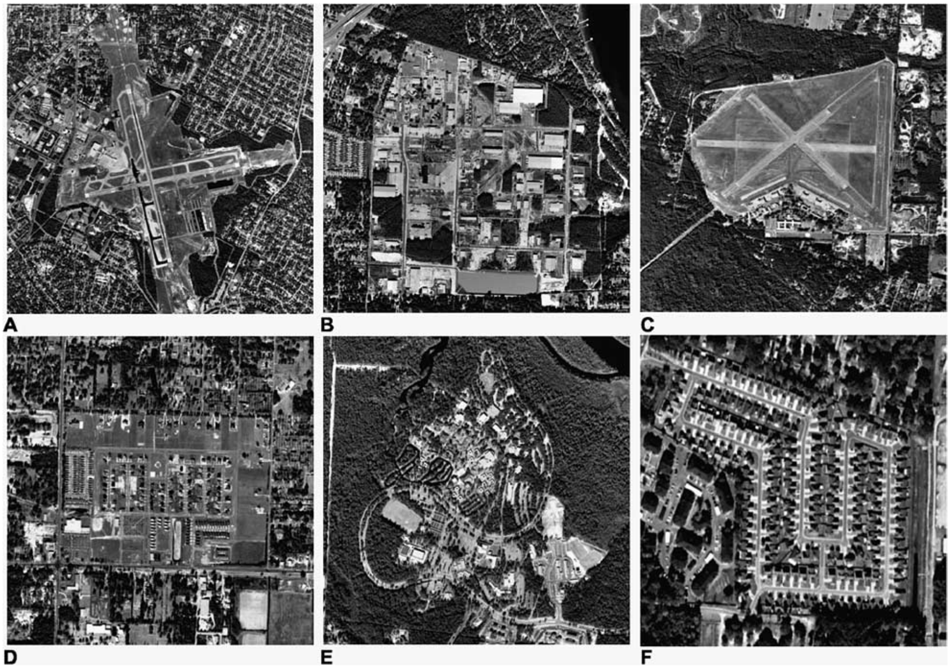

Fig. 5. Aerial photos for selected "hot" sites. These photos were taken in 1999 (*Source*: USGS). A: Pensacola Regional Airport; B: West Florida Regional Medical Center; C: Saufley Field (US Naval flight training base); D: US naval reservation; E: University of West Florida, main campus; and F: Housing subdivision.

complex with plenty of parking space. The construction site was a former flight training base affiliated with US navy. With the structural reshuffling during the past two decades, some military bases were converted into civilian uses.

Substantial increase of landscape imperviousness index is found within the main campus of the University of West Florida (Figs. 4E and 5E). As one of Florida's ten public universities, the school has experienced significant growth in student enrollment during the past decade. To accommodate with this growth, the university has completed the construction of several parking lots and new buildings, which were accomplished at the cost of primary vegetation cover (i.e. wetland and forest).

During the past decade, the Pensacola metropolitan area had experienced 19.7% and 19.8% growth in population and housing units, respectively. The construction of more than 28,000 new homes during the past decade has caused an enormous increase of the amount of impervious surfaces (e.g. Figs. 4F and 5F). The spatial pattern of these emergent impervious surfaces (in orange color) shows a general form of dispersal mixed with some degrees of concentrations along road networks throughout the study area. This indicates a major feature of the suburbanization process throughout the Pensacola metropolitan area.

5. Conclusion

Intensifying urban growth throughout the world has prompted the concerns over the degradation of our environment and ecosystems. Understanding urban spatial dynamics and managing urban growth require the rigorous use of technologies and methodologies in order to develop useful sources of information. For nearly three decades, remote sensing has been widely used in spatio-temporal assessment of urban development and landscape changes, primarily through post-classification comparison. Despite its technological soundness, the post-classification comparison approach has several limitations because it relies upon maps in which land cover is used with arbitrary, fixed value of landscape imperviousness.

This study has demonstrated the usefulness of satellite-derived landscape imperviousness as an alternative for urban spatial growth characterization. The method identified here to map continuous landscape imperviousness was based on the synergistic use of medium-resolution satellite imagery and high-resolution color orthophoto through multivariate statistical analysis. The satellite data were radiometrically normalized in order to establish a common radiometric response among these Landsat imagery. One high-resolution DOQQ scene was used as calibration data to help develop statistical models for landscape imperviousness estimation. A variety of predictive variables were initially selected and after some trials, only brightness and greenness images were retained because they were significant in explaining the imperviousness variation measured from the calibration data. The imperviousness map was assessed through an approach combining visual inspection and statistical analysis. Overall, this method has been quite effective because it does not involve any sophisticated algorithms, such as classification tree or neural networks, but offers comparable mapping accuracy. On the other hand, barren soils and urban impervious surfaces, such as parking lots, were found to be difficult to separate from each other because of the similarity of their spectral responses. Future research effort will need to develop effective strategies for improving urban imperviousness estimation in areas where barren soils exit. The comparison of imperviousness maps has been quite effective for urban spatial growth characterization. The spatio-temporal changing trend of landscape imperviousness index was found to be compatible with the urban land use/cover changing trend detected through image interpretation.

This study has also established a well-documented regional case study focusing on Pensacola, a well-known coastal tourism resort in the Gulf of Mexico. The research has revealed that significant increase of the amount of impervious surfaces occurred in connection with housing growth and business development along several major corridors and around the regional airport and several military bases. The spatial pattern of emergent impervious surfaces in connection to housing growth shows a general form of dispersal mixed with some degree of concentrations along road networks throughout the study area. This indicates a major feature of the suburbanization process throughout the Pensacola metropolitan area. Undoubtedly, these additions of urban impervious surfaces have dramatically changed the landscape structure and patterns. These findings should be useful not only to those who study urban dynamics but also to those who must manage and provide services in this rapidly changing environment. Given that many metropolises face the growing problems caused by urban sprawl or restless suburban development, the technical framework developed in the current study focusing on Pensacola can be easily applicable to other urban areas. This can improve understanding of the variation in the nature-society dynamics of landscape, thereby facilitating a sophisticated approach to environmental management and sustainable development.

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