REMOTE SENSING OF IMPERVIOUS SURFACES

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Edited by
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CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed in the United States of America on acid-free paper
10 9 8 7 6 5 4 3 2 1

International Standard Book Number-13: 978-1-4200-4374-7 (Hardcover)

Library of Congress Cataloging-in-Publication Data

Remote sensing of impervious surfaces / edited by Qihao Weng.
p. cm.
Includes bibliographical references and index.
ISBN-13: 978-1-4200-4374-7
ISBN-10: 1-4200-4374-9
1. Pavements--Location--Remote sensing. 2. Buildings--Location--Remote sensing. 3. Land use, Urban--Remote sensing. 4. Urban hydrology--Remote sensing. I. Weng, Qihao. II. Title.

TE153.W46 2008
624--dc22 2007015254

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Editor

Qihao Weng was born in Fuzhou, China in 1964. He received an AS in geography from Minjiang University in 1984, an MS in physical geography from South China Normal University in 1990, an MA in geography from the University of Arizona in 1996, and a PhD in geography from the University of Georgia in 1999. He is currently an associate professor of geography and director of the Center for Urban and Environmental Change at Indiana State University, United States. He is also a guest/adjunct professor at Wuhan University and Beijing Normal University, China. His research focuses on remote sensing and geographic information system analysis of urban ecological and environmental systems, land-use and land-cover change, urbanization impacts, and human–environment interactions. Dr Weng is the author of more than 75 peer-reviewed journal articles and other publications, and is series editor for *Taylor & Francis Series in Remote Sensing Applications*. He has published the books of *Urban Remote Sensing* (October 2006) and *Remote Sensing of Impervious Surfaces* (October 2007) by CRC Press, an imprint of Taylor & Francis. In September 2006, he coedited, with Dale A. Quattrocchi, a special issue of Thermal Remote Sensing of Urban Areas in *Remote Sensing of Environment*. Dr Weng has been the recipient of the Robert E. Altenhofen Memorial Scholarship Award by the American Society for Photogrammetry and Remote Sensing (1999) and the Best Student-Authored Paper Award from the International Geographic Information Foundation (1998). In 2006, he received the Theodore Dreiser Distinguished Research Award by Indiana State University, the university's highest research honor bestowed to faculty. He has worked extensively with optical and thermal remote sensing data, primarily for urban heat island study, land-cover and impervious surface mapping, urban growth detection, subpixel image analysis, and the integration with socioeconomic characteristics, with financial support from agencies that include: NSF, NASA, USGS, USAID, National Geographic Society, and Indiana Department of Natural Resources. Dr Weng is a national director of American Society for Photogrammetry and Remote Sensing (2007–2010).

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Remote Sensing of Impervious Surfaces: An Overview

Qihao Weng

1 Introduction

Impervious surfaces are anthropogenic features through which water cannot infiltrate into the soil, such as roads, driveways, sidewalks, parking lots, rooftops, and so on. In recent years, impervious surface has emerged not only as an indicator of the degree of urbanization, but also as a major indicator of environmental quality (Arnold and Gibbons, 1996). Impervious surface is a unifying theme for all participants at all watershed scales, including planners, engineers, landscape architects, scientists, social scientists, local officials, and others (Schueler, 1994). The magnitude, location, geometry, and spatial pattern of impervious surfaces, and the pervious–impervious ratio in a watershed have hydrological impacts. Although land-use zoning emphasizes roof-related impervious surfaces, transport-related impervious surfaces could have a greater impact. The increase in impervious cover would lead to the increase in the volume, duration, and intensity of urban runoff (Weng, 2001). Watersheds with large amounts of impervious cover may experience an overall decrease in groundwater recharge and baseflow and an increase in stormflow and flood frequency (Brun and Band, 2000). Furthermore, imperviousness is related to the water quality of a drainage basin and its receiving streams, lakes, and ponds. Increase in impervious cover and runoff directly impacts the transport of nonpoint source pollutants including pathogens, nutrients, toxic contaminants, and sediment (Hurd and Civco, 2004). Increases in runoff volume and discharge rates, in conjunction with nonpoint source pollution, will inevitably alter in-stream and riparian habitats, and result in the loss of some critical aquatic habits (Gillies et al., 2003). In addition, the areal extent and spatial occurrence of impervious surfaces may significantly influence urban climate by altering sensible and latent heat fluxes within the urban canopy and boundary layers (Yang et al., 2003). Impervious surface is found inversely related to vegetation cover in urban areas.

In other words, as impervious cover increases within a watershed/administrative unit, vegetation cover would decrease. The percentage of land covered by impervious surfaces varies significantly with land-use categories and subcategories (Soil Conservation Service, 1975). Therefore, estimating and mapping (detecting, monitoring, and analyzing) impervious surface is valuable not only for environmental management, for example, water-quality assessment and stormwater taxation, but also for urban planning, for example, building infrastructure and sustainable urban growth.

In spite of its significance, the methods for estimating and mapping impervious surfaces and applications of impervious surface data have not been sufficiently explored. Many techniques have been applied to characterize and quantify impervious surfaces using either ground measurements or remotely sensed data. Field survey with global positioning system (GPS), although expensive and time-consuming, can provide reliable information on impervious surfaces. Manual digitizing from hardcopy maps or remote sensing imagery (especially aerial photographs) has also been used for mapping imperviousness. This technique has become more heavily involved with automation methods such as scanning and the use of feature extraction algorithms in recent years. During the 1970s and 1980s, remotely sensed data started to gain popularity in natural resources and environmental studies and were used in interpretive applications, spectral applications, and modeling applications of impervious surfaces (Slonecker et al., 2001). In reviewing the methods of impervious surface mapping, Brabec et al. (2002) identified four different approaches: (1) using a planimeter to measure impervious surface on aerial photography, (2) counting the number of intersections on the overlain grid on aerial photography, (3) conducting image classification, and (4) estimating impervious surface coverage through the percentage of urbanization in a region. These reviews concluded that in the 1970s and 1980s, aerial photography was the main source of remote sensing data for estimating and mapping impervious surfaces (Slonecker et al., 2001; Brabec et al., 2002).

With the advent of high-resolution imagery and more capable techniques recently, remote sensing of impervious surfaces is rapidly gaining interest in the remote sensing community and beyond. Driven by societal needs and technological advances, many municipal government agencies have started to collect and map impervious surface data for civic and environmental uses. Given its importance but lack of books in the market that systematically examine the contents of the field, it is urgent to publish such a book. Through review of basic concepts and methodologies, analysis of case studies, and examination of methods for applying up-to-date techniques to impervious surface estimation and mapping, this book may serve undergraduate and graduate students as a textbook, or be used as a reference book for professionals, researchers, and alike in academics, government, industries, and beyond.

2 Digital Remote Sensing Methods

Various digital remote sensing approaches have been developed to measure impervious surfaces, including mainly: (1) image classification, (2) multiple regression, (3) subpixel classification, (4) artificial neural network, and (5) classification and regression tree (CART) algorithm. The image classification approach utilizes image classifiers such as maximum likelihood classifier, spectral clustering, or other supervised/unsupervised classifiers to categorize and extract impervious surfaces as land-cover or land-use type(s) (Fankhauser, 1999; Hodgson et al., 2003; Dougherty et al., 2004). The multiple regression approach relates percent impervious surface to remote sensing and geographic information system (GIS) variables (Bauer et al., 2004; Chabaeva et al., 2004). The subpixel classification decomposes an image pixel into fractional components, assuming that the spectrum measured by a remote sensor is a linear combination of the spectra of all components within the pixel (Ji and Jensen, 1999; Wu and Murray, 2003; Lu and Weng, 2004). The artificial neural network approach applies advanced machine learning algorithms to derive impervious surface coverage. Flanagan and Civco (2001) developed an artificial neural network (ANN)-based impervious surface prediction model, which consisted of a two-tier neural network series, with the final output to be per-pixel impervious predictions and the training data from Landsat TM spectral reflectance values. The CART approach produces a rule-based model for prediction of continuous variables based on training data, and yields the spatial estimates of subpixel percent imperviousness (Yang et al., 2003).

Image classification is one of the most widely used methods in the extraction of impervious surfaces (Fankhauser, 1999; Slonecker et al., 2001; Brabec et al., 2002; Yang et al., 2003), but results are often not satisfactory because of the limitation of spatial resolution in remotely sensed imagery and the heterogeneity of urban landscapes. Various impervious surfaces may be mixed with other land-cover types, such as trees, grasses, and soils. Moreover, the difficulty in selecting training areas could also lower the accuracy of image classification. As fine spatial resolution data (mostly better than 5 m in spatial resolution), such as IKONOS and QuickBird, become available, they are increasingly employed for different applications including impervious surface mapping. A major advantage of these images is that such data greatly reduce the mixed pixel problem, providing a greater potential to extract more detailed information on land covers. However, new problems associated with these image data need to be considered, notably the shades caused by topography, tall buildings, or trees (Dare, 2005), and the high spectral variation within the same land-cover class.

Because of the inverse correlation between impervious surface and vegetation cover in urban areas, one potential approach for impervious surface extraction is through information on vegetation distribution (Gillies et al., 2003; Bauer et al., 2004). The Normalized Difference

Vegetation Index (NDVI) or greenness from tasseled cap transformation or principal component analysis may be used to represent vegetation distribution. Impervious surface can then be estimated based on regression models with vegetation indices. This approach, however, has a major drawback. Different seasons of satellite images could result in large variations in impervious surface estimation. In the leaf-on season, vegetation may be considerably overestimated, whereas in the leaf-off season, vegetation tends to be underestimated, leading to the overestimation of impervious surface coverage.

3 Use of Medium-Resolution Satellite Imagery

Most previous researches for extraction of impervious surfaces in urban areas used the medium spatial resolution (10–100 m) images, such as Landsat TM/ETM+ and Terra's ASTER images (Wu and Murray, 2003; Yang et al., 2003; Lu and Weng, 2006a,b). However, their spatial resolutions are regarded as too coarse, due to the heterogeneity of urban landscapes and the complexity of impervious surface materials. Urban landscapes are typically composed of features that are smaller than the spatial resolution of such sensors and are a complex combination of buildings, roads, grass, trees, soil, water, and so on. Strahler et al. (1986) described H- and L-resolution scene models based on the relationships between the size of the scene elements and the resolution cell of the sensor. The scene elements in the H-resolution model are larger than the resolution cell and can therefore be directly detected. In contrast, the elements in the L-resolution model are smaller than the resolution cells and are not detectable. When the objects in the scene become increasingly smaller relative to the resolution cell size, they may be no longer regarded as objects individually. Hence, the reflectance measured by the sensor can be treated as a sum of interactions among various classes of scene elements as weighted by their relative proportions (Strahler et al., 1986). The medium-resolution satellite images are attributed to L-resolution model. As the spatial resolution interacts with the fabric of urban landscapes, a special problem of mixed pixels is created, where several land-use and land-cover types are contained in one pixel. Such a mixture becomes especially prevalent in residential areas, where buildings, trees, lawns, concrete, and asphalt can all occur within a pixel. The mixed pixel has been recognized as a major problem affecting the effective use of remotely sensed data in thematic information extraction (Fisher, 1997; Cracknell, 1998).

Because of its effectiveness in handling the mixed pixel problem, spectral mixture analysis (SMA), as a subpixel classifier, is gaining great interest in the remote sensing community in recent years. As a physically based image analysis procedure, it supports repeatable and accurate extraction of quantitative subpixel information (Roberts et al., 1998). The SMA approach may be linear or nonlinear. However, for most remote sensing applications, a linear SMA approach is employed. The linear approach assumes that the spectrum measured by a sensor is a linear combination of the spectra of all components within the pixel (Adams et al., 1995). Different methods of impervious surface extraction based on the linear SMA model have been developed. For example, impervious surface may be extracted as one of the endmembers in the standard SMA model (Phinn et al., 2002). Impervious surface estimation can also be done by the addition of high-albedo and low-albedo fraction images, with both as the SMA endmembers (Wu and Murray, 2003). Moreover, a multiple endmember SMA (MESMA) method has been developed (Rashed et al., 2003), in which several impervious surface endmembers can be extracted and combined. However, these SMA-based methods have a common problem, that is, impervious surface tends to be overestimated in the areas with small amounts of impervious surface, but is underestimated in the areas with large amounts of impervious surface. The similarity in spectral properties among non-photosynthetic vegetation, soil, and different kinds of impervious surface materials makes it difficult to distinguish impervious from nonimpervious materials. In addition, shadows caused by tall buildings and large tree crowns in the urban areas may also lead to an underestimation of impervious surface area.

In particular, the addition of low-albedo and high-albedo fraction images has been proven effective in estimating and mapping impervious surface to a certain degree. However, the impervious surface may be overestimated in the areas where a low amount of imperviousness is detected. This is because the low-albedo fraction image may relate to different kinds of materials/covers, including water, canopy shadows, building shadows, moisture in grass or crops, and dark impervious surface materials. On the other hand, although the high-albedo image is largely associated with impervious surfaces, it may be confused with dry soils. Additional data or improved techniques are therefore necessary to separate impervious surfaces from others. Slonecker et al. (2001) noted that the use of thermal infrared and radar imagery may aid greatly in impervious surface estimation, possibly through data fusion. Lu and Weng (2006a) have successfully utilized Landsat ETM+ thermal infrared data to enhance their estimation of impervious surfaces based on the differences in land surface temperature between impervious and nonimpervious surfaces. The land surface temperature image was used as a threshold to remove dry soils from the high-albedo fraction image and to remove water and shadows from the low-albedo fraction image. In addition, radar data have inherent advantages in the identification and estimation of impervious surfaces because of the high dielectric properties of most construction materials and the unique geometry of man-made features (Slonecker et al., 2001).

4 The Structure of the Book

This book consists of five parts. Part I introduces various methods of remote sensing digital image processing for impervious surface estimation and mapping. Part II exemplifies most recent technological advances in the field of remote sensing of impervious surfaces. Part III presents techniques for extracting and mapping transport-related impervious surfaces using different types of remotely sensed data. The techniques and case studies for estimating and mapping roof-related impervious surfaces are contained in Part IV. The final part, Part V, examines some major application areas of impervious surface data, including impact analysis of water quality, hydrological modeling of water flow, examination of the effect on aquatic fauna, and population estimation.

The chapters in Part I are concerned with four different approaches to impervious surface estimation and mapping. These methods, including regression, CART, SMA, and artificial neural network, have received wide recognition in the remote sensing community. Chapter 1 describes the method and some results of estimation and mapping of impervious surface area for the state of Minnesota in 1990 and 2000. The method uses a regression modeling to estimate the percent of imperviousness for each pixel based on its inverse relation with the greenness component of the tasseled cap transformation of Landsat TM/ETM+ data. Although this project employed satellite images in spring, summer, and fall seasons, only summer images were used for the modeling to have the greatest contrast between imperviousness and vegetation responses. In Chapter 2, a method based on ANN is established to estimate the subpixel imperviousness from IKONOS imagery. The case study conducted in Grafton, Wisconsin, which had diverse land-use types, shows that the ANN model produced reasonable high accuracy with a mean error of 7.78. The model performed even better in the urban areas, where the satellite data were highly nonlinear. Chapter 3 applies the CART algorithm developed by the United States Geological Survey (Yang et al., 2003; Xian, 2006) to two fast-growing regions, Seattle-Tacoma, Washington and Las Vegas, Nevada. This method first classified high-resolution imagery. Pixels classified as urban were totaled to calculate impervious surface as a percentage and rescaled to match the pixel size of the medium-resolution satellite imagery. The percent imperviousness datasets were then used as dependent variables in the regression tree models, while the medium-resolution image data and derived variables (such as NDVI) together with other geospatial data (such as slope) were used as the independent variables. This chapter further examines how urban growth, as indicated by impervious surface data, related to housing density in Seattle-Tacoma between 1986 and 2002 and in Las Vegas between 1984 and 2002. Chapter 4 applies SMA to Landsat ETM+ imagery to derive fraction images, which are further used to compute impervious surfaces. This approach has demonstrated its effectiveness with reasonably high accuracy (Wu and Murray, 2003; Lu and Weng, 2006a). A major drawback with this approach lies in its difficulty in extracting dark impervious surface areas, which are confused with water and shadows. Therefore, the authors of this chapter further employed IKONOS data to extract impervious surface data by using a hybrid method of decision tree classifier and unsupervised ISODATA classifier for the purpose of validation.

Part II presents new developments in remote sensing of impervious surfaces, especially in the areas of ANN-based model, object-oriented detection, fractal analysis, image fusion, and use of hyperspectral imagery. In Chapter 5, two new models are introduced for extraction of impervious surfaces using remote sensing data of multiple sources. The ANN-based subpixel proportional land-cover information transformation (SPLIT) model establishes spectral relationship between Landsat TM pixel values and the corresponding high spatial resolution, airborne, digital multispectral videography data, so that proportions of impervious surface within the Landsat TM imagery can be extracted. The object-oriented multiple agent segmentation (MASC) model extracts impervious surfaces from true-color digital orthophotos by imbedded segmentation, shadow-effect, MANOVA-based classification, and postclassification submodels. Chapter 6 examines the benefits of hyperspectral imagery for extracting impervious surfaces with a case study in Indianapolis, United States. SMA was applied to EO-1 Hyperion imagery to calculate the fraction images of green vegetation, soil, high albedo, and low albedo. The fraction images of high albedo and low albedo are then used to estimate impervious surfaces. In comparison with ALI (multispectral) imagery, the Hyperion image was found to be more effective in discerning low-albedo surface materials, which have been a major obstacle for impervious surface estimation with medium-resolution multispectral images (refer to Chapter 4). Chapter 7 applies fractal analysis (triangular prism method) for separating types of impervious land cover with a primary focus on the separation of roofs, roads, and driveways in a suburban area of New York. It demonstrates that there were statistical differences between fractal dimensions calculated for different classes of impervious land cover. Roofs and roads were found generally separable on a pairwise basis, while driveways were more frequently confused. Recognizing the strengths and limitations of synthetic aperture radar (SAR) and optical remote sensing data, Chapter 8 demonstrates how the techniques of data fusion can be applied for better feature extraction in urban areas. The methodology was based on texture analysis of both SAR and optical images for detection and exploitation of spatial patterns, followed by a joint classification of the extracted spatial features together with the original spectral features. The Markov random field classifier used for this research was found to provide better accuracy than the neuro-fuzzy classifier and to have a similar capability to cope with multiple inputs.

The next two parts of the book focus each on one functional type of impervious surface, transport-related impervious surfaces in Part III and roof-related impervious surfaces in Part IV. Specifically, Part III explores the spectral characteristics of roads under different conditions and introduces unique techniques for extracting roads by using various remotely sensed data. Chapter 9 applies hyperspectral imagery (airborne visible/infrared imaging spectrometer—AVIRIS) for road extraction and assesses the effectiveness of four advanced image classifiers. Minimum noise fraction (refer to Chapters 4 and 6) and CART (refer to Chapter 3) were used to reduce the number of spectral dimensions to be analyzed. The four classifiers examined are the spectral angle mapper (SAM), object-oriented nearest neighbor, mixture-tuned matched filtering (MTMF), and the combination method of mixture-tuned matched filtering and CART (MTMF-CART). This study found that the object-oriented nearest neighbor classification method produced the best overall result compared with MTMF, SAM, and MTMF-CART classifiers. The overall accuracies for the four classifications were 93.2%, 81.89%, 88.92%, and 84.32%, respectively. Chapter 10 first describes the strengths and limitations (arising from the side-looking illumination of the sensor) of SAR imagery for road extraction. Then, it applies the ''TUM-LOREX'' method of road extraction (Steger et al., 1997; Wiedemann and Hinz, 1999; Wiedemann and Ebner, 2000) to SAR imagery. In order to compensate for possible gaps caused by adjacent high buildings and narrow streets, dominant scattering caused by building structures, traffic signs, and metallic objects in cities, the authors suggest that additional information is needed for better extraction through data integration. SAR imagery may be combined for use with context information, road class-specific modeling, and use of multiview imagery. As high spatial resolution satellite imagery (better than 5 m in the panchromatic channel), such as SPOT 5, IKONOS, QuickBird, OrbView, or EROS, becomes available for civilian applications, there is a shift in road extraction algorithms from linear to surface models. Chapter 11 proposes a new method of road extraction from high-resolution imagery, which integrates a linear representation of the road (graph module) with a surface representation (reconstruction module). In order to overcome local artifacts, the method makes use of advanced image-processing algorithms such as active contours and the wavelet transform. Its application and evaluation on a QuickBird image over an urban area in France achieved an acceptable accuracy. The last chapter in Part III, Chapter 12, discusses common spectral characteristics of asphalt roads and the impact of different road conditions and distresses, based on the Santa Barbara asphalt road spectra library (Herold and Roberts, 2005). It further evaluates the potential of hyperspectral remote sensing to study transportation infrastructure and road surfaces (also refer to Chapter 9).

Part IV is concerned with various methods and techniques for estimation and mapping of roof-related impervious surfaces. Chapter 13 presents a method for generation of an urban 3D model, especially a digital building model via integrating image knowledge and LiDAR data. The main contribution lies in the development of an object-oriented building extraction model, which defines roof types, roof boundary coordinates, planar equation, and other parameters. These parameters were extracted from the combined processing of LiDAR and orthoimage data. In Chapter 14, state-of-the-art building extraction and city modeling techniques are presented. Aerial images, with semiautomated photogrammetric techniques, are currently regarded to be most important for city modeling. This chapter evaluates the potential of aerial laser scan data for modeling cities. Chapter 15 discusses main characteristics of the electromagnetic models with respect to SAR data. The rationale and results for a sound electromagnetic SAR modeling of the dihedral canonical elements are provided. The models discussed are appropriate for airborne and the upcoming generation of high-resolution spaceborne SAR sensors. To achieve accurate roof-mapping results, it is often necessary to fuse the spectral information of the multi-spectral image and the spatial information of the panchromatic image of a given sensor or sensors into one image. This method is called pan-sharpening the multispectral image using the pan image. In Chapter 16, two examples of pan-sharpening for roof mapping are illustrated: pixel-based postclassification for small-scale roof mapping using Landsat TM and SPOT Pan fused images and object-oriented classification for medium-scale roof mapping using pan-sharpened QuickBird images. Both case studies demonstrate that an effective image fusion can significantly contribute to an improvement in the accuracy of roof mapping, although the final results may still contain errors.

Part V presents some examples of applications of remotely sensed impervious surface data. Impervious surface coverage affects both water quality and water abundance through its influence on surface runoff. Chapter 17 discusses this relationship in detail and illustrates it through a case study in Pennsylvania. The project aimed at the development of a software that would estimate the potential impact of urbanization on water quality within the watersheds in the state. By creating an ISA map for the year 2002 and by comparing with the existing 1985 and 1995 maps, development trends though a longer time period may also be determined. Chapter 18 is closely related to Chapter 17, but focuses on the storm runoff effect of impervious surface dynamics. It provides an overview of the Simple Method and Soil Conservation Service-based hydrologic models, which were widely used to predict the effects of urbanization on precipitation-runoff processes. In addition, this chapter introduces a remote sensing-based technique for determining the extents of impervious surface in the watershed using its inverse relationship with fraction vegetation cover (Carlson and Ripley, 1997). Case studies were conducted to demonstrate runoff responses to the increased impervious areas under different climate conditions, one in the Red River of the North Basin along the state border between North Dakota and Minnesota and the other in Simms Creek watershed in Florida. Chapter 19 reviews literatures regarding the effect of growth of impervious surface coverage on the biodiversity of terrestrial and aquatic fauna. The case study illustrated in this chapter resulted from the author's articles published in 2003 (Gillies et al., 2003). By computing a time line of impervious surface area and combining with historical freshwater mussel data, it examines the effect of impervious surface area on aquatic fauna in the Flint River tributaries over a period of extensive urban growth (1979–1997) associated with the Peachtree City of Atlanta metropolitan area. The last chapter of this book, Chapter 20, presents a method of population estimation by using impervious surface data derived from a Landsat ETM+ image. The research conducted population modeling in Marion County, Indiana, United States, at all census levels (census block, block group, and census tract). The performance of models was evaluated by several criteria (i.e., relative error, mean relative error, median relative error, and the error of total in percentage). Better models were found to have higher analytical scales, and the performance reached the best at the census tract level.

Acknowledgments

I wish to extend my thanks to all the contributors of this book for making this endeavor possible. Moreover, I offer my deepest appreciation to all the reviewers, who have taken precious time from their busy schedules to review the chapters submitted for this book. Finally, I am indebted to my family for their enduring love and support. It is my hope that the publication of this book will provide stimulation to students and researchers to perform more in-depth work and analysis on the applications of remote sensing to impervious surfaces. The reviewers of the chapters for this book are listed here in alphabetical order:

Toby Carlson, Lee Decola, Fabio Dell'Acqua, Charles Emerson, Paolo Gamba, Martin Herold, Junchang Ju, Jonathan Li, Weiguo Liu, Desheng Liu, Dengsheng Lu, Assefa M. Melesse, Soe Wint Myint, Maik Netzband, Renaud Peteri, Rebecca Powell, Ruiliang Pu, Fang Qiu, Umamaheshwaren Rajasekar, Sebastian Schiefer, Jie Shan, Guofang Shao, Conghe Song, Uwe Sorgel, Uwe Stilla, Ramanathan Sugumaran, Le Wang, Yeqiao Wang, Changshan Wu, George Xian, Honglin Xiao, Jingfeng Xiao, Jiansheng Yang, Stephen Yool, Fei Yuan, Yun Zhang, and Guoqing Zhou.

My work on remote sensing of impervious surfaces has been supported by various funding sources. These include a fund from National Science Foundation (BCS-0521734) for a project entitled ''Role of Urban Canopy Composition and Structure in Determining Heat Islands: A Synthesis of Remote Sensing and Landscape Ecology Approach,'' and funds from the USGS IndianaView program and from the NASA's Indiana Space Grant program for a project entitled ''Indiana Impervious Surface Mapping Initiative.'' Dr Dengsheng Lu, Auburn University, was an excellent collaborator in all these projects.

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