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RANA AL-JAWARNEH
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BY

Dr. Jason Julian, Chair

Dr. Bruce Hoagland

Dr. Mark Meo

Dr. Sally Gros

Dr. Charles Warnken

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Table of Contents

Acknowledgements iv

List of Tables ix

List of Figures x

Abstract xii

Preface1

Role of Physiography on Urban Development 1

Research Objectives and Questions 2

Structure of Dissertation 3

References 6

Chapter 1: Development of an Accurate Fine-resolution Land Cover Timeline: Little Rock, Arkansas, USA (1857-2006) 8

Introduction 8

Study Area 11

Land Cover Data Sources 12

1857 Public Land Survey System (PLSS) records 12

1943 aerial photography 13

1975 GIRAS land cover dataset 13

Multi-Resolution Land Characteristics Consortium (MRLC) National Land Cover Databases (NLCDs) 15

Calculations 16

Spatial resolution 16

Constructing the 1857 land cover dataset 17

Constructing the 1943 land cover dataset 19
Improving the 1975 land cover dataset 19
NLCD land cover datasets 22
Results 23
Land cover dataset improvements 23
Land cover changes from 1857 to 2006 27
Discussion 29
Data quality 29
Land cover patterns in central Arkansas 32
Conclusion 34
References 35
Chapter 2: Environmental Influences on Land Development and Consequent Land Cover Changes in Central Arkansas, (USA), 1857-2006: A Historical-Environmental Framework for Long-term, Large-scale Change Analysis 42
Introduction 42
Study area: Central Arkansas 45
Data and Methods 48
Land cover data 48
Land cover proportions and patterns and landscape within- and among-ecoregions (1857-2006) 49
Biophysical and socioeconomic drivers of urban and agriculture development trends (1857-2006) 51
Results 54

Land cover patterns and proportions within- and among-ecoregions 54
Land cover complexity and topographic variation 55
Urban in Central Arkansas (1857-2006) 56
Agriculture in central Arkansas (1857-2006) 62
Discussion.. 67
Environmental-historical influences on urban development 67
Environmental-historical influences on agriculture development in central Arkansas 71
Conclusion 74
References 76
Chapter 3: The Influence of Physiography on Historical and Future Urban Growth Trends across an East-West Gradient in the Arkansas-Red River Basin, USA, 1975-2050 81
Introduction 81
Study area 83
SLEUTH-3r urban modeling 84
SLEUTH background 84
SLEUTH-3r data inputs preparation 87
Calibration of the SLEUTH-3r 93
SLEUTH-3r Results 95
Colorado Springs 95
Amarillo 98
Oklahoma City 98

Tulsa 99
Little Rock 100
Discussion.. 101
Urban growth patterns 101
Influence of Physiography on urban growth patterns..................................... 107
Conclusion.. 110
References 112
Chapter 4: Conclusions.. 116
Research Objectives and Thesis Structure 116
Development of accurate and compatible long-term land cover timeline............. 116
The Influence of Physiographic Complexity on Spatiotemporal Trends in Urban and Agriculture Development 118
Environmental Influences on Past and Future urban Development Trends at large Basin-Scale 119
Future Applications 120
References 122

List of Tables

Table 1.1. Datasets used to create land cover timeline……………………………………..14

Table 1.2. Land cover classes used for all datasets……………………………………………15

Table 1.3. Accuracy assessment for the unimproved GIRAS dataset…………………………. 24

Table 1.4. Accuracy assessment for the improved GIRAS dataset…………………………….25

Table 2.1. The biophysical and socioeconomic used in the empirical
Trend analysis………...52

Table 3.1. Goodness of fit metrics available in SLEUTH-3r…………………………..87

Table 3.2. SLEUTH-3r inputs and variables……………………………………………...89

Table 3.3. Exclusion values in SLEUTH-3r excluded layer…………………….….….90

Table 3.4. Best overall calibration results……………………………………………...96

Table 3.5. Calibration accuracy results for each study area……………………………96

List of Figures

Figure 1.1. Little Rock, Arkansas (USA) study area…………………………………...12

Figure 1.2. Comparison between areas of changed cells in the 1992-2001 NLCD Retrofit Change Product at 30 m…….………………………………………….......17

Figure 1.3. Modification of the 1975 GIRAS land cover dataset in order to make it comparable to current national land cover datasets……………………………….…………………………………………...20

Figure 1.4. Comparison between the unimproved GIRAS land cover map and the modified land cover map ………………………………………………………………26

Figure 1.5. Land cover timeline for the Little Rock study area at 60 m spatial resolution………………………………………………………………………..28

Figure 1.6. Change in land cover (percentage of study area) from 1857 to 2006……..29

Figure 1.1. Population growth and central Arkansas key socioeconomic events……...48

Figure 1.2. Land cover timeline for the Little Rock study area at 60 m spatial Resolution…………………………………………………………………………49

Figure 2.3. Land cover composition within each ecoregion and over time in Central Arkansas……………………………………………………………………....55

Figure 2.4. Trends in land cover arrangement and fragmentation in central Arkansas……………………………………………………………………..57

Figure 2.5. Landscape heterogeneity index by ecoregion and time..…………………..58

Figure 2.6. Magnitude of relative change for a pixel to be urbanized at different slope intervals and different soil available water storages interval…………………………………………………………………………….59

Figure 2.7. Magnitude of relative change for a pixel to be urbanized within wetlands, within areas adjacent to wetland, within water bodies, or within areas adjacent to water bodies……………………………………………………………………………...60

Figure 2.8. Magnitude of relative change for a pixel to be urbanized within riparian zone or within areas adjacent to the Arkansas River……………………………………..61

Figure 2.9. Magnitude of relative change for a pixel to be urbanized at different proximities from Little Rock CBD and within areas adjacent to roads……………………………………………………………………………………62

Figure 2.10. Magnitude of relative change for a pixel to be developed for agricultural use at different slope intervals and at different soil available water storage (AWS) intervals……………………………………………………………………...64

Figure 2.11. Magnitude of relative change for a pixel to be developed for agricultural use within wetlands, within areas adjacent to wetlands, within water bodies, and within areas adjacent to water bodies……………………………………………………………………………...65

Figure 2.12. Magnitude of relative change for a pixel to be developed for agriculture use within riparian zone or within areas adjacent to the Arkansas River.....……………..66

Figure 2.13. Magnitude of relative change for a pixel to be developed for agricultural use at different proximities from Little Rock CBD and within 420 m area adjacent to roads……………………………………………………………………………………67

Figure 3.1. Location of the Arkansas-Red-River Basin in the South Central US……...85

Figure 3.2. Colorado Springs input datasets to SLEUTH-3r…………………………...91

Figure 3.3. Amarillo input datasets to SLEUTH-3r…………………………………....91

Figure 3.4. Oklahoma City input datasets to SLEUTH-3r……………………………..92

Figure 3.5. Tulsa input datasets to SLEUTH-3r…………….………………………….92

Figure 3.6. Little Rock input datasets to SLEUTH-3r………………………………….93

Figure 3.7. Urban land cover 1975-2050……………………………………………....97

Abstract

Variability in physiography and land management can lead to differences in urban development rates and patterns in space and through time. While traditional studies have focused on contemporary anthropogenic impacts on the environment; relatively few have investigated and quantified the influence of biophysical forces, relative to human historical factors, on long-term and large-scale urban trends and patterns. In this research, I first developed a framework that uses readily available data to build fine-resolution historical land cover timelines over large areas. To build this timeline, I transformed pre-settlement land surveys (c.a. 1850s) and early aerial photographs (c.a. 1940s), and improved the mapping accuracy of the first national land cover dataset (GIRAS, 1975) to make it compatible with the contemporary national land cover database (1994-2006). Second, I used the compiled timeline to empirically analyze the historical development trends and rates around Little Rock city, Arkansas (USA). For this analysis, I developed a robust environmental-historical approach to emphasize the potential influences of environmental forces on shaping development transitions within and among-ecoregions. Finally, I studied the influence of physiography on historical and future (1975-2050) urban growth trends and patterns across an east-west gradient in the Arkansas-Red River basin. The products from this research have broad applications to urban planning, landscape ecology, and environmental sustainability.

Preface

Role of Physiography on Urban Development

The influence of biophysical forces (i.e., soil characteristics, topography, and water bodies) on shaping urban systems has been well recognized (Bairoch, 1988; Semple, 1911; Trewartha, 1941; Wagner, 1978); however, analyzing the effects of physiographic heterogeneity, coupled with human advancements, on historical and future urban patterns and trends has received less attention. Environmental forces, particularly climate conditions and topography, have greatly dictated early human settlements and will continue to shape future growth patterns and trends.

The origins of sedentary life are rooted back in the societal lifestyle change from gathering-hunting to cultivation. Plowing the land and having a surplus of food encouraged settled lifestyles and caused increasing population size and density and consequently, the emergence of urban systems. Therefore, the physical factors that affected urban developments are the same ones that secured crop cultivation (Bairoch, 1988).

In tropical areas, where temperature is higher at lower elevations, urban development took place in mountains, where the predominant urban patterns extended vertically (Lauer, 1993; Mcharg, 1969; Funnell & Parish, 2001). In arid and semi-arid regions, water resources have been the main climatic factor controlling urban development. The low desert regions such as the Nile of Egypt, the yellow River in China, and Mesopotamia, are examples of riverine civilizations, where proximity to rivers was crucial for the emerging and sustaining of such civilizations (Hoffman et al. 1986**;** Simmons 1993; Dearing 2006).

In North America, the European newcomers first dwelled in the frosted northeastern lands of the continent because these forests were the sources for building materials and fuel (Gotmann, 1961; Diamond, 1994). In the western United States, urban movement proceeded slowly. The European settlers moved westward with caution and founded settlements on the frontier zone (Clawson, 1979).

Since the late 18^{th} century, what some scientists label the Anthropocene (Crutzen, 2002; Zalasiewics et al., 2010); humans have greatly enhanced land cover changes across the planet (Ellis et al., 2010). The global large-scale replacement of natural land cover by anthropogenic ecosystems, especially urban areas, has raised many socioeconomic and environmental concerns (Foley et al., 2005). Urban cover has become one of the largest terrestrial biomes on the planet, containing around half of world's population (United Nations Population Division, 2009). In the U.S., more than 80% of its population lived in urban and suburban areas in 2010 and this number is expected to reach 90% in 2050.

Because urban cover is a major outcome of the interaction between human and physical systems, understanding its drivers and impacts is important for landscape ecology, urban planning, and environmental sustainability. In this research, however, I argue that it is more important to first understand the environmental drivers and preferential pathways of long-term and large-scale urban systems using compatible urban extents and logical analytical approach.

Research Objectives and Questions

The objectives of this research were to present a framework that uses readily available land cover data to develop accurate fine-resolution land cover timelines for more robust land change studies, empirically analyze historical land development trends and rates, develop an environmental-historical analytical approach, and simulate past urban dynamics and forecast urban growth trends for five 10,000 km^2 areas around the cities of Colorado Springs, Amarillo, Oklahoma City, Tulsa, and Little Rock, spread throughout the Arkansas-Red-River Basin to demonstrate how growth trends vary in response to changing physiography in the South Central U.S. The guiding question of this research was:

How do environmental attributes influence urban development?

The guiding question was answered by addressing three fundamental questions which were:

1- Can land cover datasets from different data sources be combined to create a comparable land cover timeline?
2- Is there a relationship between environmental attributes and land development rates and patterns around the city of Little Rock?
3- Are environmental drivers of urban development consistent across a large and diverse physiographic gradient?

Structure of Dissertation

Papers Presented in Chapters

This dissertation is written in the form of 3 chapters, all of which are independent manuscripts for journal submission, followed by a conclusion.

Chapter one is a methodological paper on how to develop long-term compatible land cover timelines. This chapter introduces robust mapping techniques to combine land cover datasets from different sources. First, it presents logical consistency to improve the earliest available maps for the Little Rock study area (1857) and digitize the first available aerial photographs (1943). Second, it presents new GIS modification techniques to improve the mapping accuracy of the first national land cover dataset (GIRAS, 1975) to make it comparable with the contemporary National Land Cover Database (NLCD). Finally, this chapter uses the created fine-resolution land cover timeline to characterize major land cover transitions in central Arkansas.

Chapter two introduces a historical-environmental approach to analyze the influence of environmental attributes, relative to socioeconomic factors, on land use dynamics for both urban and agriculture development in central Arkansas. First, it uses the 149-y fine-resolution land cover timeline to understand landscape composition and spatiotemporal patterns within and among-ecoregions. Second, it relates land cover complexity to physiographic complexity within each ecoregion. Third, this chapter empirically analyzes development trends and rates at a regional scale over 149-y and explains the influence of environmental forces (i.e., topography, water bodies, wetlands, and soil moisture) and human historical factors on historical urban and agriculture development patterns.

Chapter three investigates the influence of physiography on historical and future urban growth trends across an east-west gradient in the Arkansas-Red River Basin, USA, (1975-2050). First, this chapter simulates past urban growth patterns and forecasts future urban trends using a modified SLEUTH-3r urban growth model. Second, it demonstrates how historical and future growth trends vary in response to changing physiography in the South Central US.

Manuscript Details

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Chapter 4: Jawarneh, R.N., & Julian, J.P. the Influence of Physiography on Historical and Future Urban Growth Trends across an East-West Gradient in the Arkansas-Red River Basin, USA, 1975-2050. Computers, Environment, and Urban Systems.

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Chapter 1: Development of an Accurate Fine-resolution Land Cover Timeline: Little Rock, Arkansas, USA (1857-2006)

Introduction

Earth's land surface is in a constant state of change due to variability in multiple endogenic and exogenic forces. Since the late 18th century, what some scientists label the Anthropocene (Crutzen, 2002; Zalasiewics et al., 2010), humans have greatly enhanced land cover changes across the planet (Ellis et al., 2010). With increasing pressure on natural resources and fuel demands resulting from an exponential population increase, land cover changes over the past two centuries have occurred at alarming rates, particularly in developed countries such as the United States (U.S.) (Loveland et al., 2002; Goldewijk & Ramankutty, 2007). Because land cover is an outcome of the interaction between human and physical systems, understanding the drivers and impacts of land cover changes is one of the grand challenges in geography and environmental sciences for the next several decades (NRC, 2001; Skole, 2004). However, before we explore drivers and impacts, we need to first develop accurate and comparable historical land cover datasets.

Most land cover change studies rely on readily available data derived from satellite imagery, including the National Land Cover Database (NLCD) produced by the Multi-Resolution Land Characteristics Consortium (MRLC) for the U.S. (Vogelmann, et al., 2001; Homer et al., 2004; Fry, et al., 2011). The 1992, 2001, and 2006 NLCDs were generated at a 30 m resolution from Landsat-TM/ETM+ satellite imagery in conjunction with ancillary geospatial data. Imagery quality, land cover classes, and classification methods, however, varied among the three NLCDs, resulting in map accuracy and compatibility issues. Some of these issues between the 1992 and 2001 NLCDs have been addressed by the Land Cover Change Retrofit Product (Fry et al., 2009), and also between 2001 and 2006 NLCDs (Xian et al., 2009). Efforts to make all three datasets compatible are currently underway (J.A. Fry, personal communication). But even after this accomplishment, we will still be left without compatible NLCDs to document land cover changes prior to the 1990s, when most major land changes occurred in the U.S. (Carrio et al., 2010; Kim et al., 2011; Westervelt et al., 2011).

In the mid-1970s, the U.S. Geological Survey (USGS) and partner agencies led an effort to build the first national land cover dataset, popularly referred to as GIRAS for the Geographic Information Retrieval Analysis System that was designed to enable immediate cartographic and statistical retrieval of land cover information (Mitchell et al., 1977). Land cover was classified based on visual interpretation (from multiple technicians) of aerial photographs (with different scales) and mapped using digitized polygons (with different minimum mapping units; MMU). Topological and coding errors in GIRAS edited files, caused by converting GIRAS to a geographic information system format, were corrected to create a more reliable dataset (Price et al., 2003).

Although GIRAS displays important land transformations that occurred during the post-World War II era in the U.S., its mapping uncertainties and incompatibility with the MRLC NLCDs has left researchers with some doubts about the suitability of using this historical dataset. In most studies that used GIRAS, mapping errors were not assessed or corrected (Wang & Yin, 1997; Knowles-Yánez, et al., 1999; Metre & Mahler, 2005). To my knowledge, only one study has modified the GIRAS land cover dataset to improve its accuracy and compatibility with the MRLC NLCDs (Elmore & Guinn, 2010).

Numerous studies have used aerial photographs to assess land cover over long periods, but their usage has mostly been limited to small areas (Holopainen & Wang, 1998; Lopez et al., 2001; Julian et al., 2012) due to the considerable amount of time and manual effort it takes to acquire, georeference, and digitize photographs for large areas (Miller, 1999). In undeveloped areas without fixed landmarks, this task is even more difficult. Further, widespread aerial photography coverage is only available since the 1930s.

Land cover maps for periods before aerial photography have been constructed using a variety of sources, including property records, expedition narratives, and the Public Land Survey System (PLSS) records (Dahl, 1990; Julian et al., 2012). Because of their exceptional detail and accessibility, PLSS plats have been particularly popular, especially for land cover studies focusing on vegetation patterns, geomorphological features, and frontier development (He et al., 2000, DeWeese et al., 2007; Fagin & Hoagland, 2010). Although the PLSS plats contain potential errors (Schulte & Mladenoff, 2001; Whitney & DeCant, 2001), they remain the most accurate form of historical cartography in the U.S. with the broadest coverage (save Texas and the first 16 states to enter the Union).

In order for the above sources of land cover data to be combined into a land cover timeline; accuracy, compatibility, and processing problems need to be solved. In this paper, we provide a framework for the systematic construction of a representative fine-resolution (60 m) regional land cover timeline. I selected the 10,000 km² area around Little Rock, Arkansas, USA (Figure 2.1) on the premise that its diversity in land cover and physiography would pose considerable and broadly applicable challenges to producing an accurate land cover timeline. To construct the timeline, I improved the first available maps of the region (1857) and then digitized and classified the first available aerial photographs (1943). I then improved the first national land cover dataset (1975), and incorporated recent national land cover datasets (1994, 2001, and 2006). Finally, I used the 149-y timeline to assess land cover changes around Little Rock.

Study Area

Little Rock is a major urban center surrounded by large areas of forest, agriculture, open water, and wetlands. Its heterogeneous physiography results from being situated at the intersection of four different Level III ecoregions (Figure 1.1; Omernik, 1987). The Arkansas Valley ecoregion north of Little Rock is characterized by broad floodplains bounded by scattered hills and mountains, all of which were historically forested. Most of this ecoregion has been developed for urban and agricultural land uses, particularly cattle and poultry operations. The Mississippi Alluvial Plain to the east is a relatively flat ecoregion historically covered by forested wetlands and several large grasslands, but is now agriculturally-dominated. South of Little Rock lays the South Central Plains ecoregion, composed of rolling forested plains broken by numerous bottomland wetlands. The Ouachita Mountains ecoregion to the west is mostly forested, with steep slopes along east-west trending ridges. Commercial logging is the major land use in these latter two ecoregions.

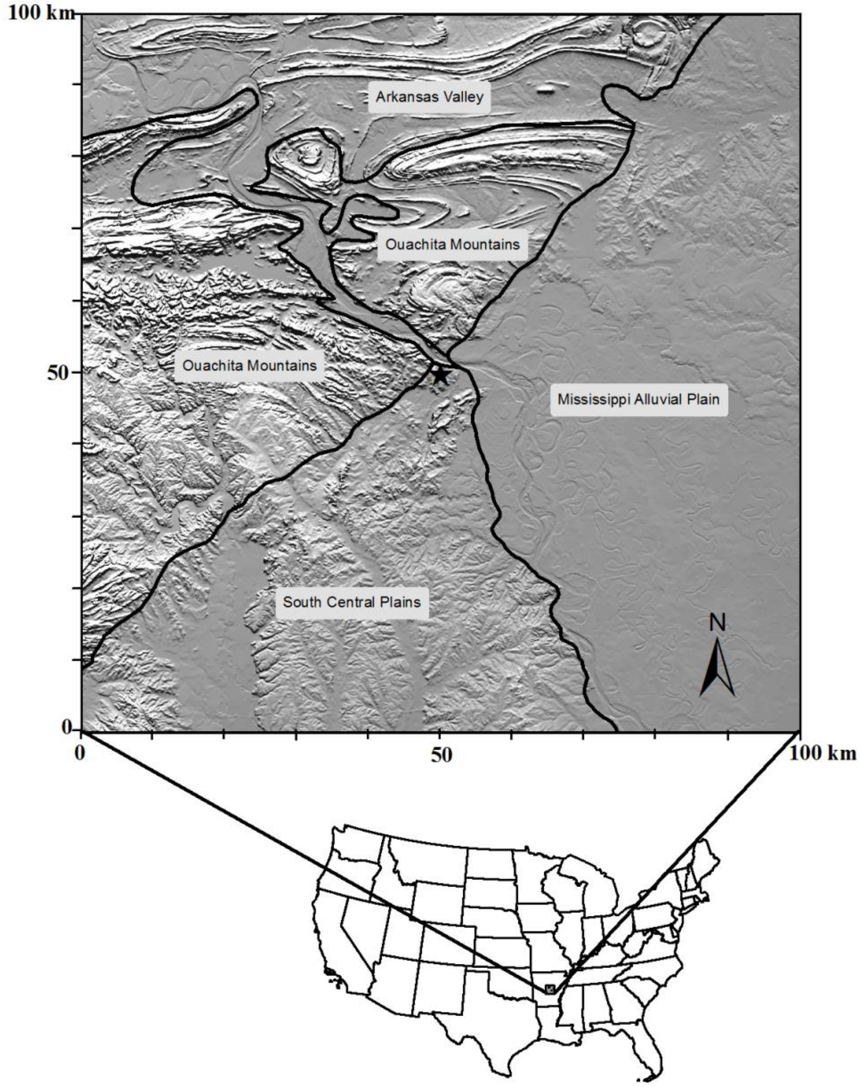

Figure 1.1. Little Rock, Arkansas (USA) study area. The base map (100 x 100 km) is a 30-m enhanced shaded-relief map with a Z-factor of 5. The four Omernik level III ecoregions of the study area are delineated. The star represents the city of Little Rock.

Land Cover Data Sources

1857 Public Land Survey System (PLSS) records

I used the PLSS plats and field notes to map pre-settlement land cover because of their thorough representation and description of land cover, vegetation, and land suitability for agriculture (Stewart, 1935; Whitney & DeCant, 2001; Linklater, 2002). A total of 121 plats from 1819 and 1857 were retrieved in high-resolution MrSID format from the Bureau of Land Management's General Land Office (Table 1.1). I chose 1857 as the timestamp because only 31 of the 121 plats in our study area were acquired in 1819. These 31 plats were located in the northeast corner of the study area where presumably no major land transformations occurred between 1819 and 1857. PLSS plats contain a total of 17 land cover classes (Table 1.2).

1943 aerial photography

For the 1943 land cover map, I used mostly high spatial resolution (1:20,000; ~1.7 m/pixel) aerial photographs acquired by the U.S. Department of Agriculture (USDA) between 1940 and 1943 (Table 2.1). Medium resolution (1:70,000) aerial photographs acquired in 1949 by the Army Map Service were used to fill in missing areas at the northern and southern edges of the study area (~10% of total area).

1975 GIRAS land cover dataset

The GIRAS land cover dataset (Mitchell et al., 1977; U. S. Geological Survey, 1998) was used to create a 1975 land cover map. This dataset consisted of polygons digitized from 1:100,000 scale photographs using 4 ha MMU for Urban and Water, and 1:250,000 scale photographs using 16 ha MMU for all other classes. GIRAS's land cover classes resemble the Anderson level II classification (Anderson et al., 1976) with a total of 36 classes, only 22 of which occurred in my study area (Table 1.2).

Table 1.1 Datasets used to create land cover timeline. Dates in bold are years represented in the timeline.

Date	Name	Description
1819	PLSS plats	Public Land Survey System records from the General Land Office. Retrieved from: http://www.glorecords.blm.gov/
1857	PLSS plats	Same as above
1943	aerial photography	High resolution aerial photos acquired by the USDA. Retrieved from: http://edcsns17.cr.usgs.gov/NewEarthExplorer/
1949	aerial photography	Medium resolution aerial photos acquired by Army Map Service. Retrieved from: http://earthexplorer.usgs.gov/
1975	GIRAS	Vector-based land cover dataset Created between 1970 and 1975. Retrieved from: http://eros.usgs.gov
1975	aerial photography	High resolution panchromatic aerial photos obtained for accuracy assessment. Retrieved from: http://edcsns17.cr.usgs.gov/NewEarthExplorer/
1975	USGS Digital Line Graph	Fine resolution vector maps used to extract 1975 roads. Retrieved from: http://www.webgis.com/dlgdata.html
1994	NLCD Change Retrofit Product	National land cover database created to enable direct comparison between 1992 and 2000 NLCDs. Retrieved from: http://www.mrlc.gov/nlcdrlc_data.php
2000	NLCD Change Retrofit Product	Same as above.
2006	NLCD	Most recent land cover database. Retrieved from: http://www.mrlc.gov/nlcd06_data.php
2010	aerial photography	High resolution multi-spectral aerial Photos acquired form the National Agriculture Imagery Program, used to validate spatial precision of the historical data sources. Retrieved from: http://datagateway.nrcs.usda.gov/

Table 1.2 Land cover classes used for all datasets. Classification was adapted from Fry et al. (2009) and based on Modified Anderson Level I. Inclusive land cover classes from other datasets are noted.

		Inclusive Land Cover Classes	
Land cover	**Definition**	**PLSS**	**GIRAS**
Water	All areas of open water with < 25% vegetation or soil cover.	Rivers, Lakes, Ponds	Streams, Canals, Lakes, Reservoirs.
Urban	Lands of low, medium, and high intensity development. Residential, commercial, industrial, construction, and transportation uses are included.	Single houses, Towns, Cities	Residential, Commercial, Industrial, Transportation, Mixed urban
Barren	Open spaces where vegetation accounts for <15% of total cover. Areas include bedrock, sand/gravel/rock deposits, and mines.	Sand bars	Salt flats, Beaches, Bare rock, Mines, Quarries
Forest	Areas dominated by trees generally taller than 5 m and > 20% of total vegetation cover. Includes deciduous, evergreen, and mixed forests.	Trees	Deciduous, Evergreen, Mixed forest
Grassland/Shrub	Areas dominated by gramminoid and herbaceous vegetation; or dominated by shrubs < 5 m and typically >20% of total vegetation cover.	Prairie	Rangeland, Shrub, Brush
Agriculture	Includes cultivated crops, pasture/hay, and active tilled land.	Corn, Orchard fields, Tilled land	Croplands, Pasture, Orchards, Grove, Vineyards
Wetlands	Woody and herbaceous areas periodically covered with water. Vegetation accounts for >20% of total cover	Swamps, Cypress swamps, Sloughs, Cane breaks, Flat wet land	Forested wetland, Non-forested wetland

Multi-Resolution Land Characteristics Consortium (MRLC) National Land Cover Databases (NLCDs)

I used the NLCD Land Cover Change Retrofit Product (Fry et al., 2008) to extract land cover maps for 1994 and 2000 (Table 1.1). Acquisition dates of Landsat-TM/ETM+ scenes were May 18, 1994 and August 14, 2000. The most recent NLCD

(Fry et al., 2011) was used to extract a land cover map for 2006, with satellite imagery from May 19, 2006. Resolution for all three of these datasets was 30 m. There are differences in land cover classes among the original versions of three NLCDs, but all three now contain the 7 land cover classes in Table 1.2.

Calculations

Spatial resolution

In selecting a spatial resolution that would be compatible among all years, my primary criteria was accuracy, in terms of both land cover and land cover change. Too fine of a resolution (30 m) would not be representative of actual land cover because some techniques (i.e., PLSS and GIRAS) mapped land cover at coarser resolutions. Too coarse of a resolution (240 m), however, would not capture land cover changes occurring in small patches. To assess how well land cover changes were captured at coarser resolutions, I compared the area of changed cells (i.e., all land cover transitions for the 7 classes) in the NLCD 1992-2001 Change Retrofit Product (30 m resolution) to the area of corresponding changed cells at coarser resolutions: 60, 120, and 240 m. That is, I resampled the 30 m dataset into a 60 m dataset by using the majority resampling method on every 2 x 2 cell window; I repeated this process for 120 m (4 x 4 cell window) and 240 m (8 x 8 cell window). I then compared the mean percentage of changed cells (7 land cover classes) across the four resolutions. The 60 m dataset captured 99% of land cover transitions (Figure 1.2), while the coarser resolutions captured a much lower percentage (< 43%). Thus, I used 60 m as our spatial resolution as it is the most representative when both land cover and land cover change are considered.

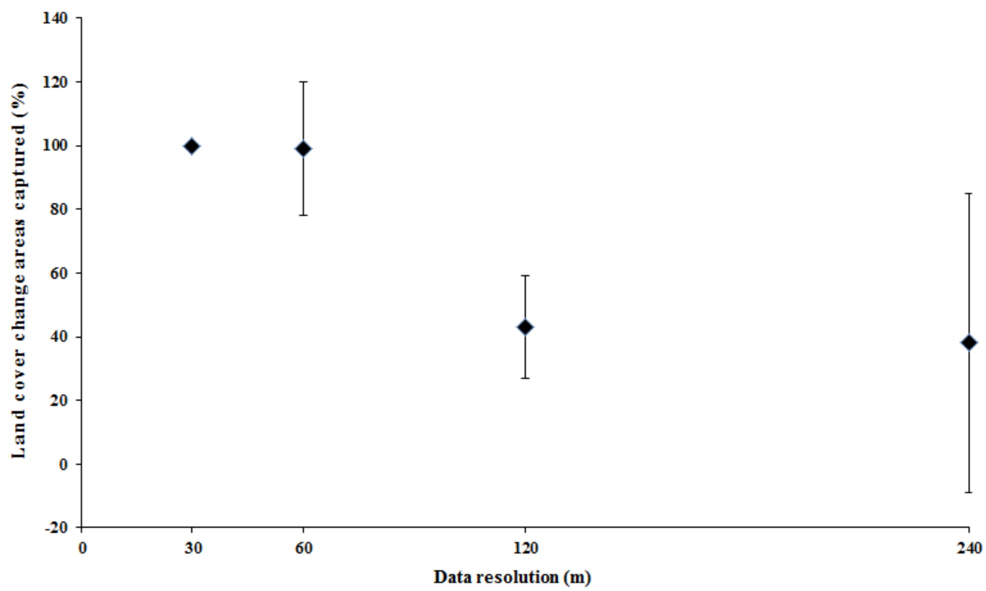

Figure 1.2. Comparison between areas of changed cells in the 1992-2001 NLCD Retrofit Change Product at 30 m with areas of changed cells in the same dataset calculated at 3 coarser spatial resolutions: 60, 120, and 240 m. Data points represent the mean of all possible land cover class transitions, with error bars representing one standard deviation.

Constructing the 1857 land cover dataset

PLSS plats were georeferenced in ArcGIS 10 (ESRI, 2011) using at least 10 ground control points for each plat; care was taken to minimize the root-mean-square error (RMSE) to less than $\pm$15 m. After edge-matching the plats, I noticed a mismatch of some polygons on adjacent plats, especially water bodies. Such error was also reported by Watkins (2007). Like Watkins (2007), I did not resolve this error here because it was minor and limited to small areas. After georeferencing, all land cover polygons were digitized, adhering to consistent mapping techniques with a MMU of

3600 m^2 (0.36 ha) and a minimum width of 60 m. The digitization process was guided by overlaying a 60 m grid over the plats and each polygon was coded to a specific land cover type from the modified Anderson Level I classification scheme (Table 1.2), ensuring proper topology. In the end, I converted our vector-based land cover map to a raster-based map using the maximum-area cell coding scheme at 60 m resolution, and using the same extent as the NLCDs for perfect cell alignment.

Because the PLSS plats have potential mapping bias errors (Schulte & Mladenoff, 2001), I reviewed historical literature for the region and made appropriate corrections to ensure our land cover map was representative. Upon visual examination of the 1857 land cover map, I found considerable underestimation of wetlands, mainly in the Mississippi Alluvial Plain and the South Central Plains ecoregions. In his expedition through eastern and central Arkansas, Hernando de Soto indicated a continuous extent of swampy lands across the bottomland of the Mississippi Alluvial Plain ecoregion where “men killed fish with clubs and had to sleep in ponds and puddles” (Adams, 1986). Moreover, the 1870s wetlands map of Arkansas by Dahl (1990) portrayed massive coverage of wetlands in both ecoregions. Based on this evidence, I added Dahl’s wetlands to the land cover map.

However, because Dahl’s map had coarse resolution, it overestimated the area of wetlands at 60 m resolution, particularly along steep slopes. To address this concern, I extracted the 2006 NLCD Wetlands (because it is the most representative of wetland coverage for our region; Fry et al., 2011) to determine an appropriate slope threshold at which most wetlands are found. The data distribution show a break at 4% slope where 92% of 2006 Wetlands occurred below this value. Using this conservative value, I subtracted all Wetlands located above 4% slope and replaced them with forest to produce the final 1857 land cover map.

Constructing the 1943 land cover dataset

Aerial photographs were georeferenced and rectified using at least 10 ground control points per photo and maintaining a RMSE less than $\pm$15 m. I manually digitized land cover (Table 2.2) at a 1:24,000 scale, using polygons with a MMU of 3600 m^2 (0.36 ha) and minimum width of 60 m. The final 60 m raster-based land cover map was created using the same mapping protocols.

Improving the 1975 land cover dataset

To make a compatible 1975 land cover map, we first grouped the 22 land cover classes of GIRAS into 7 (Table 2.2). A 60 m raster was then created using the same protocols as Section 3.2. Given the coarse (and different) scales from which the GIRAS dataset was created, several modifications were needed to improve its resolution and make it compatible with the other land cover datasets (Figure 1.3).

I first corrected for the overestimation of urban areas due to the coarse mapping scale and MMU of GIRAS. Adapting the procedure of Elmore and Guinn (2010), I subtracted all Urban pixels from GIRAS that were not mapped as Urban in 1994 (using 1994 NLCD from Retrofit Change Product) based on the assumption that non-urban pixels in 1994 were also non-urban pixels in 1975 (Jantz et al., 2005). For example, an urban area would not likely change into a forested area. These newly created non-urban pixels for 1975 were coded to the 1994 NLCD land cover they occupied using a conditional statement in the ArcGIS spatial analyst toolbox.

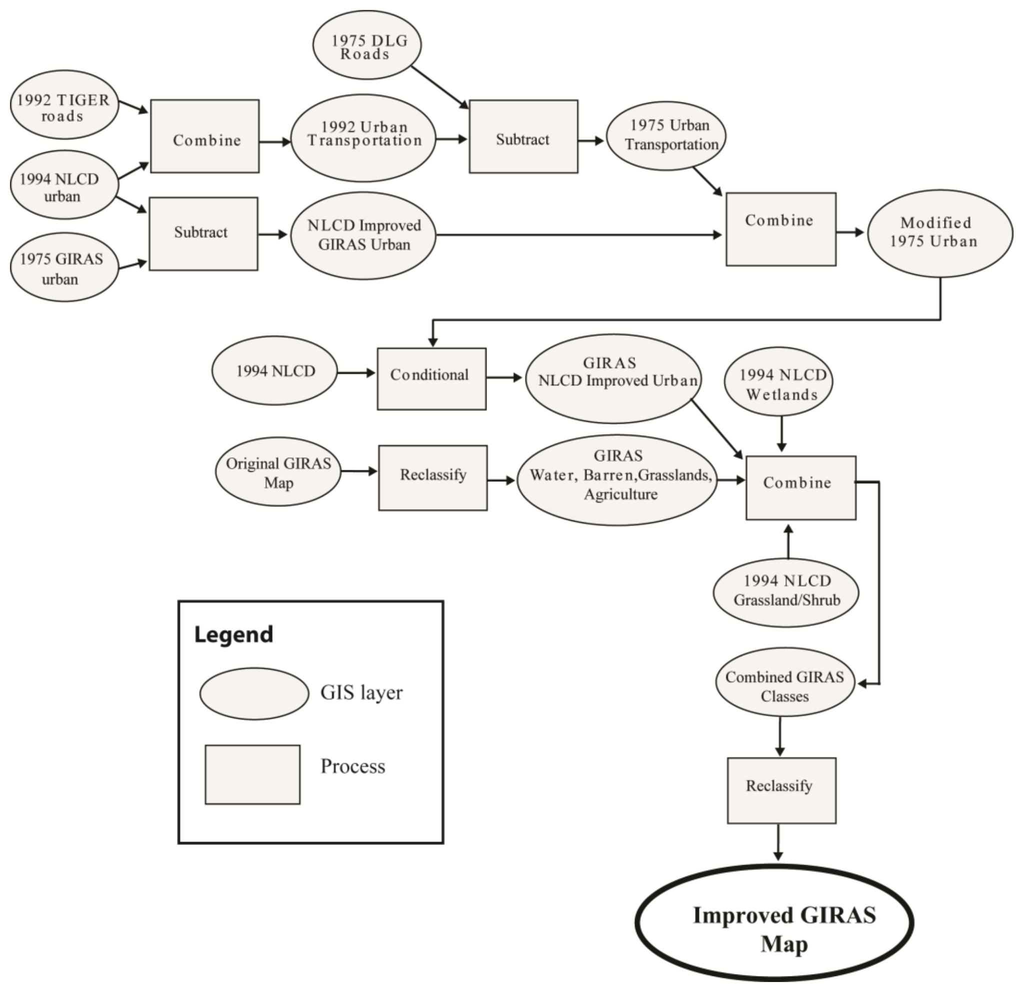

Figure 1.3. Modification of the 1975 GIRAS land cover dataset in order to make it comparable to current national land cover datasets.

While GIRAS overestimates urban coverage in dense urban areas, it underestimates urban coverage in more rural areas due to its neglect of roads, again a consequence of the large MMU. To add the missing roads, I performed the following steps. First, I mapped the 1975 transportation network in the study area using USGS Digital Line Graph data. Second, I extracted 1992 urban transportation layer from the

NLCD Retrofit Change Product using the 1992 TIGER roads. Third, I used the 1975 transportation layer to subtract all urban transportation pixels from the 1992 urban transportation layer that were not mapped as urban transportation in 1975. By following these three steps, I produced a 1975 urban transportation layer that mimicked a raster-based representation of a digitally-derived transportation network, where not all vector roads (as in TIGER and DLG roads) can necessarily be captured. Last, I combined the 1975 urban transportation layer to the NLCD improved GIRAS Urban to produce a final improved Urban layer where omission and commission errors are minimized.

GIRAS's large MMU also severely underestimated Grassland/Shrub coverage, showing less than 0.5% for our study area when it should have been over 4% according to the 1974 Agriculture Census (US Bureau of the Census, 1974). As a further check, I used FragStats 3.3 (McGarigal et al., 2002) to calculate the Grassland/Shrub mean patch area for 1994 and 2006 NLCDs. In 1994 and 2006, the mean patch size was about 2 and 3 ha, respectively, which are much smaller than the 16 ha MMU used by GIRAS to map grasslands. The only systematic method of adding the missing grasslands was to use those from the 1994 NLCD. I assessed the appropriateness of this method by using the Agriculture Censuses from 1974 to 1997. In the 1997 Agriculture Census, NLCD Grassland/Shrub (4.1% relative coverage) was best represented by the category "pastures and rangelands other than cropland and woodland pasture," which makes up 2.8% when this county-level data is area-normalized to match our study area. A timeline of six Agriculture Censuses show that this category did not change much in area between 1974 and 1997, with a relative coverage of 4.3% in 1974. Thus, I added the 1994 NLCD Grassland/Shrub layer to the modified GIRAS map.

Similar to Grassland/Shrub, GIRAS also underestimated Wetlands. According to FragStats, the mean patch size for Wetlands in the 1994 and 2006 NLCDs was about 4 ha and 8 ha, respectively; again much smaller than the 16 ha MMU of GIRAS. Like the Grassland/Shrub correction, I added the 1994 NLCD Wetlands layer to GIRAS to resolve these omission errors, using the conservative assumption that there was no wetland gain between 1975 and 1994.

All the above steps allowed us to improve the resolution of the GIRAS dataset so that it would be comparable to the other land cover maps. Accuracy assessments for the original and improved land cover maps (Tables 1.3 & 1.4) were carried out by analyzing 740 pixels randomly stratified from each land cover map. The multinomial probability theory was used to determine the number of sampling pixels because it is reliable for creating an error matrix where classes causing confusion can be identified (Foody, 2002; Jensen, 2005; Congalton & Green, 2009). Given the large size of the study area, I randomly selected eight 9 x 9 km testing blocks for our sampling areas. Ground truth data were produced from visual interpretations at a scale of 1:24,000, guided by a 60 m grid overlay, of USGS high-resolution (1:40,000) panchromatic aerial photographs acquired in 1975.

NLCD land cover datasets

Using the majority resampling method, all three 30-m NLCD land cover maps (1994, 2000, and 2006) were resampled into 60 m maps (2 x 2 cell window) using the nearest neighborhood algorithm. An updated version of NLCD 2000 was released with the 2006 NLCD, which we considered using. However, we calculated negligible (0.2%)

spatial differences between the two versions of the 2000 NLCD, and therefore kept the original 2000 NLCD.

Results

Land cover dataset improvements

PLSS plats

The original PLSS plats vastly underestimated wetland coverage in our study area, depicting only 171 km2 (1.7% relative coverage). By adding the wetlands from Dahl's (1990) map and subtracting those that were located on slopes greater than 4%, Wetlands coverage increased to 3882 km2 (39 % of study area). While I cannot assess the accuracy of this new 1857 land cover map, the new wetland coverage is more consistent with the historical literature and is comparable to the 1943 land cover map after taking into account the Swamp Land Act of 1850 and 1927 Flood Control Act, which drained most wetlands in the region for conversion to agriculture.

GIRAS

The eclectic modifications to the GIRAS dataset transformed it into a land cover map with finer resolution and consequently greater heterogeneity (Figure 1.4). Small patches of forest, grasslands, and wetlands became visible in the improved map. Urban transportation networks in rural areas also became visible. In comparing the improved GIRAS's urban clusters that were smaller than 4 ha against the 1994 urban clusters, the improved GIRAS captured 52% of those clusters.

Table 1.3. Accuracy assessment for the unimproved GIRAS map (Figure 2.4A), using 740 pixels (60 x 60 m) distributed across eight testing blocks (9 x 9 km) using stratified-random sampling.

Class	Water	Urban	Barren	Forest	Grassland/ Shrub	Agriculture	Wetlands	**Total**	Commission Error (%)
Water	**26**	2	1	0	0	2	3	34	22.0
Urban	0	**29**	1	16	4	7	1	58	49.0
Barren	7	10	**5**	10	1	0	0	33	79.3
Forest	1	2	1	**228**	44	8	28	312	21.7
Grassland/Shrub	0	0	0	0	**4**	7	0	11	77.8
Agriculture	1	4	0	14	17	**170**	26	232	28.7
Wetlands	0	0	0	20	0	10	**30**	60	49.2
Total	35	47	8	288	70	204	88	**740**	
Omission Error (%)	23.2	39.8	20.0	28.8	92.3	26.1	63		
Overall Accuracy (%)	**66.5**								

Table 1.4. Accuracy assessment for the improved GIRAS dataset (Figure 2.4B), using the same 740 pixels as Table 2.3

Class	Water	Urban	Barren	Forest	Grassland/ Shrub	Agriculture	Wetlands	**Total**	Commission Error (%)
Water	**25**	1	0	0	0	10	2	38	34.2
Urban	0	**40**	2	5	0	2	0	49	18.4
Barren	4	2	**6**	8	0	1	0	21	71.4
Forest	0	3	0	**237**	33	7	10	290	18.3
Grassland/Shrub	0	0	0	8	**27**	1	0	36	25.0
Agriculture	3	1	0	16	10	**175**	10	215	18.6
Wetlands	3	0	0	14	1	8	**66**	91	27.5
Total	35	47	8	288	70	204	88	**740**	
Omission Error (%)	28.6	14.9	25.0	17.7	61.4	14.2	25.0		
Overall Accuracy (%)	**77.8**								

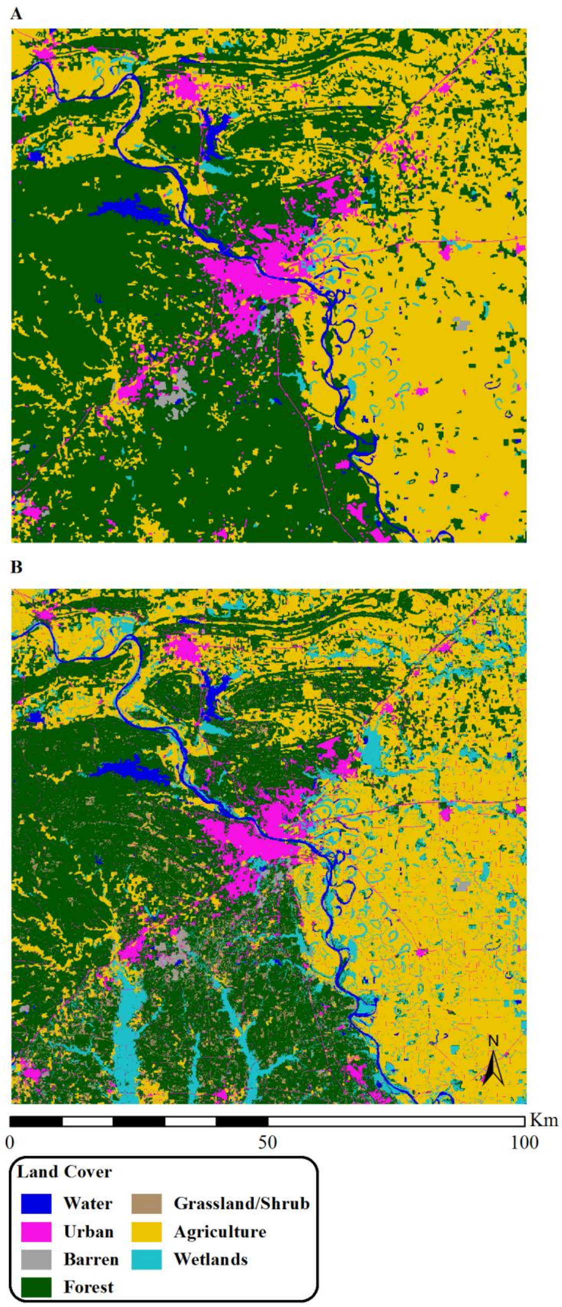

Figure 1.4. Comparison between the unimproved GIRAS land cover map (A) and the modified land cover map (B). Data resolution (cell size) is 60 m. Note the areas of wetlands, grasslands, and roads that are now accounted for in the improved map.

The greatest change to the 1975 land cover map was the addition of large areas of wetlands. The original GIRAS dataset underestimated wetland coverage considerably at 1.3%, likely due to technicians classifying forested wetlands as forest. Adding the

1994 NLCD Wetlands to the GIRAS dataset increased its coverage to 9%. With all modifications, Forest decreased from 48.8% to 40%, Grassland/Shrub increased from 0.004% to 4%, Agriculture decreased from 41.5% to 37.6%, and Urban increased from 5% to 6%. Water and Barren were virtually unchanged.

The accuracy assessment, using ground truth pixels from 1975 aerial photographs, show that my modifications greatly improved the accuracy of the 1975 land cover map (Table 1.3 vs. Table 1.4). Overall accuracy improved from 66.5% to 77.8%. The original GIRAS dataset had high levels of omission error (low Producer's accuracy), particularly for Grassland/Shrub (92.8%), Wetlands (63.0%), and Urban (39.0%). Major confusions in specific land cover classes included Urban being confused for Forest and Agriculture, Forest for Grassland/Shrub and Wetland, and Agriculture for Grassland/Shrub and Wetlands (Table 1.3).

The improved GIRAS land cover map reduced the omission and commission errors for every land cover class (Table 1.4). The greatest improvements were in Grassland/Shrub, followed by Wetlands. The overall accuracy of the improved 1975 land cover map (77.8%) was comparable to the 1994 (74%), 2000 (79%), and 2006 (78.36%) NLCDs.

Land cover changes from 1857 to 2006

Adding the modified datasets (1857 and 1975) and the newly created map (1943) to the NLCDs (1994, 2000, and 2006) allowed me to construct a fine-resolution land cover timeline for a 10,000 km^2 area of central Arkansas (Figures 1.5 & 1.6). Remarkable land cover changes occurred across this study area during the 149 y. In 1857, Forest (57% of total study area) was the dominant land cover in uplands and

Wetlands (39%) were the dominant land cover in lowlands. Little Rock was only a small localized city at this time. From 1857 to 1943, Little Rock grew nearly fourfold. Urban area and Agriculture became the dominant land cover across the study area at 45%. Forest and Wetlands coverage declined to 38% and 12%, respectively.

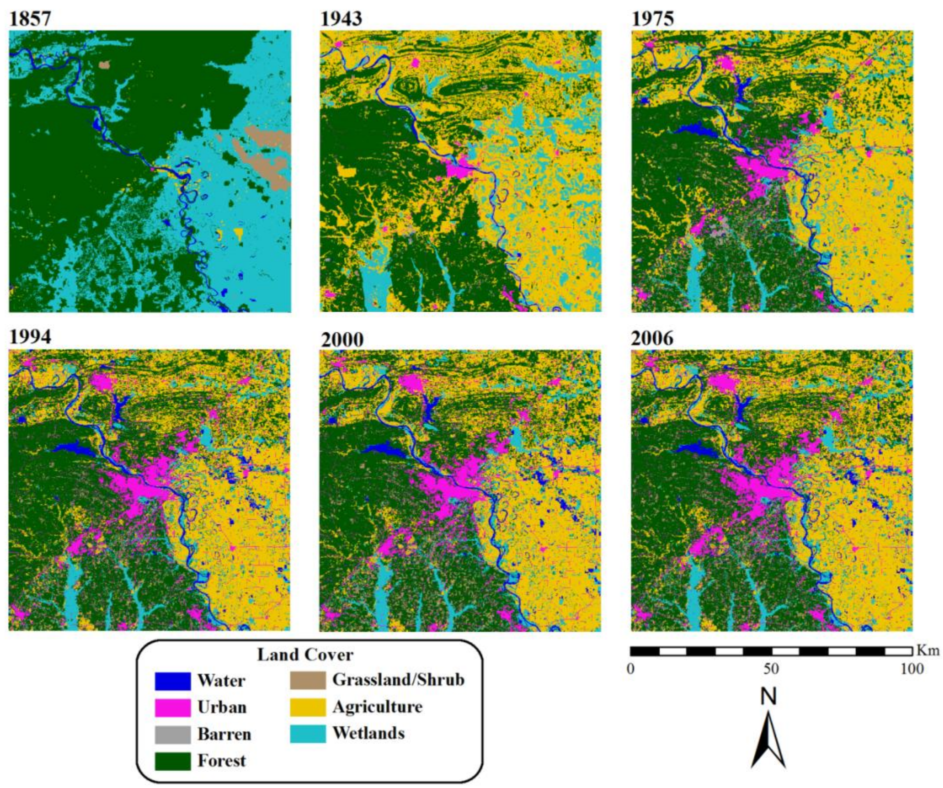

Figure 1.5**.** Land cover timeline for the Little Rock study area at 60 m spatial resolution. Refer to Figure 2.1 to compare land cover changes among ecoregions.

The second half of the 20th century was marked by widespread Urban expansion, mostly at the expense of Agriculture. Wetlands continued to decline between 1943 (12%) and 1994 (8%), but slightly increased after that (8.6% in 2006). Due to widespread reservoir construction, Water increased over this period, from 1% in 1943 to 3.5% in 2006. Grassland/Shrub also increased, from 1% in 1943 to 5% in 2006, likely due to abandoned agricultural fields. By 2006, no one land cover was dominant across the study area.

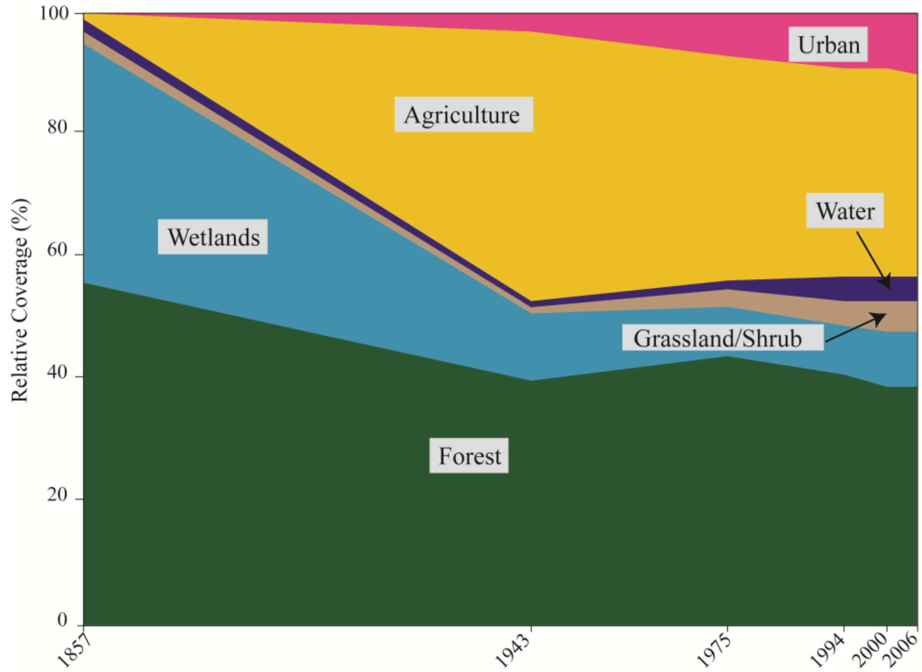

Figure 1.6. Change in land cover (percentage of study area) from 1857 to 2006. Barren is not graphed because it represented less than 1% across the timeline. Definitions of land cover classes are in Table 1.2.

Discussion

Data quality

When constructing a land cover timeline, data quality should always be assessed, especially on datasets that predate aerial imagery. The PLSS surveys provide a valuable source of historical land cover in the U.S.; however, concerns have been raised about their accuracy (Whitney & DeCant, 2001). The first PLSS surveys of Arkansas (1812-1824) were particularly suspect (Braag, 2004), and therefore I used the more reliable PLSS surveys from 1857 for our initial date. Most frauds and biases should have been resolved in these resurveys (Braag, 2004). Nevertheless, I compared this 1857 land cover map to historical accounts and maps and found that wetland coverage was vastly underestimated, which I attribute to (1) surveyors not using the currently accepted definition of a wetland (Cowardin et al., 1979) and therefore classified woody wetlands as forest; and (2) surveyors' inability to travel through such treacherous environments to accurately map wetland coverage (Stewart, 1935; Braag, 2004). To resolve this omission, I added the wetlands from Dahl's (1990) map and corrected for slope. While this addition may overestimate wetland coverage, it is far more representative than the original plats. One method that could be used to refine this wetland modification is hydrologic modeling (e.g., Bolger et al., 2011), but this was beyond the scope of my study. I also checked the spatial accuracy of the plats by comparing cemeteries and historical structures from the plats to the 2010 National Agricultural Imagery Program (NAIP) photos, and found the plats accurately denoted these features.

There was a data gap between 1857 and 1943 due to the absence of land surveys and aerial photography during this period. This gap is present in most land change studies (Ramankutty & Foley, 1999; Rhemtullah et al., 2007; Julian et al., 2012). Aerial photography did not become popular until late-1930s, when the USDA Aerial Photography Field Office (APFO) was established with the Agricultural Adjustment Act. Topographic maps could be a potential solution for some regions, but the earliest topographic maps for my study area were the USGS quadrangles of 1955.

The panchromatic aerial photographs used to delineate the 1943 land cover map were the earliest and finest dataset we could find that covered my entire study area. It was impossible to perform statistical accuracy assessment due to the absence of higher spatial resolution ground truth data. Instead, I preformed simple but adequate comparisons between landmarks from the 1943 panchromatic photos and the 2010 NAIP images; and found the spatial precision to be exceptional.

My most thorough accuracy assessment was performed on the 1975 land cover map because of the numerous modifications we made to the GIRAS dataset (Figure 1.3) and because of the availability of high resolution reference aerial photography. My modifications improved mapping accuracy in all land cover types (Table 1.4, Figure 1.4). The most drastic improvements were for Grassland/Shrub and Wetlands, due primarily to their high omission errors in the original dataset. Another great improvement was in Urban, largely due to the addition of transportation networks in rural areas and the increase in resolution of large, continuous urban clusters (i.e., added heterogeneity). If the random training windows I used to assess mapping accuracy would have been located over more or larger developed areas, Urban accuracy in the improved dataset would have been even higher. Although the overall accuracy (77.8%) did not reach the accepted level (85%) known within the remote sensing community (Jensen, 2005; Congalton & Green, 2009), it was similar or in some cases higher than the accuracy in well-known databases.

The thematic accuracy of the 1994 (Region 6) and 2000 (Region 7) NLCDs at Anderson level I for my study area was 74% and 79%, respectively (Wickham et al., 2010). The accuracy of the most recent 2006 NLCD ranged from 78.32% to 88.57%, with the closest study site to ours (Jackson, MS) having 78.36% accuracy (Xian et al., 2009). Low thematic accuracies are common in our region due to the occurrence of temporally dynamic land cover types (wetlands) and land use practices (commercial logging) (TNC, 2003). Wetlands are perhaps the most challenging land cover type to classify because of local and seasonal hydrologic variability as well as changes in bottom substrata, vegetation, and wildlife (Turner et al., 2000). Central Arkansas experiences frequent droughts (Stahle et al., 1985), further complicating the identification of wetlands. Commercial logging operations also cause major mapping uncertainties due to successional changes in vegetation following cuttings (Cain & Shelton, 2001). Differentiating between Grassland/Shrub and pastures (included under Agriculture) is yet another reason for low thematic accuracies in our study area, as well as other regions (Karstensen, 2009). As mentioned earlier, I purposefully selected central Arkansas for my study so that I could confront these issues and provide a broadly-applicable framework for constructing compatible land cover maps, even in physiographically-complex areas such as mine.

Land cover patterns in central Arkansas

My land cover timeline made it possible to observe spatial patterns of land cover change at a relatively high resolution (60 m) and examine historical changes around Little Rock since early-development. The changes I observed (Figures 1.5 & 1.6) largely followed general global land cover transitions since pre-settlement (Foley et al., 2005), where forests were cleared and wetlands drained for agriculture initially (depicted in 1943), followed by urban expansion and agricultural intensification (depicted in 1975 and onwards). In 1857, central Arkansas had only a few fragmented settled sites concentrated along transportation corridors, and small agricultural lots (<

1%) were found mostly on floodplains close to settled sites. During this "pre-settlement" period, forests dominated the mountainous regions and wetlands dominated low-lying areas.

After the Civil War, "frontier" forest clearing and wetland drainage began, opening areas for development and agricultural expansion (Dahl & Allord, 1996). If I would have had a land cover map that characterized the "subsistence" stage (c.a. 1900), it would have likely show diversified and fragmented farming practices, similar to the 1943 map but not as broadly developed. In the "intensifying" stage between 1943 and 1975, rapid technological developments transformed American agriculture into large corporate farms to meet the accelerating demands for food following the Depression era and World War II (Dimitri et al., 2005). Urban expansion also occurred during this stage.

The "intensive" land cover stage is represented by the last three maps (1994 – 2006), where the landscape is dominated by urban and agricultural areas. In accordance with the "intensive" stage, protected and recreational lands increased, which comprised 4% of our study in 2006 (CBI, 2010). Current land cover in my study area is characterized by mostly forests on steep slopes and at higher elevations, and by dominance of agriculture at lower elevations and on gentler slopes. Urban areas are distributed mainly along the primary transportation corridors that spread out from the urban core of Little Rock. In less than 150 years, my study area had been completely transformed into a mostly anthropogenic landscape.

Conclusion

The main contribution of this paper is a framework that uses readily available data to develop historical land cover timelines over large areas with fine resolution. By transforming pre-settlement land surveys and early aerial photographs, I added historical value to my land cover timeline. The modifications and subsequent accuracy assessment we performed on the U.S.'s first national land cover dataset (GIRAS) demonstrated that it can be made compatible with the current national land cover database. When combined, these eclectic land cover datasets allowed me to create a 149 y land cover timeline with 60 m resolution over a 10,000 km^2 area.

Although the effort required to retrieve, georeference, delineate, and compile historical sources was time-intensive, this level of detail is essential to understand human-environment interactions. Without these historical maps, I am missing land cover information from the period in which the landscape was most drastically altered. The adaptation of historical records also reflects an appreciation for the exceptional efforts made to survey and map undeveloped landscapes. Through this work, I aim to encourage researchers to integrate early geospatial data with contemporary land cover databases to build accurate land cover timelines for long periods. I hope that my framework will be applied to many other regions so that I may begin to understand the drivers and impacts of land cover changes.

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Chapter 2: Environmental Influences on Land Development and Consequent Land Cover Changes in Central Arkansas, (USA), 1857-2006: A Historical-Environmental Framework for Long-term, Large-scale Change Analysis

Introduction

The global large-scale replacement of natural land cover by anthropogenic ecosystems, urban and agricultural areas, has raised many socioeconomic and environmental concerns (Foley et al., 2005 ; Houghton, 1994). The natural ecosystem services, human prosperity, and the long-term sustainability are endangered. Agricultural and urban ecosystems have become the largest terrestrial biomes on the planet. While agricultural lands occupy ~ 40% of land surface, urban areas contain around half of world's population, and the number will exceed 6 billion people by 2050 (United Nations Population Division, 2009). In the United States (U. S.), more than 80% of its population lived in urban and suburban areas in 2010 and this number is expected to reach 90.2 % in 2050 (United Nations Population Division, 2009).

Since mid-20th century, American agriculture acreages began to decline steadily while urban areas began to accelerate dramatically, resulting in creating new land development patterns (i.e., exurban and intensive commercial agricultural uses) and shifting change drivers (Theobald, 2001). In 1992, anthropogenic ecosystems comprised roughly one-third of the conterminous U.S., and in 2001 these systems expanded by 3.1%. Natural land cover types of wetlands, forests, and grasslands were influenced by these expansions; however, wetlands were particularly the most affected (Theobald, 2010).

Many of change studies analyzed traditional relationships between demographic and agricultural changes but not particularly powerful enough for understanding historical urban-rural determinants and transitions (Deyong, Hongbo, Peijun, Wenquan, & Yaozhong, 2009; Imhoff et al., 2004; Maizel et al., 1998; Nizeyaimana et al., 2001). The historic debates on agriculture and urban development share deficiency impeded by incomplete understanding of their interrelated histories and the lack of engaging environmental influences on urban and agriculture change trends, rates, and patterns of transitions (Brown, Johnson, Loveland, & Theobald; 2005; Gustafson & Parker, 1992; Plaut, 1980). While traditional studies might address the physiography of an urban and agricultural system but not necessarily measure their influences on dictating their patterns and change trends or whether environmental influences could decrease or increase through time with technological advancements.

With the increasing computational power and availability of geospatial data sources, recent efforts have been made to capture and model development trends by incorporating a set of socioeconomic factors and a few environmental attributes, that would to some extent represent the complexity of anthropogenic ecosystems and their consequent land cover changes (Jantz, Goetz, Donato, & Claggett, 2010; Oguz, Klein, & Srinivasan, 2007; Verburg et al., 2002). In these models, however, there should be only one established pattern of growth throughout the period covered by land cover datasets. Since 1950s, development patterns in the U.S. have dramatically shifted. As a result, it is extremely unlikely that development patterns prior to the 1950s resembles the patterns observed after 1950s or so (Levy, 2009; Theobald, 2001).

Prior to investigating the role of physiography on urban and agriculture development, it is more important to first understand general spatiotemporal land cover patterns at appropriate operational level. Therefore, I analyzed land cover proportions and complexity within and among-environmentally uniform units of Omernik level III ecoregions. Not only do these ecoregions correspond well to spatiotemporal landscape patterns and composition, but they also help extrapolate relationships among natural and anthropogenic factors that are affecting ecosystem services and land resource management (Griffith, Stephen, & Loveland, 2003; Omernik, 1987; Ramsey, Falconer, & Jensen, 1995). I then investigated the relationship between topographic characteristics (terrain ruggedness) of the ecoregions and the degree of land cover complexity. Measurement of terrain ruggedness could be effective tool for land change scientists to map contemporary land cover types, change trajectories, and the level of land cover heterogeneity within- and among-ecoregions, which in turn helps establish more accurate linkage between the surface characteristics and land cover types which leads to better understanding of driving forces of land development patterns in central Arkansas.

Because I incorporated historical development patterns from periods prior to the 1950s, and therefore it is important to select a compatible approach to establish valid spatiotemporal comparisons between development patterns and their driving forces. To do this, I first developed a probability equation thereby the magnitude of relative change (MRC) in certain period is empirically measured in relative to many driving forces of development and normalized by total years in each period. In doing this, I provided new opportunities to identify major environmental determinants of urban and agriculture developments and to understand their preferential trajectories through time and over space.

I finally explained my findings using a historical-environmental-institutional approach in which the environmental and institutional histories of the study area are brought together to understand long-term, large-scale land development dynamics and consequent land changes. The motivation behind developing this analytical approach was due to the underestimation of the interrelated histories between humankind and its web of life (Semple, 1911; Tatham, 1957;Wagner, 1978).

The main objectives of this research are to: 1) identify and investigate the environmental influences on land development relative to socioeconomic factors using our developed analytical, historical environmental approach, and 2) understand the relationships and feedbacks between urban and agriculture development, and 3) analyze the effects of physiographic heterogeneity on spatiotemporal trends of land cover patterns within and among-ecoregions in our study area.

Study area: Central Arkansas

The study area is a 10, 000 km^2 around Little Rock city in central Arkansas, (USA). This area captures the three principle cities of the Little Rock-North Little Rock-Conway metropolitan area and 70% of its incorporated communities. The physiographic settings of the central Arkansas region introduced an ideal platform to study the environmental influences on past and present land development patterns. In Arkansas, temperature is very mild and water sources are abundant (Harper & McBrien, 1931). The topography is designated by a geological line into the bottomlands to the east and the high mountain plateau (Ozark range) to the west. In the bottomlands, soil is rich loamy suitable for large-scale rice, cotton, and soybeans plantations. In the mountains, the soil is less fertile and more suitable for logging, grazing activities, and urban uses (Brister, 1977; Hanson & Moneyhon, 1989).

The study area stretches across four diverse Omernik Level-III ecoregions. The South Central Plains ecoregions lays south of the metropolitan area, composed of irregular forested plains and broken by numerous hardwood bottomlands and small fragmented cultivated areas on the floodplain. The Ouachita Mountains ecoregion to the west is mostly forested with steep slopes along east-west trending ridges. Commercial logging is the major land use in these latter ecoregions (EPA, 2010; Hanson & Moneyhon, 1989). The Arkansas Valley ecoregion, north of Little Rock, is characterized by broad floodplains bounded by scattered hills and mountains with fragmented pastures. The Mississippi Alluvial Plain to the east is composed of relatively broad flat plains with river terraces that historically were covered by forested and herbaceous wetlands, but are now agriculturally-dominated with small scattered rural communities.

Historically, Arkansas became a territory after first being part of the Louisiana Purchase and then under Missouri territory. At this time, Arkansas Post (located at the mouth of Arkansas River) served as its temporary capital and to be later removed to a more central location on more preferable land (Adams, 1986; Richards, 1969). The 'point of rock' landmark (present Little Rock), located on gentle slopes ranging from 5 and 10% on elevated hills of the Arkansas River's south bank and outside the River bend, held great potentials to establish a major urban center to serve as the capital because it was away from the swampy unhealthy lands on the north shore. This landmark was first recognized in 1722 by the French explorer *Bernard de la Harp* as a trading post with Indians to control the trade of the Arkansas and Canadian Rivers and to make other alliances with the Indians in the region (Cadwell, 1942; Herndon, 1933; Lyon, 1949). Wealthy Indians (the Quapaw) populated areas north to the Arkansas River, but settlements were scattered and hemmed in by swamps (Lyon, 1949).

Later, land speculators realized the favorable environmental settings of the landmark and bought land in the vicinity of present Little Rock (Gates Wallace, 1942; Richards, 1969). Settlers started dwelling at the location and by 1820 three certificates were recorded and surveyed (Adams, 1986; Gentry, 1954; Lewis, 1932). After designating the new capital, newcomers arrived to the town (Bradburn, 2004); however, the overall population growth in the study area was modest but consistent (Figure 2.1). In 1820, the estimated residents were 13 with one frame building surrounded by three or four pine log huts. Ten years later, the total citizen of Little Rock jumped to 430, and with the announcement of Statehood in 1836 the number increased to 726 (Richard, 1969). A few years later Little Rock became one of the largest urban points west of the Mississippi (total population of 1531) and a frontier hub to the vast west.

Although the environmental influences on land development in central Arkansas are complex and interwoven, they enrich our understanding of rural-urban dynamics in agriculturally-dominated State. I found this study area interesting to study for several reasons. First, Arkansas has rich environmental and institutional histories. Second, central Arkansas captures clear transition between major agriculture and urban systems. Third, central Arkansas consists of paradoxical physiographic settings allowing for more robust land development dynamic studies. Finally, there are readily available contemporary and developed historical geospatial datasets to use in this study.

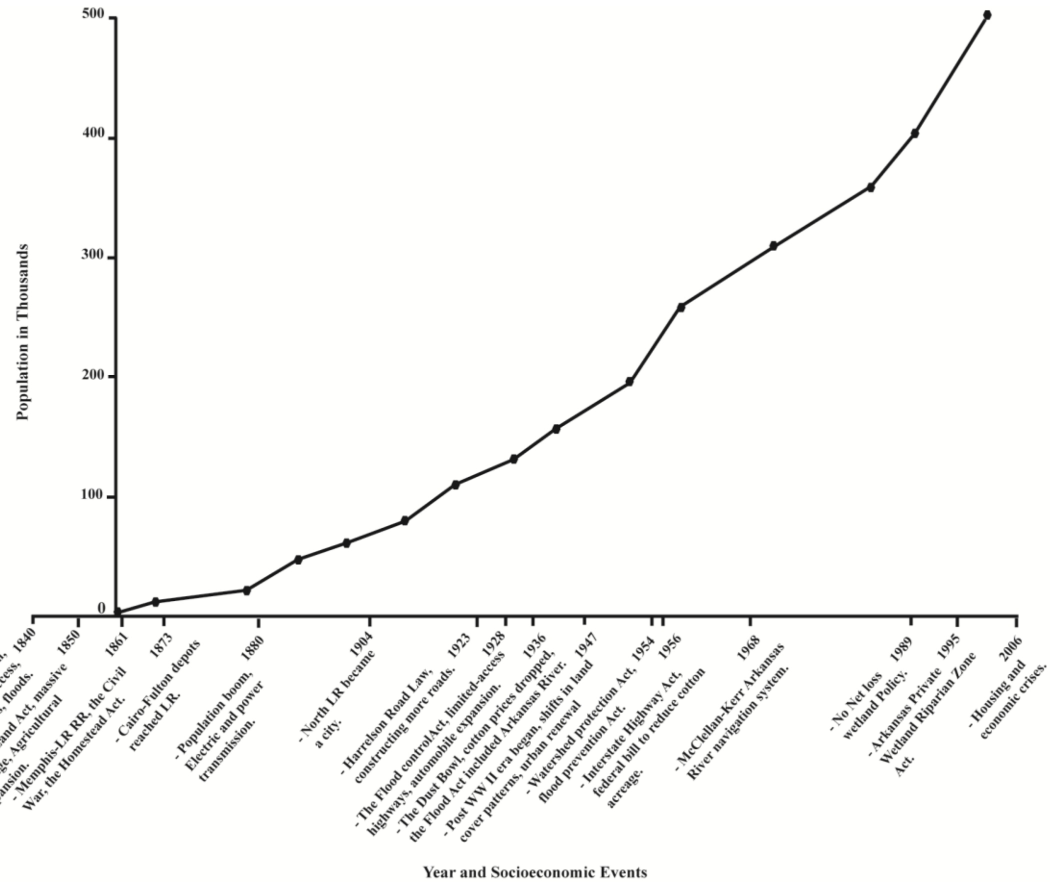

Figure 2.1. Population growth and central Arkansas key socioeconomic events relevant to land cover changes.

Data and Methods

Land cover data

I extracted land cover information from a 60 m land cover timeline for the years: 1857, 1943, 1975, 1994, and 2006 (Figure 2.2). I used 60 m spatial resolution because it was most representative in terms of land cover and land cover change (Jawarneh & Julian, in review). This fine resolution land cover timeline was developed by improving the earliest available maps of the region (1857), digitizing the first available aerial photographs (1943), modifying the first national land cover dataset (GIRAS 1975), and incorporating contemporary NLCD land cover database (1994 – 2006).

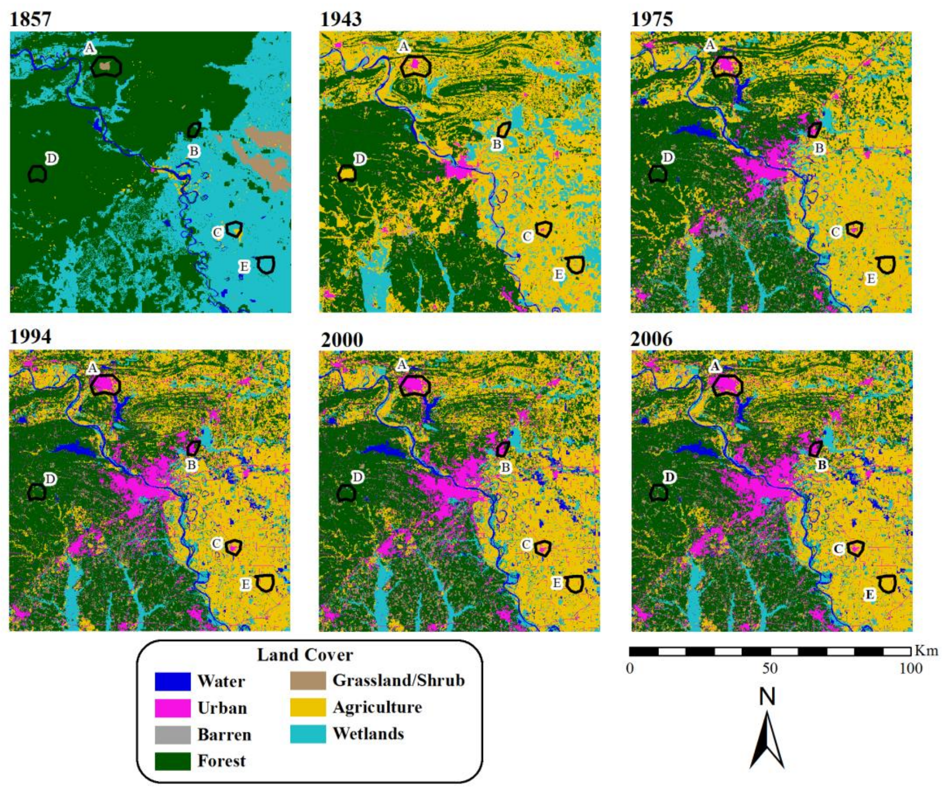

Figure 2.2. Land cover timeline for the Little Rock study area at 60 m spatial resolution. Polygons A, B, C, D, and E represent examples on different land development transitions relative to physiographic attributes and other socioeconomic events.

Land cover proportions and patterns and landscape within- and among-ecoregions (1857-2006)

Spatiotemporal patterns and composition of land cover types were analyzed with FRAGSTATS 3.3 (McGarigal, Cushman, Neel, & Ene, 2002). I first partitioned the study area into the four ecoregions for all six land cover maps (1857, 1943, 1975, 1994, 2000, and 2006) using ArcGIS 10 spatial analyst toolset. Landscape and land cover metrics provide indicators on the types of land cover change and of relating change to human and ecological processes; however, there is no consensus regarding which set of landscape metrics to use (Griffith, et al., 2003; Gustafson & Parker, 1992; Pijanowski & Robinson, 2011).

In this paper, a suite of standard landscape pattern metrics describing the percentage, number, area, fragmentation, and diversity were calculated for the entire study area and for each ecoregion in each period. Those metrics were: percent forest, percent agriculture, percent wetlands, percent urban, number of forest patches, number of agriculture patches, number of wetlands patches, number of urban patches, forest area-weighted mean patch size, agriculture area-weighted mean patch size, wetlands area-weighted mean patch size, urban area-weighted mean patch size, and Shannon's diversity index. I chose those metrics because they are proven to represent the main aspects of landscape patterns and give indicators on land cover proportions as well as landscape fragmentation (Griffith, Stephen, & Loveland, 2003; Wang & Malanson, 2007).

I then investigated the relationship between land cover complexity and surface topographic characteristics by calculating the ruggedness values for the entire area and for each ecoregions. I used Vector Ruggedness Measure (VRM) (Sappington, Longshore, & Thomson, 2007). This index measures terrain ruggedness as variation in three-dimensional orientation grid cells within a neighborhood. It incorporates the heterogeneity of both slope and aspect and is proved to decouple terrain ruggedness from slope better than ruggedness indices such as Terrain Ruggedness Index (TRI). I used a 3 x 3 neighborhood for analysis because computing VRM with larger neighborhoods (i.e., 5, 7, or 21) results in a smoothing effect on the landscape.

Biophysical and socioeconomic drivers of urban and agriculture development trends (1857-2006)

I identified major environmental and socioeconomic driving forces of urban and agriculture development in central Arkansas by developing a magnitude of relative change (MRC) equation that empirically measures temporal development trends relative to the examined attributes. The MRC of a pixel to be developed for either urban or agriculture development relative to any random pixel being urbanized or agriculturally developed MRC*(x)* can be defined by:

$$MRC(x) = D_x / D_t \quad (1)$$

Where D_x is the yearly change of urban or agriculture pixels within attribute x per area and D_t is the yearly change of urban/agriculture pixels for the entire study area.

$$D_x = dLC_x/A_x \quad (2)$$

Where dLC_x is the yearly change of the target land cover type (in our case urban and agriculture) within attribute x and Ax is the total area of x attribute.

$$dLC_x = (LC_xY_n – LC_x\, Y_1) / (Y_n –Y_1) \quad (3)$$

Where LC_xY_n is the total land cover type area within x attribute in the end year and LC_xY_1 is the total land cover area within x attribute in the beginning year.

Using this equation, we calculated preferential pathways for urban and agriculture trends for five periods: 1857-1943; 1943-1975; 1975-1994; 1994-2000, and 2000-2006. We used a combination of environmental attributes and infrastructure proximities, which were created and processed in ArcGIS version 10 (ESRI, 2011) based on 60 m x 60 m cell size (Table 2.1).

Table 2.1. The environmental attributes and infrastructure proximities used to identify preferential pathways for urban and agriculture development. "Dynamic" means that the attribute differed from one period to another while "Static" means that the attributes remained the same throughout all periods.

Variable	Status	Description
Wetland	Dynamic	Obtained from the land cover maps for the years 1857, 1943, 1975, 1994, and 2000
Wetlands adjacency	Dynamic	420 m buffer outside wetlands
Water bodies	Dynamic	Obtained from the land cover maps for the years 1857, 1943, 1975, 1994, and 2000
Water adjacency	Dynamic	420 m buffer around water body
Riparian Zone	Static	30 meter riparian zone on each side of the streams
Arkansas River adjacency	Static	420 m buffer on each side of the river
Slope (%)	Static	Obtained from National Elevation dataset. It included 5 intervals: >5 %, 5-10%, 10-15%, 15-20%, and > 20%
Soil available water storage (in centimeters) for 150 cm depth	Static	Obtained from the SSURGGO dataset. The map included 5 equal intervals: 0 - 6.47 cm, 6.47 - 12.95 cm, 12.95 - 19.42 cm, 19.42 - 25.90 cm, and 25.90 - 32.37 cm.
proximity to Little Rock CBD (km)	Static	The map included 5 distances; 0-10 km, 10-20 km, 20-30 km, 30-40 km, and 40-50 km.
Roads adjacency	Static	420 m buffer on each side of the primary roads

The environmental attributes included wetlands, water bodies, soil available water storage for 150 cm depth, slope, and riparian zone. Layers for wetlands and water bodies were dynamic, meaning that I extracted them from the land cover maps of the start date in each period (1857, 1994, 1975, 1994, and 2000 land cover maps). For wetlands and water bodies' adjacency, I created a 420 m buffer outside those features. The 420 m dimension was selected because it represents the size of land allotments.

For soil water available storage (AWS), I used the SSURGO dataset (NRCS, 2012).In this dataset, AWS is defined as “the total volume of water (in centimeters) that should be available to plants when the soil, inclusive of rock fragments, is at field capacity.” For the derivation of AWS, only representative value for available water capacity is used. This representative value indicates the expected value for this soil attribute. I used the National Elevation Dataset (NED) to create the slope layer (in percentage) (Gesch et al., 2002). And for the 30 m riparian zone on each side of the streams, I used the National Hydrography Dataset (NHD) (USEPA, & USGS, 2005).

The infrastructure proximities contain distances to the CBD of Little Rock and roads adjacency. I created a 420 m buffer around the primary roads, in particular, because I believe that land developments at this large scale are highly influenced by those roads. The 420 m buffer was selected for consistency in analyses for other attributes. The selection of these variables was guided by intensive study of early history of the study area. In selecting those variables, I avoided difficulties associated with obtaining socioeconomic factors, such as population density and unemployment, which might not exist for early periods.

To better characterize agriculture development, I compiled long-term data on agriculture and farm characteristics using the U.S. Census of Agriculture. I summarized the number of farms and total lands in farms for the 12 counties in the study area. I area-normalized the number of farms and land in farms for 11 counties, that were not completely contained within the study area.

Results

Land cover patterns and proportions within- and among-ecoregions

Spatiotemporal analysis of land cover patterns within- and among-ecoregions show different arrangements and disproportionate distributions of land cover types from one ecoregion to another. Both the South Coastal plains and the Ouachita Mountains had the highest coverage of forest and urban areas during the study period. The Mississippi Alluvial and the Arkansas valley, however, had the highest agricultural coverage. The massive agricultural areas in the Mississippi Alluvial, in particular, were originally massive wetlands that were drained in early 20^{th} century for cultivation purposes (Figure 2.3). The results show, however, a decline in agricultural areas, especially in the highlands (the Arkansas Valley and the South Coastal Plains), partially due to agriculture abandonment and in part due to urban encroachment. Wetlands cover dramatically shift from being a predominant and continuous land cover type in central Arkansas, especially in the low-lying regions, into relatively minor and fragmented type.

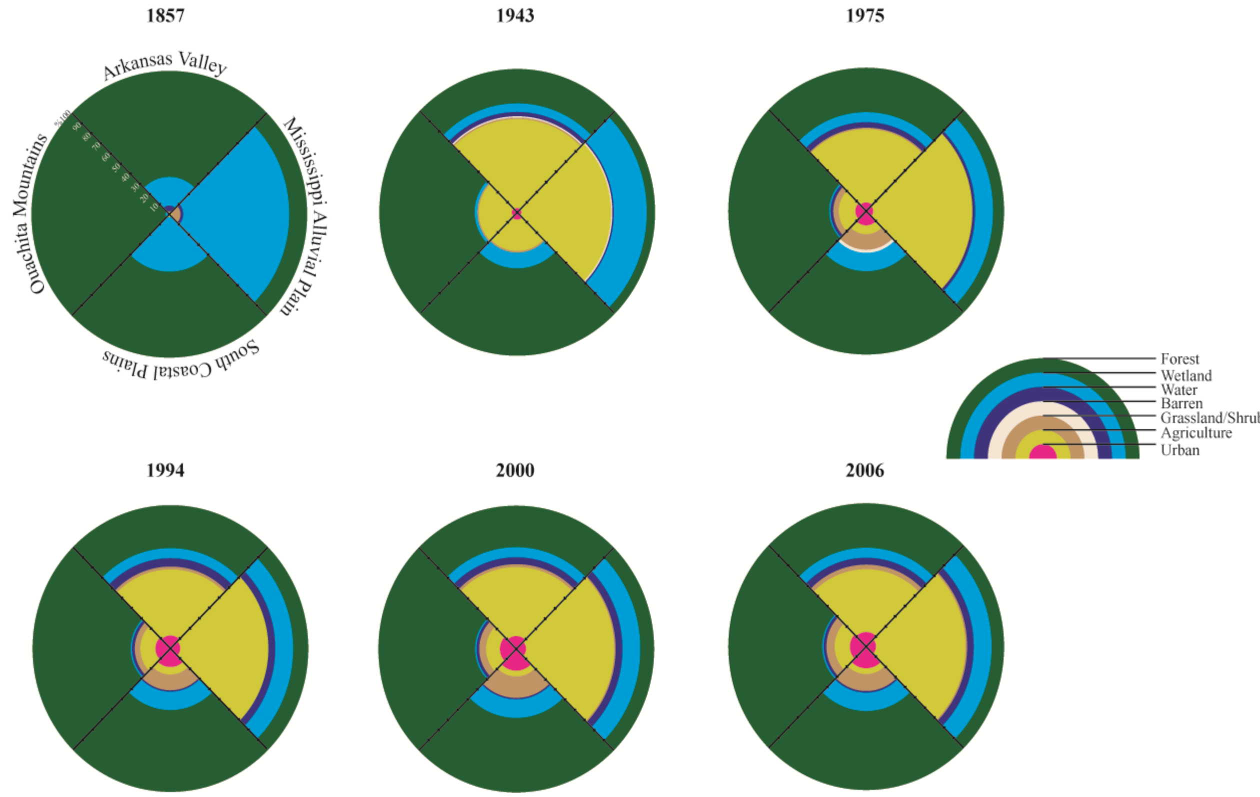

Figure 2.3. Land cover composition within each ecoregion and over time in central Arkansas.

Land cover complexity and topographic variation

The results for land cover arrangement and fragmentation, as reflected by number of patches and area weighted-mean indices (Figure 2.4), show different trends of increasing fragmentation in land cover patches within- and among-ecoregions. Overall and during the study period, the Ouachita Mountains had the largest continuous forest cover and the least number of forest patches. The South Coastal Plains and Mississippi Alluvial Plain; however, had the largest number of forest patches (5004 patches) but the least continuous forest cover among the four ecoregions (AWM patch size 11,733 ha) (i.e., more numerous and smaller forest patches) (Figure 2.4).

The Mississippi Alluvial Plain had the lowest number of wetlands patches (621 patches) in 1857, but it had the largest continuous wetlands cover (AWM patch size 231,930 ha). In later periods, wetlands became more fragmented with increasing number of patches and declining AWM patch size declined. Wetlands in the South Coastal Plains, however, remained large and less fragmented. Agricultural operations in central Arkansas during the study period were fragmented in all ecoregions, except in the Mississippi Alluvial Plain. The most fragmented agricultural patches were found in the Ouachita Mountains and the South Coastal Plains.

The results of landscape heterogeneity, as reflected by SHDI (Figure 2.5) show similar trends of increasing land cover heterogeneity and complexity among-ecoregions. The rate of diversity was greatest in the Arkansas Valley, followed by the South Coastal Plains, and the Mississippi Alluvial Plain.

The results for topographic complexity, as reflected by VRM, show no significant topographic variation in central Arkansas and the terrains are natural. Typically, ruggedness values in the output raster can range from 0 (no terrain variation) to 1 (complete terrain variation), however, values on natural terrains rarely exceed 0.2. In central Arkansas, the values for VRM ranged from 0 to 0.08. Ruggedness was highest in the Ouachita Mountains ($\overline{X}$ = 0.0017, SD = 0.0031), followed by the Arkansas Valley ($\overline{X}$ = 0.0005, SD = 0.0017), the South Coastal Plains ($\overline{X}$ = 0.0002, SD = 0.0005), and the Mississippi Alluvial Plains ($\overline{X}$ = 0.0000, SD = 0.0000).

Urban in Central Arkansas (1857-2006)

During the study period, urban coverage increased from less than 0.1 % in 1857 to 10.3 % in 2006. The increase in percent urban was greatest in the South Coastal Plains, followed by the Ouachita Mountains, and the Arkansas Valley.

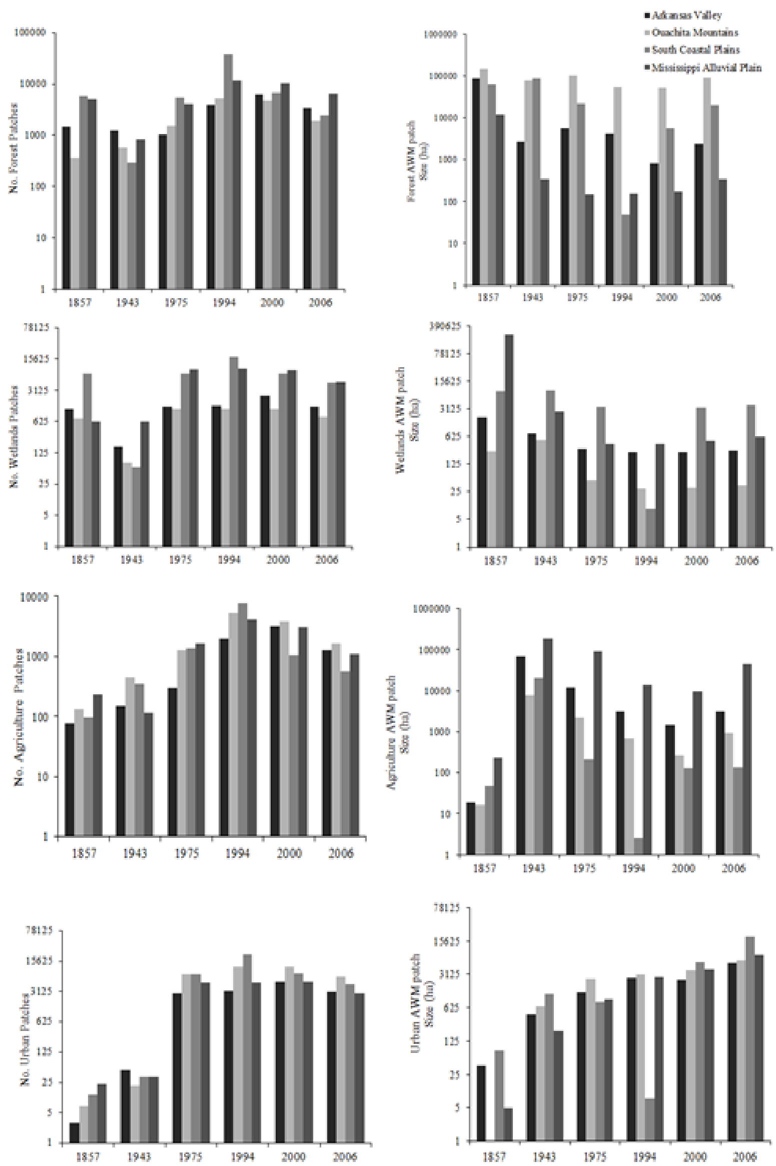

Figure 2.4 Trends in land cover arrangement and fragmentation within- and among-ecoregions in central Arkansas.

In central Arkansas, urban growth patterns occurred at the edges of the four ecoregions and had a northeast-southwest growth trend along the geological line that separates the highlands from the low-lying region.

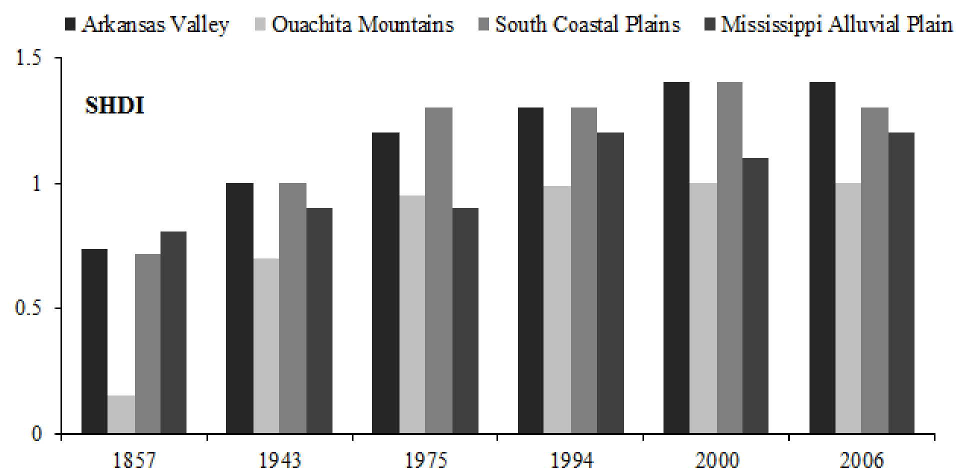

Figure 2.5 Landscape heterogeneity index by ecoregion and time.

The results of the empirical trends of urban development in the study area show different and inconsistent relationships between urban patterns and environmental attributes through time. In 1857-2000, slopes from 5 to 10 % were the most preferred for urban development (MRC values ranged from 1.3 to 1.8). In 2000-2006, less preferred slopes (15-20%) were developed for urban uses; the MRC was 2.1 (Figure 2.6A).

During the first half of the 20th century, soils with no, mostly impervious surfaces, or with the least available water storage (AWS) were most preferred for urban development in central Arkansas (Figure 2.6B). Urban development in more recent periods, however, encroached on soils with relatively high water storage (AWS values ranged from 6.45 cm to 12.9 cm). In 2000-2006, urban development extended on soils with higher AWS values (13-19.4 cm).

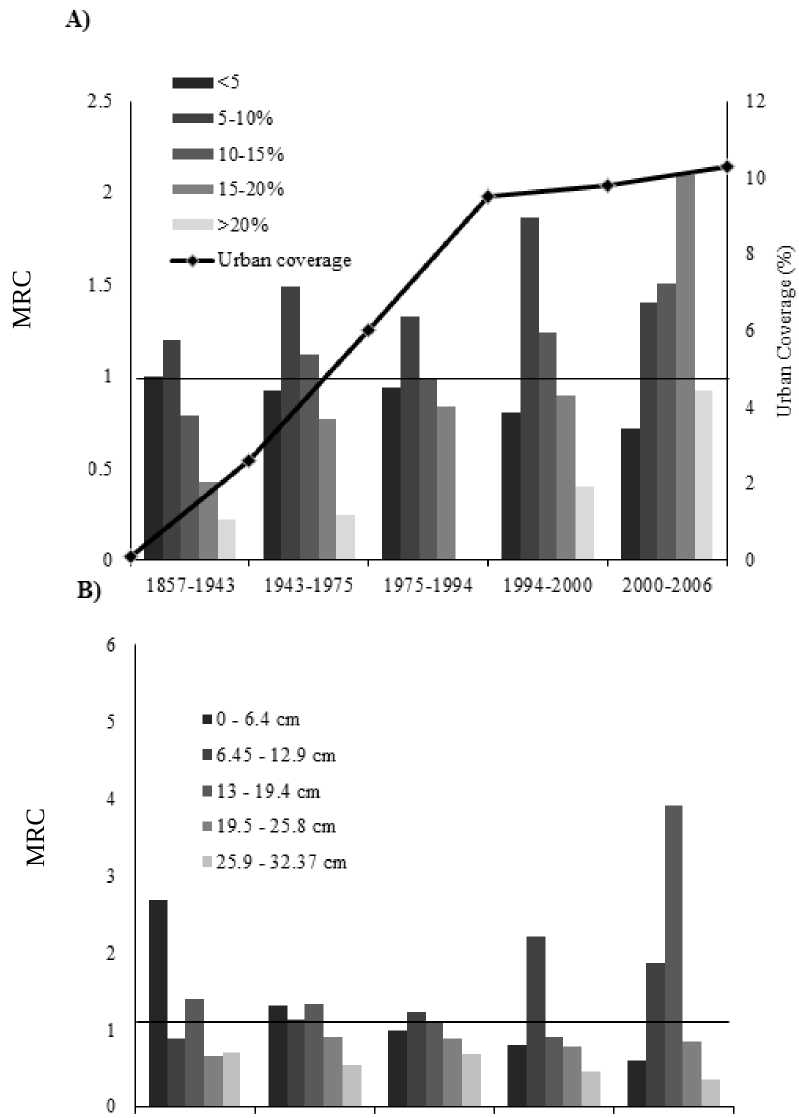

Figure 2.6. A) Magnitude of relative change for a pixel to be urbanized at different slope intervals relative to any pixel being urbanized in the study area; the trend line represents relative urban coverage during the study period. B) Magnitude of relative change for a pixel to be urbanized at different soil available water storage (AWS) intervals relative to any pixel being urbanized in the study area. The horizontal line at the value of 1 is the reference line which represents the status quo.

Wetlands and their adjacent areas were not preferentially developed for urban spaces during the study period with MRC values less than 1 (Figure 2.7A). Water bodies were also not preferential for urban development. In all periods except in 1975-1994, areas adjacent to water bodies were not preferred for urban development (Figure 2.7B).

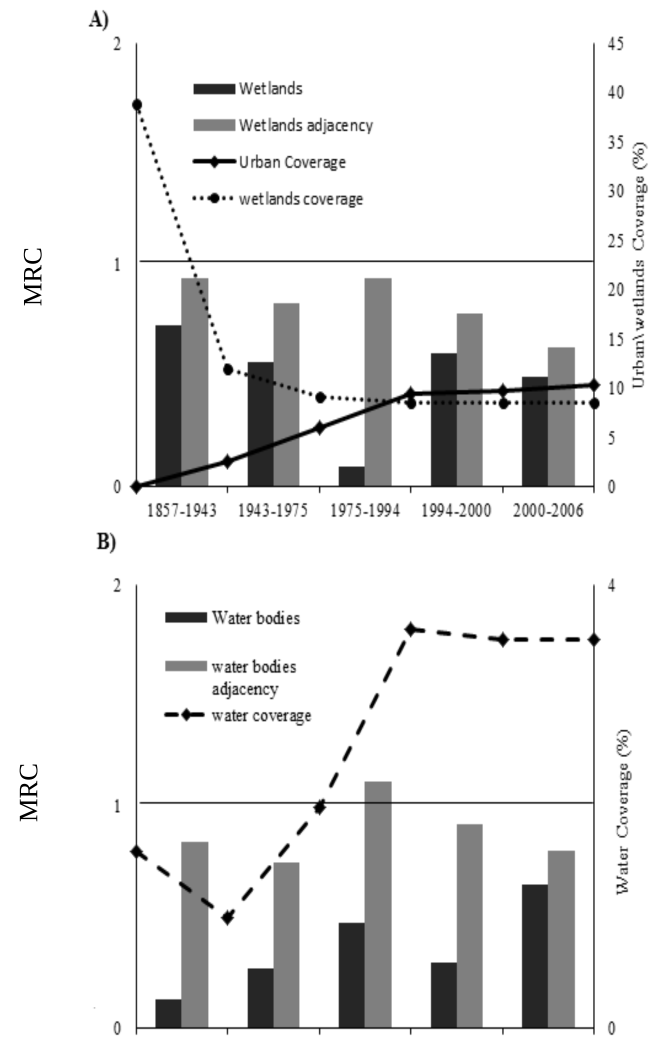

Figure 2.7. A) Magnitude of change for a pixel to be urbanized within wetlands or within areas adjacent to wetlands relative to any pixel being urbanized in the study area; the trend lines represent relative urban and wetlands overages during the study period. B) Magnitude of change for a pixel to be urbanized within water bodies or within areas adjacent to water bodies relative to any pixel being urbanized in the study area; the trend line represents relative water coverage during the study period.

The results also show that riparian zones were not preferential for urban development during the study period, except in 2000-2006 (Figure 2.8). Further, areas adjacent to the Arkansas River were most preferential for urban development during the first and the last periods (Figure 2.8).

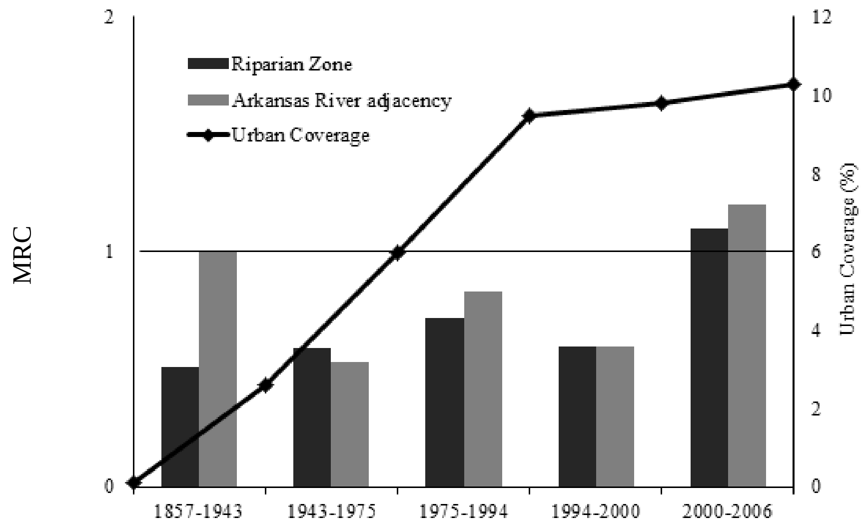

Figure 2.8 Magnitude of change for a pixel to be urbanized within riparian zone or within areas adjacent to the Arkansas River relative to any pixel being urbanized in the study area.

Areas within less than 10 km from the center of Little Rock city were most preferred for urban development during most of the study period (Figure 2.9A). Urban development on distances between 10 and 20 km from the CBD occurred in 1943-1975. Since then, areas within this distance range increasingly developed for urban uses. Primary roads were major attractor for urban development during the study period (MRC values ranged from 2.8 to 7) where the highest value was between 1943 and 1975 (Figure 2.9B).

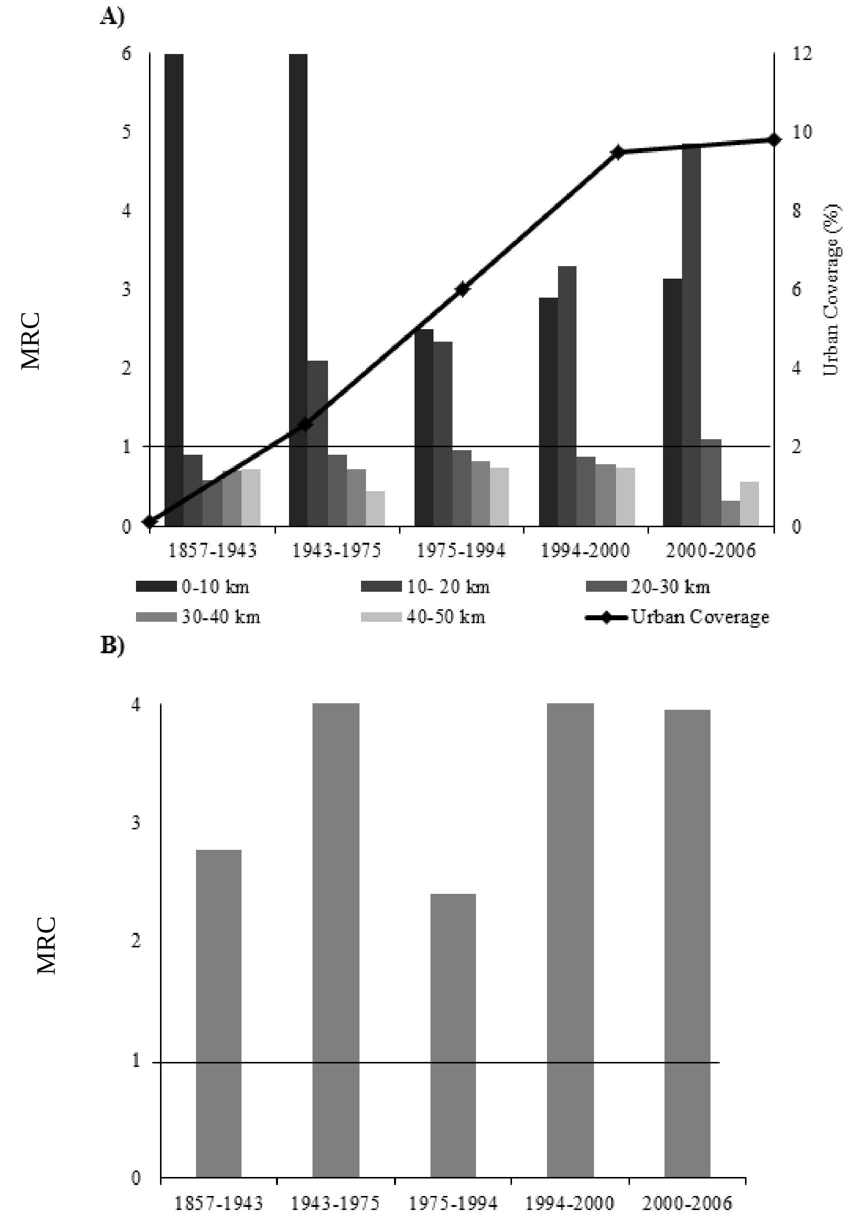

Figure 2.9. A) Magnitude of change for a pixel to be urbanized at different proximities from Little Rock CBD relative to any pixel being urbanized in the study area. B) Magnitude of change for a pixel to be urbanized within 420 m area adjacent to roads relative to any pixel being urbanized in the study area.

Agriculture in central Arkansas (1857-2006)

By 1943, agriculture had become one of the predominant land cover types in central Arkansas, occupying almost half of the study area. Most of these areas were located in the Mississippi Alluvial Plain ecoregion. After 1943, agricultural areas relatively declined in all ecoregions, except in the Mississippi Alluvial Plain. The environmental attributes, especially topography, had significant influence on agriculture patterns in central Arkansas.

Although agriculture development occurred at different slopes, slopes less than 5% were the most preferred for agriculture development (Figure 2.10A). Slopes within this range contained 99.8% of the 1857 wetlands. In 1943-1975, percent agriculture declined with increasing slope; however, the greatest temporal decrease was on slopes from 5 to 10%. In 1975-1994, the decline was greatest for slopes ranging from 10 to 15%. Although there was an overall net loss in agriculture development during this period, there were new areas were being developed for agriculture at steeper slopes. In 1994-2000, there was an overall net gain in agriculture; most of this gain took place on slopes ranging between 5 and 10 % (Figure 2.10A).

In all periods, agricultural operations expanded on soils where available water storage (AWS) ranged between 19.5 and 32.37 cm (Figure 2.10B). In 1943-1975, there was net loss of agriculture development on all AWS ranges, however, agriculture development on soils where AWS ranged from 25.9 to 32.37 cm were the least affected. The loss was greatest on soils where AWS ranged from 0 to 12.9 cm. Although there was a net loss in agriculture in 1975-1994, new areas were being developed for agriculture on soils where AWS ranged between 13 and 32.37 cm. Regardless of the net increase in agriculture development between 1994 and 2000, agricultural areas continued to decline on soils where AWS ranging from 0 to 6.4 and from 13 to 19.4 cm (Figure 2.10B).

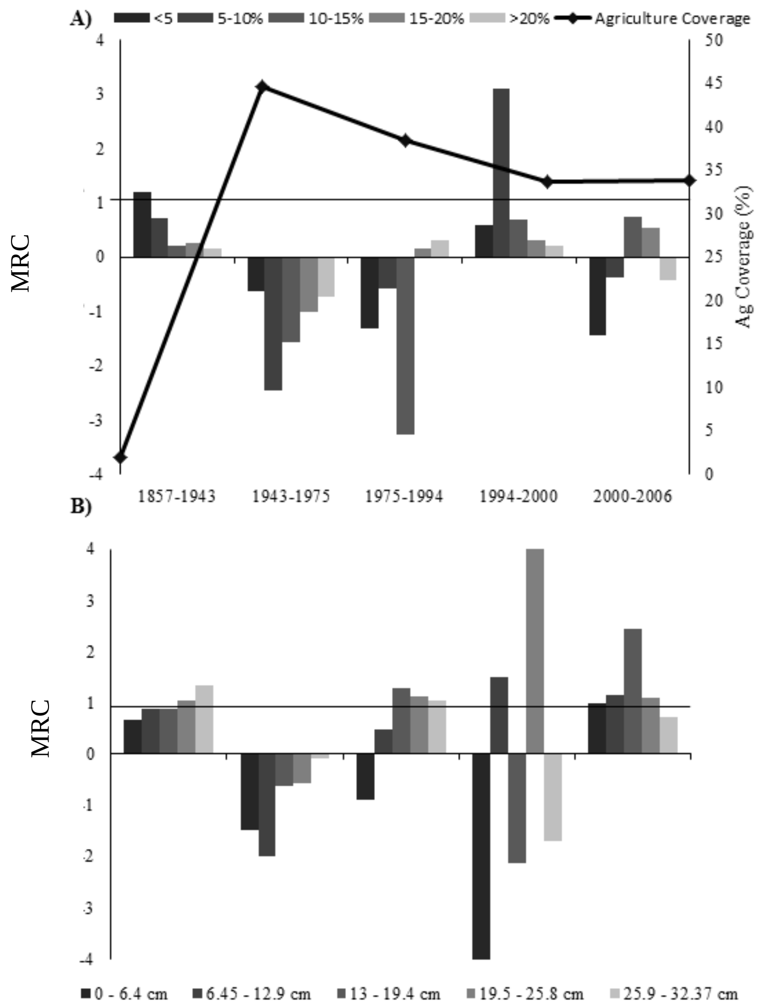

Figure 2.10 A) Magnitude of change for a pixel to be developed for agricultural use at different slope intervals relative to any pixel being developed for agricultural use in the study area; the trend line represents relative agriculture coverage during the study period. B) Magnitude of change for a pixel to be developed for agricultural use at different soil available water storage (AWS) intervals relative to any pixel being developed for agricultural use in the study area.

Wetlands were attractor for agriculture development mostly in 1857-1994 and in 1994-2000 (Figure 2.11A & 2.2 polygon E). In 1857-1943, massive wetlands in the low-lying region were drained and transformed to agricultural areas. Areas adjacent to wetlands were not preferential for agriculture development, except in 2000-2006 (Figure 2.11A). The results show that water bodies attracted agriculture development between 1943 and 2000. Areas adjacent to water bodies were not preferential for agriculture development in all periods, except in 1994-2000 (Figure 2.11B). Riparian zones were not preferential for agriculture development, except in 1994-2000 (Figure 2.13). Areas adjacent to the Arkansas River were most preferred for agriculture development in only two periods, 1857-1943 and 1994-2000 (Figure 2.12).

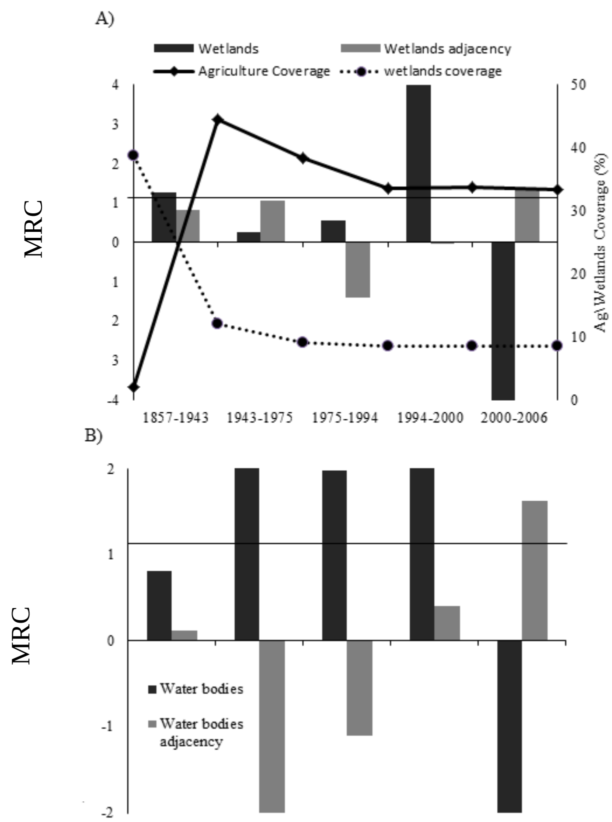

Figure 2.11. A) Magnitude of relative change for a pixel to be developed for agricultural use within wetlands and areas adjacent to wetlands relative to any pixel being developed for agricultural use in the study area; the trend lines represent relative wetlands and agriculture coverage during the study period. B) Magnitude of relative change for a pixel to be developed for agricultural use within water bodies and within areas adjacent to water bodies relative to any pixel being developed for agricultural use in the study area.

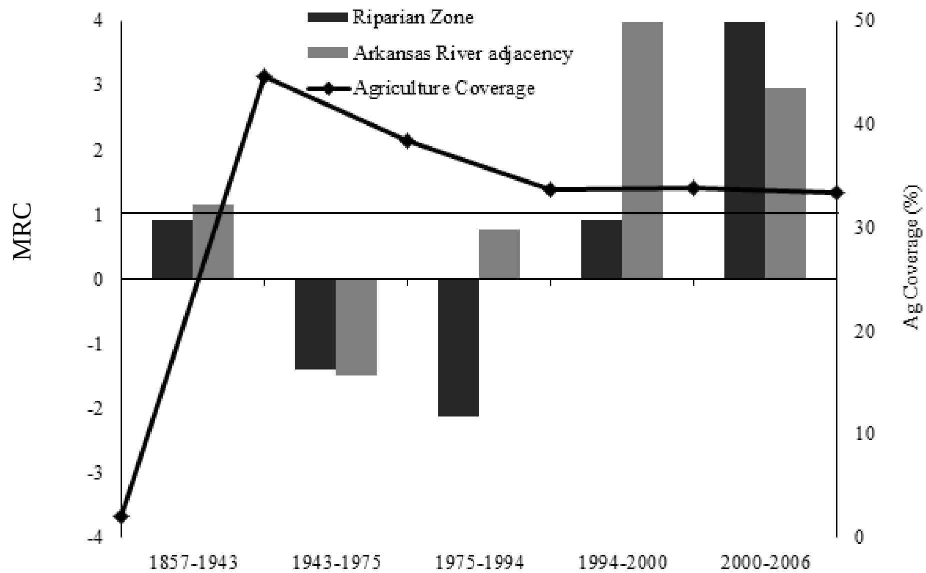

Figure 2.12. Magnitude of relative change for a pixel to be developed for agriculture use within riparian zone or within areas adjacent to the Arkansas River relative to any pixel being developed for agriculture use in the study area.

Agriculture development increased with increasing distances from Little Rock CBD (Figure 2.13A). In general, areas between 30 and 50 km from the CBD were the most preferred for agriculture development in central Arkansas. In 1943-1975, most agricultural decline occurred at distance within 20 km from the CBD. Later, most of agriculture net loss occurred on distances within 20 km from CBD and within 50 km from the CBD. The typical distance for flourishing agriculture development in central Arkansas was between 20 and 40 km (Figure 2.13A). In all periods, except in 1994-2000, areas adjacent to primary roads were the least preferred for agriculture development (Figure 2.13B). There was considerable decline of agricultural lands within areas adjacent to primary roads.

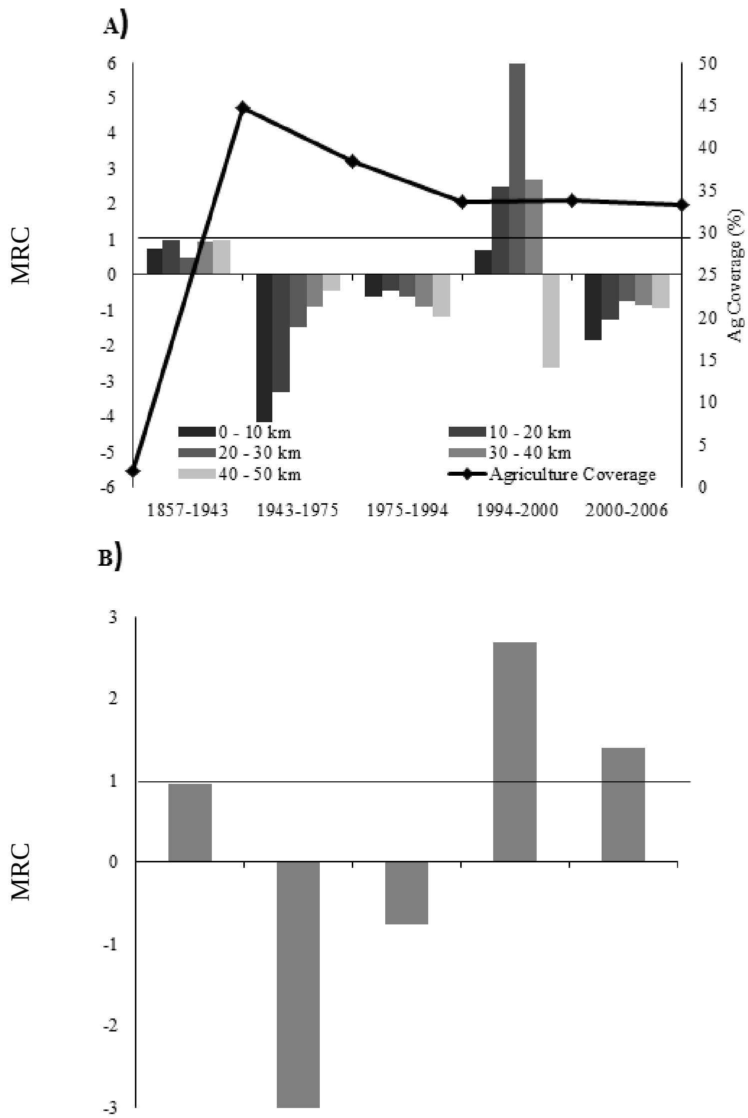

Figure 2.13 A) Magnitude of relative change for a pixel to be developed for agricultural use at different proximities from Little Rock CBD relative to any pixel being developed for agriculture use in the study area. B) Magnitude of relative change for a pixel to be developed for agriculture use within 420 m area adjacent to roads relative to any pixel being developed for agricultural use in the study area.

Discussion

Environmental-historical influences on urban development

Land development history in central Arkansas began with the foundation of Little Rock city in central Arkansas. However, early development phases in central Arkansas were generally low and slow compared to other regions of central U.S. such as Memphis and St Louis which are located on the Mississippi River. The slow growth rate in Arkansas resulted from the absence of dwellings in the basin in particular and the West in general. Further, there were already well-established urban centers with older urban histories and higher population number on the Mississippi River. And finally, the treacherous environment and flooding hazards were challenging to establish long-lasting urban center in early history.

Historically, the site of Little Rock was the most preferred for urban development in the area because of its central location, topographic settings, and proximity to the Arkansas River. In later development phases, institutional policies, acts, and technological advancement influenced urban and agriculture patterns and trends (Figures 2.1 & 2.14). Overall and during the study period, there was no one predominant factor dictating urban development in central Arkansas. Instead, a combination of one or more environmental factors in relation to either distance to CBD or distance to primary roads best explained urban development trends. In 1857-1943, slope, soil AWS, Arkansas River, and distance to CBD were major highly important to urban development. In 1943-1975, slope and distance to CBD remained the most determinants of urban development. From 1975 to 2006, primary roads were the most major driver of urban development.

Flat regions, where slopes are less than 5%, were not greatly preferred for urban development mainly due to flooding hazard. Floods have been a major influence that shaped urban development patterns in central Arkansas, especially in the Mississippi Alluvial Plains. For instance, in early stages several lots were sold to establish a settlement (D'Cantillon) on the north bank of the Arkansas River, but this town never got off the ground because large portions of it was washed away by the 1840's flood (Adams, 1986; Nutt, 1993; Richards, 1969). As a result, urban development took place on gentle slopes and during the second half of the 20th century, urban areas expanded on steeper slopes, which are less preferred areas for development, as the most refereed slopes were already consumed by urbanization.

To mitigate flooding hazard and consequently open the flat region for development, many institutional policies were issued; the Swampland Grant in 1850 and the Flood Control Act in 1927. In 1936, the Flood Control Act was extended to include the Mississippi tributaries. While the Swampland Grant enabled the State of Arkansas and others to reclaim the swamplands, unfit for cultivation, within their limits by constructing necessary levees and drains (Bearden, 1984), those early levees were poorly constructed and located too close to the caving banks (Harrison & Kollmorgen, 1947; Pearcy, 2002). During the years of unusual heavy precipitation, the swelling Mississippi overflowed, damaging the new settlers' newly cultivated fields. Later, urban areas consistently began to expand towards flat regions due to technological advancements and constructions of large impoundments (McClellan-Kerr Arkansas River navigation system).

While these institutional laws triggered urban development in the low-lying region in central Arkansas, the rate of urban growth was slow. Within this region, settlements were mostly small rural communities (Figure 2.2 polygon C) and the few large urban areas here fall on the edges between the Mountains and the Plains regions (Figure 2.2 polygon B). In addition, the alluvial loamy soil of the flat region is sedimentary, deep, and unstable for major urban activities. Further it has high water available storages and therefore less preferred for urban development. Larger and better established urban centers, however, were founded in the highlands region, where soil is less fertile and has less water storage (Figure 2.2 polygon A).

Little Rock city was founded on the elevated Plains adjacent to the Arkansas River. The River played influential role in shaping urban development patterns in central Arkansas because it represented the main source for water supplies and the only dependable means of transportation and commerce. Accordingly, areas adjacent to the Arkansas River were preferentially developed for urban uses, especially in early settlement phase.

Although the Arkansas River Basin itself has relatively low potential for runoff as soil permeability is high and precipitation is generally low (Juracek, 1999), Little Rock was positioned on the outer bend of the River to avoid flooding hazards from the Mississippi River. Other large cities in the region were also founded on the outer bend such as in Tulsa and Memphis.

Transportation infrastructure and institutional laws were relatively influential in early urban development. In 1853, a transportation bill was passed to build Little Rock-Memphis railroad, which first reached Huntersville town in 1861 (on the north shore of the Arkansas River). This railroad had minimal impact on land urban and agriculture development because it ran through swamplands. In contrary, the Cairo and Fulton railroad had substantial impacts on development because it ran near the richest farmlands along the foothills of the Ozark range. In addition, this railroad helped erect the first bridge, baring Cross Bridge, over the Arkansas River in 1873 (Richards, 1969).

Following the Civil War, heavily timbered countryside surrounding the city was cleared, opening more spaces for urban expansion in the highlands. At this time, population numbers tripled due to increasing domestic migration and railroad expansion (Figure 2.1) (Watkins, 1979). Towards the end of the 19th century, the innovation of electric and power transmissions caused dramatic population growth in Little Rock. Meanwhile, a reform movement to annex some fifteen additions was carried out, increasing the city's population and limits. During the second half of the 20th century, urban growth patterns extended to outward the urban centers and became more driven by primary roads (Figure 2.2 polygon A).

Environmental-historical influences on agriculture development in central Arkansas

Agriculture development in central Arkansas flourished in nonmetropolitan counties of the flat region. The physiography and topography of this region influenced agriculture development patterns. Flat areas, which used to be wetlands, covered with highly available water supplies soils were the most preferred for agriculture development.

In early history, the upland region of Arkansas, where most new settlers dwelled, dominated agricultural production, while the flat regions were covered with wetlands. The farms in the Ozark heights were relatively small and diversified due to low soil fertility and consequent crop failure (Figure 2.2 polygons A & D). The most fertile soil in the region was located in the Mississippi Alluvial Plains, where there is no topographic variation, allowing for intensive large-scale cotton and rice plantations. The Swampland Grant Act of 1850 initiated the first attempts to cultivate this region.

However, the region remained under flood hazards until the Mississippi River Commission was created to help the Army Corps of Engineers to build levee that theoretically granted no more floods. Accordingly, massive wetlands were transformed to large-scale farmlands (Figure 2.2 polygon E).

Therefore, slopes less than 5% were more preferential for agriculture development, while agricultural areas at steeper slopes had consistent temporal decline for either abandonment (Figure 2.2 Polygon D) or for urban expansion (Figure 2.2 polygon A). Areas with slopes less than 5% were the same areas with highest water available storage. During the study period, agriculture development expanded on soils where AWS ranged between 19.5 and 32.37 cm. During the first half of the 20th century, however, the low-lying region suffered two devastating floods before the 1928 Flood Act was extended to all Mississippi tributaries in 1936 (Bearden, 1984). Building dams and water projects to control dams highly contributed to creating more established and broadly developed agricultural lands.

Following the Depression era and during World War II, agriculture development underwent intensifying phase due to the rapid technological advancements and increasing demands for food. At this time, agriculture development expanded to already low fertile soils in the highlands, where agricultural practices continued to be fragmented and diversified (i.e., orchards, grazing livestock, mowing hay, and cultivating crops). Nevertheless, crop farming did not last long and most of these farms were abandoned (Smith, 1986).

Farming practices in late 19th and mid-20th century reflected subsistances stage, in which diversified and fragmented farming practices were predominant in all ecoregions. The agricultural statistics during the first half of the 20^{th} century show an increase of number of farms from 8,109 in 1880 to 16,179 farms in 1940 accompanied with an overall increase in land in farms from 3,762 km^2 to 5,074 km^2 over the same period. During the second half of the 20^{th} century, land in farms tended to be more stable with temporary fluctuations. Intensive and large-scale farming operations were predominant; rice and soybean plantations largely replaced cotton plantations in the flat region; a federal farm bill was passed to reduce cotton acreage in 1956. Since then number of farms declined from 11245 to 3620 farms in 2007, and at the same time land in farms declined from 5,184 km^2 to 3,626 km^2. Here, it is important to indicate that since 1850 the Ag census definition of a farm has changed nine times and these changes could have impacted the statistics

During the periods of agriculture decline, lowlands were relatively the least impacts. Agriculture development stabilized in the plains region, while it decreased in the uplands for agriculture abandonment, urban expansion, or forest regenerating (Figure 3.2 polygon D). In fact, the south Central region of the U.S. had the largest increase in forest area of any region between 1982 and 1997 (Alig & Plantinga, 2004). Nevertheless, agriculture development continued to be the major contributor to the State's economy. In 1970s, the value of farmlands increased 200%, and between 1992 and 2008, the value increased 11% a year on average (Griffin, 2011). Further, the 2006 annual report of the U.S. exports ranked Arkansas first in rice exports and second in cotton and linter exports, total export value of $ 660.9 million and $ 536.2 million, respectively.

Land development trends in central Arkansas demonstrated interrelated relationships between agriculture and urban dynamics. The decrease in agricultural lands in the uplands, where soil fertility is low and agricultural activities (orchards, grazing) have less economic values, attributed to increase in urban expansion on peripheral farmlands as a natural spread patterns. Urban development in lowlands mainly took place at the edge of the region and this is actually the common scenario in most urban areas where the boundaries of urban development fall on ecoregion edges (Gallant, Loveland, Sohl, & Napton, 2004). Urban pace within this region was dispersive and highly attributed to building rural roads and low growth rate around the small rural communities.

Conclusion

During the study period, central Arkansas was transformed from natural landscape into human-induced landscape dominated by agriculture and urban development. Landscapes among-ecoregions experienced land cover heterogeneity and fragmentation due to topographic and edaphic variation from one ecoregion to another. In addition, building large impoundment projects, increasing protected lands; issuing many conservation acts, such as the No Net loss Wetlands policy and the Arkansas Private Wetlands Riparian Zone Creation and Restoration Incentive Act, contributed to creating remarkable urban-rural convergence zone. While the study area was initially growing as urban area in the late 19^{th} century, the conflicting physiographic settings in central Arkansas helped flourish a relatively balanced urban-rural fringe. Here, the initial trajectories of land development were environmentally shaped, but later these trajectories became socioeconomically driven.

Analyzing long-term and large-scale preferential pathways for land development is a complex task that requires adopting of appropriate analytical approach thereby the complex relationships and feedbacks between anthropogenic ecosystems are revealed and well understood. In my analysis, I found that the environmental attributes of the study area highly influenced past land development patterns and trends. While current urban areas maintained growing boundaries at the edges of ecoregions and along primary roads, massive agricultural lands were contained completely within the flat region and the fragmented farmlands founded in the heart of upland regions.

As the majority of us are aware of the manifestation of environmental sustainability and believe that human have been disturbing the environment for centuries, it is now time to stop fighting nature and believe in its limiting forces. While it is true that building dams on major rivers might guarantee hazard free zones, climate conditions have become unpredictable, especially with growing concerns about Global Warming. We have been in need for practical and analytical framework that appreciates both environment and human advancements and integrates historical perspectives because the value of studying land development history is not in prediction, but in realizing the complex variables involved in human-dominated ecosystems.

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Chapter 3: The Influence of Physiography on Historical and Future Urban Growth Trends across an East-West Gradient in the Arkansas-Red River Basin, USA, 1975-2050

Introduction

More than one-third of all lands developed in the conterminous United States (U.S.) were developed during the last four decades, and the coverage of this urban land is expected to increase from 3.1% in 2000 to 8.1% in 2050 (NRCS, 2009; Nowak & Walton, 2005). The typical urban landscape consists of low-density, non-contiguous artificial surfaces that spread out along the urban-rural fringe (Ewing, 2008; Warren, Ryan, Lerman, & Tooke, 2011). In the U.S., exurban land uses have been growing at a rate between 10 and 15% per year and occupying five to ten times more area than urban and suburban densities. Sprawl is defined as low-density residential and commercial development scattered outside of suburbs and cities and along roads outside cities (Ewing, 1994; Theobald, 2005). Such land use patterns are rapidly dominating the growth patterns of the Western and Southern cities (Alig & Plantinga, 2004; Glaeser & Shapiro, 2001; Rappaport, 2003; Xian & Crane, 2005).

Sprawl is taking place at the expense of natural land cover types such as wetlands and grasslands. Accordingly, there is a need for more research on regional predictions of future urban extents to provide a basis for ecological and socioeconomic assessment of urban change. As a result, there has been increasing interests in modeling urban dynamics and their consequent land cover changes. These models are beneficial for exploring the interwoven set of socio-economic and biophysical forces affecting past and future land transformations (Verburg, Schot, Dijst, & Veldkamp, 2004; Verburg et al., 2002).

Prior to the 1960s, urban growth models were economically oriented and viewed cities as local abstract of zones and sectors (Chen et al., 2002). With the geospatial revolution, there was a need for more realistic models that can use remotely sensed data and view urban ecosystems as livable and dynamic environments and be able to capture complex processes imbedded within these urban systems at regional levels. Therefore, a dynamic modeling approach is highly preferred for understanding the drivers and spatial consequences of urban change.

Among the documented dynamic models, Cellular Automata (CA) based models, which were first introduce in the 1980s by Batty et al. (1989), have been the most popular in the geography discipline (Dietzel & Clarke, 2007; Garcí, Santé, Boulló, & Crecente, 2012). These models avoid many shortcomings of traditional models. In addition, their organizational structure of cell, state, neighborhood, and transition rules matches land cover/use data structure (Oguz, Klein, & Srinivasan, 2007). CA models take the temporal dynamics into account by using initial land use as a principle for possible change through decision rules. They also proved remarkable results for regional scale modeling (Jantz, Goetz, Donato, & Claggett, 2010; Rafiee, Mahiny, Khorasani, & Darvishsefat, 2009).

The SLEUTH urban growth model is one of the most suitable CA model to simulate past urban growth patterns and forecast the growth to the future due to its ability to model urban growth, capability to incorporate environmental and socioeconomic drivers of urban development, transferability to other different regions around the world, and flexibility (Dietzel & Clarke, 2007; Jantz, et al., 2010; Oguz, et al., 2007). In addition, SLEUTH is public-domain software that can be easily downloaded and compiled.

Numerous studies have widely utilized SLEUTH to simulate and predict American urban dynamics within the metropolitan counties for many eastern and western cities (Clarke, Hoppen, & Gaydos, 1997; Herold, Goldstein, & Clarke, 2003; Yang & Lo, 2003). Urban areas in the South Central region of the U.S., which represents the frontier of eastern urban development, were largely neglected. We are only aware of one study in the South, which was carried out by Oguz et al. (2007) to characterize urban dynamics around Houston Metropolitan area. The main goals of this and other traditional studies, however, were to mitigate urban dynamics and assess the anthropogenic and socioeconomic impacts of urban growth within metropolitan counties. No study has yet used SLEUTH model as a platform to relate different urban patterns and trends to physiography.

In this paper, our main objective is to simulate past (1975-2006) urban dynamics and forecast urban growth trends for five 10,000 km^2 areas around the cities of Colorado Springs, Amarillo, Oklahoma City, Tulsa, and Little Rock, located across the Arkansas-Red-River Basin to demonstrate how urban growth patterns differ in response to changing physiography in the South Central region.

Study area

The Arkansas and the Red River basins are two large river basins that drain the Great Plains of the US from northwest to southeast. I combined the two basins into one for the purpose of this study due to physiographic similarities between the two and to ensure representativeness of urban systems spread throughout the region. The Arkansas-Red-River Basin (AARB) is the last and largest tributary of the Mississippi River in the lower Great Plains with a total area of 584,800 km² (Mathews, Vaughn, Gido, & Marsh-Mathews, 2005; Sharif, Crow, Miller, & Wood, 2007).

For the purpose of this study, I selected five 10,000 km^2 areas around the cities of Colorado Springs, Amarillo, Oklahoma City, Tulsa, and Little Rock (Figure 3.1). I chose the 10,000 km² area around each city to better simulate urban dynamics and more accurately establish relationships between urban patterns and environmental attributes. The distribution of these cities guaranteed representation of the east-west climatic gradient in the ARRB as well as ecoregional heterogeneity. Each city is located at the edges of at least two Omernik level III ecoregions. The number and areas of urban spaces in the ARRB are small; there are only seven large cities with population greater than 100,000. Three (Colorado Springs, Amarillo, and Oklahoma City) of the five study areas were categorized as high fliers with urban growth rates that exceeded 10% between 1990 and 2000 (Glaeser and Shapiro 2003).

SLEUTH-3r urban modeling

SLEUTH background

SLEUTH is a CA urban growth model and its name comes from the abbreviation of its data inputs (Slope, Land cover, Exclusion, Urban, Transportation, and Hillshade). In SLEUTH, the socioeconomic and biophysical factors are accounted for within the excluded layer, which guides the model to where urban growth is prohibited or allowed.

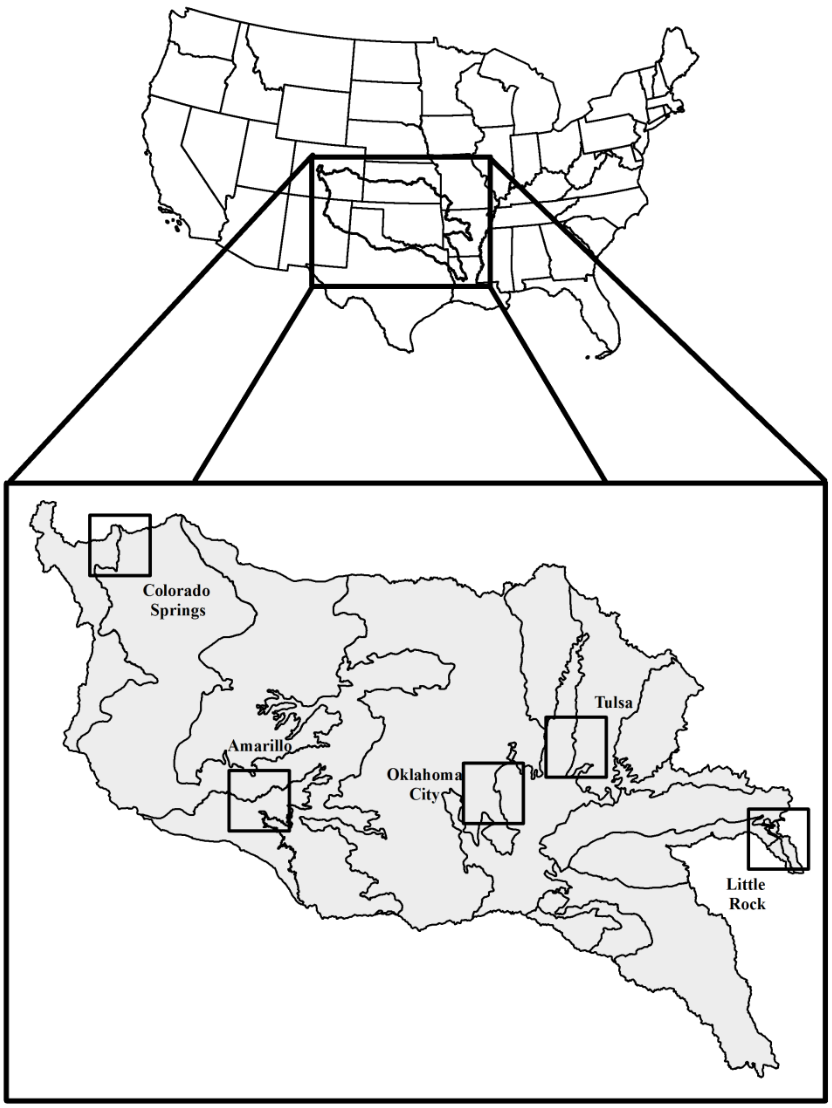

Figure 3.1. Location of the Arkansas-Red-River Basin in the South Central US. The five urban areas are displayed in relation to Omernik Level III ecoregions.

SLEUTH simulates four types of urban growth: spontaneous growth, new spreading center growth, edge growth, and road-influenced growth. These growth types are applied sequentially during each growth cycle and controlled through the interactions of growth coefficients: dispersion, breed, spread, slope resistance, and road gravity.

The model is run in two phases; calibration and prediction. The main goal of the calibration phase is to select the "best fit" set of parameter values for these control coefficients that can replicate past urban development and forecast future development (Clarke, et al., 1997). There are 13 parameters to evaluate the goodness of fit of the SLEUTH model (Dietzel & Clarke, 2007) (Table 3.1). The prediction phase is dependent on running set of coefficients parameters that were identified in the previous phase to determine the appropriate growth control coefficients; diffusion, breed, spread, slope resistance, and road gravity coefficients. In the end, the future growth cycle of an urban system is identified according to four different types of urban growth: 1) Spontaneous growth, representing random urbanization; 2) New spreading center growth; 3) edge growth; and finally 4) road-influenced growth (Clarke, et al., 1997; USGS, 2011).

A modified version of SLEUTH was recently released and due to significant improvement we used this version in this study (Jantz et al., 2010). This version (SLEUTH-3r) can capture dispersed settlement patterns more efficiently through modifying the diffusion multiplier value. Now the user can interactively set the diffusion coefficient multiplier. In the early version, the multiplier was static (0.005) and determined based on San Francisco Bay study area. In addition, SLEUTH-3r creates new tabular files, including differences and ratio metrics *(Population Fractional Difference* (PFD) and *Cluster Fractional Difference* (CFD)), that directly compare the modeled variable with the observed variable for all control sets.

Table 3.1. Goodness of fit metrics available in SLEUTH-3r. The model writes these metrics to *control_statistics.log* file and the *Cluster Fractional Difference* and the *Population fractional difference* statistics are written to a *ratio.log* file. Source (Dietzel & Clarke, 2007; Jantz et al. 2010).

Metric	Description
Product	All other scores multiplied together
Compare	Modeled population for final year/actual population for final years
Population	Least squares regression score for modeled urbanization compared to actual urbanization for the control years
Edges	Least squares regression score for modeled urban edge count compared to actual urban edge count for the control years
Clusters	Least squares regression score for modeled urban clustering compared to known urban clustering for the control years
Cluster Size	Lease squares regression score for modeled average urban cluster size compared to known average urban cluster size for the control years
Lee-Salle	A shape index, a measurement of spatial fit between the model's growth and the known urban extent for the control years
Slope	Least squares regression of average slope for modeled urbanized cells compared to average slope of known urban cells for the control years
% Urban	Least squares regression of percent of available pixels urbanized compared to the urbanized pixels for the control years
X-Mean	Least squares regression of average x_ values for modeled urbanized cells compared to average x_values of known urban cells for the control years
Y-Mean	Least squares regression of average y_ values for modeled urbanized cells compared to average y_values of known urban cells for the control years
Rad	Least squares regression of standard radius of the urban distribution
F-Match	A proportion of goodness of fit across land use classes

These metrics allow for using two historic urban extents instead of four. More importantly, these metrics can be used as an alternative for measures of fit used to evaluate simulated urban distributions in the calibration phase. The source code was also modified to decrease memory requirements and improve processing speed.

SLEUTH-3r data inputs preparation

A set of inputs for each study area, based on 60 m x 60 m cell size, were extracted and processed for the model in ArcGIS 10 from different sources (Table 3.2).

I used 60 m spatial resolution because it proved to be the most representative when both land cover and land cover change are considered (Jawarneh & Julian, in review). A 30 m resolution National Elevation Dataset (NED) was used and resampled to create 60 m resolution inputs for slope and hillshade. For the excluded layer, I incorporated several variables; protected lands, wetlands, water bodies, and riparian zone. Each variable in the excluded layer was given an exclusion probability scaling from 50 (no exclusion, area open for development) to 100 (completely excluded, area repulsive for development). These values were calculated based on yearly empirical urban change within the examined variable between 1990s and 2006.

For protected lands, I used the Protected Areas Database (PAD-US 1.1) from the Conservation Biology Institute (CBI, 2010) layer. In this layer, protected lands are coded with GAP status codes ranging from 1 to 4. Lands with codes 1 and 2 have the highest degree of management for conservation purposes and therefore had exclusion value of 100. Protected lands coded 3 are areas that support multiple uses. I used these lands to calculate exclusion probabilities. Wetlands were extracted from the National Inventory Wetland (NIW) layer (U. S. Fish and Wildlife Service, 1980). However, there was no full coverage of the (NIW) for Little Rock case in digital format. I digitized missing wetlands (around 50% of the study area) from the USGS Digital Raster Graph dataset using the classification of wetlands and deep water habitats of the United States (Cowardin et al., 1979). For the riparian zone, I used the National Hydrography Dataset (NHD) to create a 30 m riparian buffer on each side of the streams.

Table 3.2. SLEUTH-3r inputs and variables

Input	Data Source
Slope, Hillshade	Derived from the National Elevation Dataset (NED). Retrieved from: http://datagateway.nrcs.usda.gov/
Protected lands	Derived from PAD-US 1.1 Conservation Biology Institute Edition. Retrieved from: http://databasin.org/protected-center/features/PAD-US-CBI
Wetlands	Derived from the National Wetlands Inventory layer and digitized USGS Digital Raster Graph. Retrieved from: http://www.fws.gov/wetlands/ and http://earthexplorer.usgs.gov/
Riparian zone	Derived from the National Hydrography Dataset. Retrieved from: http://nhd.usgs.gov/
Water bodies	Derived from 2006 NLCD
1975 Urban extent	Adopted from modified GIRAS land cover map (Jawarneh& Julian, in review). Original map retrieved from: http://eros.usgs.gov
1990s & 2000s Urban extents	Derived from the 1992-2000 NLCD Change Retrofit Product. Retrieved from: http://www.mrlc.gov/nlcdrlc_data.php
2006 Urban extent	NLCD. Retrieved from: http://www.mrlc.gov/nlcd06_data.php
1975 road network	Derived from the USGS Digital Line Graph. Retrieved from: http://earthexplorer.usgs.gov/
1992, 2000, and 2007 road networks	Derived from TIGER\Line files. Retrieved from: http://www.census.gov/geo/www/tiger/

Water bodies were extracted from the 2006 land cover map and they were completely excluded from urban development in all five cases with a value of 100. The final values of exclusion probabilities for each variable are summarized in Table 3.3. All the exclusion variables were combined in one excluded layer using *Maximum* function in ArcGIS raster calculator.

For urban maps, I used four urban extents extracted from different land cover maps (Table 3.2). We obtained the 1975 urban from a modified GIRAS land cover map

(Jawarneh & Julian, in review; Mitchell, Guptill, Anderson, Fegas, & Hallam, 1977). I used the NLCD Land Cover Change Retrofit Product (Fry, Coan, Homer, Meyer, & Wickham, 2008) to extract urban extents for 1990s and 2000s. Acquisition dates of Landsat-TM/ETM+ scenes varied among the five cases. For Amarillo, the dates of the acquisition were July 7, 1991 and May 23, 2001, and for Colorado Spring were acquired on July 4, 1994 and August 13, 2000. For Oklahoma City, the dates were July 9, 1991 and June 2, 2001, and for Tulsa were June 29, 1990 and June 22, 2002. Acquisition dates of Landsat-TM/ETM+ scenes for Little Rock were May 18, 1994 and August 14, 2000.

Table 3.3. Exclusion values in SLEUTH-3r excluded layer for the five study areas.

	Riparian Zone	Wetlands	Protected Land (PAD-3)
Colorado Springs	93	100	100
Amarillo	74	67	61
Oklahoma City	61	63	42
Tulsa	74	57	82
Little Rock	60	79	78

The road networks that were used in SLEUTH-3r represented the primary roads in each study area. I only included primary roads because major regional urban expansion is highly influenced by this type of transportation network. I used the USGS Digital Line Graph to derive 1975 primary roads and TIGER shapefiles to derive the primary roads for the years 1992, 2000, and 2007. For each study area, all the map inputs for slope, exclusion, urbanization, roads, and hillshade backdrop were converted to 8-bit GIF format used by the SLEUTH-3r model (Figures 3.2, 3.3, 3.4, 3.5, and 3.6).

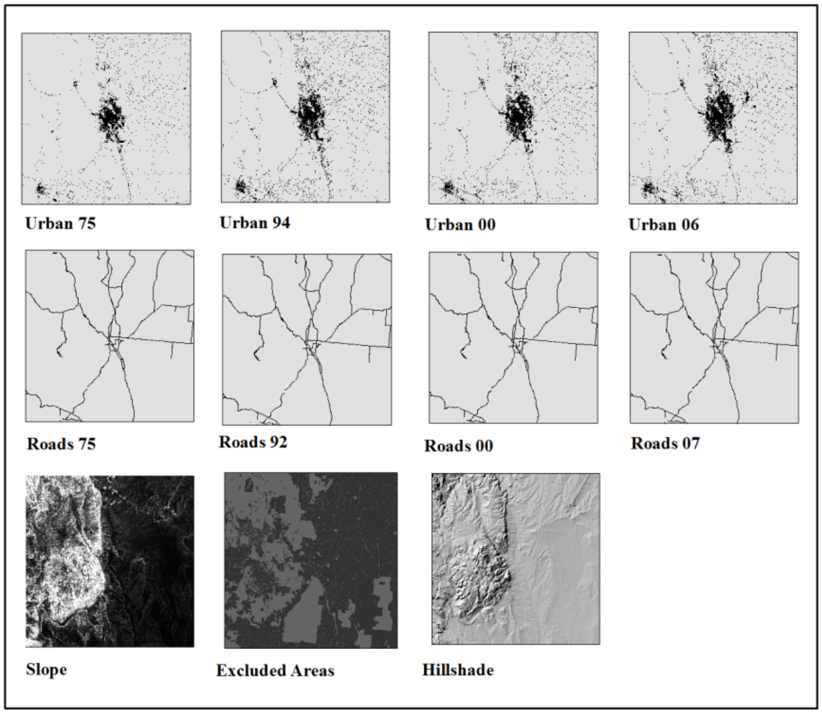

Figure 3.2. Colorado Springs input datasets to SLEUTH-3r.

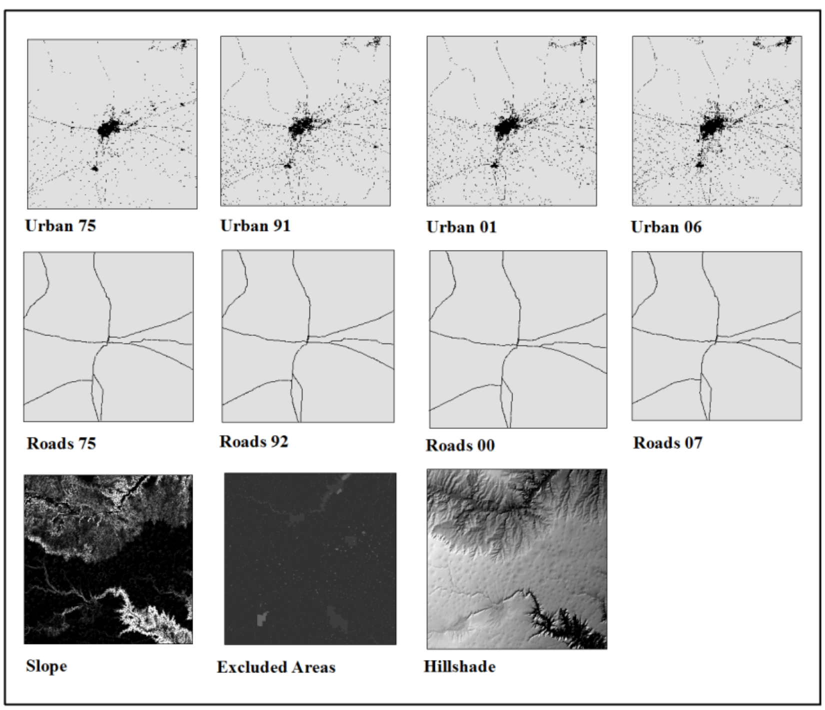

Figure 3.3. Amarillo input datasets to SLEUTH-3r.

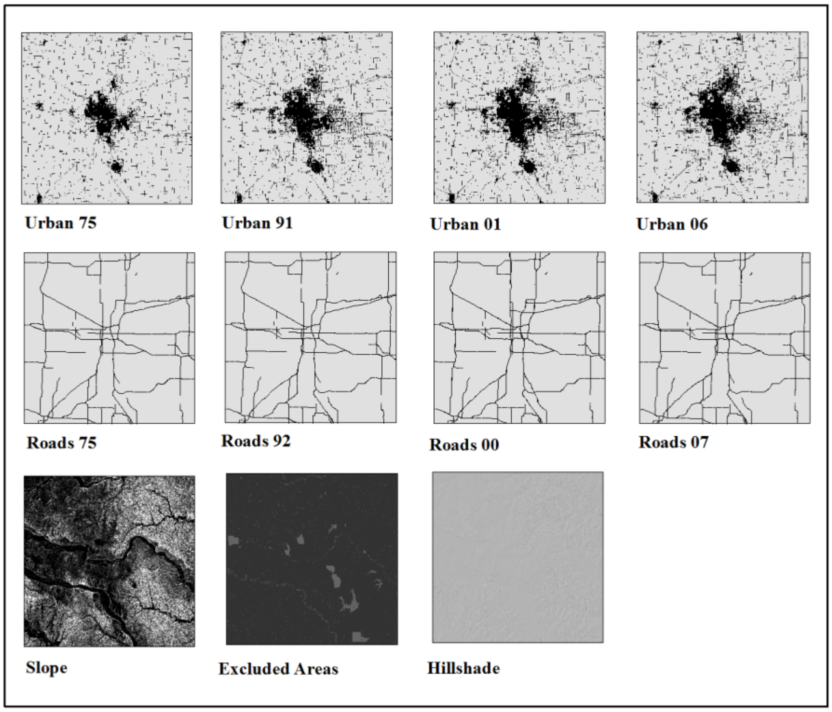

Figure 3.4. Oklahoma City input dataset to SLEUTH-3r.

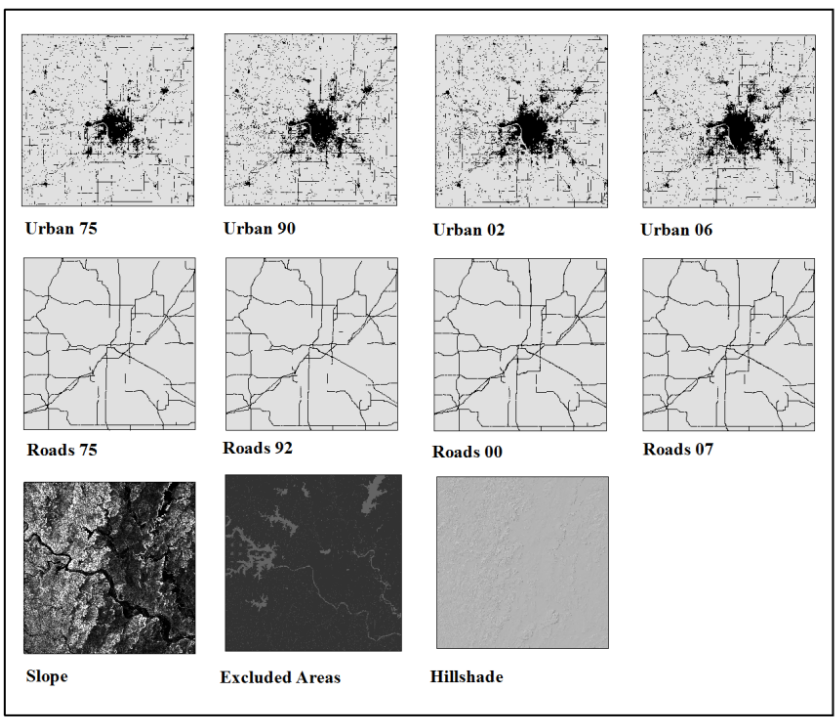

Figure 3.5. Tulsa input datasets to SLEUTH-3r.

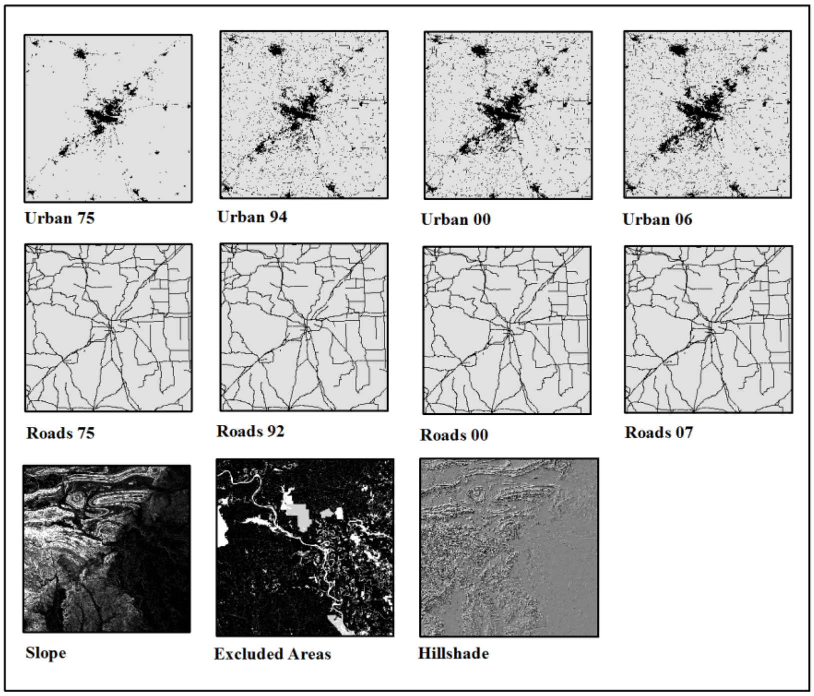

Figure 3.6. Little Rock input datasets to SLEUTH-3r.

Calibration of the SLEUTH-3r

The calibration process is typically undertaken using a "brute force" methodology, in which a large number of combinations of parameter values are tested automatically. In this process, both growth rules and self-modification rules are refined to the locale. SLEUTH has a "self-modification" function to more realistically simulate different rates of growth over time. When the urban growth rate exceeds a specified critical threshold, the growth coefficients are multiplied by a factor greater than one, simulating a development "boom" cycle. Similarly, when the urban growth rate falls below a specified critical threshold, the growth coefficients are multiplied by a factor less than one, simulating a development "bust" cycle. While calibration process is usually performed in three phases; coarse, fine, and final, researchers proved negligible gains in performance among these phases (Jantz, et al., 2010).

Therefore, I only performed coarse calibration in which all growth coefficients values ranged from 1 to 100 but only increments of 25 were tested. I initiated the coarse calibration process for each study area to first set the appropriate Diffusion Multiplier value (D_M) that can capture dispersive growth around each city. In this process, I set the SLEUTH-3r's diffusion growth coefficients to produce the maximum level of dispersive growth (i.e. diffusion coefficient was set to 100 and all other growth coefficients set to 0). The proper D_M value was when the *cluster fractional difference* first exceeded zero.

I then preformed the coarse calibration to develop growth coefficients for each area, including the four control years (1975, 1990s, 2000s, and 2006) and using all five growth coefficients with 25 Monte Carlo trials for each study. To better evaluate the performance of the simulation phase and chose the appropriate growth coefficients values, I had to select representative goodness of fit measures. Selecting proper fit statistics is crucial for an accurate future forecast; however, there is no agreement on standard set. Because I used SLEUTH-3r and had four control years, I selected the PFD and CFD ratios because they are the most relevant to the application of SLEUTH-3r. We also selected the metrics of *Compare, Edges, clusters, X-mean,* and *Y-mean* because they proved to provide the most robust results (Dietzel & Clarke, 2007; Jantz, et al., 2010). In selecting both sets, I guaranteed more accurate validation process and consequently more accurate prediction results.

After the best-fit parameters were identified for all five areas, I initialized the model in 1975 and ran it in predict mode to 2006, with 25 Monte Carlo trials. This resulted in a predicted development probability surface for 2006, which I then compared to the observed patterns in 2006 to assess the accuracy of the calibration process. After preforming the accuracy assessment, I initialized the model in 2006 and ran it to forecast future urban growth around the study areas to 2050 using 25 Monte Carlo iterations.

SLEUTH-3r Results

Colorado Springs

I found the default diffusion multiplier value of 0.005 to be sufficient to capture dispersive growth around Colorado Springs. The coarse calibration results (using all growth coefficients) provided the best-fit parameter set and corresponding fit metrics that best describe growth patterns around Colorado Springs (Table 3.4). The values marked in bold define the results of the optimum values for diffusion, breed, spread, slope, and road gravity parameters. The values of the parameters were equally high for slope and roads (both had a value of 100).

Comparison of the simulated urbanization against the actual urbanization of the four control years, reflected in the compare_score, show that the model simulated the evolution of urbanization in the study area (a score of 0.77). Therefore, I can state that the prediction of the model based on the initial seed year of the present urban pattern was close to what happened in reality. The form of urbanization seems to confirm that calibration adjusted the values to reflect local characteristics. The final calibration correlations were 0.98 in the case of the cluster_r², and 0.84 and 0.94 in the case of the r²_ X mean and r²_ Y mean, respectively (Table 3.4). In the additional accuracy assessment, we were able to match the amount of urban development and the number of urban clusters within 10% (Table 3.5).

Table 3.4. Best overall calibration results

	Colorado Springs	Amarillo	Oklahoma City	Tulsa	Little Rock
Compare r^2	0.77	0.93	0.99	0.99	0.99
Edges r^2	0.59	0.75	0.73	0.99	0.65
Cluster r^2	0.98	0.95	0.99	0.91	0.77
X mean r^2	0.84	0.73	0.97	0.97	0.99
Y mean r^2	0.95	0.76	0.98	0.88	0.99
Diffusion	**75**	**1**	**1**	**75**	**25**
Breed	**75**	**1**	**1**	**25**	**25**
Spread	**50**	**50**	**75**	**50**	**75**
Slope	**100**	**75**	**25**	**75**	**25**
Roads	**100**	**75**	**50**	**50**	**75**

Table 3.5. Calibration accuracy results for each study area. The number of urban pixels, the number of urban clusters for 2006 are given along with the simulated number of pixels and clusters for 2006. For the pixels and clusters fractional difference metrics, a zero value indicates a perfect match between the simulated and observed datasets. Negative values indicate underestimation; positive values indicate overestimations.

Case Study	2006 pixels	2006 Simulated pixels	Pixel fractional difference	2006 clusters	2006 simulated clusters	Clusters fractional differences
Colorado Springs	170224	154984	-0.09	11537	12340	0.06
Amarillo	141032	135930	-0.03	8660	8168	-0.05
Oklahoma City	402380	420453	0.04	9976	9253	-0.07
Tulsa	360562	376414	0.04	17041	18030	0.05
Little Rock	285316	283422	-0.01	17311	16592	-0.04

The result from executing the prediction mode was a probabilistic map which portrayed the probability of grid cells being urbanized in the future. In these maps, I set the model to consider every cell with a probability above 85% would convert to urban.

The map was produced for every year from the first year (2007) to the last year (2050). However, I evaluated the maps for 2025 and 2050 (Figure 3.7). The forecast for Colorado Springs area show slight continuation and intensification of development patterns, especially in urban transportation. The continuation and intensification will likely continue to dictate a northeasterly growth trend towards open spaces (Figure 3.7).

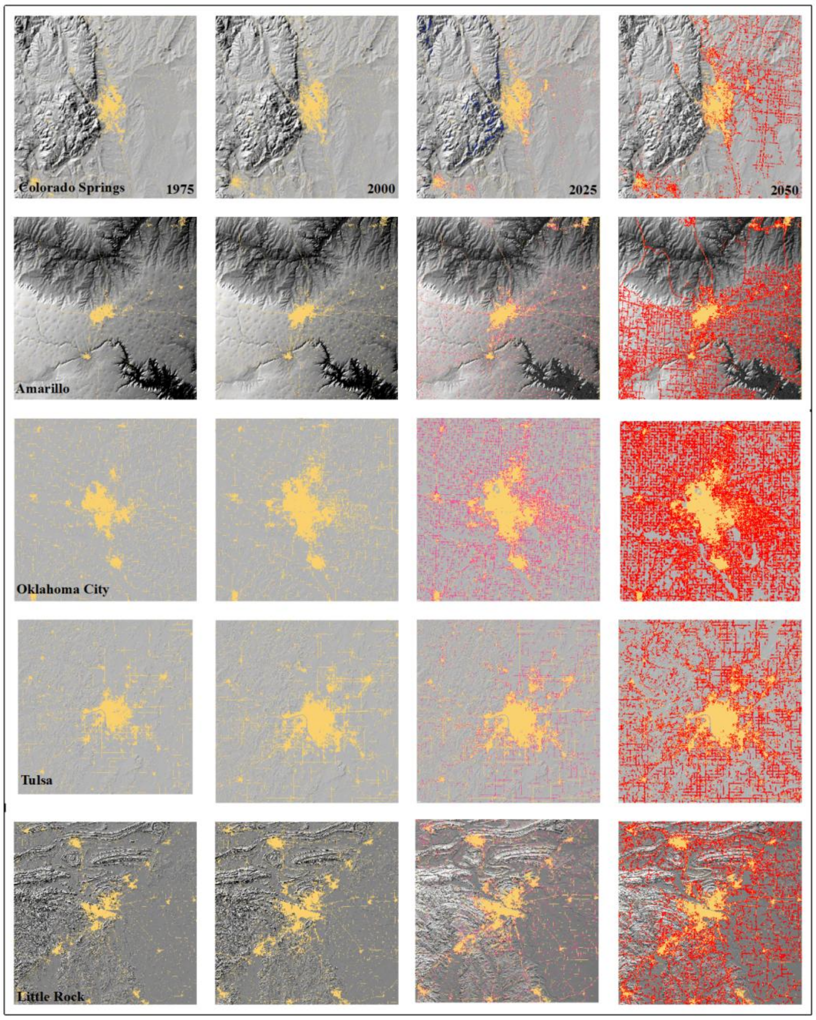

Figure 3.7. Urban land cover 1975-2050. Years 2025 and 2050 are forecasted using SLEUTH output, and assume linear population growth. Urban growth in the forecasted maps is presented by pink (2025) and red (2050). Base layer is a hillshade map. Each study area is 100 x 100 km, centered on the city's central business district.

Amarillo

The default of the D_M of 0.005 was sufficient to capture dispersive growth around Amarillo. The values of the best-fit parameters (Table 3.4) show that historic urban growth patterns around Amarillo were influenced by slope and roads. Both coefficients were high at 75. Comparison of the simulated urbanization against the actual urbanization of the four control years reflected in the compare_score, show that the model reflected the evolution of urbanization in the study area (a score of 0.93). Therefore, I can state that the prediction of the model based on the initial seed year of the present urban pattern was similar to what happened in reality. The final calibration correlations were 0.95 in the case of the cluster_r^2, and 0.73 and 0.76 in the case of the r^2_ X mean and r^2_ Y mean, respectively (Table 3.4). In the additional accuracy assessment, I was able to match the amount of urban development and the number of urban clusters within 5% (Table 3.5).

The forecasted results for Amarillo show high rate of continuation and intensification of development patterns that were highly influenced by transportation. The growth patterns will likely continue to dictate a southerly and southeasterly growth trends (Figure 3.7).

Oklahoma City

I found the default value for D_M to be sufficient to capture dispersive growth around Oklahoma City. The values of the best-fit parameters (Table 3.4) show that historic urban growth patterns around Oklahoma City were predominantly edge-growth and highly influenced by roads. The spread and road coefficients were 75 and 50, respectively.

Comparison of the simulated urbanization against the actual urbanization reflected in the compare_score, show that the model reflected the evolution of urbanization in the study area (a score of 0.99). Therefore, the prediction of the model based on the initial seed year of the present urban pattern was similar to what happened in reality. The final calibration correlations were 0.99 in the case of the cluster_r^2, and 0.97 and 0.98 in the case of the r^2_ X mean and r^2_ Y mean, respectively (Table 3.4). In the additional accuracy assessment, we were able to match the amount of urban development within 5%, but the number of urban clusters within 10% (Table 3.5).

The forecasted results show remarkably high rate of continuation and intensification of development patterns, and clearly along transportation infrastructure. The growth patterns will likely continue in all directions, with more obvious northeasterly and southerly growth trends (Figure 3.7).

Tulsa

The default value of 0.005 was sufficient to capture dispersive growth around Oklahoma City. The high score in diffusion parameter reflected the high probability of spontaneous growth and establishment of new urban centers. Also, the high score of road gravity show that historic urban growth was affected by transportation infrastructures. The score for slope resistance was also high, reflecting of topographical influence on growth patterns around Tulsa. The spread parameter was also high which reflected high probability of urbanization outward the existing urban centers (Table 3.4).

Comparison of the simulated urbanization against the actual urbanization reflected in the compare_score, show that the model reflected the evolution of urbanization in the study area (a score of 0.99). Therefore, the prediction of the model based on the initial seed year of the present urban pattern was similar to what happened in reality. The final calibration correlations were 0.91 in the case of the cluster_r^2, and 0.97 and 0.88 in the case of the r^2_ X mean and r^2_ Y mean, respectively (Table 3.4). In the additional accuracy assessment, we were able to match the amount of urban development within and the number of urban clusters within 5% (Table 3.5). The forecasted results show an increasing rate of continuation and intensification of development patterns along transportation networks. The growth patterns will likely continue to growth to the southeast and northeast (Figure 3.7).

Little Rock

The default value of 0.005 was sufficient to capture dispersive growth around Little Rock. The high score of road gravity parameter show that historic urban growth was affected by transportation infrastructures. The spread parameter was also high which reflected high probability of urbanization outward the existing urban centers.

Comparison of the simulated urbanization against the actual urbanization reflected in the compare_score, show that the model reflected the evolution of urbanization in the study area (a score of 0.99). Therefore, the prediction of the model based on the initial seed year of the present urban pattern was similar to what happened in reality. The final calibration correlations were 0.75 in the case of the cluster_r^2, and 0.99 and 0.99 in the case of the r^2_ X mean and r^2_ Y mean, respectively (Table 3.4). In the additional accuracy assessment, we were able to match the amount of urban development within and the number of urban clusters within 5% (Table 3.5). The forecasted results show continuation of development patterns along transportation networks. The growth patterns will likely continue in northeasterly-southwesterly growth trends along the geological line that separates the Mountains from the Plains (Figure 3.7).

Discussion

Urban growth patterns

Urban growth patterns, trends, and rate varied across the Arkansas-Red River Basin. The road-influenced and spreading growth types were the two predominant growth types throughout the basin. However, the rate and trends varied from one study area to another in response to each city's urban and demographic histories. The urban growth rate was greatest in the middle, northeastern, and southeast parts of the basin. Urban areas in the western side of the basin experienced the lowest urban growth rate. The urban history of these cities is relatively young and population number is low in comparison to the cities in the middle and the east of the basin.

Colorado Springs is a sizable and growing community located on the upper streams of the Arkansas River. The city owes its existence to the Pike's Peak Gold Rush and eventually to its climate conditions and scenic characteristics (Olien & Olien, 1982). In 1892, Colorado Springs was a health and summer resort, and in the 1940s and

1960s the city began a period of rapid growth with the opening of I-25, the U.S. Air Force Academy and other military installations.

During the study period, population number increased from 215,150 in 1980 to 399,452 in 2006. The city witnessed several rapid growth periods, especially during the last few decades of the 20^{th} century. Between 1980 and 1990, urban population of Colorado Springs increased by 27.5% and between 1990 and 2000 the city was categorized as a high flier with urban growth rates that exceeded 10% (Glaeser & Shapiro, 2003). This population growth rate will likely continue to the future and the city's population is expected to exceed 500,000 by 2030 (City of Colorado Springs Planning Department, 2007).

As a result of this dramatic population increase, urban areas expanded substantially in the Front Range region. Between 1975 and 2006, the urban area around Colorado Springs increased from 381 km^2 to 612.8 km^2 at a growth rate of around 7.5 km^2 per year. Assuming linear growth trend, new 115.4 km^2 urbanized area is expected to be added by 2025. A longer prediction to 2050 shows that new 274.2 km^2 urbanized area will likely be added to the study area. This growth pattern has been triggered by the development of transportation infrastructures and dictated by military installations. Therefore, the predominant growth type around Colorado Springs is road-influenced and we also expect a domination of spontaneous growth type in near future.

The development of transportation infrastructure in the east and northeast sides of the area and the limiting forces of growth by military installations (Fort Carson to the south and the Air Force Academy to the north) will likely continue to push urban development to the east and northeast sides of the area, resulting in growing dispersed residential areas and new spreading urban centers to the northwest side of the area (Figure 4.7) (Timlin, Johnston, & Deal, 2002). The modern new transportation technologies have made new areas of the urban fringe around Colorado Springs accessible and therefore the dominant growth type here was road-influenced growth. Due to subsidizing sprawl and increasing water transfers to the urban areas in this region, new transportation, commercial and residential corridors (i.e., Powers Boulevard) were built and public infrastructure and services in the new sprawling development were provided. In addition, the number of unincorporated areas around the City increased dramatically (Coyne, 2003; Howe, Lazo, & Weber, 1990).

Similar growth patterns were found south of Colorado Springs in Amarillo. The city of Amarillo is the largest city in Texas panhandle and is considered a major commercial hub of the five surrounding States. Historically, the city was first established in 1877 for its central location on the way of the Fort Worth and Denver City Railroad (Carlson, 2006). The U.S. Route 66, which ran through the heart of the city, connected the Texas Panhandle with the Midwest and therefore triggered urban development. Amarillo's geographical location contributed to its prominent ranching industry which made Amarillo a fast growing cattle marketing center. Along with its ranching popularity, Amarillo was once known as the "Helium Capital of the World" for having one of the country's most productive helium fields.

The city experienced inconsistent population growth, especially in the mid-20th century. Although the city of Amarillo grew in population at a faster rate than that of the State of Texas between 1890 and 1970, its population number declined following the closure of the Amarillo Air Force Base in late 1960s. Since the 1970s, Amarillo's population growth has been slow and steady due to the expansion of food and technology industries in the area. Tyson Foods Corporation, for instance, opened in the city in late 1980s, which helped increase the city's population to 149,230 people. Between 1990 and 2000, Amarillo had a population growth of more than 10% (Glaeser and Shapiro 2003), and in 2006, the city had a population of 184, 941.

The rapid population growth was accompanied with increasing urban areas. It was estimated that in 1975 urban land covered an area of 282 km^2 and this land increased to 507.7 km^2 in 2006 at an average annual growth rate of 7.3 km^2. Assuming a linear growth trend, the forecasted urban map of 2025 show an increase of 134.2 km^2 new urbanized land in the study area, and a 324.7 km^2 urban area is expected to be added by 2050. Urban areas flourished around Amarillo due to opening the Interstates 27 and I-40. Consequently, the dominant growth type was the road-influenced growth type. Transportation pushed urban growth to the south side of the area and the influence of transportation infrastructure will likely continue to drive urban growth towards the south and southwest (Figure 3.7).

However, urban growth patterns in areas located in the middle of the basin experienced edge-growth growth type with higher annual growth rate. Oklahoma City, located in the heart of the ARRB, is the central metropolis of the Great Eight-States in the South-west (Shirk, 1957). The city was founded in a single day on April 1889, when the unassigned lands were opened for settlement (Dale & Wardell 1948). The Choctaw and the Frisco railroads were powerful in promoting settlements in Oklahoma City. By 1908, Oklahoma City had reached the stage of a boom town with paved streets, beautiful residential areas and other development features (Gibson, 1981; Scott, 1939).

In 1980, the city had a population of 404,014 people and the number increased to 506, 132 people in 2006. As in 2000 census, the city had a population growth of more than 10%, and by 2025 the city's population is expected to exceed 581, 860 people (Oklahoma Department of Commerce, 2008).

Therefore, urban areas witness rapid increase between 1975 and 2006 and this growth is likely expected to continue in future. Around Oklahoma City, urban land increased from 891.6 km^2 in 1975 to 1448.6 km^2 in 2006, with an average annual growth rate of 18 km^2. By 2025, 360.8 km^2 new urbanized land is expected to be added in the area, and an urbanized area of 841.7 km^2 will potentially be added to the area by 2050 (Figure 3.7).

Edge-growth type has been the dominant growth type around Oklahoma City, and has been facilitated by intense transportation infrastructures, including many major highways and interstates (I-40, I-44, and I-35). These highways run through and around the city, allowing for easy accessibility from the suburbs to the city centers. This spreading growth type is expected to continue outside the core, creating one of the largest cities in the U.S. by land area.

In the northeast section of the basin, however, the road-influenced growth type was predominant. The city of Tulsa, located in the northeast section of the ARRB, is the second-largest city in the state of Oklahoma. Historically, Tulsa's rapid growth began about the time of statehood due to flourishing the petroleum industry in the area and to the influence of Frisco railroad (Dale & Wardell, 1948). The city was one of the gateways cities connecting the east and west, and claimed to be the birthplace for U.S. Route 66 (Boyd, 2006; Abbott, 2008). Early urban development phases in Tulsa were also triggered by Port of Catoosa, at the head of the McClellan-Kerr Arkansas River Navigation System. The city population grew from 360,919 residents in 1980 to 381,780 in 2006, and the number is expected to exceed 444,300 people by 2025. Historic urban land cover also increased from 867.4 km^2 in 1975 to 1298 km^2 in 2006 at average annual growth of 14 km^2. Assuming this linear growth trend will likely continue to the future, the forecasted 2025 urban map show that a 240.7 km^2 new urbanized area is expected to be added in the area, and by 2050, the total new urbanized area will likely reach 582.4 km^2.

Early growth patterns, in Tulsa area, were concentrated around the railroad and expanded around the central city. During the study area, the predominant urban growth type was edge-growth. Later with the expansion of transportation infrastructure in the area, the predominant growth type became road-influenced growth. Nowadays, urban development greatly has been taking place around the highways, Interstate 44 and the Broken Arrow Expressway. The development of highway infrastructure has triggered suburbanization and increased dispersed residential and commercial areas to the northeast and southeast sides of the study area. And this urban growth pattern is expected to continue in the future and development will most likely be centered on the newly developed highways and new urban centers are expected to emerge (Figure 3.7).

The predominant growth type in the southeastern section of the ARRB was edge-growth. The city of Little Rock, located in the southeast section of the basin, is the capital city of Arkansas and the largest urban center in the state. Although the city was founded in 1821, the city did not become a major urban hub till early 1990s. At this time, the electric and power transmissions were invented and the forests were cleared for urban expansion. Overall, the city's population growth was modest but steady. In 1980, the city had a population of 159, 151 and the number grew to 184,422 people in 2006. Consequently, urban land cover in the study area increased from 603.4 km^2 in 1975 to 1027.3 km^2 at average annual growth rate of 13 km^2. A 258.4 km^2 new urbanized land is expected to be added to the area by 2025, and by 2050 424.5 km^2 new urban land will be added (Figure 3.7).

Urban areas around Little Rock took place at the periphery of existing urban centers. This spreading growth was empowered by the expansion of transportation technology, especially building highways and Interstates in the region. Urban development in central Arkansas was heavily centered on the I-40, I-30, and U.S. Rout 67. This spreading growth type around Little Rock is expected to grow growth type will most likely continue in the future due to other limiting factors of growth (Figure 3.7).

Influence of Physiography on urban growth patterns

Urban growth patterns and rates in the South-Central region of the U.S. were influenced by east-west topographical gradient across the ARRB. Each city has its unique physiographic characteristics that shaped its past growth patterns and will likely continue to shape future growth. In this research, I found that steep slopes represent a major limiting factor of urban growth in the basin. Cities located at the foothills of rigid mountains tend to grow away towards flatter areas or more gentle slopes, cities located on the Plains tend to expand in all directions.

Urban growth patterns and trends around the city of Colorado Springs were greatly shaped by the topography of the surrounding area. Colorado Springs is located in a semi-arid region at the edges between the Southern Rockies and the Southwestern Tablelands ecoregions (Omernik, 1987). The Southern Rockies to the west are composed of high elevation and steep rugged mountains, while the Southwestern Tablelands to the east is elevated tableland covered with grassland. The influence of slope on urban growth in this area was reflected through the high score for the slope-resistance parameter in the SLEUTH model, indicating that steep slopes in the region were a major physiographic obstacle for urban growth, reinforcing the justification for the influence of physiographic settings on urban growth patterns. Such high slope resistance enforced a northeasterly urbanization trend around Colorado Springs and this trend is expected to continue in this area and therefore the Tablelands will likely be highly urbanized (Figure 3.7).

Steep slopes also had influential role on urban growth trends around Amarillo city. The city is located in the semi-arid Texas Panhandle between the Southwestern Tablelands to the north and the Southern High Plains to the South. Amarillo is part of the *LIano Estacado* region, which is the same region as the High Plains. To the northeast of the city is the Canadian River (with steep cliffs) and to the southeast is a canyon system of the *Caprock Escarpment* (Figure 3.7) (USEPA 2002). Due to these rigid northern and southeastern boarders, growth towards these directions was very limited and consequently resulted in southerly and southwesterly growth trends. However, slopes in the eastern parts of the basin were relatively less steep, but influenced urban growth trends as in Little Rock and Tulsa areas.

The steep slopes of the Osage Hills landforms influenced urban growth trends around the city of Tulsa. Tulsa is located in a subtropical region between the Cross

Timbers and the Central Irregular Plains regions. The Central Irregular Plains are topographically more irregular than adjacent Plains. Areas west to U.S. Highway 75 are part of the Osage Hills landforms, in the Cross Timbers, with steep slopes exceeding 20%. These landforms enforced a southeasterly growth trend around Tulsa, which will likely continue in future.

The impact of slope on urban growth patterns was also clear in Little Rock study area. The city of Little Rock is located in more humid region and its boundaries lie at the boarders of four ecoregions. The Arkansas Valley ecoregion north of Little Rock is characterized by broad floodplains bounded by scattered hills and mountains, while the Mississippi Alluvial Plain to the east is a relatively flat ecoregion. South of Little Rock lays the South Central Plains ecoregion, composed of rolling forested plains broken by numerous bottomland wetlands, while the Ouachita Mountains ecoregion to the west, composed of steep slopes along east-west trending ridges. Due to the topographic variation in this area, urban development extended diagonally along the Ozark foothills, enforcing a northeasterly-southwesterly growth trend. This trend will likely continue as the Mountains to the north and the bottomlands to the south will continue to slow growth.

Topography, however, had a minimal or even no influence on urban development in Oklahoma City area. Here, urban areas are mostly located in the Great Plains. Oklahoma City, near the middle of the basin, lies between the Central Great Plains to the west and the Cross Timbers to the east. While the Cross Timbers is a mosaic of woodland, tallgrass prairie, and forests, the Central Great Plains is covered in prairie, steppe, and grassland. In this area, urban growth tended to expand in mostly all direction around the central core. Therefore, topography does not represent a major influence on urban growth patterns around Oklahoma City.

Another limiting factor of urban growth in the basin is the Arkansas River. Rivers in general can be important attractors for urban development; however, most urban areas that were founded close to rivers are located on the outer bend of the river, as the case in Tulsa and Little Rock, to avoid flood hazard. The Arkansas River, to the west of Tulsa, limited growth to the west and southwest. It also limited urban growth to the southeast of Little Rock on the bottomlands. Major rivers will likely continue to dictate urban development in the basin regardless of the technological and human advancements to control floods.

Conclusion

This paper compared past and future growth patterns and trends across heterogeneous physiographical settings in the South Central region. In present research, it is important to consider changes and feedbacks between urban dynamics and their surrounding environmental settings. Through my research, I demonstrated how environmental characteristics such as topography and water bodies have the potentials to dictate urban growth and impose a unique growth patterns in relation to the placement of the examined urban landscape. And these forces will continue to drive urban growth patterns in relation to the east-west topographical gradient in the region.

Urban landscapes have become a regional phenomenon that threats environmental sustainability. More importantly, the placement of urban landscape, relative to environmental settings, within regions plays crucial roles in managing the flows of natural and socioeconomic land resources. Therefore, more research on the driving forces of urban growth is needed to help mitigate urban dynamics, maintain natural resources, and create more environmentally- and socioeconomically-balanced landscapes. I believe that this work presented important sustainability approach by relating the positions of urban systems at regional scale to their surrounding physiography. In doing this, I have widened the scope of urban change studies and strengthen the research on sustainable landscapes.

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Chapter 4: Conclusions

Research Objectives and Thesis Structure

The main objective of this research was to investigate the environmental influences on past and future urban development across an east-west gradient in the Arkansas-Red-River Basin. The fundamental questions answered were:

1. Can land cover datasets from different data sources be combined to create a comparable land cover timeline?
2. Is there a relationship between environmental attributes and land development trends and patterns around the city of Little Rock?
3. Are environmental drivers of urban development consistent across a large and diverse physiographic gradient?

These questions were dealt with collectively and hierarchically. Studying historical and future environmental influences on urban development at a regional scale is dependent on the quality and accuracy of the utilized land cover timeline, and therefore required combining geospatial data from different sources and understanding the land transitions and dynamics of anthropogenic ecosystems at a smaller scale. As a result, the structure of this dissertation followed transition from small to large scales.

Development of accurate and compatible long-term land cover timeline

Investigations began with introducing a transferable GIS framework to compile long-term land cover datasets from a variety of sources for 10,000 km^2 area around the city of Little Rock (USA). I was the first to build a long land cover timeline by introducing a consistent GIS framework to incorporate Public Land Survey Plats (PLSS), early panchromatic aerial photography, the first national land cover dataset

(GIRAS), and contemporary remotely-sensed derived national land cover datasets (NLCD) (Chapter 2). In our framework, I first calculated an appropriate spatial resolution that would be compatible among all years. I found that 60 m resolution was best because too fine of a resolution (30 m) would not be representative of actual land cover because some techniques (i.e., PLSS and GIRAS) mapped land cover at coarser resolutions. Too coarse of a resolution (240 m), however, would not capture land cover changes occurring in small patches. I also adapted consistent mapping techniques with a Minimum Mapping Unit (MMU) of 3600 m^2 and a minimum width of 60 m and representative classification scheme.

The GIRAS dataset suffered mapping uncertainties that could have affected the accuracy and compatibility of the land cover timeline if they were not corrected. Therefore, we introduced robust modifications techniques. I was the second to modify the GIRAS land cover dataset (Elmore & Guinn, 2010), but the first to introduce more comprehensive modification techniques that accounted for urban omission error, wetlands omission error, and grassland/shrub omission error (Jawarneh & Julian, in review). The modifications increased the thematic accuracy of GIRAS from 66.5% to 77.8%, mainly by improving its resolution so that small, heterogeneous land cover patches were represented.

By transforming pre-settlement land surveys and early aerial photographs, we added historical value to our land cover timeline. The modifications and subsequent accuracy assessment we performed on the U.S.'s first national land cover dataset (GIRAS) demonstrated that it can be made compatible with the current national land cover database. When combined, these eclectic land cover datasets allowed us to create a 149-y land cover timeline with 60 m resolution over a 10,000 km^2 area.

The Influence of Physiographic Complexity on Spatiotemporal Trends in Urban and Agriculture Development

I used the 149-y timeline to investigate the relationship between physiographic heterogeneity and land cover complexity within- and among-ecoregions. In addition, I empirically analyzed the influence of environmental attributes on long-term and large-scale development trends around Little Rock. For this purpose, I developed a robust environmental-historical approach thereby the potential influences of environmental forces on dictating development were assessed in combination with human technological and economic advancements (Chapter 3). The empirical analysis results revealed that during the study period environmental forces of topography, soil moisture, water bodies, and wetlands played profound roles in urban and agriculture development in central Arkansas.

However, there was no one predominant environmental force dictating urban development in the study area. Instead, a combination of one or more forces along with either distance to CBD or primary roads best explained urban development trends. The results show that during the first half of the 20th century, slope, soil available water storage, water bodies, and distance to Little Rock CBD were highly important determinants of urban development. During the second half of the 20th century, the influential magnitude of environmental forces on urban development decreased while the influence of primary roads, in particular, increased. In contrary, the magnitude of environmental influences on agriculture development was more consistent and obvious during the study period. Flat areas in rural counties of central Arkansas where soils are fertile and moist were preferred for agriculture development.

Environmental Influences on Past and Future urban Development Trends at large Basin-Scale

Past and future urban growth trends vary across spatial heterogeneity. Modeling the preferred environmental pathways of urban development across an east-west gradient in the South Central region of the US is important due to the region's vital geographical placement in the urban transition zone between the highly developed coasts most developed regions in the United States. Very limited research has been done on urban growth in this region. To our knowledge, only one study forecasted urban growth trends and pattern within the metropolitan area of Houston, TX (Oguz, Klein, & Srinivasan, 2007); however, this study did not intend to investigate the relationship between physiographic/topographic heterogeneity and urban growth trends. We, however, selected five 10,000 km² urban areas around Colorado Springs, Amarillo, Oklahoma City, Tulsa, and Little Rock to capture the environmental diversity across the basin (Chapter 4). We first compared and contrasted the physiography of those areas. We simulated and forecasted past and future growth patterns using a SLEUTH urban growth model to accurately explain the major drivers of urban growth across the basin.

In the Arkansas-Red River Basin, the results show relatively increasing urban area growth rates towards the west with the greatest increase having occurred in the least physiographically heterogeneous area (Oklahoma City). The urban history of these areas, however, played a role in these growth rates. The eastern and mid-eastern cities in the basin were founded earlier and therefore experienced their rapid growth during different eras than the western cities in the basin. The results revealed a considerable relationship between topographic heterogeneity and predominant growth patterns in the study areas. Urbanized areas around Colorado Springs will continue to grow to the northeast, while trends of growth around Amarillo will continue to expand to the south and southeast. Urbanization trends around Oklahoma City will continue to the north, south, and northeast, while Tulsa's growth trends will continue to the southeast. The northeast-southwest diagonal growth trend around Little Rock will likely continue to grow.

Future Applications

This research investigated the link between physiography and past and future urban growth patterns. While many general urban patterns and trends have been presented previously (Clarke, Hoppen, & Gaydos, 1997; Yang & Lo, 2003; Jantz, Goetz, Donato, & Claggett, 2010), this was the first study to investigate and compare the effects of environmental attributes on urban growth patterns among different urban systems. This study also presented the first methodological framework to build a comparable land cover timeline spanning long time intervals and combining a variety of geospatial data sources from old cadastral maps to contemporary digitally-derived land cover datasets. Further, I presented a regional historical-environmental analytical approach to study land development dynamics relative to environmental attributes and human and institutional advancements.

Despite the many advances in modeling land cover transitions, most urban growth modeling is used to study the environmental and socioeconomic impacts of contemporary and future urbanization. Because sustainable and balanced landscapes are key components of any land cover change studies, more research on positions of urban areas in relation to surrounding physiography is needed. Through my study, I have added new perspectives to the field of land change studies and more aspects will be covered in future research.

My mapping techniques and GIRAS modifications provide great opportunity to expand land change analyses to understand the complexity of human-induced systems and consequently make more sustainable and efficient decisions. In addition, by incorporating environmental and institutional histories in land change research, I present a comprehensive analytical approach to validate land dynamics and make more accurate forecasts. My combined methodological and analytical approaches provide a robust framework for future land cover models to assess the role of physiography and human advancements in land development dynamics.

The introduced mapping techniques and analysis approaches will be further developed in future researches as they will be applied in other counters than the U.S. I expect to expand and widen the application of these techniques and include other variables that were not observed in the U.S. landscapes.

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