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Research Paper

The influence of physiography on historical and future land development changes: A case study of central Arkansas (USA), 1857–2030

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HIGHLIGHTS

- We developed an equation to measure development relative to physiography.
- We used a historical approach to reveal complex interrelationships in urban systems.
- Past and future urbanization in central Arkansas is dictated by local physiography.

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ABSTRACT

The intricate interrelationships between environment and society result in unique landscapes, each with its own development patterns and rates. While many studies have focused on how development impacts the environment; this study quantifies the influence of the environment, relative to human historical factors, on long-term (1857–2030) and large-scale (10,000 km^2) development patterns in a region with diverse physiography. A major component of this paper is the development of a Magnitude of Relative Change (MRC) equation to empirically measure long-term development trends and rates at regional scale in relation to multiple physiographic factors. We simulated past urban development trends and forecasted future patterns for the central Arkansas (USA) region using a modified SLEUTH-3r urban growth model. In doing this, we investigated the relationships and feedbacks between physiographic settings of the study area and past and future development patterns. Another vital component of this research is the adoption of an environmental historical approach to examine and evaluate development dynamics within and among ecoregions. Our analytical approach emphasizes the potential of environmental forces to influence land development transitions and at the same time appreciates the role of human advancements on shaping those dynamics.

1. Introduction

Landscapes are the result of intricate relationships and co-evolution between human development and surrounding environments (Aretano, Petrosillo, Zaccarelli, Semeraro, & Zurlini, 2013; Barau & Ludin, 2012; Lovell & Johnston, 2009). In an effort to understand these interrelationships, studies have begun to assess long-term land cover timelines in the context of environmental datasets (Bakker & Veldkamp, 2012; Julian, Thomas, Moursi, Hoagland, & Tarhule, 2012; Walker & Solecki, 2004). Further efforts have been made to simulate historical land cover changes and model future development by using a suite of geospatial data (Goldewijk & Verburg, 2013; Jantz, Goetz, Donato, & Claggett, 2010; Oguz, Klein, & Srinivasan, 2007; Verburg et al., 2002). Indeed, these sophisticated and spatially explicit models are beneficial for exploring the interwoven influence of socioeconomic and biophysical forces on urban growth patterns (Verburg, Schot, Dijst, & Veldkamp, 2004). While physiography is used as a template for urban growth studies, it is not typically considered as a main driver or constraint on urban growth.

Urban growth models were initially economically oriented in which cities were only dealt with as economic zones (Chen et al., 2002). With the geospatial revolution in the 1970s (Clarke, McLafferty, & Tempalski, 1996), there was a need for more realistic

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models that could use multiple sources of spatial data and view urban areas as dynamic environments in order to capture complex processes imbedded within urban systems especially at regional levels. First introduced in the 1980s by Batty, Longley, & Fotheringham (1989), cellular automata (CA) models have been the most popular in this regard. CA models avoid many shortcomings of traditional urban growth models because their organizational structure of cell, state, neighborhood, and transition rules matches land cover/use data structure (Oguz et al., 2007; Suarez-Rubio, Lookingbill, & Wainger, 2012). Even more importantly, CA models take into account temporal dynamics by using initial land use as a principle for possible change through decision rules.

After three decades of experience and technological advances, CA models represent the state-of-the-art for modeling urban growth at regional scales (Jantz et al., 2010; Rafiee, Mahiny, Khorasani, & Darvishsefat, 2009), particularly for their ability to simulate interactions among biophysical and socioeconomic drivers of land change (White & Engelen, 1997). The SLEUTH model (slope, land cover, exclusion, urban, transportation, and hillshade) is one of these CA models that uses physiography to guide urban growth, and has been widely used on account of its public-domain software with extensive documentation, adoption by many leading land change scientists, and transferability to any region of any size (Clarke, Hoppen, & Gaydos, 1997). In SLEUTH, some of the socioeconomic and biophysical factors are accounted for within an exclusion layer, which guides urban growth based on user-defined exclusions such as water and protected lands (Jantz et al., 2010). Mahiny and Clarke (2012) made a new enhancement to the SLEUTH model by incorporating multi-criteria evaluation (MCE). This urban suitability layer along with the exclusion layer helps to simulate more realistic development patterns given ecological and socioeconomic factors. While useful, SLEUTH and similar models have yet to fully exploit the inherent linkage between pattern and process to explore the empirical relationships between physiography and land development.

While numerous studies have widely utilized SLEUTH to simulate and predict American urban dynamics for many eastern and western cities (Clarke et al., 1997; Herold, Goldstein, & Clarke, 2003; Yang & Lo, 2003), urban areas in the South Central region of the US, 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 the 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 the SLEUTH model as a platform to relate urban development patterns and trends to physiography.

In this study, we examine physiography's influence on urban and agricultural development by using two perspectives: ecoregion perspective (*sensu* Omernik, 1987; Level III Ecoregions) and cellular perspective (60-m square cells). The ecoregion perspective provides information on growth patterns within regions that are relatively homogenous in terms of topography, climate, potential natural vegetation, and soils. Ecoregions not only correspond well to spatiotemporal landscape patterns and composition, but they also help extrapolate relationships among natural and anthropogenic factors across broad scales (Griffith, Stephen, & Loveland, 2003; Omernik, 1987; Ramsey, Falconer, & Jensen, 1995). Omernik ecoregions were delineated at different hierarchical levels based on the variability of environmental characteristics within regions at the national and state level. While Level I provides the least variability at the national level, Level III provides better environmental details of subregions at state level (Gallant, Whittier, Larsen, Omernik, & Hughes, 1989). The cellular perspective, on the other hand, provides information on local interactions (i.e., cell-to-cell) between human development and the environment, which may help to explain human decisions based on physiographic constraints. For example, is a parcel of land near a river more likely to be developed than a parcel near a wetland? When combined, these two perspectives allow us to connect landscape pattern at multiple spatial scale and land-use change decision processes.

Here, land cover change patterns and processes were examined across a 10,000-km^2 area in central Arkansas, USA. We selected this region for several reasons. First, central Arkansas has a heterogeneous physiography, lying at the intersection of four vastly different ecoregions. Second, central Arkansas captures a diversity of land cover: large areas of forest, grassland, agriculture, wetlands, open water, and a variety of urban environments with different growth patterns. Finally, there are compatible medium-resolution (60 m) land cover maps readily available for this study area that date back to 1857 (via Jawarneh & Julian, 2012), which allow us to observe the beginning of land development in the region. The objective of this study was thus to analyze the role of physiography in spatiotemporal patterns of land cover change. While we focus on physiographic variables, we also discuss the influence of broad-scale socioeconomic variables on land development and address how these two factors interact.

2. Data and methods

2.1. Study area

2.1.1. Physiographic setting of central Arkansas

The 10,000-km^2 study area is centered on Little Rock, the capital city of Arkansas, USA (Fig. 1). In combination with the region's vast urban network, the heterogeneous physiographic setting of central Arkansas provides an ideal platform to study the environmental influences on past and present urban growth patterns. The temperate climate of central Arkansas is characterized by high rainfall (130 cm annual average), hot summers, and mild winters (Woods et al., 2004). The topography is defined by the fall line that separates the Gulf Coastal Plain to the southeast from the Interior Highlands to the northwest. The fertile, loamy soil of the coastal plain provides for large-scale rice, cotton, and soybean plantations. In the highlands, the soil is less fertile and more suitable for plantation forestry, poultry operations, and livestock grazing (Brister, 1977; Hanson & Moneyhon, 1989). These topographic regions are dissected by the Arkansas River, a major tributary to the Mississippi River that provides many valuable resources to the region, including navigation, recreation, flood control, hydropower, and water supply for agriculture, industry, and municipalities.

The study area stretches across four diverse ecoregions. The South Central Plains ecoregion to the south of the metropolitan area is composed of irregular forested plains 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 two ecoregions (Hanson & Moneyhon, 1989; Woods et al., 2004). 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.

2.1.2. Settlement history

Central Arkansas has been inhabited for thousands of years by such cultures as the Folsom, Mississippian, Caddo, and Quapaw

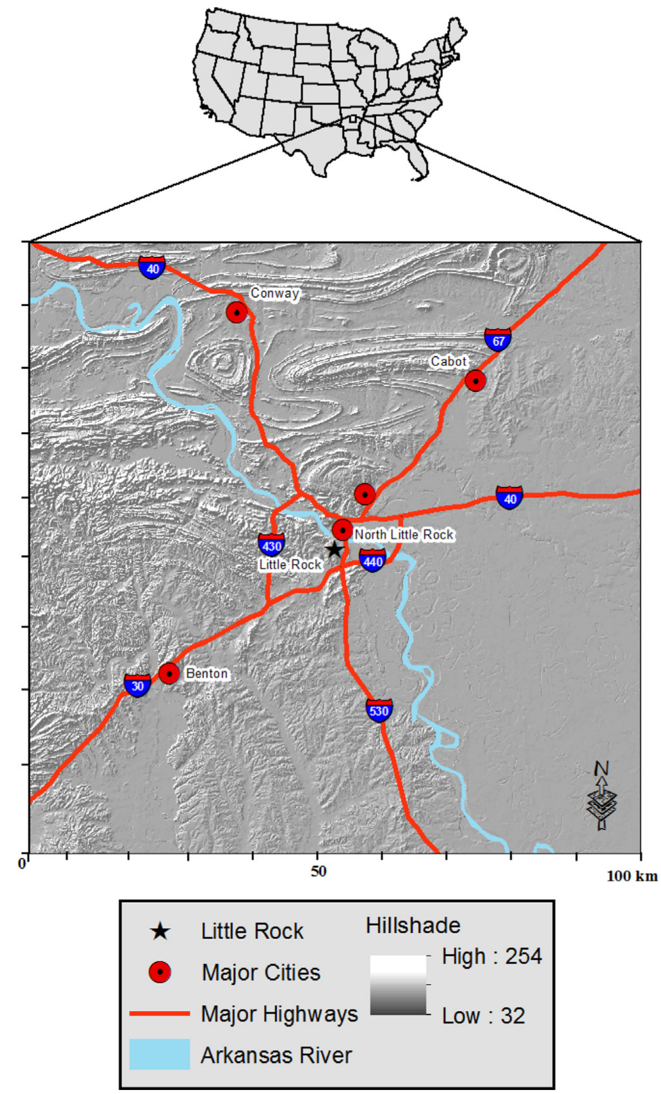

Fig. 1. Central Arkansas (USA) study area.

(Cadwell, 1942; Lyon, 1949). After being part of the Louisiana Purchase followed by the Missouri territory, Arkansas became its own territory in 1819. At this time, Arkansas Post – originally a Quapaw village located at the mouth of the Arkansas River – served as its temporary capital, but the capital was later moved to a more central location on more preferable land (Adams, 1986; Harper & McBrien, 1931; Richards, 1969). The 'point of rock' landmark (present Little Rock), located on the south bank (cut bank) of the Arkansas River, was chosen because it was away from the frequently flooded 'unhealthy' swamp lands on the north bank (point bar floodplain) and because it was the fall line of the Arkansas River.

Realizing the favorable environmental settings of this landmark, settlers began arriving in Little Rock by 1820 (Adams, 1986; Gentry, 1954; Lewis, 1932), with widespread land speculation also occurring (Gates, 1942; Herndon, 1933; Richards, 1969). The overall population growth in the study area was modest but consistent (Fig. 2). In 1820, there were 13 known residents with one frame building surrounded by three or four pine log huts. Ten years later, the total population of Little Rock jumped to 430. With the announcement of statehood in 1836, the number increased to 726 (Richards, 1969). A few years later, Little Rock became one of the largest urban centers west of the Mississippi (population of 1531) and a frontier hub to the West. Our study starts with the year 1857 and captures the three major cities of the Little Rock-North Little Rock-Conway metropolitan area and 70% of its incorporated communities.

2.2. Data

2.2.1. Land cover data

We extracted historical land cover information from the land cover timeline developed by Jawarneh and Julian (2012) for the years: 1857, 1943, 1975, 1994, 2000, and 2006. We used 60 m spatial resolution because it was the highest resolution at which all six datasets were compatible. This compatible medium resolution land cover timeline was developed by improving the earliest available surveys of the region (1857), digitizing the first available aerial photographs (1943), modifying the first national land cover dataset (GIRAS 1975), and incorporating contemporary National Land Cover Databases (NLCDs) (1994–2006). The accuracy and mapping techniques were solved to make the different sources of land cover data be combined into one timeline. 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. Although it was impossible to assess the accuracy of the 1857 and 1943 land cover maps due to the lack of reference maps, the two datasets were consistent with historical literature, especially on wetlands coverage (Jawarneh & Julian, 2012).

2.2.2. Physiography and infrastructure data

We obtained the physiographic and infrastructure data from different data sources (Table 1). Wetlands were extracted from the land cover maps and the National Wetlands Inventory (NWI) (U.S. Fish and Wildlife Service, 1980). However, the NWI did not have full coverage for Little Rock in digital format, and so we 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, Carter, Golet, & LaRoe, 1979). We used the National Hydrography Dataset (NHD) (USGS, 2011) to create 30 m riparian buffers on each side of the streams, consistent with recommended riparian protection zones buffer widths (Wenger & Fowler, 2000). The riparian buffer layer was then converted to a 60-m grid based on the *Cell Center*

Table 1
Physiographic and infrastructure variables used to identify preferential pathways for development from the cellular perspective. "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
Wetlands	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 buffer on each side of the streams
Protected areas	Static	Obtained from the PAD-US Conservation Biology Institute edition
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%
Distance to ecoregion boundary (km)	Static	The map included 5 distances: 0–5 km, 5–10 km, 10–15 km, 15–20 km, and 20–25 km.
Roads adjacency	Dynamic	420 m buffer on each side of the primary roads

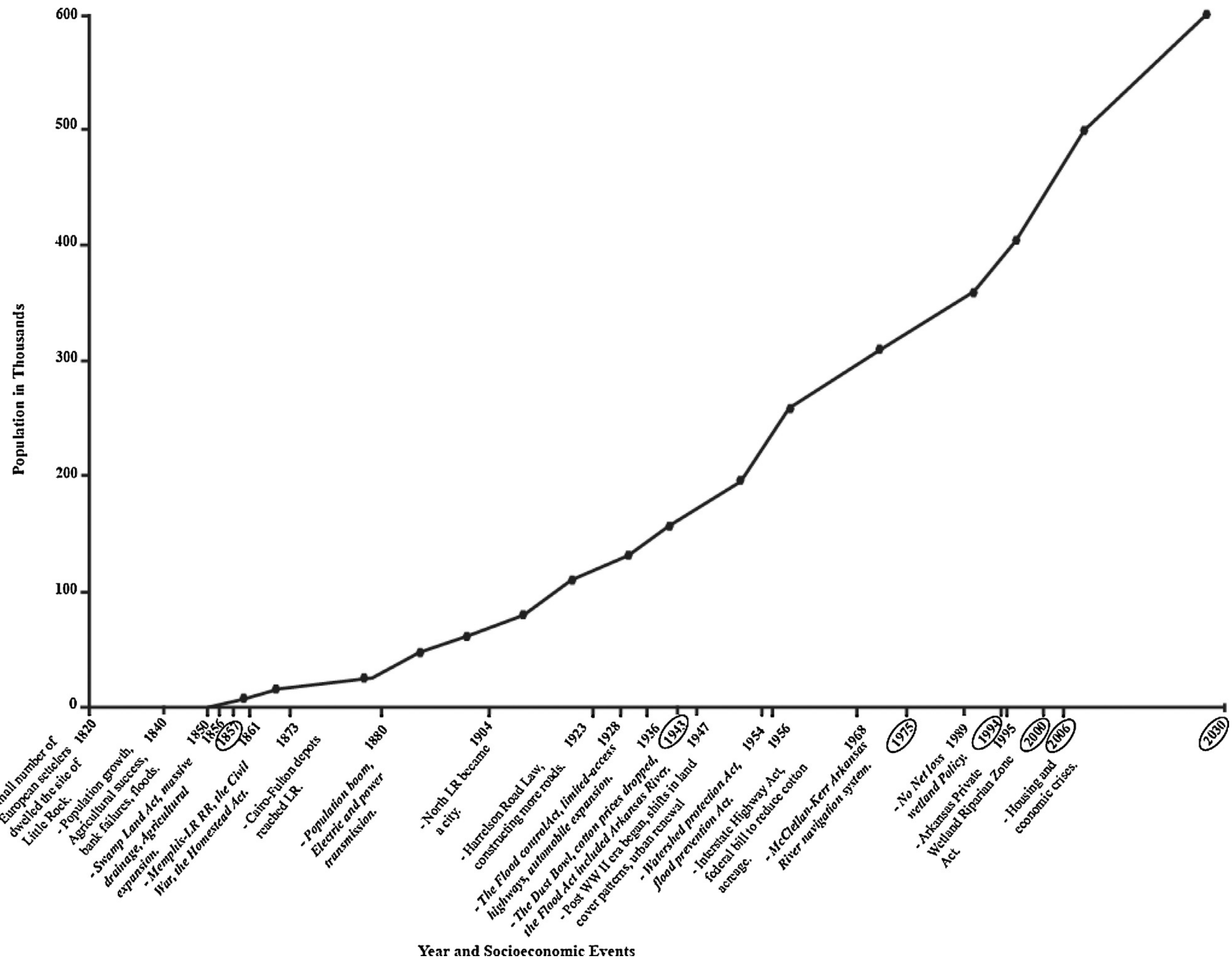

Fig. 2. Population growth and key socioeconomic events relevant to land cover changes in central Arkansas. Ellipses denote dates of land cover datasets and bold italic text indicates key socioeconomic events. Population in 2030 was derived from Arkansas Population Projections: 2005–2030 http://sitemaker.umich.

coding scheme in ArcGIS. A slope layer (in percentage) was processed and created using the National Elevation Dataset (NED) (Gesch et al., 2002). We extracted water bodies from the land cover maps for the years: 1857, 1943, 1975, 1994, 2000, and 2006. We used Omernik ecoregions (Omernik, 1987) to create a distance to ecoregion boundary layer. The selection of these physiographic attributes was guided by intensive study of the early history of the study area.

Given that infrastructure also influences development, we included data on roads (which promote development) and protected areas (which limit development). Roads were obtained from the U.S. Census Bureau TIGER/line files (U.S. Census Bureau, 2012). Protected areas were obtained from the Protected Areas Database (PAD-US 1.1) (CBI, 2010), which includes all national available spatial data on designated protected areas. In this layer, protected lands are coded with GAP status classes ranging from 1 to 4. Classes 1 and 2 have the highest degree of protection from development and therefore were given an exclusion value of 100. Class 3 has some level of protection, but also supports multiple uses that may lead to eventual development. Class 4 has no known public/private institutional mandates and therefore we assumed these areas are open for development.

Some of the attributes were static (i.e., maintained the same space throughout the entire study period) while others (e.g. water bodies and wetlands) were dynamic, meaning that we extracted them from the land cover maps of the start date in each period. Adjacency to some features was established by creating a 420 m buffer outside of the features. This value of 420 m was selected because it represents a typical size of land allotments.

2.3. Urban growth model

2.3.1. SLEUTH description and inputs

A modified version of SLEUTH (SLEUTH-3r) was released with considerable improvements in capturing dispersed settlement patterns, model processing speed, and more relevant statistical metrics (Jantz et al., 2010). We used the SLEUTH-3r to model urban growth at 60 m resolution (60 m × 60 m cells) to the year 2030. The 2030 simulation was based on historical growth patterns from 1975 to 2006 and assumed a linear population growth over this period, which Fig. 2 approximates. This is as far into the future as we felt comfortable modeling because 2030 was the extent of confident population and economic predictions at the time of our study. In addition, the uncertainty for long-term urbanization projections increases beyond 30–40 years (Fragkias, Günerlap, Seto, & Goodness, 2013).

Being a cellular automata model, SLEUTH simulates urban growth as a grid of cells that can change state via cell interactions. Whether or not a cell becomes urbanized is determined by four growth rules: spontaneous growth, new spreading center growth, edge growth, and road-influenced growth. These four growth types are applied sequentially during each growth cycle, and are controlled through the interactions of five growth coefficients: dispersion, breed, spread, road gravity, and slope (more details in

Table 2
SLEUTH urban growth model inputs.

Input	Data source
Slope, hillshade	Derived from the National Elevation Dataset (NED). Retrieved from: http://datagateway.nrcs.usda.gov/
1975 Urban extent	Adopted from modified GIRAS land cover map (Jawarneh & Julian, 2012). Original map retrieved from: http://eros.usgs.gov/
1994 & 2000 Urban extents	Derived from the 1992 to 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 roads	Derived from TIGER\Line files.
	Retrieved from: http://www.census.gov/geo/www/tiger/
Exclusion layer	Multiple variables and different sources; refer to Table 3

Table 3
SLEUTH exclusion layer variables and values.

Input	Data source (reference)	Exclusion values
Protected lands	Derived from PAD-US 1.1 (CBI, 2010)	100 (Classes 1 and 2); 78 (Class 3)
Wetlands	Derived from the National Wetlands Inventory (U.S. Fish and Wildlife Service, 1980) and digitized USGS Digital Raster Graph (USGS, 1996)	79
Riparian buffer (30 m)	Derived from the National Hydrography Dataset (USGS, 2005)	60
Water bodies	Derived from 2006 NLCD (Fry et al., 2011)	100

Clarke et al., 1997). Although SLEUTH is a pattern-based model, its ability to simulate the complex behaviors of cities to recreate the spatial patterns of urban development is comparable to other socioeconomic models, especially at regional scales (Jantz, Goetz, & Shelley, 2003; Suarez-Rubio et al., 2012).

The inputs we used for SLEUTH were: 1975, 1994, 2000, and 2006 urban extents; 1975, 1992, 2000, and 2007 road networks; land surface slope; hillshade image; and exclusion layer (Table 2). Urban coverage was obtained from the land cover timeline of Jawarneh and Julian (2012). For the road network, we used "primary roads" (i.e., roads with TIGER Census Feature Class Code (CFCC) of "A"), which were derived from USGS Digital Line Graphs (1975) and TIGER shapefiles (1992, 2000, and 2007). We only included primary roads based on the assumption that regional urban expansion is highly influenced by this type of transportation network (Jantz et al., 2010). A 30 m resolution National Elevation Dataset (NED) was resampled to create 60 m resolution inputs for slope and hillshade. All the map inputs for slope, exclusion, urbanization, roads, and hillshade were converted to 8-bit GIF format used by the SLEUTH-3r model (Fig. 3).

2.3.2. *Derivation of Magnitude of Relative Change (MRC)*

In SLEUTH's exclusion layer, each variable is given an exclusion probability from 0 (no exclusion; attracts development) to 1 (completely excluded; prevents development). A value of 0.5 indicates neutrality, neither attracting nor preventing development. For compatibility with other SLEUTH inputs (range: 0–100), these probabilities were multiplied by 100. To empirically calculate exclusion probabilities, we first developed a Magnitude of Relative Change (MRC) model by which historical urban growth within a given attribute (e.g. riparian buffer) is measured relative to historical urban growth across the entire study area:

$$\mathrm{MRC}(x) = \frac{U_x}{U_t} \qquad (1)$$

where U_x is the yearly change of urban pixels per area within attribute x and U_t is the yearly change of urban pixels per area for the entire study area. These U values are calculated by taking the difference of urban land in attribute x between two consecutive land cover datasets, dividing that difference by the number of years between datasets, and finally dividing this value by the area of attribute x (or entire study area for t). An MRC value of 0.33 indicates that urban land grew in the riparian buffer at a third of the rate as urban growth in the entire study area, hence Magnitude of Relative Change. Once the MRC is known, the exclusion probability for attribute x (Ep_x) can be calculated as follows:

$$\mathrm{Ep}_x = \frac{(1 - \mathrm{MRC})}{2} + 0.5 \qquad (2)$$

which takes into account the 0.5 neutral value. In this example, riparian buffers would have an exclusion value of 84 in the SLEUTH model, which limits urban growth in riparian buffers. If the MRC was 2 (i.e., urban land in riparian buffers grew at twice the rate of urban growth in study area), then the exclusion value would be 0, which attracts growth in riparian buffers. Any MRCs greater than 2 were constrained to 2 in order to prevent negative exclusion probabilities.

2.3.3. *SLEUTH exclusion probabilities*

In order to develop a comprehensive exclusion layer, we incorporated several physiographic and infrastructure attributes that are believed to influence land cover change. These variables were: protected lands, wetlands, water bodies, and riparian buffers. We used the 1994 and 2006 NLCDs to calculate MRC and exclusion probabilities for each of the above variables (Table 3).

We identified protected lands with class 3 code and calculated exclusion probabilities using the MRC model. Water bodies were extracted from the 2006 land cover map and they were completely excluded from urban development ($\mathrm{Ep}_{water} = 100$). All the variables were then combined into one exclusion layer using the *Maximum* function in ArcGIS raster calculator (ESRI, 2011).

2.3.4. *Calibration of the SLEUTH-3r model*

While the calibration process is usually performed in three phases; coarse, fine, and final, prior research has shown negligible gains in performance among these phases (Jantz et al., 2010). To avoid inaccuracies resulted from cell size sensitivity; the full spatial resolution (60 m) dataset was used. We performed coarse calibration of SLEUTH-3r in which all growth coefficients were tested in increments of 25, from 1 to 100. We first tested for and set the appropriate Diffusion Multiplier (D_{M}), which captures dispersive growth around each city. We then used 25 Monte Carlo simulations to perform the coarse calibration and derive the five growth coefficients for our study area, including the four control years of 1975, 1994, 2000, and 2006. Our four control years allowed us to use multiple metrics for model validation: *pixel fractional difference* (*PFD*), *cluster fractional difference (CFD)*, *compare*, *edges*, *clusters*, *X-mean*, and *Y-mean* (Dietzel & Clarke, 2007; Jantz et al., 2010). After the best-fit parameters were identified for our study area, we initialized the model in 1975 and ran it in predict mode to 2006 in order to compare to the 2006 NLCD for further comparison and validation.

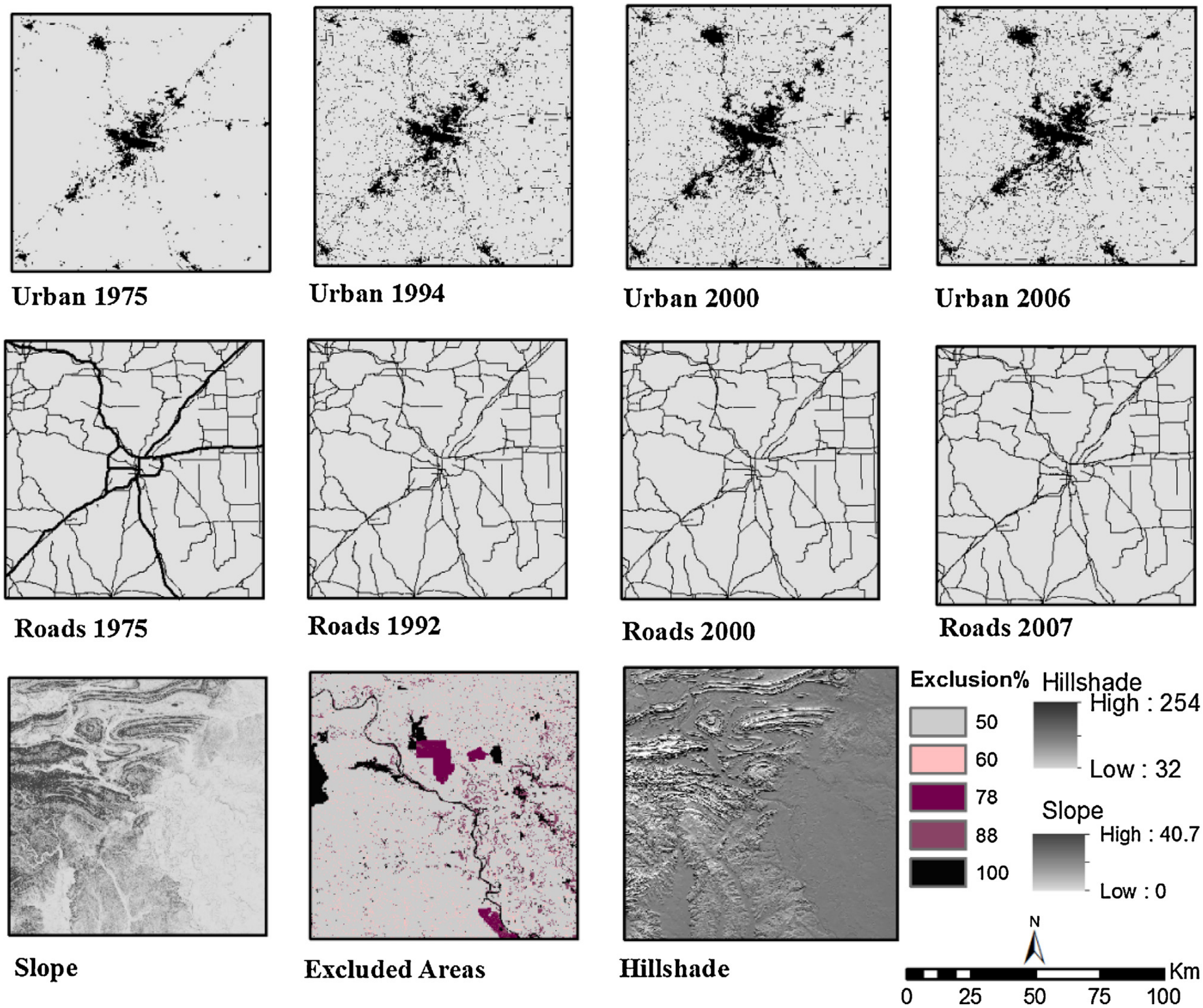

Fig. 3. Central Arkansas input datasets to SLEUTH-3r.

2.3.5. Forecasts to 2030

Once calibrated and validated, we ran the SLEUTH-3r model in prediction mode, beginning in 2006 and ending in 2030. We performed 25 Monte Carlo simulations using the same exclusion layer used for calibration. We did not invoke the self-modification function in SLEUTH-3r because we assumed approximate linear growth in central Arkansas.

2.4. Preferential pathways of development in central Arkansas

In an effort to identify preferential pathways (cell-by-cell) of land development, we used the MRC model (Section 2.3.2) to assess changes in agriculture and urban development in relation to various physiographic features and infrastructure. We calculated land cover changes and MRC for all of the variables provided in Table 1 for five periods: 1857–1943; 1943–1975; 1975–1994; 1994–2000, and 2000–2006. Given the limitations of characterizing agricultural changes with moderate-resolution, we also compiled long-term data on agriculture and farm characteristics using the U.S. Census of Agriculture. The number of farms and total area in farms for the 12 counties in the study area were summarized. We area-normalized these data for the 11 counties that were not completely contained within the study area.

2.5. Ecoregion perspective of land cover change patterns

Spatiotemporal patterns of land cover patches among the four ecoregions were analyzed using FRAGSTATS 3.3 (McGarigal, Cushman, Neel, & Ene, 2002). Because there is no consensus on which set of landscape metrics best characterizes spatiotemporal patterns (Griffith et al., 2003; Gustafson & Parker, 1992; Pijanowski & Robinson, 2011), we only used the percentage of coverage metric, which has been shown to represent the main aspects of landscape patterns and composition (Wang & Malanson, 2007).

We then calculated a change matrix from the land cover timeline and from the SLEUTH output to analyze leading conversions between classes and the percentage of change for the following periods: 1857–1943; 1943–1975; 1975–1994; 1994–2000; 2000–2006; 2006–2030. Further, we quantified the number of times each pixel changed in each ecoregions to identify the most dynamic ecoregions.

3. Results

3.1. Land cover changes 1857–2030

3.1.1. Historical development

In the time frame 1857–2006, changes in agriculture and urban development (Fig. 4) followed general global land cover transitions

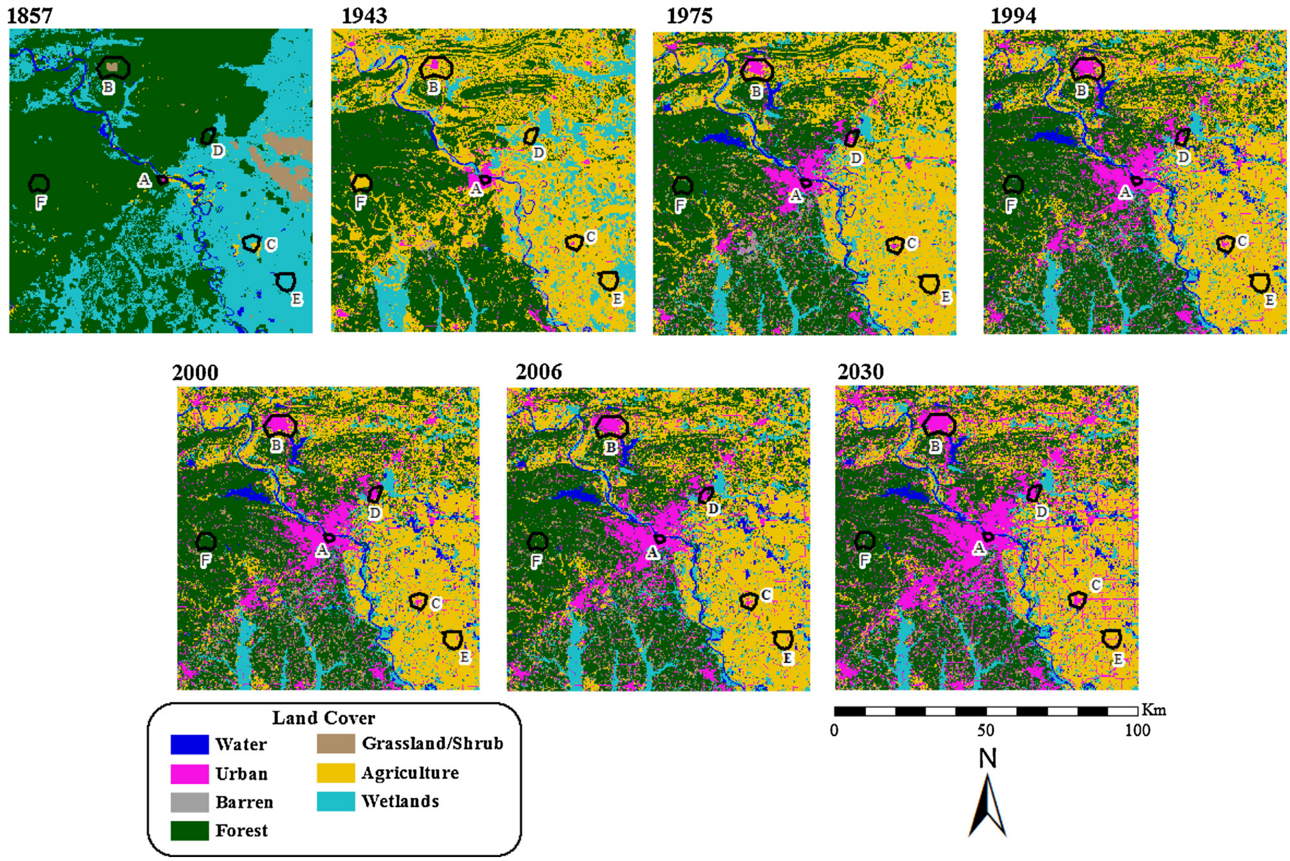

Fig. 4. Land cover timeline for the Little Rock study area at 60 m spatial resolution. Polygons A–F represent examples of different land development transitions relative to physiographic attributes and infrastructure proximity.

since pre-settlement (Foley et al., 2005), where forests were cleared and wetlands were drained for agriculture initially (depicted in 1943), followed by urban expansion and agricultural intensification (depicted in 1975 and onwards) (Jawarneh & Julian, 2012). In 1857, central Arkansas had small agricultural lots (<1%) that were found mostly on floodplains close to settled areas. After the Civil War, forest clearing and wetland drainage began, opening areas for agricultural expansion (Dahl, 1990).

Between 1943 and 1975, rapid technological developments transformed agricultural operations into large corporate farms to meet the accelerating demands for food following the Depression era and World War II (Dimitri, Effland, & Conklin, 2005). Urban expansion also occurred during this stage and onwards (depicted in the last three maps (1994–2006)). Urban areas were transformed from only a few fragmented settlements concentrated around the urban core of Little Rock into spreading areas mainly along the primary transportation corridors.

The long-term land cover dataset allowed us to capture and simulate the growth patterns in central Arkansas with high agreement when compared against historical urban growth patterns (Table 4). The 2006 modeled urbanization was highly correlated with the observed urban land cover for that year ($r^2 = 0.99$). High correlation values were also attained for the form (*cluster* r^2 of 0.77) and shape of urban area (*edges* r^2 of 0.65) between the two maps. In addition, 99% of both the longitudinal (X) and latitudinal (Y) variability in development of the historical map was explained by the simulation.

The final calibration was spatially concordant with the historical map for 95% of the cluster formations (Table 4). The high score of the road gravity parameter showed that historic urban growth was affected by transportation infrastructures (Table 4). The spread parameter was also high, reflecting a high probability of urbanization spreading outward from the existing urban centers.

3.1.2. *Projected urban growth to 2030*

The results for the 2030 SLEUTH forecasts for central Arkansas (Fig. 4) indicate a continuation of urban development along the major transportation networks, particularly along I-30 towards Benton and I-67 towards Cabot (see Fig. 1 for reference). This intense northeasterly–southwesterly spread in urban growth also follows the geological boundary that separates the mountains to the west from the plains to the east. Further, the 2030 land cover map shows a tendency of urban development to spread out of the existing urban centers toward northwest along the I-40 corridor, particularly in the Arkansas Valley and the Ouachita Mountains ecoregions.

Table 4
Calibration and accuracy results for central Arkansas. The actual number of 2006 urban pixels and urban clusters with the simulated 2006 urban pixels and urban clusters are presented in the first four rows. The best growth coefficients scores are out of 100.

Parameters	Count
2006 pixels	285,316
2006 simulated pixels	283,422
2006 clusters	17,311
2006 simulated clusters	16,592

Growth coefficient	Score
Roads gravity	75
Spread	75
Breed	25
Slope	25
Diffusion	25

Table 5
Magnitude of Relative Change (MRC) results for urban development in central Arkansas. Shaded MRCs are >1, indicating considerable urban growth relative to the entire study area. Bolded MRCs are <−1, indicating considerable urban losses relative to the entire study area. Note that there were no considerable urban losses for any period.

Variables	Time intervals				
	1857–1943	1943–1975	1975–1994	1994–2000	2000–2006
Urban coverage (%)	0.1	2.6	6	9.8	10.3
Distance to primary roads	2.8	7	2.4	4.6	4
Distance to Little Rock CBD (km)					
0–10	8.2	8.5	2.5	2.9	3.1
10–20	0.9	2.1	2.3	3.3	5
20–30	0.6	0.9	1	0.9	1.1
30–40	0.7	0.7	0.8	0.8	0.3
40–50	0.7	0.5	0.8	0.7	0.6
Slope					
<5	1	0.9	0.9	0.8	0.7
5–10%	1.3	1.5	1.3	1.9	1.4
10–15%	0.4	0.8	1	1.2	1.5
15–20%	0.4	0.3	0.8	0.9	2.1
>20%	0.2	0.3	−**0.4**	0.4	0.9
Adjacency to river	1	0.5	0.8	0.6	1.2
Adjacency to water body	0.8	0.8	1.1	0.9	0.8
Adjacency to wetlands	0.9	0.8	0.9	0.8	0.6
Wetlands	0.7	0.6	0.1	0.6	0.5
Distance to ecoregion boundaries					
0–5 km	1.7	1.9	1.4	1.9	2.2
5–10 km	0.7	0.7	1.2	0.9	0.7
10–15 km	0.6	0.3	0.7	0.6	−**0.1**
15–20 km	0.5	0.4	0.5	0.1	0.2
20–25 km	0.5	0.4	0.5	−**0.2**	0.6
Water bodies	0.1	0.3	0.5	0.3	0.7
Riparian zone	0.5	0.6	0.7	0.6	1.1

3.2. Land development changes relative to physiography and infrastructure

The Magnitude of Relative Change (MRC) results varied, between agriculture and urban development as well as among periods (Tables 5 and 6). Urban development increased mainly in areas close to primary roads, especially in the second time period (MRC of 7). It also increased in areas that were located within 20 km from Little Rock. For urban growth, slopes from 5 to 10% were the most preferred, almost exclusively until 2000 (Table 5). Only

Table 6
Magnitude of Relative Change (MRC) results for agricultural development in central Arkansas. Shaded MRCs are >1, indicating considerable agricultural growth relative to the entire study area. Bolded MRCs are <−1, indicating considerable agricultural losses relative to the entire study area.

Variables	Time intervals				
	1857–1943	1943–1975	1975–1994	1994–2000	2000–2006
Ag coverage (%)	44.6	38.4	33.6	33.8	33.3
Distance to primary roads	1.1	−**4.5**	−0.8	2.7	1.6
Distance to Little Rock CBD (km)					
0–10	0.8	−**4.2**	−0.6	0.7	−**1.8**
10–20	1	−**3.3**	−0.3	2.5	−**1.3**
20–30	0.5	−**1.5**	−0.6	6	−0.7
30–40	0.9	−0.9	−0.8	2.7	−0.8
40–50	1	−0.4	−**1.2**	−**2.6**	−0.9
Slope					
<5	1.2	−0.6	−**1.3**	0.6	−**1.4**
5–10%	0.7	−**2.5**	−0.5	3.1	−0.4
10–15%	0.2	−**1.6**	−**3.2**	0.7	0.8
15–20%	0.3	−**1**	0.2	0.3	0.5
>20%	0.2	−0.7	−0.3	0.2	−0.4
Adjacency to river	1.2	−**1.5**	0.8	5.1	3
Adjacency to water body	0.1	2.1	1.1	−**1**	1.6
Adjacency to wetlands	0.8	−**1.1**	1.4	−**1.5**	1.3
Wetlands	1.3	−0.3	−0.6	9	−**10.8**
Distance to ecoregion boundaries					
0–5 km	1	2.2	1.1	6.2	1.6
5–10 km	1	1.6	−0.9	0.8	1.1
10–15 km	0.9	0.6	0.8	4	−0.7
15–20 km	0.9	−0.6	1.2	−**6**	0.6
20–25 km	0.9	−0.5	1.2	−**8**	0.5
Water bodies	0.8	−**2.4**	−**2**	5	−**10.4**
Riparian zone	0.9	−**1.4**	−**2**	0.9	4.3

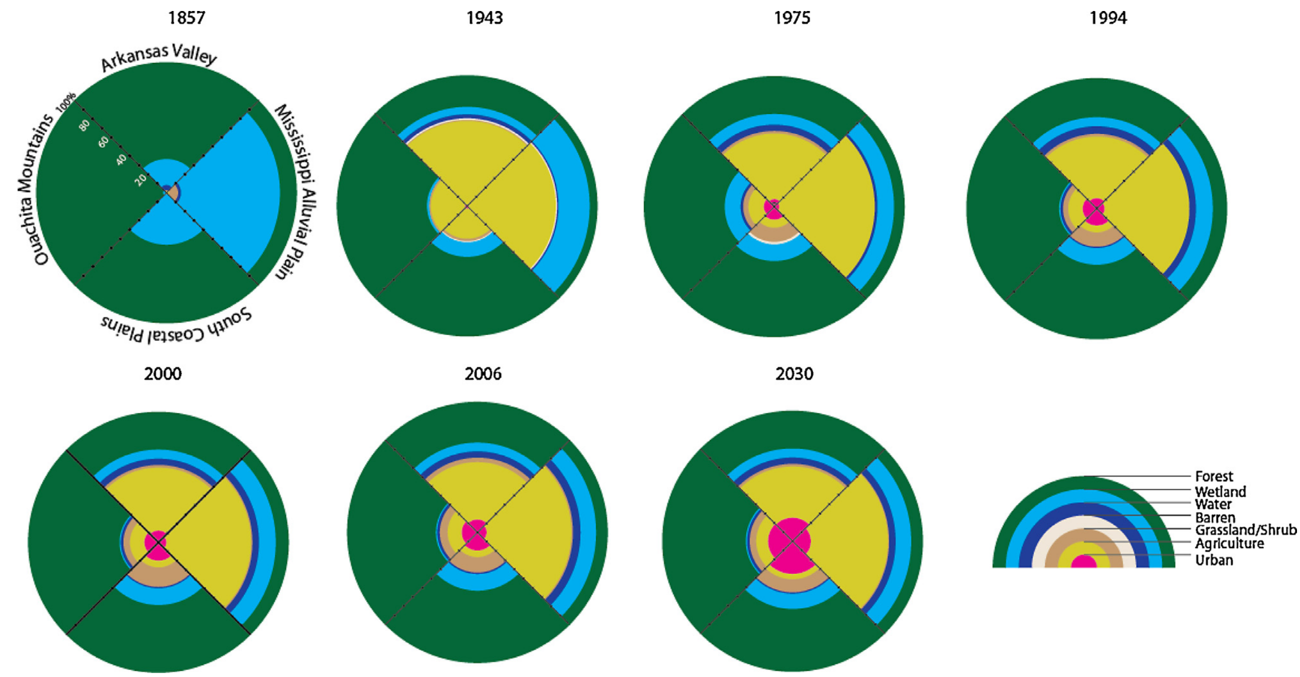

Fig. 5. Land cover composition within each ecoregion and over time in central Arkansas.

after 2000 was there substantial development along steeper slopes. Urban growth in central Arkansas was common within 5 km from ecoregion boundaries. Beyond these attributes, there were no consistent patterns of urban growth with other landscape features (i.e., water bodies, wetlands, and riparian zones). Interestingly, there were no quantifiable losses of urban land anywhere within the study area for the entire period.

Agricultural change was more sporadic. The overall amount of agriculture in central Arkansas decreased from 44.6% to 33.3% of the landscape from 1857 to 2006 (Table 6). While urban land increased during every study period, total land area in agriculture increased from 1857 to 1943 but decreased by more than 13% between 1943 and 2006. The early increases in agriculture occurred mostly in flat areas, particularly in former wetlands or near the Arkansas River. Results also showed that areas adjacent to primary roads were preferred for agricultural development, particularly in the first and later periods. Note that the losses of agriculture near primary roads between 1943 and 1994 coincided with urban gains in those locations. Like urban development, areas adjacent to ecoregion boundaries were also preferred for agricultural development.

3.3. Ecoregion perspective of land cover change

Patterns of land cover change varied among ecoregions (Fig. 5). In 1857, forest dominated the Ouachita Mountains, the Arkansas Valley, and the South Coastal Plains ecoregions while wetlands dominated the Mississippi Alluvial Plain. By 1943, the Mississippi Alluvial Plains and the Arkansas Valley ecoregions had the highest agricultural coverage in the region. Vast areas of wetlands in the Mississippi Alluvial Plain were transformed into agricultural lands. Urban areas were found on the more elevated areas in the South Coastal Plains, Ouachita Mountains, and Arkansas Valley ecoregions. While the Ouachita Mountains and the Mississippi Alluvial Plain had a single, relatively predominant land cover type (forest and agriculture, respectively), the Arkansas Valley and the South Coastal Plains ecoregions had more mixed land covers.

Some ecoregions were more dynamic in term of land conversion than others. Mapping the spatial pattern of land cover transition over the six periods allowed us to determine where among the four ecoregions most change occurred and how dynamic the change was (Fig. 6). The Arkansas Valley experienced the highest rate of change with 30% of the pixels in the ecoregion changing at least twice. A large number of pixels changed at least three times and some pixels changed six times, meaning that the pixel experienced land conversion in each time step analyzed. Around 80% of the Ouachita Mountains ecoregion experienced no change (forest stayed forest during the study period), and around 15% of the ecoregion changed only once (from forest to urban). Approximately 80% of the Mississippi Alluvial Plain changed only once (from wetlands to agriculture).

The from-to change matrix maps highlighted the dominance of one or two types of land conversions in central Arkansas (Fig. 7). In the 1857–1943 period, the leading conversion was from wetlands to agriculture (21.4%) followed by the conversion from forest to agriculture (20.2%). The transformation from forest to urban happened during this period at a low rate (1.6%). In the next two periods, the leading land conversion was from agriculture to forest (9.4% from 1943 to 1975 and 5.2% from 1975 to 1994). Land conversions from 1994 to 2006 were more evenly mixed among multiple land cover classes.

4. Discussions

4.1. Development processes from the local perspective

Local interactions with the physical environment are a primary determinant of human land use decision-making. Cellular-level analyses and models allow us to better understand these complex, spatial relationships. Development patterns and processes in central Arkansas reflected the layout of the transportation networks and the unique landscape settings. Distance to major roads and distance to major urban clusters highly influenced urban and agricultural development during the study period. While urban growth expanded around already existing urban clusters in the metropolitan counties in the SLEUTH model, agricultural development occurred away from the metropolitan centers. Both types of development occurred at relatively high magnitudes along major roads (i.e., I-40).

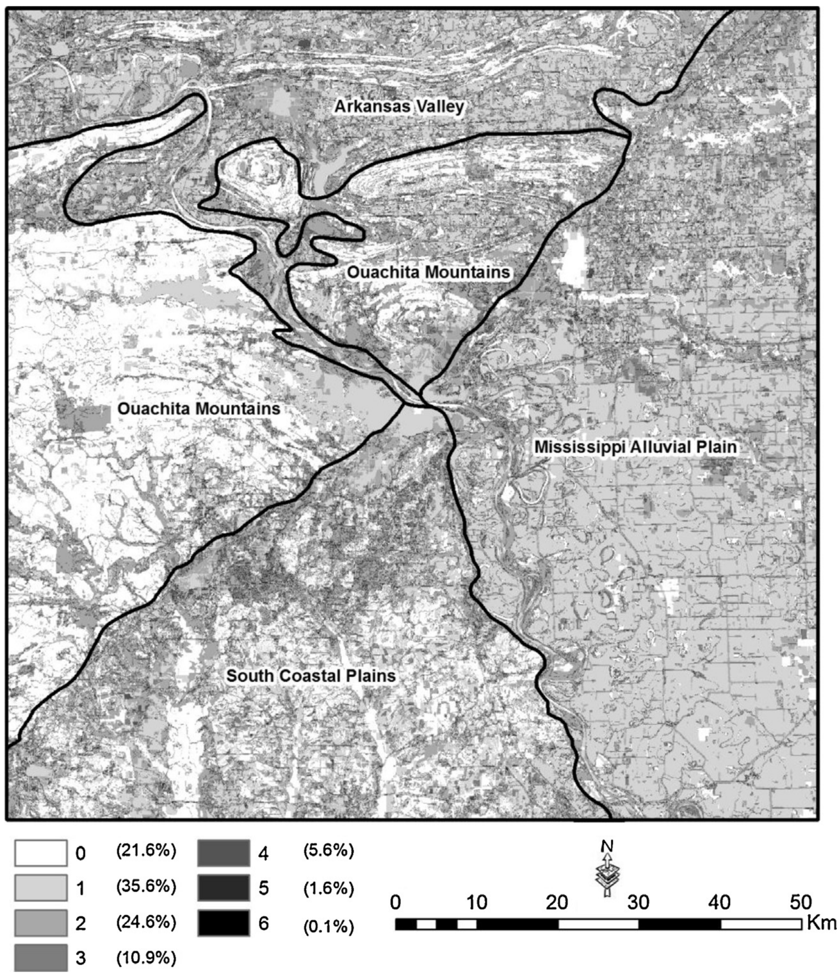

Fig. 6. Number of times that pixels changed in central Arkansas, with percentage of total area in parentheses.

As central Arkansas progressed from Early Settlement to the Post-Industrial phase (Fig. 8), variability in climate and topography dictated land use options and contributed to creating distinct land development patterns. Originally, urban clusters were founded on topographically suitable, higher elevation sites, away from the considerable "swamplands" of the region. These highlands with gentle slopes (5–10%) provided protection from Arkansas River floods (Fig. 4 Polygon A). The soil underlying these urban centers also had less economic value than the fertile soil of the surrounding low-lying grounds. The dispersive small rural-communities scattered over the flat region of central Arkansas (Fig. 4 Polygon C), were founded later, following technological advancements such as the construction of large impoundments (McClellan-Kerr Arkansas River navigation system). This flat region (with slope less than 5%) was more suitable for large-scale plantation operations due to its sedimentary, deep alluvial loamy soil, which is unstable for many urban activities.

While the flat region attracted heavy agricultural operations, diversified and fragmented farming activities (i.e., orchards, livestock grazing, hay fields, and cultivated crops) were begun in the highlands during a period of Agricultural Expansion in the early 20th century (i.e., the number of farms and the amount of land in agriculture both doubled from 1880 to 1940). Following this era, agricultural area declined in the highlands and was replaced by either urban expansion (Fig. 4 Polygon B) or by forest regeneration (Fig. 4 Polygon F). However, the flat region maintained the highest proportion of agricultural areas. At this time, urban areas flourished in the highlands, particularly around the ecoregion boundaries between the mountains and the plains and along major transportation corridors (Fig. 4 Polygons A and D). The importance of physiographic boundaries, such as those occurring along topographic fall lines, in catalyzing urban development has been well documented elsewhere (e.g. Gallant, Loveland, Sohl, & Napton, 2004). The placement of major metropolitan cities (e.g. Baltimor and Richmond) in the US falls on ecoregion edges, which is primarily related to transportation technology. In fact, these boundaries marked goods transfer point from one form of transportation to another.

Later, as peripheral farmlands on steeper slopes were abandoned, the land was consumed by urbanization during the Post-Industrial era. Although topography played a less prominent role than in earlier years due to advances in technology, urban development on the flat areas continued to be topographically constrained by their propensity to flood and the very deep and sedimentary soil. Such interlinked relationships between topography and development at fine-scale lead to more comprehensive land change processes at the ecoregional level.

4.2. Land cover patterns from regional perspective in central Arkansas

While detailed understanding of physiography helps to explain the processes that dictate land cover change at fine scales, land cover changes can also exhibit broader, regional patterns associated

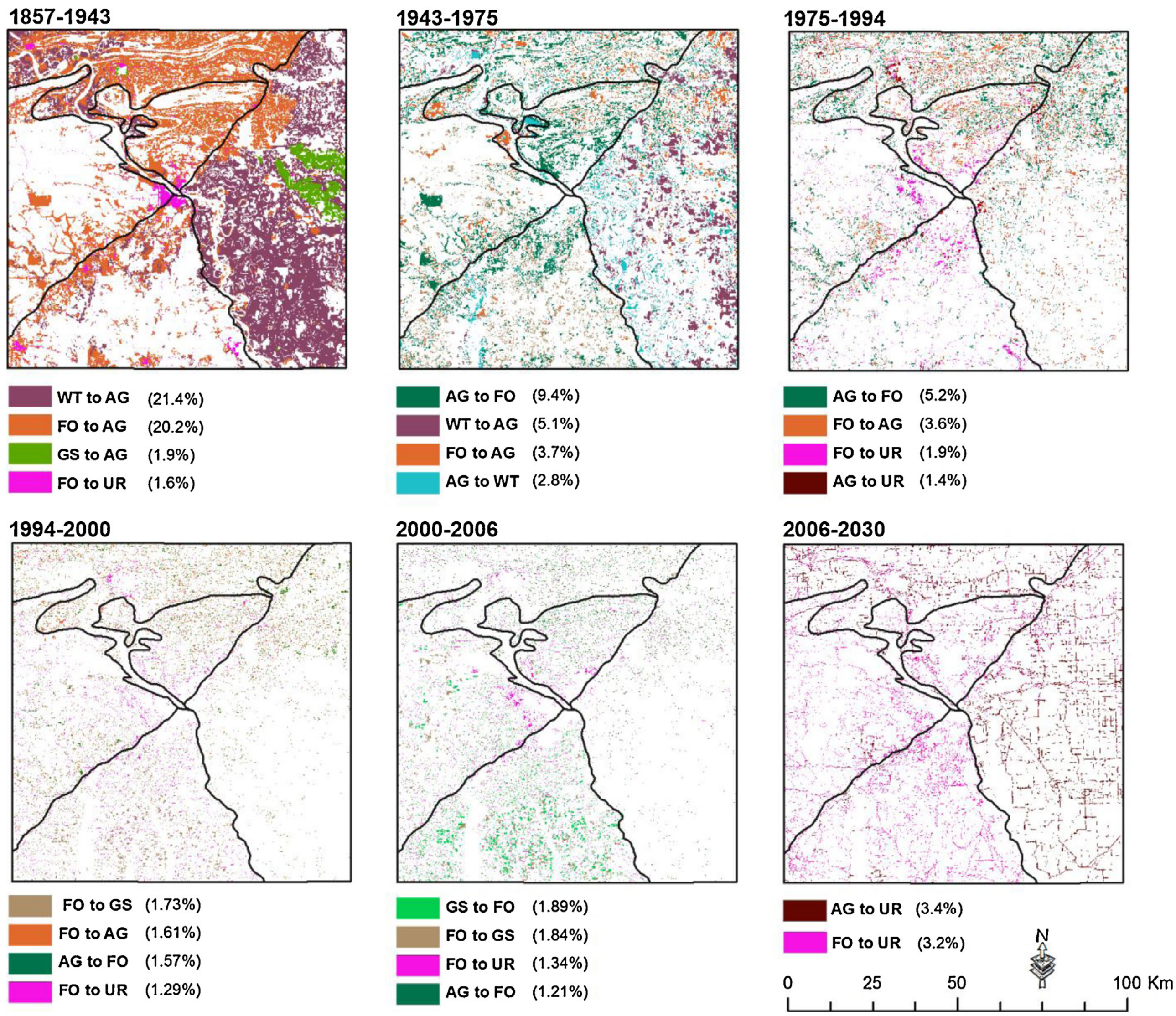

Fig. 7. Land cover conversions in central Arkansas, with percentage of land area in each time interval in parentheses. The 2030 map only contains urban conversions due to limitation of only using urban growth model. FO, forest; UR, urban; AG, agriculture; GS, grassland/shrubland; WT, wetlands.

with physical geography that are captured by cellular automaton model (Loveland & Mahmood, 2014). Indeed, we found distinct patterns for each of the four ecoregions in our study area, which we detail below.

4.2.1. *Arkansas Valley*

The broad floodplains and the scattered hills, mountains, and terraces of the Arkansas Valley ecoregion promote a highly mixed pattern of forests, agriculture, grasslands, and water bodies (Fig. 5). The heterogeneity of land cover types in this ecoregion results from the heterogeneity in landscape terrains. The Arkansas River floodplain includes natural levees, meander scars, oxbow lakes, point bars, swales and back swamps. Vegetation within the floodplain is dominated by bottomland deciduous forest. The Arkansas Valley hills are more rugged than the Arkansas River floodplains and support natural vegetation of oak-hickory-pine forest. This ecoregion is the most dynamic among the four. Over 30% of the pixels in the ecoregion changed at least three times during the study period and some parts changed in all six time steps (Fig. 6). The Arkansas Valley experienced the highest rate of change in the entire Eastern United States (Reker et al., 2014).

4.2.2. *South Coastal Plains*

Occupying the rolling plains, the South Coastal Plains ecoregion has nearly homogenous forest cover, with numerous bottomland wetlands (Fig. 5). These two predominant land covers were promoted by the homogenous landscape terrains. Whereas the rolling uplands are dominated by managed-commercial pine plantations, the floodplains and low terraces are nearly level and covered with forested wetlands (Reker et al., 2014). Many small urban clusters are found along the physiographic boundary on the northern edge of the ecoregion (TNC, 2003). This ecoregion is the second most dynamic among the four. Over 20% of the pixels in the ecoregion changed at least three times during the study period and small parts changed in all six time steps (Fig. 6).

4.2.3. *Ouachita Mountains*

The rugged terrain, steep slopes, and infertile soil of the Ouachita Mountains ecoregion promote one predominate pattern of forest cover (Fig. 5). Small agricultural operations (mainly hayland, pasturelands, poultry production) are limited to valley bottoms. The homogeneity of land cover in this region is due to the homogeneity in landscape terrains. The ridges and hills of the ecoregion are covered with oak-hickory-pine forest and extensive pine plantation

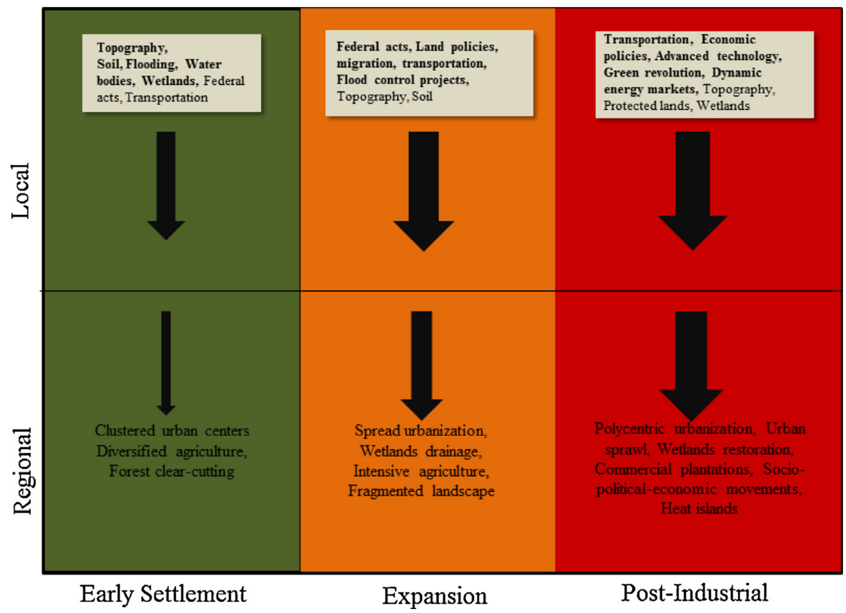

Fig. 8. Conceptual framework showing the influential factors affecting land development in different stages (top) and the predominant land cover changes (bottom). Drivers (on the top) in bold indicate primary factors affecting land development. The color of each stage denotes the predominant land cover type: green indicates natural landscape; orange indicates heavily agricultural landscape; and red indicates human-induced landscape. Arrow width indicates footprints of change at the local and regional scales. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(Woods et al., 2004). This ecoregion is the least dynamic among the four. Over 70% of the pixels in the ecoregion did not change during the study period and some parts changed only once in all six time steps (Fig. 6).

4.2.4. Mississippi Alluvial Plain

The broad flat plains of the Mississippi Alluvial Plain ecoregion promote a highly unique pattern of large-scale farming and continuous wetlands (Fig. 5). This homogeneity of land cover results from the homogenous level terrain. In fact, this ecoregion includes the largest continuous system of wetlands in North America and contains the major agricultural operation in the state of Arkansas (Woods et al., 2004). Bottomland deciduous forest cover was historically predominant but cleared and drained for cultivation. Currently, most of the region is in cropland and receives heavy treatments of insecticides and herbicides. Soybeans, cotton, and rice are the major crops; however, commercial catfish farms are growing (Omernik & Griffith, 2012). Over 80% of the pixels in this ecoregion changed only once during the study period (Fig. 6).

4.3. Connecting development patterns and processes

Clearly, physiography has been an influential driver of landscape change in central Arkansas. However, the patterns of land development observed, at both the local and ecoregion levels, can only be fully understood within the context of a multivariate framework of human decision processes. These processes are representative of a general land use trajectory from forested Early Settlement to an urban Post-Industrial society (Fig. 8). The distinguishable physiographic boundaries in central Arkansas largely set the initial locations for rural–urban transitions (through 1975) and maintained a relatively balanced urban–rural fringe. These initial land conversions are typically strongly shaped by the physical environment, as they were in central Arkansas. Later transitions are increasingly influenced by socioeconomic factors.

In the Early Settlement stage, the physiographic settings (i.e., topography, landscape, soil) of central Arkansas played the primary role in dictating land development process (Fig. 8). The site of present Little Rock was initially founded as a small-clustered urban center on the south bank of the Arkansas River. Agricultural practices were limited to small fragmented farms around the urban cluster. The north bank of the Arkansas was a flood-prone area, which constrained land development. Early attempts to develop this flat northern shore largely failed. For example, several lots were sold to establish a settlement (D'Cantillon) on the north bank, but this town never got off the ground because large portions of it were washed away by the 1840s flood (Adams, 1986; Nutt, 1993; Richards, 1969). Following the Civil War, the population began to increase in the region and the countryside was cleared of timber to meet the need for more open spaces. The population tripled during this period due to increasing domestic migration and railroad expansion (Fig. 2) (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 wards was carried out, further increasing the city's population and metropolitan area.

To meet the subsequent need for additional food and housing, new institutional policies were introduced to mitigate flooding hazard and open the flat region for development. At the national level, the Swamp Land Grant/Act was declared in 1850. While the Swamp Land Grant enabled the State of Arkansas and others to reclaim swamplands unfit for cultivation by constructing 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 years of unusual heavy precipitation, the swelling Mississippi overflowed, damaging the new settlers' newly cultivated fields. In 1936, the Flood Control Act of 1927 was extended to include the Mississippi tributaries, meaning that the Arkansas River became included in the act.

Transportation infrastructure in this early stage had minimal impact on land development. In 1853, a transportation bill was passed to build the Little Rock-Memphis railroad, which first reached the town of Huntersville in 1861 (on the north shore of the Arkansas River). This railroad did not influence urban and agriculture development, because it ran primarily through swamplands. However, the Cairo and Fulton railroad had substantial impacts on development, because it ran near some of the richest farmlands in the state along the foothills of the Ozark range. This railroad helped erect the first bridge, Baring Cross Bridge, over the Arkansas River in 1873 (Richards, 1969). More technological advancements were made in the fields of flood control and transportation that led to increased opportunities for urban and agriculture development. These advances moved the region into a new stage that was relatively less dictated by the environment.

During the Expansion stage (early and mid-20th century), urban growth extends outward from the urban centers and becomes more strongly associated with primary roads. This spatial patterning was clearly evident in central Arkansas. Also, urban areas consistently began to expand towards flat regions due to the construction of large impoundments (e.g. the McClellan-Kerr Arkansas River navigation system). Massive wetlands were transformed to large-scale farmlands as a response to new dams and similar water projects. In this stage, agriculture intensified due to rapid technological advancements and increasing demand for food following the Depression era and during World War II. Row crop farming did not last long in these settings and most of these farms were eventually abandoned (Smith, 1986).

During the second half of the 20th century, additional technological advances and strict land management policies further influenced land development processes: intensive, large-scale farming operations dominated; rice and soybean plantations largely replaced cotton plantations in the flat region; and a federal farm bill was passed to reduce cotton acreage in 1956. The number of farms in central Arkansas declined from 11,245 in 1956 to 3620 farms in 2007 (U.S. Bureau of the Census, 2007). At the same time, the extent of farmland declined from 5184 km^2 to 3626 km^2. Here, it is important to note that since 1850 the USDA Census of Agriculture definition of a farm has changed nine times, and these changes could have impacted the statistics. It is also noteworthy that although the total amount of land in agriculture declined, the amount of agriculture in lowland areas remained relatively unchanged. The processes of agriculture abandonment, urban expansion, and forest regeneration occurring in the uplands have been largely absent from the plains region.

The Post-Industrial stage was also characterized by the expansion of urban areas around the periphery of existing urban centers. This widespread growth was empowered by improvements to the transportation infrastructure, especially the building of highways and interstates in the region. Urban development in central Arkansas now tracks the I-40, I-30, and U.S. Route 67 corridors. These highways were originally built to fit the topographic variation in the area. Consequently, urban development extended diagonally along the Ozark foothills, enforcing a northeasterly–southwesterly growth trend. Other policy factors influencing land transitions during recent years included an increase in the amount of protected lands and the issuance of conservation acts such as the ‘No Net Loss’ wetlands policy, and the Arkansas Private Wetlands Riparian Zone Creation and Restoration Incentive Act. In a switch from local scale forces being the dominant drivers of regional pattern, broad-scale influences such as socio-political movements and regional heat island effects begin to dictate local decision-making in a more pronounced way.

Our conceptual multivariate framework of human decision processes broadly summarizes the drivers of land development across a large heterogeneous region. By including these multi-scale drivers in a land use model linked to MRC analysis, this framework can be applied to other regions around the world. The study area was situated in one of the most complicated physiographic settings in the US, which allowed us to observe a wide range of environmental drivers of land development, especially in early stages. It is likely that only a subset of these drivers will be applicable in most regions. The drivers in the Post-Industrial stage are now recognized as potential global drivers of land development. How these drivers and consequent land cover change will impact global (and regional) climate and ecosystem services is yet to be full explored.

5. Conclusions

Studying the historical patterns of land use change provides valuable insights into the complex and interdependent variables that drive development at local and regional scales. Landscape change in central Arkansas was strongly influenced by local physiography, especially in the Early Settlement phase of development, but continuing into later phases. These relationships can be modeled effectively with a cellular automaton calibrated with a Magnitude of Relative Change (MRC) analysis. As ecological processes become increasingly entangled with social and political processes, land development decision-making will be determined by a balance of physiographic and socio-economic factors (Grimm et al., 2008). Unraveling these relationships must additionally confront the challenge of their interlinkages with factors such as climate change, dynamic energy markets, and evolving urban values. The type of moderate resolution spatial modeling of long-term land use data provided here lays the foundation for future policy assessment and predictive analysis of landscape change within increasingly human-dominated systems.

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