Simulating Sprawl

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Suburban sprawl, a relatively recent phenomenon, is among the most important urban policy issues facing contemporary cities. To date, a well-accepted rationale has not been settled on for explaining and managing the causes of sprawl. Our contention is that consideration of geography is essential—that geographical explanations offer much potential in informing the debate about sprawl. Similarly, spatial simulation could support sprawl-related research, offering what-if experimentation environments for exploring issues relating to the phenomenon. Sprawling cities may be considered as complex adaptive systems, and this warrants use of methodology that can accommodate the space-time dynamics of many interacting entities. Automata tools are well-suited to representation of such systems, but could be better formulated to capture the uniquely geographical traits of phenomena such as sprawl. By means of illustrating this point, the development of a model for simulating the geographic dynamics of suburban sprawl is discussed. The model is formulated using geographic automata and is used to develop three sprawl simulations. The implications of those applications are discussed in the context of exploring geographic explanations of sprawl formation and the potential for managing sprawl by geographic means. *Key Words: cellular automata, geosimulation, GIScience, multiagent systems, suburban sprawl.*

Urban systems are evolving and emerging in surprising ways. This is particularly true in the United States; its urban geography has essentially been redrawn over the past fifty years. The phenomenon of suburban sprawl is the poster-child for these kinds of transformations. Sprawl is a relatively new form of urbanization, falling somewhere between Ebenezer Howard's ideas for Garden Cities and Le Corbusier's notions of a ubiquitous urban form, yet it is altogether different—a "geography of nowhere," as authors have referred to it (Kunstler 1993).

Sprawl is among the most important topics in urban studies. Its implications are well-understood, but the factors behind the phenomenon are less so. Several drivers are suggested in the literature but are not easily experimented with on the ground. Growth management policies are present in several U.S. cities, but their efficacy has yet to be determined. This article discusses construction of a computer model of suburban sprawl drivers used to test ideas about the geographical factors underlying sprawl formation. Automata-based tools are used, with an extension to the conventional automata scheme, intended to represent geographic dynamics of agents of change that are responsible for sprawl. The resulting simulations are used as an artificial laboratory for exploring scenarios for urban growth.

There are several motivations underpinning the work that we present here. First, simulation is crucial to understanding sprawl and exploring alternative growth scenarios. Second, an automata approach has advantages in this regard, particularly in representing the agents of change that may be responsible for sprawl. Third, geography is essential to the phenomenon and must be incorporated directly into the methodology and model design.

The article is organized as follows. The topic of sprawl is introduced through discussion of its consequences and causes, as well as the need for a geographical perspective. Existing work relating to sprawl is described, with a focus on our contention that automata models are the most appropriate tools for simulating sprawl and should be the foundation for further research in this area. We present a conceptual model of sprawl based on sprawl drivers and agents of change, followed by description of the design of a computer model of sprawl. Several simulation experiments were run using the model, each exploring different aspects of sprawl formation from a geographical perspective. The empirical measurement of sprawl in those simulations is described, and implications of the experiments for understanding sprawl are discussed.

Sprawl Characteristics and Consequences

Sprawl is a new form of urbanization with characteristics that are distinct when compared to the urbanization that came before it or the urbanization that is developed under alternative (smart growth) regimes. A number of attributes are important in defining sprawl.

First, sprawl is a process of urbanization—urban growth by suburbanization. This process is quite rapid and is characteristic of the expansion of some of the fastest-growing cities in the United States (Table 1). The

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Table 1. The top ten fastest-growing cities in the United States

Rank	Metropolitan area name	Census population		Change 1990–2000	
		April 1990	April 2000	Number	%
1	Las Vegas, NV–AZ	852,737	1,563,282	710,545	83.3%
2	Naples, FL	152,099	251,377	99,278	65.3%
3	Yuma, AZ	106,895	160,026	53,131	49.7%
4	McAllen–Edinburg–Mission, TX	383,545	569,463	185,918	48.5%
5	Austin–San Marcos, TX	846,227	1,249,763	403,536	47.7%
6	Fayetteville–Springdale–Rogers, AR	210,908	311,121	100,213	47.5%
7	Boise City, ID	295,851	432,345	136,494	46.1%
8	Phoenix-Mesa, AZ	2,238,480	3,251,876	1,013,396	45.3%
9	Laredo, TX	133,239	193,117	59,878	44.9%
10	Provo–Orem, UT	263,590	368,536	104,946	39.8%

Source: Original data taken from the *U.S. Census Bureau*, *Census 2000 Redistricting Data (P.L. 94-171) Summary File* and 1990 Census.

dynamics of sprawl often leave the phenomenon open to interpretation in the literature:

> The sprawl of the 1950s is frequently the greatly admired compact urban area of the early 1960s. . . . The concept of time span is important in the identification and measurement of sprawl. The application of static measures to dynamic areas can easily result in the misidentification of an area as sprawl when it is really a viable, expanding, compacting portion of the city.
>
> —(R. O. Harvey and Clark 1965, 6)

Second, sprawl manifests on the periphery of cities, often in previously nonurban areas on the metropolitan fringe. (In Europe, similar phenomena are referred to in the context of peri-urbanization.) Third, sprawl is commonly characterized as low-density in development (Peiser 1989; Ewing 1997; Gordon and Richardson 1997). Specifically, sprawl is considered to be lower in density than smart growth, urbanization in older cities, or development in central cities. Fourth, sprawl is a piecemeal form of development. The urban morphology of sprawl is scattered and fragmented in pattern—areas of sprawling suburbs in active use are often interspersed among tracts of land out of active use, or with little functional use (Lessinger 1962; Benfield, Raimi, and Chen 1999). Fifth, sprawl may be characterized by homogeneity of land use. Single-family uses lead the activity patterns of its residential landscape; commercial uses are more likely to be arranged as ribbon-sprawl (R. O. Harvey and Clark 1965) or retailscape (Gordon and Richardson 1997)—swaths of activity buffering highways and highway entry/exit ramps, with relatively little provision for nonautomobile access.

Sixth, sprawl has well-argued aesthetic characteristics. The urban form associated with suburban sprawl often garners criticism for the blandness of its design (Duany, Plater-Zyberk, and Speck 2000; Calthorpe, Fulton, and Fishman 2001; Duany, Speck and Plater-Zyberk 2001). Lessinger's (1962, 169) commentary in this regard is particularly illustrative of this: "Urban sprawl, roller-painted across the countryside, is often without form, grace, or a sense of community. Planning philosophies aimed to strike down this amorphous creature should only gladden our hearts." Seventh, sprawl exists under a relatively loose planning regime compared with that which operates in central urban areas or suburbs under growth management policy (Pendall 1999; Carruthers 2003).

Sprawl is understood to be problematic for several reasons. These include the direct costs of providing infrastructure and services over low-density areas on the urban periphery that often hold a minority of the city's total population. A series of indirect externalities are associated with sprawl: poor water and air quality, increased travel and accessibility costs, and unwelcome social justice costs (Real Estate Research Corporation 1974; Frank 1989; James Duncan & Associates et al. 1989; Environmental Protection Agency 1993, 2000; Downs 1994; Ewing 1994; American Farmland Trust 1995; Burchell et al. 1998; Benfield, Raimi, and Chen 1999; Johnson 2001). At the same time, sprawl satisfies residential demand (National Association of Home Builders 1999), and in some cases researchers have argued in favor of sprawl on the grounds that it provides relatively affordable housing (OTA 1995). Also, in areas like Los Angeles, the scattered and low density nature of sprawl is useful in dispersing air pollutants (Bae and Richardson 1994).

Geography is essential to understanding the factors that drive sprawl. Sprawl operates within the space-time dynamics of the city and behavior of its inhabitants. It is prevalent in some cities, but not others. Sprawl is present in distinct locations within a metropolitan area or systems of cities. It is also unforgiving in its consumption of space and may be characterized with distinctive spatial patterns and structure. Moreover, plans and policies to manage sprawl are overwhelmingly geographical in nature. European green belts introduce an absolute spatial constraint on the outward expansion of suburban growth, whereas much of the growth management policy in the United States attempts a similar goal by geographical means, dictating where development may take place and what uses land may be put to in specific locations, and introducing activity-place incentives and disincentives to influence urbanization.

Research regarding sprawl generally falls under the remit of urban planning, design, and public policy and reflects those perspectives. Much of the work relates to issues such as as tabulation of the economic, social, and environmental costs of sprawl (Benfield, Raimi, and Chen 1999; Johnson 2001); case studies regarding the role of the planning regime in fostering sprawl or alternative growth regimes (Pendall 1999; Carruthers 2003); the urban design of sprawling suburbs and New Urbanist alternatives (Duany, Plater-Zyberk, and Speck 2000; Calthorpe, Fulton, and Fishman 2001; Duany, Speck, and Plater-Zyberk 2001); and identification of the most sprawling cities (Ewing, Pendall, and Chen 2002). Geographers have contributed to the debate (Gottmann and Harper 1967; Yeh and Li 1999; Herold and Clarke 2002; Hasse and Lathrop 2003a, 2003b; Herold, Liu, and Clarke 2003; Wilson et al. 2003; Hasse 2004). However, explanatory work examining geographical determinants is relatively less well-developed when compared to research into other sprawl drivers.

Modeling Approaches to Sprawl

We regard simulation as essential to the study of sprawl. Our assertion is based on several motivations. Modeling and simulation may serve as generative science (Epstein 1999). We can gain understanding of the phenomenon of sprawl, and the factors that combine to produce it, by piecing elements of sprawling systems together in simulation, and studying the ways in which they interact to form system dynamics. Moreover, sprawl is not easily experimented with on the ground. It is infeasible to think that sections of the city could be reduced in density or set upon alternative growth regimes en masse without popular upheaval. Realistic but synthetic computer simulations can be built, however, as a laboratory for exploring ideas and plans that we would not otherwise be able to effect on the ground. Modeling can be used as a planning support system (PSS), to pose what-if questions and evaluate likely or alternative outcomes.

Simulation may also be used to examine future, unforeseen consequences of actions. The implications of urban policies and plans may take decades to manifest. However, in simulation, time can be accelerated or decelerated, into the past or the future, at will. Models may also be used as tools to think with. They can help to convey key properties of a problem or phenomenon to affected parties, stakeholders, policymakers, students, and other researchers. Moreover, this can be done in an interactive and visual context.

Models of urban growth abound, but exploration of sprawl is not generally the primary motivation for construction of those models. There are some exceptions, however, and a variety of models have been developed that touch on various characteristics of sprawl individually. Urban modeling in PSSs is quite relevant. Three such systems stand out in particular: the California Urban Futures models (Landis 1994, 1995, 2001; Landis and Zhang 1998a, 1998b), the What If? system (Klosterman 1999, 2001), and UrbanSim (Waddell 2000, 2001, 2002; Waddell et al. 2003). None of these PSSs are designed to simulate sprawl, although they might be employed for that task and UrbanSim comes particularly close in this regard.

Relatively recently, a series of automata models—either cellular automata (CA) or agent automata (agent-based models, agent models, multi-agent systems) in form—have been developed and applied in contexts of relevance to consideration of sprawl. These include cellular and CA models built around a development and/or land-use perspective, focusing on the conversion of land from nonurban to urban use. Early models were developed by Chapin and Weiss (1962, 1965, 1968), Tobler (1970, 1979), and Nakajima (1977). More recent models have been developed in a similar tradition and include the Dynamic Urban Evolution Model (Batty and Xie 1994, 1997; Xie 1996; Batty, Xie, and Sun 1999); the Research Institute for Knowledge Systems models (White and Engelen 1994, 1997, 2000; Engelen et al. 1995; White, Engelen, and Uljee 1997; Power, Simms, and White 2000; Engelen, White, and Uljee 2002; Straatman, White, and Engelen 2004) and models built on the same scheme (Arai and Akiyama 2004); models developed by Yeh and Li (Li and Yeh 2000, 2002; Yeh and Li 2000, 2001, 2002), by Wu and Webster (Wu 1996, 1998b, 1999; Webster and Wu 1998; Webster, Wu, and Zhou 1998; Wu and Webster 1998, 2000), and by Semboloni (1997, 2000); the Queensland models by Ward, Murray, and Phinn (2000); and the SLEUTH model developed by Clarke and colleagues (Clarke, Hoppen, and Gaydos

1997; Clarke and Gaydos 1998; Silva and Clarke 2002; Goldstein, Candau, and Clarke 2004).

A handful of automata models deal with urbanization as a polycentric process. These models treat sprawl in terms of the formation of subcenters outside dominant urban cores. This includes work by Krugman and Fujita (for an overview, see Fujita, Krugman, and Venables 2001; Krugman 1996) and by Wu (1998a). Yeh and Li (2002) also developed models of polycentricity to explore compact growth. Other automata models deal with peripheral urbanization. Examples include models for South Australia (Bell, Dean, and Blake 1999) and Guangzhou, China (Wu 2002). Models have also been developed that consider ecological effects of fringe sprawl in abstract cities (Brown et al. 2002; Rand et al. 2002). There are also several fringe urbanization models relating to land cover change as a result of urbanization (see Parker et al. 2003 for a review).

The existing foundation of modeling work, and the literature relating to sprawl causes, characteristics, and consequences suggest a likely conceptual model of sprawl formation on which we may build our work.

A Conceptual Model for Sprawl

Several suggestions have been offered to explain the causes of sprawl. These are multifaceted for the most part, and causes are generally understood to be tightly-bound to characteristics and consequences of the phenomenon. Several of these causes are geographical in nature or have strong geographical implications. We can consider these causes generally; we might also consider sprawl from the perspective of the agents of change that are responsible for building and populating sprawling cities.

General Causes of Sprawl

At a broad level, sprawl can be considered as a mature stage in the evolution of a city toward a compact urban structure. Hall (1983), for example, discusses sprawl in the context of a city passing from a condition of primary industrialization to absolute centralization, relative centralization, relative decentralization, and absolute decentralization. Sprawl, he argues, is characteristic of the latter two stages.

Population growth is one of the most important engines of change in any urban system and this is also true of sprawl. The expansion of a city beyond its periphery requires, at a minimum, population growth and/or spatial redistribution of that growth. There are at least three ways in which population growth has contributed to sprawl: absolute growth, increasing urbanization, and restructuring in the dynamics of household demography. First, cities in North America are—with only a handful of exceptions—growing in terms of absolute population. Even the infamous Detroit metropolitan area, long observed as the preeminent example of the withering American rust belt, has been gaining population on aggregate. Second, at the same time, the percentage of the population living in what can be classified as urban areas is also growing. Of that urban population, the numbers residing in small cities is swelling at a striking rate. Third, and in parallel, there has been an associated decrease in household sizes and a related increase in the number of housing units.

If urban populations swell, the city must expand upward or outward, and sometimes beyond its previous boundaries, stretching into agricultural or resource land. This is not news. However, at the same time that urban populations have been growing in absolute terms, the distribution of that growth has been allocated in a spatially distinct manner, largely on the urban fringe as sprawl.

The downtown's pull on location has also been weakened by the growth of the highway system in the United States. No longer indebted to central cities as interchange points for raw material and finished goods, industry has diffused rapidly through the city to the suburbs, following its labor forces and pursuing cheap land and easy access to an expanding network of interstate highways. Suburban highways have become the new centers of gravity around which urbanization has begun to orbit. Coupled with these developments, there has been a dramatic growth in the use of the automobile and the dominance of its position in American society. Prolific use of automobiles facilitates dispersion of activities, making lower densities possible. This has been reinforced by a long-term trend of decline in gas prices in the United States (although recently the trend has been on an upward trajectory!). The inflation-adjusted price of gasoline in the United States in 1996 was lower than that in 1974 (Gordon and Richardson 1997). This has allowed households to substitute housing for transportation costs by moving to the suburbs and living at lower sprawl-type densities. Rather than having a dampening effect on trip-making, suburban dwellers are shopping and recreating in record numbers.

Internet and communications technologies may well reinforce these trends. Although calls for the death of distance likely overestimate the degree to which this is the case (Cairncross 1995), there is general agreement that technological advances have greatly extended the effective radius of the city (Gordon and Richardson 1997). Disparate parts of the city may be separated spatially but linked functionally.

Agents of Change

Households. Why have urban populations been steadily redistributed toward the periphery? A simple and obvious explanation is that people want to live in these areas, whether or not planners and academics consider it to be sustainable. "[L]ike it or not, the great majority of mankind is praying for [sprawl] to come, to develop and satisfy them" (Gottmann 1967, 5). For all the criticism leveled against suburban living, it is still the preferred living arrangement for many; at least 80 percent of some survey groups prefer sprawl over other types of setting (Morrill 1991).

There are a number of likely motivating factors underlying these preferences. Some authors have accused outwardly mobile city dwellers of being racially and socially motivated in their decisions to move to the periphery. It has also been argued that suburban preferences are rooted in long-standing tradition of ideals based on the exclusion of lower-income groups (Audirac, Shermyen, and Smith 1990), and it has been suggested that white households are moving even further out on the urban fringe and into exurbs (Galster 1991), although older studies had suggested otherwise (Farley et al. 1978). Public perception is another likely motivation, particularly regarding the inner city. Public sentiment is of worsening conditions in large cities in some cases, and there is evidence to suggest that opinion matches reality. Data from the U.S. Congress's Office of Technology Assessment (OTA 1995) show, for example, that crime rates have risen in the Baltimore area since 1985, but at faster rates in the inner city (+32.6 percent) than in the suburbs (+13.4 percent).

Employers. The movement and redistribution of population toward suburban locations may have a positive feedback influence on economic activity. Jobs are understood to follow population and in this sense population redistribution has a pull factor on urban economic activity. There are further draws to the suburbs for employers, including lower land and development costs compared to more central locations, and transport networks that facilitate lower costs of movement in outer suburban and exurban locations. This has been supported by shifts in the U.S. economy toward service industry, which is more mobile than other industries.

Developers. Developers have been blamed for encouraging scattered development in expanding suburban areas of North America. For the most part, in growing cities developers act independently in their development decisions (R. O. Harvey and Clark 1965), which promotes a discontinuity in the spatial pattern of their developments. It encourages speculation, the withholding of land for development, which means that large areas of land in the suburbs may become priced out of any market save urban use (Clawson 1962). Pendall (1999) has argued that fragmentation in the ownership of agricultural land exacerbates this problem.

Planners and Policymakers. Planners and policymakers might be considered as agents of change in sprawling systems. For the most part, planning and public policy act to control sprawl through zoning constraints, development caps, historic preservation orders, or growth management legislation such as green belts, transit-oriented development, and developer impact fees (Downs 1994; National Association of Home Builders 1999; Duany, Plater-Zyberk, and Speck 2000; Calthorpe, Fulton, and Fishman 2001; Duany, Speck, and Plater-Zyberk 2001). However, there is a general concern that planning and policy can also act to encourage sprawl, directly and indirectly.

Audirac, Shermyen, and Smith (1990) argue that the agency of planning practice in the United States can be connected to sprawl. Barnett (1995) makes a similar argument, that outdated planning regulations are responsible in large part for sprawl. Commercial strips, a design from the 1920s, were painted over the landscape with vigor in the 1950s; "apparently no one stopped to contemplate the effect of mapping commercial land exclusively in narrow strips along highways where the only means of access was the automobile" (Barnett 1995, 47). Similarly, lot-by-lot zoning and subdivision was not intended to become the only development control over large sections of the city (Barnett 1995). The geography of land-use controls exercised by planners may also be to blame. When applied spatially with varying degrees of enforcement, land-use controls can create an imbalance in the attractiveness of competing areas. If there is a discrepancy between controls inside and outside a city's boundary, for example, land-use planning may make the less-controlled area—the urban fringe—more attractive (R. O. Harvey and Clark 1965; Pendall 1999).

Bahl (1968) makes the claim that tax policy that fosters speculation in the sale of land is a factor in promoting sprawl. Others point to tax policies that essentially subsidize the costs of home-ownership over renting, with a bias toward new homes and single-family housing: "It is generally agreed that in the past the public sector encouraged low-density suburbanization through tax deductions, mortgage guarantees, and depreciation formulas favoring new construction over the upgrading and repair of existing structures" (OTA 1995, 200). Peterson has made a similar argument: "The new, low-density construction favored by tax laws is obviously most suitable for location outside the central metropolitan core" (Peterson 1980, 48–49). The federal tax code also emphasizes creation of subdivisions in small and discontinuous increments. Land is commonly sold to developers in installments so as to minimize capital gains on income tax returns. In addition, subdividers and developers may limit their projects for any taxable year so as not to slip into higher tax brackets that might incur increased taxation of their profits (R. O. Harvey and Clark 1965).

There are more direct examples of public policy as an agent of change in the fostering of sprawl. State incentives—free land grants, subsidized training, tax breaks, tax-exempt industrial development bonds, low interest loans—may be biased against central cities. There are well-documented examples where public policy has intervened in land markets with the intent of suburbanizing large employers; the relocation of Sears to Hoffman Estates in Illinois garnered \$100 million in subsidies for the company (OTA 1995).

The Geography of Sprawl

The factors that drive sprawl are relatively difficult to isolate, simply because so much contributes to the phenomenon. Nevertheless, taken together, the characteristics, causes, and consequences of sprawl that have been discussed in the literature suggest a conceptual model of the phenomenon that we can use as a foundation for model-building. Not all of these factors can be simulated tractably; several do not lend themselves to empirical measurement or representation and likely lend themselves to other forms of analysis (D. Harvey 1969). Nonetheless, we can make use of several others in simulation.

First, it is important that sprawl be represented in space and time as a dynamic phenomenon. American sprawl is voracious in its appetite for land. Moreover, sprawled areas of the city may develop into relatively sustainable urban areas with time, as larger single-lot land parcels become subdivided and developed at higher densities, and previously-fragmented areas are subject to in-fill.

Second, geography is essential to considering the phenomenon, and describing its space-time dynamics. Geographical inertia is important; the future development of a city is a function of its history. The spatial pattern of sprawl as peripheral, low density, scattered, transport-adjacent development and settlement is also crucial to understanding its impacts. Similarly, the mechanisms of sprawl are geographical in nature: fringe urbanization, decentralization, and leap-frog development and settlement.

Third, growth is important. Sprawling cities exist under regimes of absolute population growth, by in-migration or through endogenous dynamics, or of relative growth and redistribution of population to the urban fringe.

Fourth, we may identify several geographical agents of change that might be considered as driving sprawl, and as mechanisms by which growth is allocated and distributed, spatially and temporally, over an urban area. These include developers, responsible for manufacturing the urban physical environment, and relocating households that populate that environment and drive its geography through demand. Employers are also important, as are planners and policymakers.

A Computer Model for Simulating Sprawl

Our sprawl model is based on the conceptual model offered in the preceding section. The model includes exogenously- and endogenously-considered growth, which is distributed over a simulated landscape using mechanisms designed to represent geographic drivers of sprawl: geographical inertia, diffusion, and mobile agents of change. The methodology is based around an automata core, extended as geographic automata (GA). The modeling scheme is illustrated in Figure 1, details of the model are discussed in the following subsections.

Geographic Automata

A basic automaton (A) (a Turing machine, finite state machine, central processing unit) is generally characterized with state variables (S) that describe its condition at a finite moment in time (t), and state transition rules (R_S) that govern how those state variables change in time, based on current state information $S(t)$ and current information input ($I(t)$) from an external source or from other automata:

$$A \sim (S, R_S, I);\ R_S : (I(t),\ S(t)) \rightarrow S(t+1) \qquad (1)$$

CA are a class of basic automata, defined within the discrete confines of a cellular boundary. When many CA are considered together, they may be understood to form a lattice-like configuration, with each discrete automaton representing an individual unit in the lattice. State information exchange between automata is considered within the context of neighborhoods (N)—localized areas of the lattice, composed of several CA neighboring a target automaton. The only source of

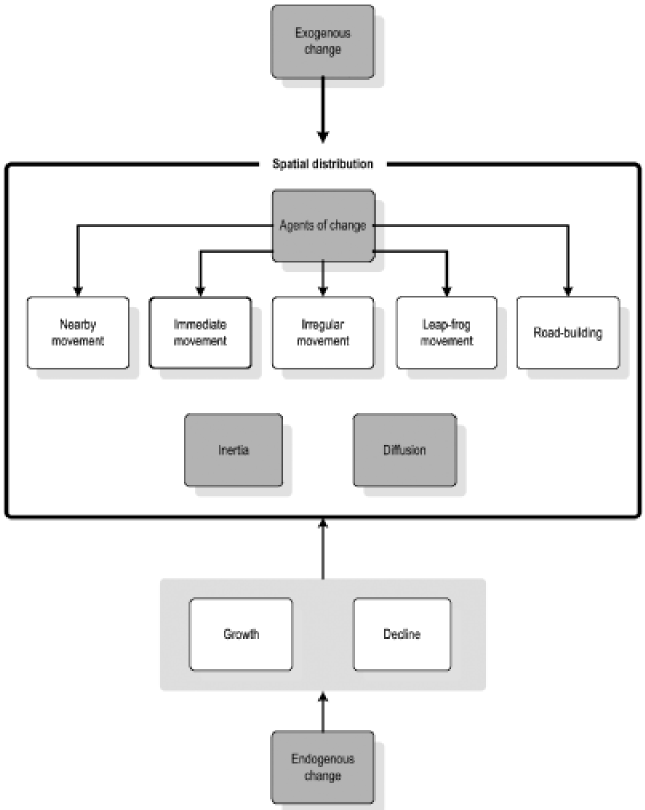

Figure 1. Schematic overview of the model engine.

external information for a single automaton A in the CA is the set of its neighbors; that is, $I = I_N$, and for each automaton A in the CA:

$$A \sim (S, R_S, I_N); R_S : (I_N(t),\ S(t)) \rightarrow S(t+1) \qquad (2)$$

Agent automata constitute another class of automaton, with origins in Artificial Intelligence and many varying specifications (see Ferber 1999; Russell and Norvig 1995; Benenson and Torrens 2004a). States are generally interpreted with respect to characteristics of agency: proactivity, goals, intent, and so forth. In addition, agents are often endowed with the ability to roam freely, as automata, within a lattice of other automata or another environment; this is characteristic of agents used in animat research (Meyer and Guillot 1994) and animation (Reynolds 1987).

The GA methodology that we propose begins with a basic automaton skeleton and adds components from CA (neighborhoods) and animat agent automata (movement). Additional spatial functionality is added: GA are located by means of georeferencing conventions L and are endowed with the ability to move through the spaces in which they reside, by locomotion or other movement regimes (R_L). Georeferencing conventions (L) allow GA to be registered, spatially, to environments in which they reside in time; that is, $L = L(t)$. This may be performed by direct means. GA may be located based on their actual position in the environments, allowing them to be registered to a Cartesian space, a network space, and so forth, at a finite moment in time. Indirect conventions may also be employed, relating GA's locations relative to other objects in the space, or tracking their progression through space and time. The introduction of a typology or ontology (K) of GA entities mediates the nature of L and R_L. At a basic level, K is defined with respect to fixture in space. Information input streams from the general automaton approach are considered *geographically* as neighborhoods of interaction and influence (we deal with neighborhoods N instead of input I). Additional neighborhood functionality is added; neighborhoods of different automata may differ in extent and shape and may change in time so that $N = N(t)$. A set of neighborhood rules is also introduced (R_N) and these rules determine how neighborhoods should change over time. Neighborhoods in the CA scheme are fixed and static. The introduction of neighborhood rules allows for a more flexible treatment of relationships between automata; neighborhood relationships, expressed as geometric areas, network links, far-from-local pointers, and so forth, can be introduced and allowed to vary over space and time.

Many GA may be combined in a systems context, formulated as follows:

$$\begin{aligned} &GA \sim (K,\ S,\ R_S,\ L,\ R_L,\ N,\ R_N) \\ &R_S : S(t) \rightarrow S(t+1) \\ &R_L : L(t) \rightarrow L(t+1) \\ &R_N : N(t) \rightarrow N(t+1), \end{aligned} \qquad (3)$$

where GA refers to a collective of individual geographic automata G. The rules are applied to each G from the GA collective. The methodology, and its connections with GIS and GIScience, are explained more fully in Torrens and Benenson (2005).

Geographic automata offer several advantages over existing automata tools commonly used in geographic simulation. The methodology is based on use for exploring geographical phenomena; theories about such phenomena dictate the components of the methodology, rather than having the tool constrain the theory that it may support. The methodology is actually capable of supporting all CA and multiagent urban models that we are aware of (Torrens and Benenson 2005). GA are also consistent with complex adaptive systems; they support the emergence of novel spatial ensembles. They may be designed with a relatively seamless interface to raster, and more importantly, to vector-GIS. Also, it is possible to form a symbiotic relationship between GA and object-oriented programming paradigms, object-oriented database management systems, and entity-relationship models (Benenson and Torrens 2004b; Torrens and Benenson 2005). GA offer much potential in modeling sprawl, particularly in capturing its geographical components.

External Change

Sprawl is a dynamic reaction to urban growth. This growth may come in many forms: growth that migrates to the city system from outside, as well as growth endogenous to the system. The relationship between external change and urban growth may be handled in modeling through the use of some form of allocation or spatial assignment mechanism. Commonly these are formed as Markov, raster, or CA models. Markov models allocate change (e.g., land-use transition) over space in a city, based on existing land-use in a previous time-step. Raster models determine allocation based on a vector of multivariate influences. CA models add consideration of neighboring states, on a proximity basis, to these general schemes (Tobler 1970).

The source of external change may be derived from a variety of sources. Change can be a parameter of the model, to be defined by the user (Xie 1996). It may also be extrapolated from historic land-use maps or remotely-sensed data (Clarke and Gaydos 1998; Herold and Clarke 2002). In other cases, change is derived from loose- or tight-coupling of an allocation model to exogenous demographic or cohort-survival models (White and Engelen 1997).

External change is accommodated in our models at a macrolevel. It enters the model as population growth or decline (which may be expressed as a rate or absolute volume), which is distributed spatially thereafter at a more microscale. Change is a parameter to be defined by the user in our abstract simulations; it is derived from historical Census Bureau data in our real-world applications. Rates are normalized in our model, such that the rate of change of a major or central city is proportional to change in smaller cities in the simulation. These rates may be positive or negative, with the possibility of decline.

External change may be introduced to a simulated city-system as a volume $D(t)$ of growth or decline at a given time-step t (positive or negative vales of $D(t)$ respectively), such that the population P_i of a land unit i at a subsequent time-step $t+1$ is derived using the following equation:

$$P_i(t+1) = P_i(t) + D_i(t), \tag{4}$$

where $D_i(t)$ is a part of $D(t)$ assigned to land unit i, $\sum_i^n D_i(t) = D(t)$.

Rates of growth or decline (above unit if growth, below unit if decline) may also be used to introduce change in a land unit's population:

$$P_i(t+1) = P_i(t) \cdot \lambda_i(t). \tag{5}$$

External change may also be introduced on a *per-city* basis, rather than systemwide. This allows specification of differential growth and decline within the city-system. Once again, this may be specified as a volume of change or as a rate of change per city. These per-city growth/decline rates may be scaled relative to each other such that a balance is maintained between the fastest- and slowest-growing cities in the city-system.

Once the volume of externally-derived change has been determined in absolute or rate terms, that growth or decline is distributed, in space-time, over the simulated city-system using dedicated GA designed to function as agents of change responsible for sprawl. Details of these automata are discussed in a later subsection, "Mobilizing Agents of Change."

Geographical Inertia

The model also includes historical, autoregressive functionality to represent geographical inertia in urban dynamics. Simulated urbanization proceeds based on development established in previous time-steps of a simulation run. Agents of change in the model thus observe a reality as established by the previous iteration (generation). If a land unit enjoys consistent development, urbanization has an opportunity to take hold over time and establish a spatial presence.

Endogenous Change

The model also incorporates functionality for representing growth or decline that originates within the system. We make a distinction between *urban* population and *urbanizing* population. The former are dormant agents of change that are counted toward the population density of a land unit; the latter are active agents of change, mobilized as GA or diffusing population.

Individual land units are endowed with the ability to decrement and generate population endogenously. We follow Sanders and colleagues (Sanders et al. 1997) in this way, affording a level of agency to the state values associated with automata units in the model. Land units in the model are automata at that level of geography, with a population state descriptor; but we also consider the automaton to contain a limited microworld within the geography of the land unit, which is composed of newly-birthed population and newly-declining population. This allows us to establish a spatial ecology within the land unit, as the basis for endogenous change to be communicated between automata units at a higher level of geography. A similar mechanism is employed in the urban growth models developed by Batty and Xie (1994). The mechanism provides means for incorporating birth and death dynamics in simulation, synonymous with demographic dynamics at an intra-urban scale within a city.

User-defined endogenous birth and death rates are set at the level of land units i, across land units belonging to a given city, or across the entire system. Formulation of these rates mimics that of Equation (5), but we consider endogenously-derived change $\delta_i\ (t)$ in terms of immigration (im) of population to the land unit, emigration (em), the birth rate (b), and the death rate (d):

$$P_i(t+1) = P_i(t)\delta_i(t), \text{ where } \delta_i(t) = im(t) - em(t) + b(t) - d(t). \quad (6)$$

Alternatively, this growth or decline may be mobilized beyond the land unit, into the surrounding neighborhood N_i of a land unit i by diffusion or by GA that are beyond the neighborhood (action-at-a-distance). This may be determined by a user-controlled set of threshold capacities. If the population exceeds a land unit's maximum population capacity, then the excess is mobilized into the neighborhood (or farther if action-at-a-distance is employed).

Diffusion

A diffusion mechanism is used to represent very local neighborhood change—either the diffusion of urbanization or urban decline. The inclusion of diffusion also serves to introduce a decentralization mechanism in the model, which is important in representing sprawl.

Let us consider a land unit i within a neighborhood N_i. From the perspective of a neighboring land unit $j \in N_i$, the population change at j is a balance between the inflow of population by diffusion from land unit i and the diffusion outflow from j itself, and is formulated as

$$P_j(t+1) = P_j(t) + \frac{P_i(t)}{A_i} - \frac{P_j(t)}{A_j}, \quad (7)$$

where A_i denotes the number of i's neighbors (e.g., $A_i = 5$ for a von Neumann neighborhood).

Mobilizing Agents of Change

GA in the model operate as urbanizing agents of change under several movement regimes designed to mimic development and settlement patterns known to be important to consideration of sprawl formation on the ground. A volume of GA are activated under the movement rule and released in the immediate neighborhood of a land unit. These automata proceed through their surroundings with a heading and defined length of movement, carrying population growth or decline with them and thereby distributing that growth or decay spatially over the simulated landscape by means of action-at-a-distance. The movement rule contains several parameters, which can be adjusted to make the resulting patterns of development and settlement more or less compact in form, or may be used to mimic sprawl-like patterns. Moreover, the resulting nodes of development or decline can be endowed with a greater or lower propensity for survival in subsequent simulation steps—new edge cities or urban blight can take root or not.

Generally, the movement rule R_L: $L(t-1) \rightarrow L(t)$, as applied to the geographic automaton G located at $L(t-1)$ at time $t-1$, can be formulated as follows:

$$R_L : L(t-1) = L_0^{t-1} \rightarrow L_1^{t-1} \rightarrow L_2^{t-1} \rightarrow L_3^{t-1} \rightarrow \ldots \rightarrow L_m^{t-1} = L(t), \quad (8)$$

where $\mathbf{L^{t-1}} = < L_0^{t-1}, L_1^{t-1}, L_2^{t-1}, L_3^{t-1}, \ldots, L_m^{t-1} >$ is the series of locations that G passes through during movement, from initial to final position.

In the case of endogenous change, the geographic automaton is mobilized with a volume of endogenously-derived growth or decline $\delta_i(t)$. If the GA are distributing externally-derived change, they are mobilized with a volume of externally-derived change, either growth or decline $D_i(t)$. Positive values of D yield a likelihood that the resulting pattern of development and settlement will expand through subsequent time-steps; negative values of D have a shrinking effect.

The trajectory $\mathbf{L^t}$ of G's movement (i.e., the rule R_L that determines the series of locations L_i^t) could be designed to take place within the neighborhood N_i of a land unit i. Varying the nature of L_i during the interval (t, $t+1$) allows the introduction of different levels of action-at-a-distance beyond the neighborhood, and, further, accommodates different levels of action-at-a-distance when $\mathbf{L^t}$ takes G beyond the neighborhood. In doing so, well-known sprawl patterns can be derived in simulation, with related volumes of growth or decline.

Movement takes place during (t, $t+1$), and the number of locations that are visited by the geographic automaton can vary. For example, geographic automaton G may move, preserving the trajectory with length l accumulated during a given time unit. We can think of movement over space-time, from the start of the process until t, as being composed of t subtrajectories during the entire period (0, t) with varying rules. An overall volume of growth or decline (D or δ) is distributed spatially over the locations traversed by G, with proportions of that growth or decline being deposited in land unit automata as packets of change within that simulation step. As G moves, it distributes growth or decline over a larger or smaller area, depending on the distance G covers during its movement.

Immediate movement. The immediate movement rule mimics initial development processes, whereby a site is settled very locally. GA move in a very confined range of an origin cell under this rule. If we consider GA defined on a two-dimensional grid, then the neighborhood of the GA located at ij is formulated as

$$N_{ij}(t) = (i+1, j),\ (i-1, j),\ (i, j+1),\ (i, j-1),\ (i+1, j-1),\ (i+1, j+1),\ (i-1, j-1),\ (i-1, j+1) \tag{9}$$

(see Figure 2). Generally, the movement rule confined to such a neighborhood results in very compact pattern of growth or decline in a confined radius around a target site.

Nearby movement. The nearby movement rule is similar in specification, except the neighborhood window for movement is much larger in size (25-automata) and the movement of G takes place within $N_{ij}(t) = ij,\ i \pm 2,\ j \pm 2$ over every t. Generally, the rule yields *clusters* of growth equivalent to New Urbanist (Calthorpe, Fulton, and Fishman 2001) or transit-oriented village (Cervero 1998) types of patterns, or patches of decline synonymous with urban blight (Knox 1989; Figure 3).

Irregular movement. The irregular movement rule is used to mimic the irregular patterns of urbanization associated with natural barriers such as mountains, rivers, wetlands, etc., or administrative confines. Under the irregular movement regime, the locations of geographic automaton G at $t+1$ is randomly assigned within a user-defined range around $L(t)$. This results in varying sinuosity of G's trajectory, the rule of choice of consecutive positions $L(t)$ of each move, and the range of perturbation for those values (Figure 4).

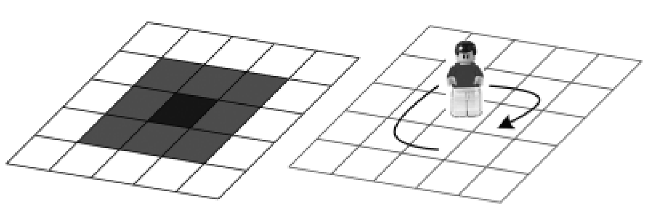

Figure 2. Immediate movement. Black cells are origin automata; gray cells are affected units in the movement space around that origin. Arrow denotes the path an automaton takes.

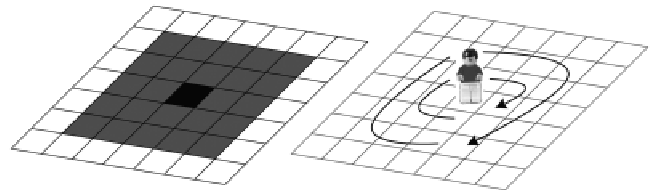

Figure 3. Nearby movement. Black cells are origin automata; gray cells are affected units in the movement space around that origin. Arrows denote the path an automaton takes.

Leap-frog movement. GA may also move by leap-frogging. Under this rule, G moves in hops and L_{i+1}^{t} is not necessarily confined to the nearest neighborhood of L_i^t. Growth or decline is deposited in land units at the termination of each hop. This mimics the land speculation leap-frog development patterns associated with sprawl that are the subject of much discussion in the literature (Lessinger 1962; Figure 5).

Road-like movement. The road-like movement rule is used to mimic road-building. Previous automata-based models of urban growth have introduced road development as an accretive process—roads grow, sequentially, by diffusion-limited aggregation (Xie 1996). There is some debate about growing roads in urban models (see Ward, Murray, and Phinn 2000 for a discussion of the problems they had growing roads in their models); an alternative approach might be to construct roads as links, but only open them once completed. In this model, roads are developed first as nodes, then those nodes are connected by strips of development, indicative of

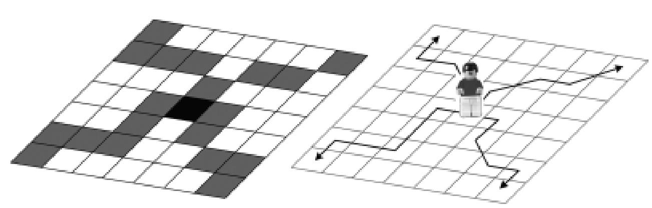

Figure 4. Irregular movement. Black cells are origin automata; gray cells are affected units in the movement space around that origin. Arrows denote the path an automaton takes.

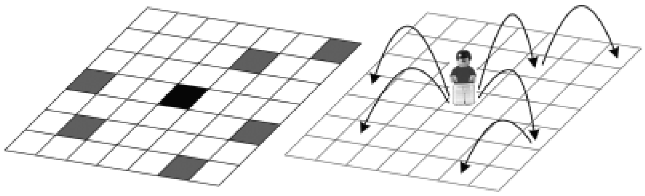

Figure 5. Road-like movement. Black cells are origin automata; gray cells are affected units in the movement space around that origin. Arrows denote the path an automaton takes.

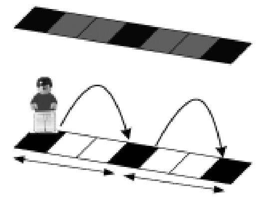

Figure 6. Leap-frog movement. Black cells are origin automata; gray cells are affected units in the movement space around that origin. Arrows denote the path an automaton takes.

transport-oriented growth flanking road infrastructure. GA move by means of the leapfrog or irregular movement rules. However, instead of depositing population growth or decline, GA lay down nodes as they progress during (t, $t+1$). At simulation time step $t+1$, those nodes are connected with a strip of population that is determined based on the growth at origin i of the geographic automaton's journey and may be perturbed by a parameter to be defined by the user. This results in ribbon patterns of growth radiating from land-units (Figure 6). Upon being laid down, those ribbons may continue to urbanize.

In addition, rules may be combined—a geographic automaton can exercise rules in isolation or can execute a sequence of rules within t before terminating its movement. For example, after moving by leapfrog, a geographic automaton might initiate either an immediate or nearby movement. Depending on which rule followed the leap-frog, the resulting pattern would be a sprinkling of isolated settlements or more polycentric forms consisting of adjacent clusters that may fill in through diffusion.

Constraints

A variety of constraints are introduced to the model to confine simulation runs within specified bounds and this facilitates the introduction of what-if scenarios in simulation.

Land units within the simulation may be coded as either "developable" or "non-developable," allowing for certain areas of the simulation to be withheld from transition. This follows the introduction of fixed and functional cells in the CA models developed by Engelen, White, and Uljee. Moreover, the specification of gateway automata introduces a spatial constraint, binding state transition to certain seed sites in the simulation.

A hierarchy of land-use transition is also imposed, ensuring realistic transition of land units between uses. This follows similar hierarchies in urban growth CA (Semboloni 1997; White and Engelen 1997). Developable areas may become urbanized, with a population count. They may only return to nonurbanized form if the population count decrements to zero.

Simulation Experiments

The purpose of this work is to explore the geography of sprawl through simulation. Using the model, simulations were built based on two scenarios for sprawling urbanization within an abstract city-system. Both simulations evolve a city-system in a realistic fashion, with emphasis on the processes driving space-time dynamics, the patterns generated by the simulation, and the rate of simulated urbanization. A third simulation is also described, as applied to a *real* city-system (the Midwestern megalopolis of the United States). In these simulations, it is assumed that the rate of growth is known a priori. (In the Midwestern simulation, growth rates are based on population data from the United States Census.)

General Growth Scenario

In the first example, the model is used to build a simulation in which a dominant central city evolves in the context of a larger city-system with two additional, competing, urban centers (Figure 7).

The simulation is programmed with initial seed conditions that introduce gateway sites in five locations: the center of the lattice, two sites in almost immediate proximity, and two other gateways on the right and left areas of the lattice space (Figure 7). The ability for the growing cities to compete for space as they sprawl is specified in two ways. First, the central city is afforded an advantage from the start of the simulation by virtue of the introduction of two adjacent gateway sites; as hinterlands of the adjacent cities merge with that of the central core, they add population to the central urban mass. Second, the growth rates of the cities are treated differently, thereby influencing the temporal evolution of the urban system as well as its spatial development. The supply of growth to competing cities (denoted as A and B in Figure 7) is cut off roughly 75 percent of the way through a simulation run, mimicking conditions

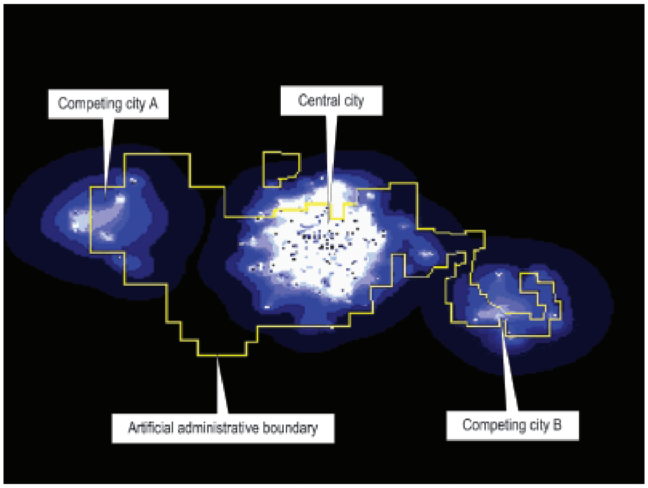

Figure 7. The central city and its two competing neighbors ($t = 213$). Light blue/white areas denote densities that are higher than dark blue/black areas.

whereby the critical mass of a dominant central city begins to draw incoming migration and activity away from cities with comparatively less attraction. In the simulation, this occurs when the hinterlands (suburbs) of the competing cities meet those of the central city. At this point, exogenously-derived growth (in-migration) ceases in the peripheral cities and only endogenous growth continues in those areas.

The patterns of growth generated in the simulation are synonymous with those that would be expected in a real city-system, both visually and empirically (empirical measurements of this fit are described in the following section). In addition, the timing of evolution of the system is sensible (Figures 8 and 9).

The three cities begin their early evolution as compact cities: dense monocentric masses with a surrounding lower-density suburban hinterland. As the density of settlement in the centers grows, the expanse of the suburban hinterland extends further in the simulated space (Figure 10B), and at an increasingly rapid rate. (The diffusion rule actively disperses a greater volume of settlement as the mass of settlement in the system grows.)

At $t = 186$ (roughly 50 percent of the way through the simulation run), the effect of the leapfrog rule becomes more pronounced; the urban mass has grown, spawning a greater number of subcenters on the periphery of the cities (Figure 10B).

By $t = 200$, the peripheral cities have become largely dispersed, with the remnants of formerly-dominant central seed areas barely visible (Figure 9). At $t = 222$, the hinterlands of the central city and competing city B have sprawled to such an extent that the two urban masses begin to merge (Figure 10C). At this point, the supply of growth to competing cities A and B is stopped. The downtown areas of the competing cities rapidly begin to decline in density, as growth is distributed through the system without a replenishing supply to the gateways of competing cities A and B.

Around this time, the road rule also begins to generate visible patterns—"fingers" of dense development begin to appear (Figure 10D), manifesting as corridors of growth extending from the main urban mass (Figure 10E). Competing cities A and B actually begin to develop a linear-like development pattern, succumbing to path-dependence because of initial road-like development. By $t = 291$, some suburban subcenters have begun to evolve as growth centers in their own right, and the overall structure of the central city becomes largely irregular, with pockets of lower-density settlement that have been by-passed by the urbanization process evident within the evolving city mass (Figure 10F).

Overall, the city-system sprawls dramatically, while maintaining a realistic pattern of regional-scale urbanization. It is particularly noteworthy that the spatial extent of the entire city-system evolves to a condition whereby the low-density suburbs cover roughly the same area as the denser central cores. Of course, the low-density of that sprawled area means that those sections of the simulated city house a minority of the population.

Polycentric Growth Scenario

In the second simulation, a growth scenario is devised in much the same way as the last example, with identical growth rates and seed conditions, and the termination of growth at a point in the evolution of the simulation. However, in this scenario, the model is parameterized to encourage more polycentric development. The simulation is specified with greater propensity for the formation of peripheral clusters.

This simulation essentially operates under a smart growth regime. Growth is accommodated, but focused in a polycentric fashion. This is achieved using combinations of leapfrog, road, and irregular movement rules as part of a combined sequence that terminates in a nearby movement rule. The propensity for these clusters to generate internal and diffusing population is also greater. This combined regime is used alongside normal execution of the other rules in isolation. This approach establishes a large number of dense peripheral clusters—edge cities—as the simulation proceeds (Figures 11 and 12). Essentially, this is sprawl in characteristic form, but with emphasis on polycentricity.

The city-system evolves at a much faster rate, due to internal growth. In fact, the central city and competing city B begin to merge very early in the simulation, at $t = 65$ (Figures 9 and 11). A significant number of successful clusters are established early and these incubate a volume of internal growth that diffuses within the system. This is roughly equivalent, in a sense, to similar phenomena in real-world contexts, as in Silicon Valley in Northern California, and similar patterns in the Seattle–Tacoma area of Washington. In each of these cases, former less-urbanized areas gain some form of innovative advantage that establishes a future base for impressive growth—Palo Alto and Santa Clara in the California example and Redmond in the Washington example. Growth in the simulation is still cut off 75 percent of the way through the simulation run, but at that stage there is more than enough internal momentum in competing cities A and B, and the cut-off has relatively little impact, compared to its use in the general growth simulation.

This is much like events that take place in many sprawling cities. Once peripheral areas garner enough of a foothold they often incorporate as independent

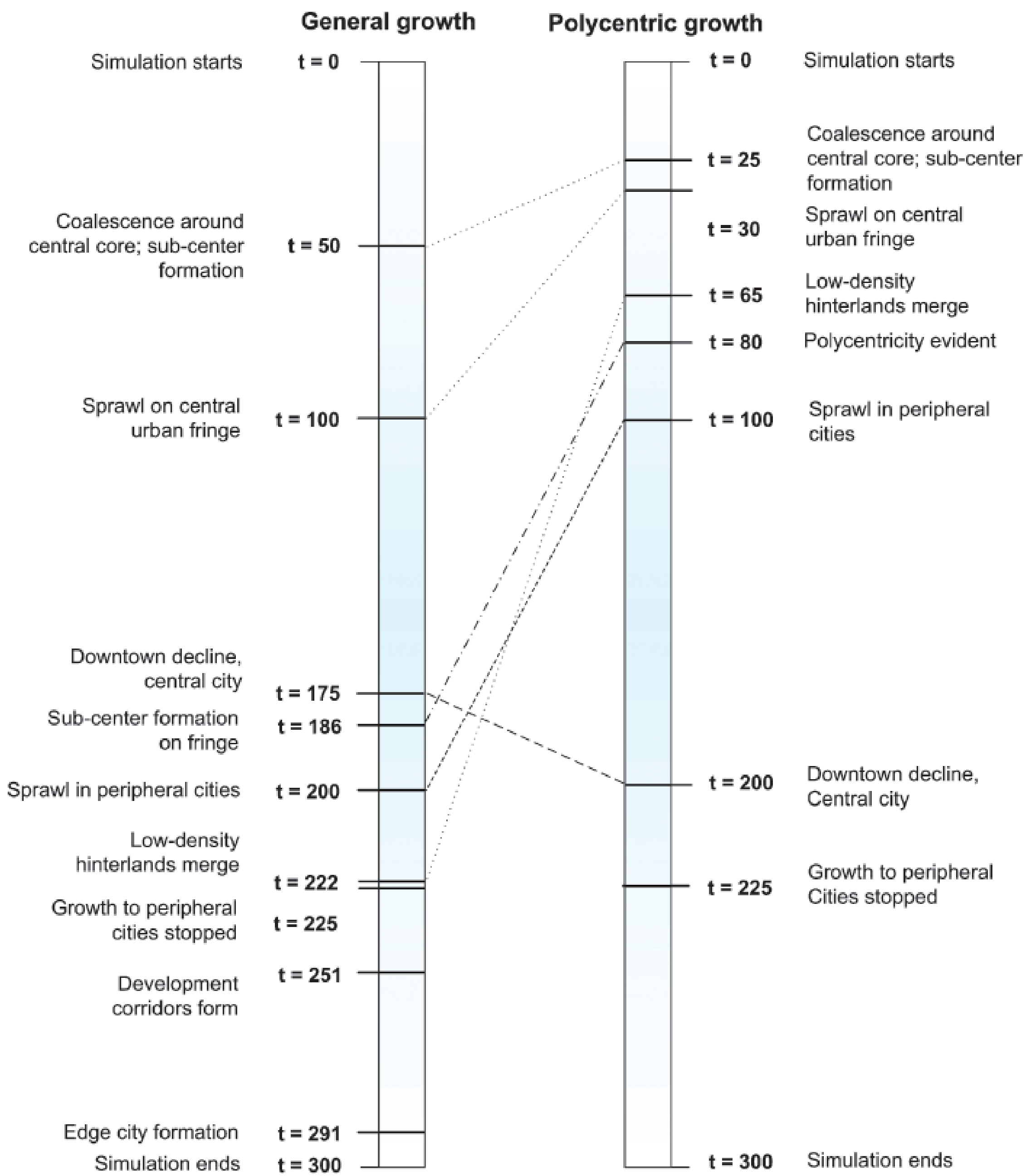

Figure 8. Timeline for the simulations.

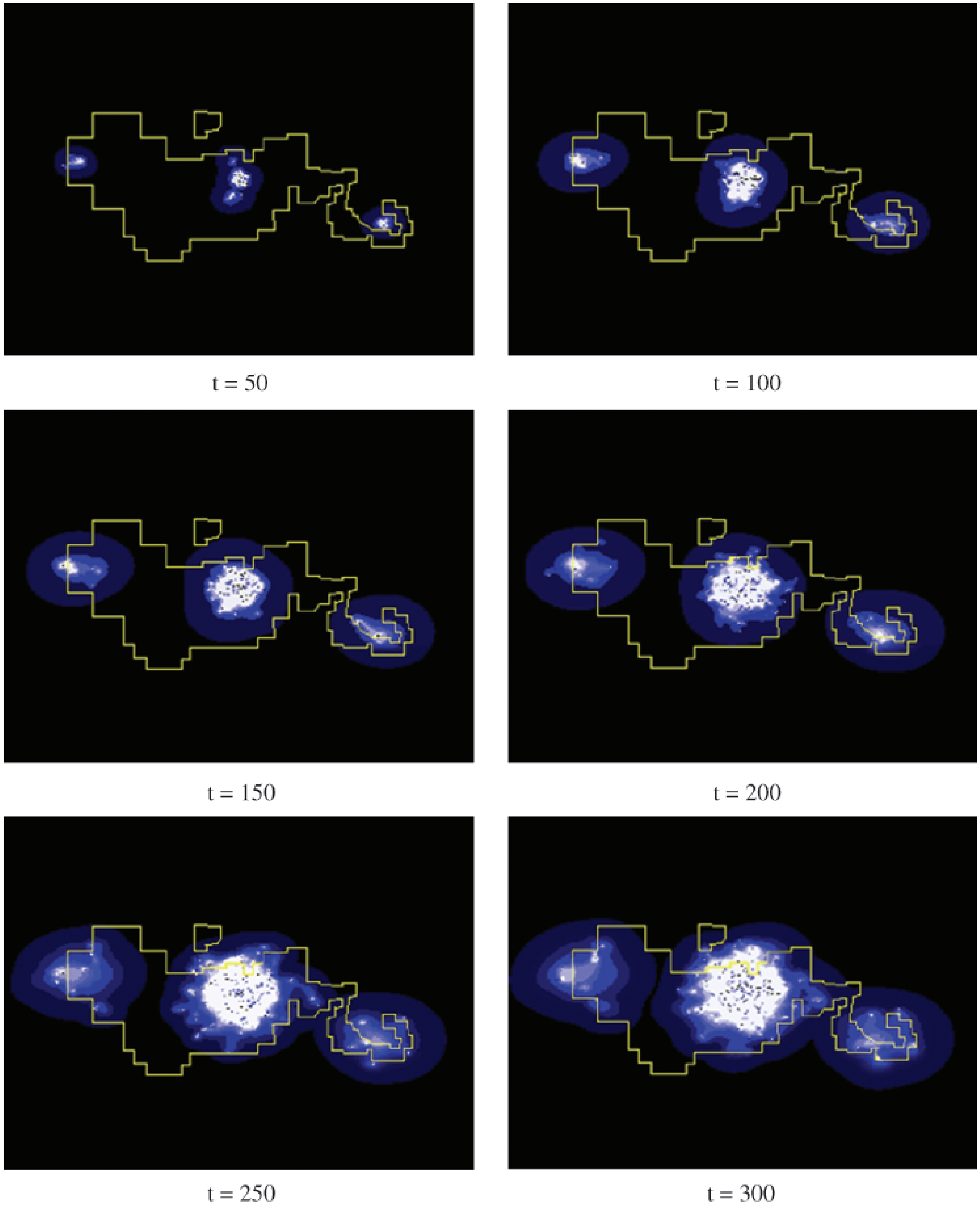

Figure 9. The evolution of the general growth simulation. Light blue/white areas denote densities that are higher than dark blue/black areas.

townships, with independent control over local land-use and zoning. (Gilbert and Chandler in Arizona are examples. These former suburbs of Phoenix are among the top five fastest-growing cities in the United States.) Invariably, the status quo—low density sprawl—is protected, rather than more compact forms of development.

The polycentric approach generates suburbanization as in the general growth simulation, but the generated urban structure is much different. The city-system is

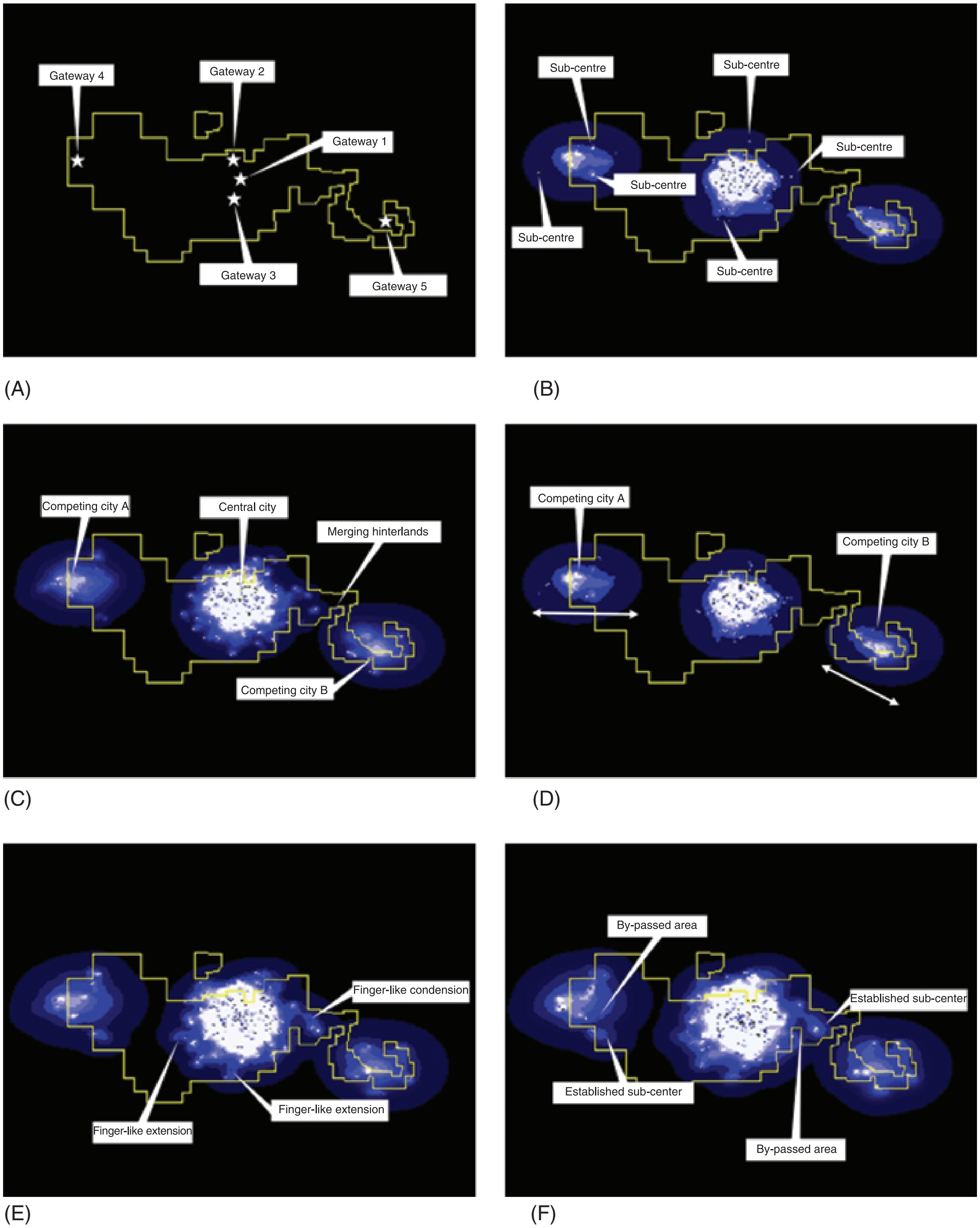

Figure 10. Noticeable features in the general growth simulation. (A) Gateway sites ($t = 0$); (B) The formation of subcenters ($t = 186$); (C) Merging hinterlands ($t = 222$); (D) Linear development ($t = 251$); (E) Corridors of settlement ($t = 260$); (F) Well-established subcenters, with by-passed interstitial areas ($t = 291$). Light blue/white areas denote densities that are higher than dark blue/black areas.

surrounded by a buffer of low-density sprawl, as before, but the main urban mass exhibits a much more polycentric structure with *many* well-established cores (Figure 12). This generates a different urban future to that observed under general growth. In the general growth scenario, low-density peripheral sprawl dominated, and it was mentioned that this was synonymous with situations whereby peripheral areas might organize locally—in a politically fragmented manner—and reinforce a regime of low-density sprawl. By comparison, growth under polycentricity is focused, early on, in peripheral *cores*. While sprawl is present, the overall spatial structure is

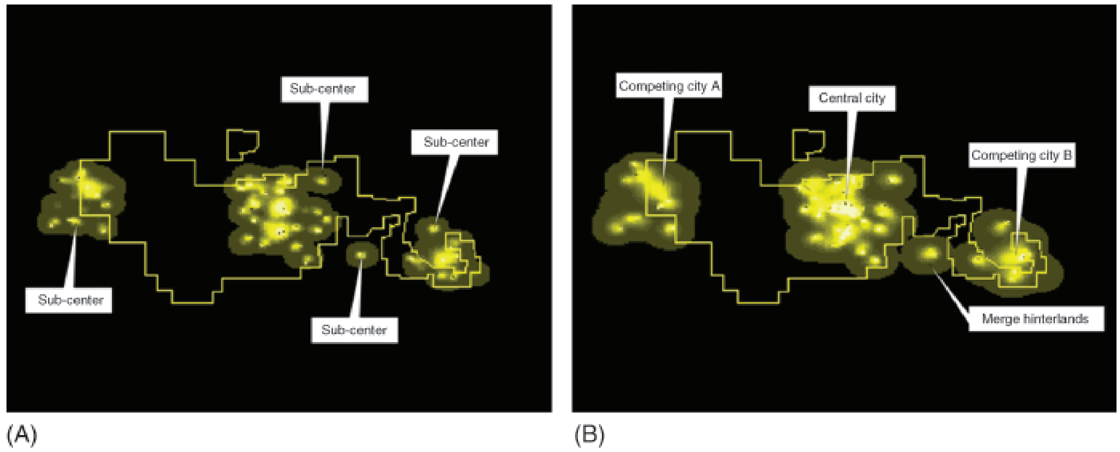

Figure 11. Noticeable features in the polycentric growth simulation. (A) Subcenter formation ($t = 25$); (B) Merging cities ($t = 65$). Light yellow/white areas denote densities that are higher than dark yellow/black areas.

much more cohesive due to polycentricity in dense core distribution.

The implication for sprawl costs would, likely, be significant. The urban pattern in the polycentric case could be associated with greater system-wide accessibility and potentially lower vehicle miles traveled and vehicle emissions. The general growth scenario generated a city in which the population living in dense urban settings was roughly equal to that housed in low-density sprawl. If we assume that sprawl dwellers may follow a particular socioeconomic profile commensurate with "white flight" scenarios, the social justice implications are significant. The general growth example is indicative of large-scale systemwide sociospatial segregation; the polycentric scenario accommodates a potentially more balanced distribution.

Simulating Sprawl in the Midwestern Megalopolis

In the next example, the model is applied to the Midwestern megalopolis region (Gottmann 1967) around Lake Michigan in the United States. The area provided some unique characteristics for applying the model, in particular the boundary formed by Lake Michigan.

The simulated landscape was derived from a Landsat TM image (Figure 13). Each pixel in the image was coded as an individual automaton in a regular lattice structure. The simulated region occupies a 52,125 km^2 area in the real world. The automaton lattice comprises a grid 520 automaton units wide and 630 long—327,600 units in total, with a real-world resolution of 180,093 m^2 per automaton. The Midwestern simulation is specified in much the same way as the abstract simulations described earlier. The simulation is based on the same model engine. The simulation is distinct from the general growth and polycentric simulations in its constraint parameters, however.

The Midwestern simulation is constrained geographically through the introduction of known seed sites for development. The seed sites are specified with respect to those locations in the area that came to dominate as urban centers in the region—namely, the city centers with the largest current population. Seven such sites were identified and introduced: Madison, WI; Milwaukee, WI; Chicago, IL; Gary, IN; South Bend, IN; Lansing, MI; and Grand Rapids, MI (Figure 13). Each of these sites serves as a gateway for the introduction of exogenous change to the simulation, thereby ensuring that the simulation retains some basic regional (and geographic) similarities with conditions in the real world.

The simulation is constrained in one additional way, and this relates to both geography and rates of change in the model. The *volume* of growth introduced at each time step is designed to roughly match known growth values for the particular cities (Figure 14). (This allows us to track the development of individual cities [Figure 15].) The growth rates were varied for different simulation runs to examine the patterns generated, but in the run illustrated in Figure 16 growth rates were scaled relative to known growth. Agents of change originating from these gateways are georeferenced to the sites through which they are introduced. A greater volume of growth was introduced through Chicago, relative to the other cities; Milwaukee had more growth than Madison, and so forth. This ensures that the rate of evolution in the simulation is plausible and allows the simulation exercise to focus on the relative impact of the general state transition rules and movement rules in the model.

Using these specifications, the simulation was run with varying parameters. The example illustrated in

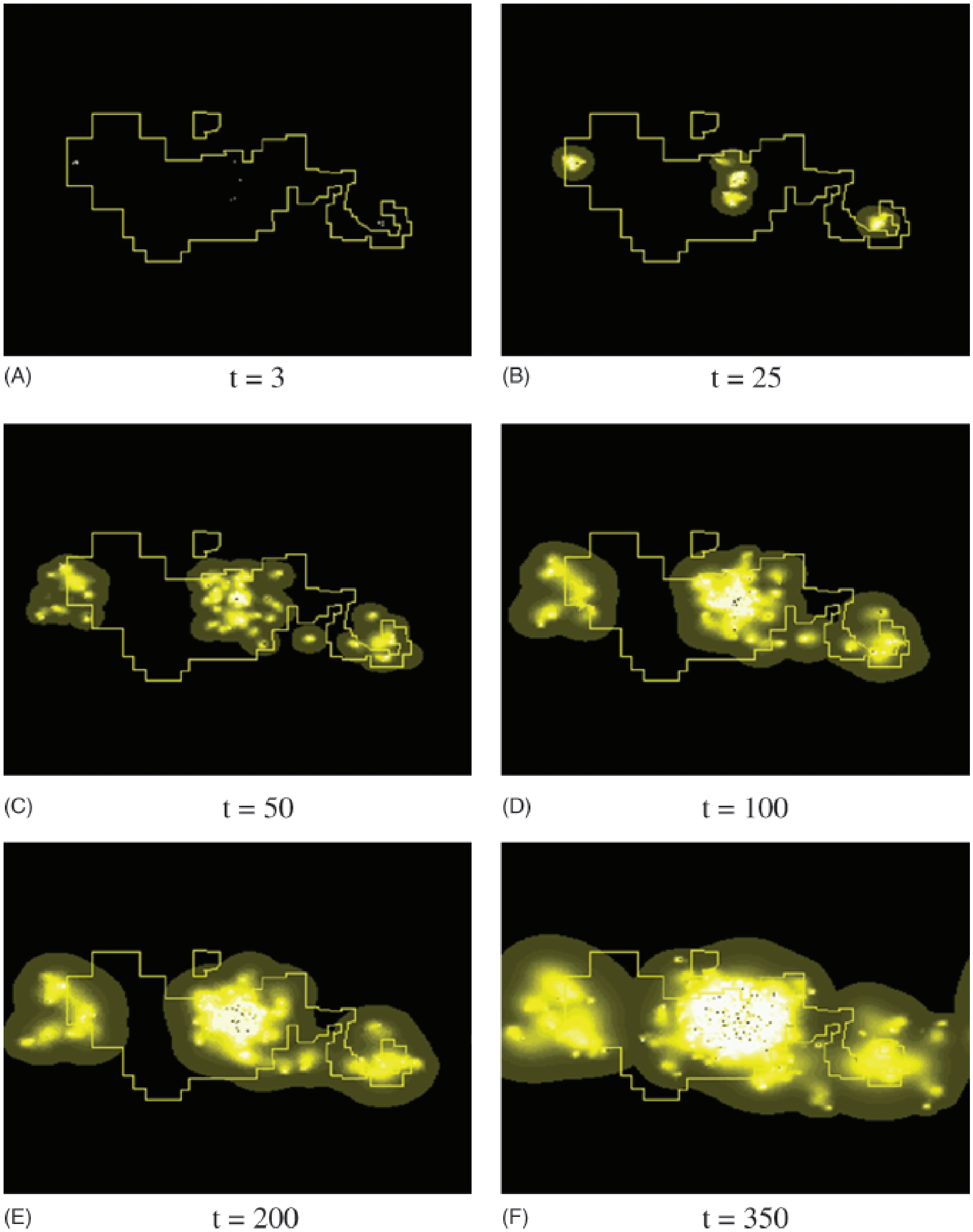

Figure 12. The evolution of the polycentric growth simulation. Light yellow/white areas denote densities that are higher than dark yellow/black areas.

Figure 16 was run with equal weighting of transition rules, for 200 iterations, from a state of only minor settlement in the seed sites (roughly synonymous with conditions in the area at the turn of the nineteenth century). These specifications generated a plausible pattern of urbanization (plausibility is discussed in the next section). The simulated city-system began developing as a loose constellation of urban clusters, scattered in the immediate vicinity of the seed sites identified in Figure 13. By $t = 50$, the relative dominance of Chicago and urbanized lower Wisconsin is evident in the system (Figure 16). By $t = 100$, the city-system has begun to coalesce, with road-influenced fingers of growth connecting spatially separated spheres of development.

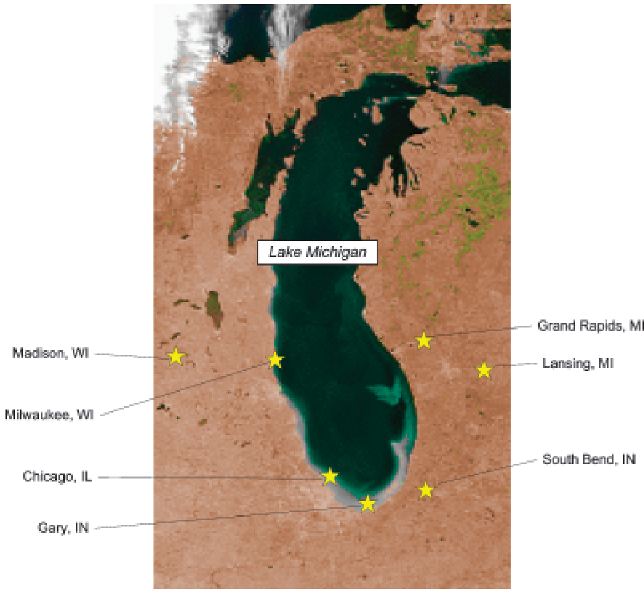

Figure 13. Seed sites in the Midwestern Megalopolis model.

By $t = 200$, the system has begun to sprawl, with fragmented and lower-density settlement on the urban periphery, while expanding into previously undeveloped areas.

In another simulation, the model was run far ahead into the future as a speculative exercise to examine what the pattern of urbanization might look like if growth continued unchecked (Figure 17A). The end-result was decentralization without end, reminiscent of forecasts written about in the 1980s (Hall 1983).

The relative impact of movement rules—as proxies for the behavior of agents of change—was also tested. By emphasizing one or more movement rules over others, it is possible to explore potential growth scenarios under alternative development regimes. Setting the road-like and irregular rules as the prevailing force in a simulation generates a pattern dominated by linear strips of urbanization (Figure 17B). Density within those strips is relatively high, but the overall pattern of adjacent growth is very scattered, with infill only occurring in areas where there is a dense network of strips in physical proximity to each other. Emphasizing the leapfrog rule relative to other rules generates an altogether different pattern of urbanization, dominated by small isolated clusters of dense settlement, with little to bind them within the urban system (Figure 17C). Combinations of clustering rules—the immediate, nearby, and leap-frog rules—lead to a very polycentric urban structure, characterized by a tight jigsaw of urban clusters, loosely merged by their respective bands of peripheral low-density hinterland (Figure 17D).

Measuring Sprawl

The nature of sprawl generated in simulation was analyzed based on its composition and configuration, using landscape metrics and fractal dimensionality (Turner 1989; Turner and Gardner 1991; White and Engelen 1993; Batty and Longley 1994). *Composition* refers to the presence and amount of different patch types (urban, nonurban) within a landscape, without explicit reference to their spatial features. *Configuration* refers to the spatial distribution of patches within a landscape. *Patches* are distinct spatial agglomerations—blobs of urbanization in this case.

Configuration metrics have advantages as a measure of sprawl, providing an index of the amount of space-filling and fragmentation in a city's urban pattern. Three configuration measures are used here to assess the degree of sprawl in simulated scenes, each at a landscape scale.

Perimeter-area fractal dimension (PAFRAC) measures the extent to which patches fill a landscape. Differences in PAFRAC value can suggest differences in the underlying pattern-generating process (Krummel et al. 1981). PAFRAC ranges in value from one to two, and is calculated using the slope of a regression line obtained by regressing the log of patch area against the log of patch perimeter. It is calculated as a double-log fractal dimension. A PAFRAC value greater than one for a two-dimensional landscape denotes a departure from Euclidean geometry and an increase in patch shape complexity. High values of PAFRAC denote situations in which patches fill-up a space; low values are synonymous with cases in which patches fill space to a lesser extent (i.e., sprawl).

$$PAFRAC = \frac{2}{\dfrac{\left[N\sum_{i=1}^{m}\sum_{j=1}^{n}\left(\ln p_{ij} - \ln a_{ij}\right)\right] - \left(\sum_{i=1}^{m}\sum_{j=1}^{n}\ln p_{ij}\right)\left(\sum_{i=1}^{m}\sum_{j=1}^{n}\ln a_{ij}\right)}{\left(N\sum_{i=1}^{m}\sum_{j=1}^{n}\ln p_{ij}^{2}\right) - \left(\sum_{i=1}^{m}\sum_{j=1}^{n}\ln p_{ij}\right)^{2}}} \quad (10)$$

In the formula above, a_{ij} is the area of patch j of type i, p_{ij} is the perimeter of patch j of type i (urban/nonurban), m is the number of patch types, n is the number of patches of type i, and N is the total number of patches in the landscape.

Contagion is the probability that two randomly-chosen adjacent cells belong to the same class (state). It is calculated on a cell-by-cell basis rather than a patch-by-patch basis. Contagion is the product of two probabilities: the probability that a randomly chosen cell belongs to category type i, and the conditional probability that,

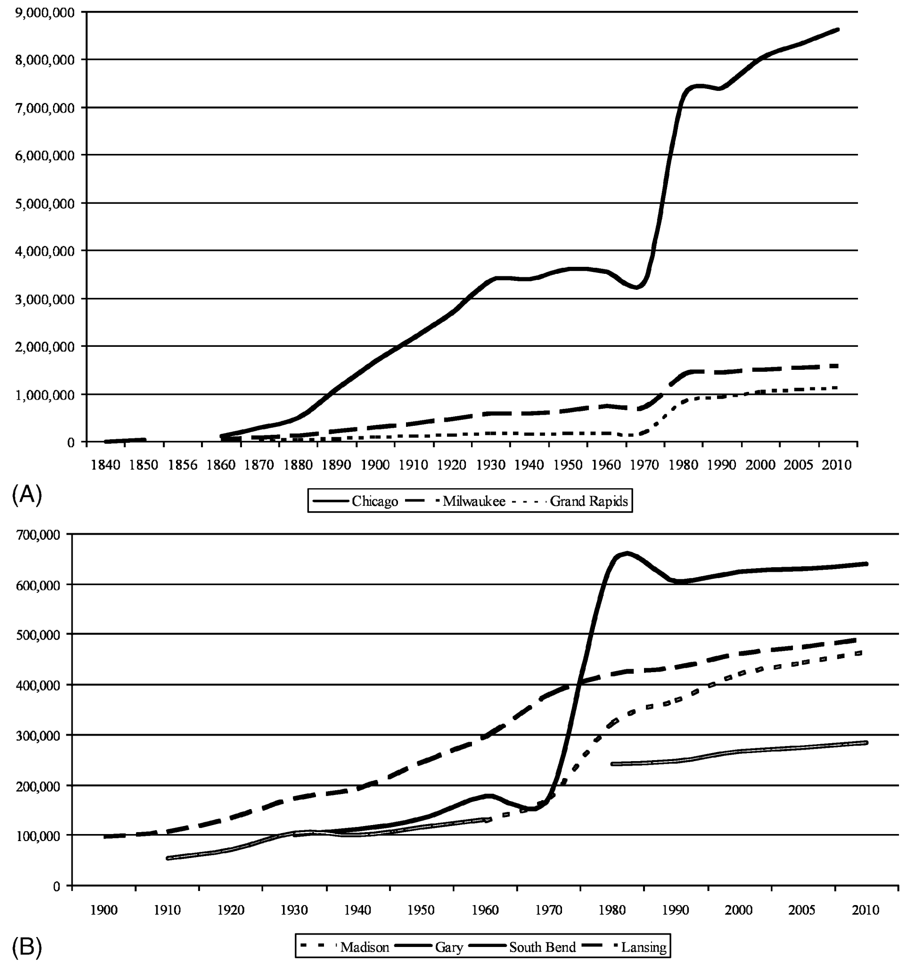

Figure 14. Population growth in America's Midwestern Megalopolis. Dates beyond 2000 are projected. Data before 1970 refer to town and city boundaries; data after 1970 refer to Metropolitan Statistical Area boundaries, which creates an artificial ramp in the illustration. (Note: Gaps in data for Chicago and South Bend are indicated by breaks in the line graphs.) *Source*: U.S. Bureau of the Census.

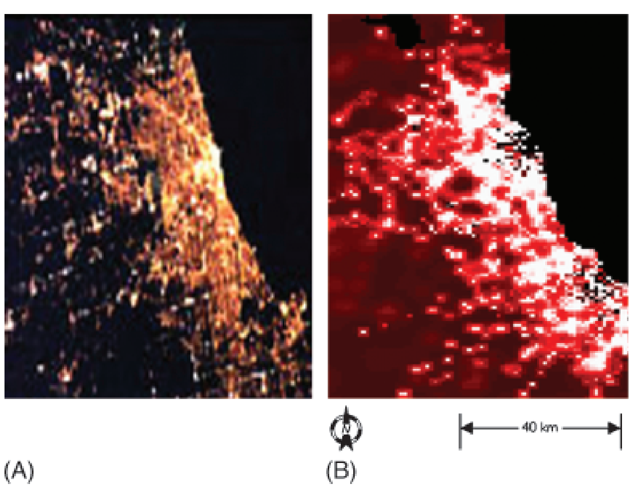

Figure 15. Observed and simulated conditions in Chicago. (A) The pattern of urbanization as revealed by night lights (*Source*: NASA; http://science.nasa.gov/headlines/images/lights/chicago_lights.jpg); (B) a section of the simulated world corresponding to the Chicagoland area. Light red/white areas in (B) denote densities that are higher than dark red/black areas.

given a cell belongs to category i, one of its neighboring cells belongs to category j (McGarigal and Marks 1995). Where contagion is low, a landscape can be said to be composed of many small and dispersed clusters of cells—that is, it is fragmented. High contagion values are indicative of more compact landscapes.

$$C = \left[1 + \frac{\sum_{i=1}^{m}\sum_{j=1}^{m}\left[\left(P_i \frac{g_{ij}}{\sum_{j=1}^{m} g_{ij}}\right)\cdot\left(\ln P_i \frac{g_{ij}}{\sum_{j=1}^{m} g_{ij}}\right)\right]}{2\ln(m)} \right] \cdot 100, \quad (11)$$

where C is the percentage of contagion, P_i is the proportional abundance of category type i, g_{ij} is the number of adjacencies between cells of category type i and all

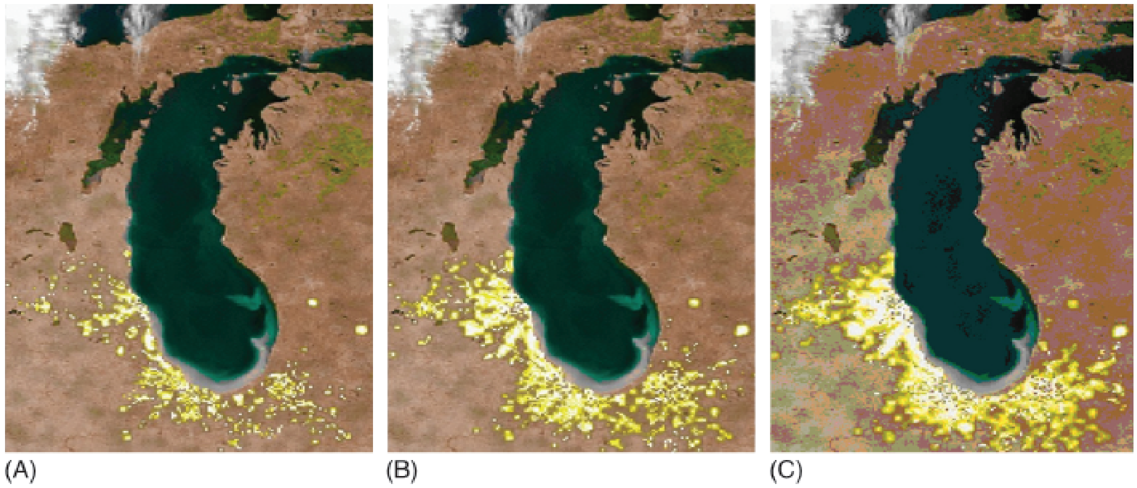

Figure 16. Simulated Midwestern growth at various stages. Light yellow/white areas denote densities that are higher than dark yellow/black areas.

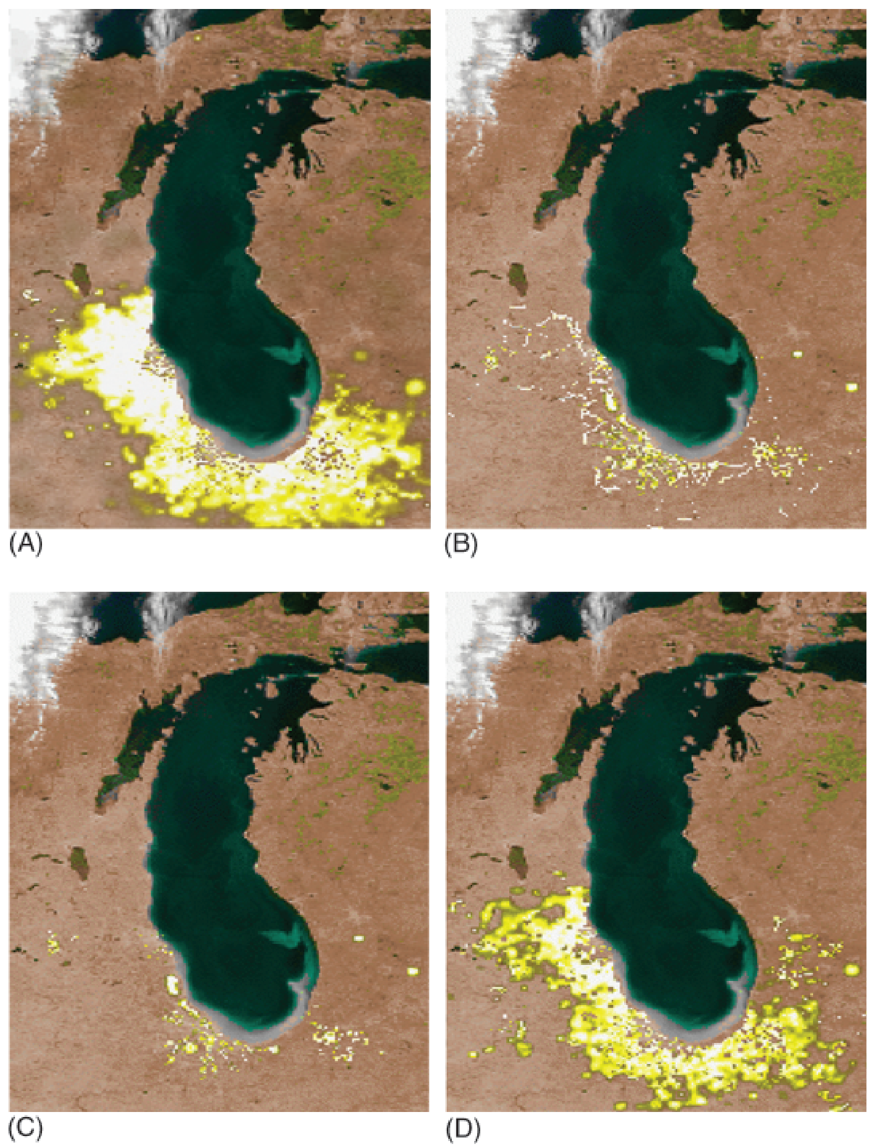

Figure 17. Simulated Midwestern urbanization under different scenarios. Light yellow/white areas denote densities that are higher than dark yellow/black areas.

other category types, and m is the total number of category types.

The *Interspersion and Juxtaposition Index* (IJI) measures adjacency on a patch-by-patch basis. Higher values are synonymous with landscapes in which patch types are well interspersed (equally adjacent to each other). Lower values occur when landscapes contain patches that are poorly interspersed (there is a disproportionate distribution of patch type adjacencies). When IJI is zero in value, there is an uneven distribution of adjacencies between patch types. A value of 100 is indicative of a situation in which all patch types are equally adjacent to each other (McGarigal and Marks 1995). High values of IJI thus represent a relatively greater degree of homogeneity in a landscape. IJI is expressed as a percentage, and can be calculated using the following formula,

$$\mathrm{IJI} = \frac{-\sum_{i=1}^{m}\sum_{j-i+1}^{m}\left[\left(\frac{e_{ij}}{E}\right) - \ln\left(\frac{e_{ij}}{E}\right)\right]}{\ln(1/2[m(m-1)])} \cdot 100 \qquad (12)$$

where IJI is the value of the *Interspersion and Juxtaposition Index*; e_{ij} is the total length of edge in the landscape between patch types i and j, including landscape boundary segments representing true edge only involving patch type I; E is the total length of edge in the landscape; and m is the number of patch types in the landscape. The results of measuring simulated sprawl are shown in Table 2. The two abstract simulations demonstrate very different sprawl-like characteristics. The general growth simulation generated more patches than the polycentric simulation. The patch total was 14,375 for the general growth scenario and 3,066 for the polycentric scenario. This indicates that the landscape generated by the polycentric simulation was relatively less fragmented than its counterpart. The values for PAFRAC support this contention. The general growth example had a fractal dimension of 1.5305; the value for the polycentric scenario was higher at 1.5321. Both of these values are commensurate with the fractal dimension of cities in real-world contexts (Table 3). The higher value for the polycentric example also suggests that the simulated city in that experiment did a better job of filling the space it occupied, although the values are not dramatically different. The values for contagion further support the hypothesis that the two simulations generated cities with different spatial structures and patterns of sprawl. There is a dramatic difference in the percentage of contagion recorded for the two simulations. The general growth simulation yielded a contagion value of 48 percent; the figure for the polycentric example was much higher at 65 percent. Higher contagion is indicative of a greater degree of compaction of cells in a landscape. The city generated in the polycentric scenario can thus be considered less sprawling than its general growth counterpart. The results for interspersion and juxtaposition produced similar results: general growth demonstrated a relatively high IJI (54 percent), indicative of a landscape in which patches are well-interspersed. Polycentricity produced a much lower IJI (37 percent), suggesting poorer interspersion between patches. The higher value of IJI for the case of general growth suggests that landscape is more homogeneous than that generated under a polycentric scenario.

Table 2. Fractal and landscape metrics for the simulation scenarios

Metric	General growth	Polycentricity	Midwestern example
No. of patches	14,375	3,066	3,782
PAFRAC	1.5305	1.5321	1.5479
Contagion	48%	65%	45%
IJI	54%	37%	20.15%

Notes: PAFRAC = perimeter-area fractal dimension; IJI = Interspersion and Juxtaposition Index.

Overall then, the city generated by the polycentric simulation can be regarded as more compact and less sprawled than that generated under a more general growth scenario.

The number of patches generated by the Midwestern simulation was consistent with the abstract polycentric example—the Midwestern scenario produced 3,782 patches by the end of the simulation run. The fractal dimension was also consistent with the abstract simulations, and with real-world cities, at a value of 1.5479 at the end of the run. The degree of contagion was 45 percent, the amount of interspersion and juxtaposition was 20.15 percent. The contagion score was low relative to the abstract simulations, suggesting that the Midwestern model generated a more sprawl-like landscape. Interspersion and juxtaposition was much lower than that found in the abstract simulations, indicative of relatively lower homogeneity in the landscape, again an indicator of sprawl.

Analysis of the simulation run was performed across the lifetime of the simulation for the Midwestern simulation, to explore changes in the structure of the simulated city as it evolved within the simulation. Analyzed across time-steps, the results suggest that the simulated city-system developed in stages, with rapid changes in initial conditions, followed by a period of relative stability, and a sharp transition toward sprawl at the end of the model run. This is consistent with the life-cycle stages of an urban system, whereby cities go through periods of relative compaction, expansion, and decentralization (Hall 1983). The end result of that evolution, however, is the now-all-too-familiar sprawl that is readily apparent in much of the urbanized United States, and elsewhere.

The number of patches demonstrated a progressive increase from just a handful of seed sites to more than 5,000 by $t = 138$. After that point, the number of patches started to decline steadily, as fragmented areas began to coalesce (Figure 18). The fractal dimension fluctuated over the course of the simulation run, although it remained within a reasonable range, as compared to dimensions for other cities that have been mentioned in the literature (Table 3). This suggests that the simulated city went through stages of growth, with rapid space-filling at the beginning of its evolution followed by a period of relatively stable growth. The value climbed toward the end of the simulation run as the simulated city began to sprawl at a growing rate (Figure 19). Contagion and interspersion and juxtaposition demonstrated an almost inverse relationship over the simulation run. The degree of contagion in the landscape grew early in the simulation, declining thereafter before climbing rapidly toward the end of the model run (Figure 20). This is consistent with the results suggested by the other metrics—the city went through an early growth stage dominated by compaction. The decline in contagion thereafter is indicative of relative sprawl. The value of interspersion and juxtaposition in the simulation started off quite high, and subsequently declined quite rapidly before rising in value, mostly, throughout much of the simulation run (Figure 20). Once again, there was a sharp change at the end of the model run, where the value dipped to its lowest level. This suggests that the simulated city started off with relatively homogenous conditions, losing homogeneity thereafter and entering into a sustained period in which there was poor interspersion. Toward the end of the simulation, there is a strong tendency for interspersion, with a growth in homogeneity, which we can associate with sprawl.

Table 3. Fractal dimensions for other cities

City	Year	Fractal dimension	Source
Albany, NY	1990	1.494	Batty and Longley (1994)
Beijing	1981	1.93	Frankhauser (1988)
Berlin	1980	1.73	Frankhauser (1988)
Boston	1981	1.69	Frankhauser (1988)
Budapest	1981	1.72	Frankhauser (1988)
Buffalo, NY	1990	1.729	Batty and Longley (1994)
Cardiff	1981	1.586	Batty and Longley (1994)
Cleveland	1990	1.732	Batty and Longley (1994)
Columbus	1990	1.808	Batty and Longley (1994)
Essen	1981	1.81	Frankhauser (1988)
Guatemala City	1990	1.702	Smith (1991)
London	1962	1.774	Doxiadis (1968)
London	1981	1.72	Frankhauser (1988)
Los Angeles	1981	1.93	Frankhauser (1988)
Melbourne	1981	1.85	Frankhauser (1988)
Mexico City	1981	1.76	Frankhauser (1988)
Moscow	1981	1.6	Frankhauser (1988)
New York	1960	1.71	Doxiadis (1968)
Paris	1960	1.862	Doxiadis (1968)
Paris	1981	1.66	Frankhauser (1988)
Pittsburgh	1981	1.59	Frankhauser (1988)
Pittsburgh	1990	1.775	Batty and Longley (1994)
Potsdam	1945	1.88	Frankhauser (1988)
Rome	1981	1.69	Frankhauser (1988)
Seoul	1981	1.682	Batty and Longley (1994)
Stuttgart	1981	1.41	Frankhauser (1988)
Sydney	1981	1.82	Frankhauser (1988)
Syracuse	1990	1.438	Batty and Longley (1994)
Taipei	1981	1.39	Frankhauser (1988)
Taunton	1981	1.636	Batty and Longley (1994)
Tokyo	1960	1.312	Doxiadis (1968)

Source: Adapted from Batty and Longley (1994).

Implications for Understanding Sprawl

It is evident from each of the simulations discussed in this article that sprawl is, to a certain extent, inevitable. It is the likely end-state in the natural evolution of a city-system. This is obvious in the context of most well-established cities in the United States. However, it is particularly important in the context of newly-forming cities, such as those developing and growing rapidly in previously-termed "Sun Belt" cities, predominantly situated in the southwestern region of the United States. For these cities, there is a propensity for urban evolution to jump or skip the natural evolution process, fueled by higher-than-average growth rates and contemporary development regimes, and go straight to sprawl. However, there is also opportunity to plan cities in such a way that this situation does not occur. The simulations described in this paper suggest a few—geographic—ways in which policies could be developed to mitigate circumstances.

Unchecked growth leads to low-density, blanket sprawl, with all the associated costs discussed in the literature implied. Essentially, controlling sprawl requires mechanisms to *manage* growth sustainably. A number of mechanisms are understood to drive sprawl, and several of these are represented in the simulations described here. We are most interested in geographic scenarios, and the results of the simulation exercises advocate some options.

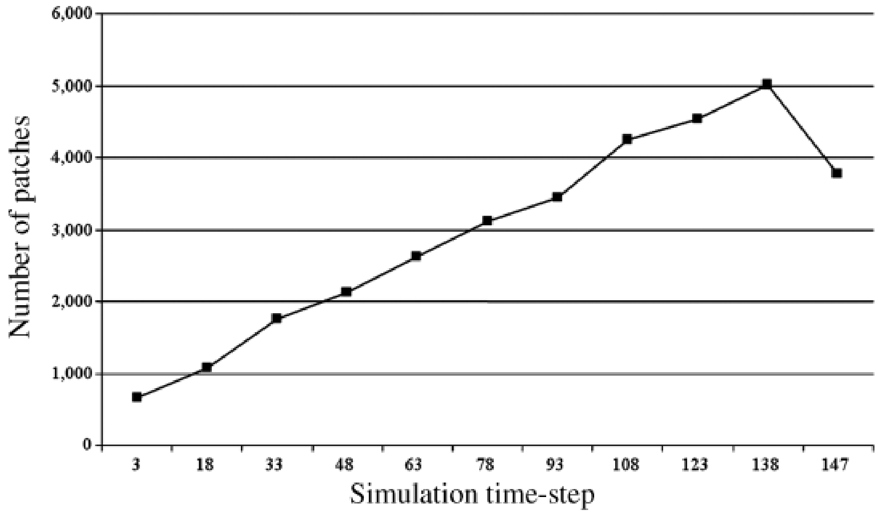

Figure 18. Change in the number of patches in the Midwestern simulation.

Encouraging polycentric development appears to be one solution—allowing leap-frogging, but encouraging sustainable and compact independent clusters, in close proximity, rather than isolated patches. Edge cities (Garreau 1992) may be one way to achieve this; transit villages (Cervero 1998) are a more likely, sustainable, option; desakota-style clusters have been successful in Asia (Heikkila, Shen, and Kaizhong 2003). It is important to actually *permit* sprawl to occur *locally* on the periphery of these clusters, to facilitate infill and to avoid by-passing large areas of land. This idea is reminiscent of much older theories of urban development, notably the idea of central place theory. Road-like growth can also be used effectively to link isolated clusters. (Transit-oriented development may have even greater potential.) However, care must be taken to avoid isolated linear development—ribbon sprawl.

Conclusions

This article has demonstrated the application of a geographically-derived automata methodology to the simulation of sprawl. The framework is particularly beneficial in modeling sprawl, allowing for the description of system dynamics as a function of spatial interactions between mobile, agent-like entities and a static, CA-like environment. Moreover, the framework allows for the generation of very realistic macroscale urban structures from these local-scale mechanisms.

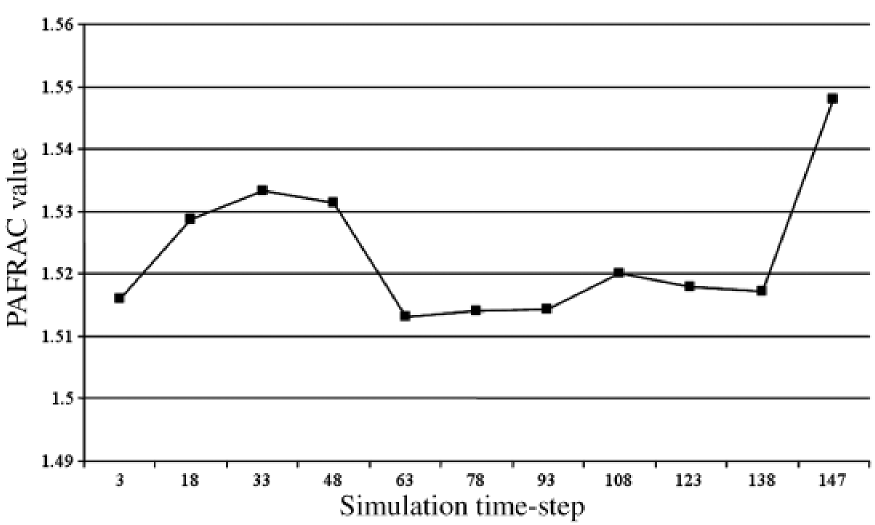

Figure 19. Perimeter-area fractal dimension change (PAFRAC) in the Midwestern simulation.

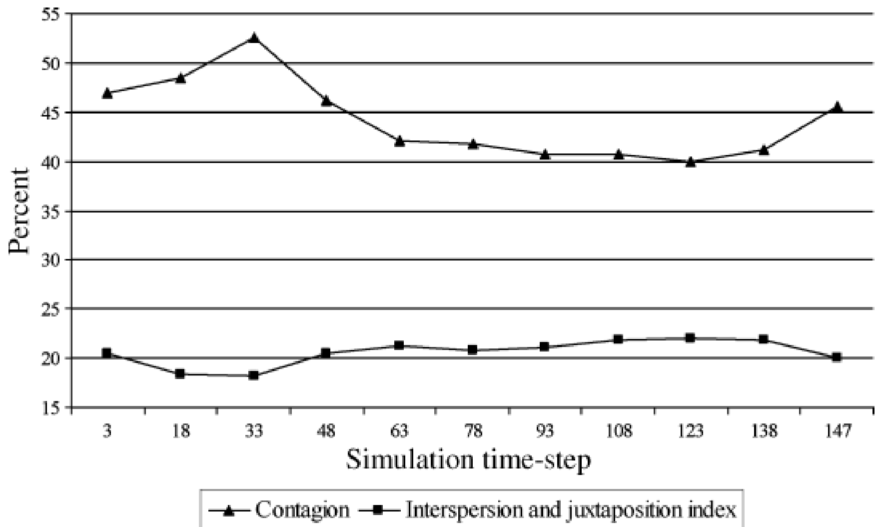

Figure 20. Contagion and interspersion change in the Midwestern simulation.

The simulations described in this paper were developed as artificial laboratories for exploring the relative—and geographic—impact of proposed causes of sprawl. The model generated sprawl-like cities in each of the simulation scenarios, and by varying the influence of rules within the model, facilitated exploration of the potential drivers of sprawl.

After measuring sprawl through the use of fractal analysis and metrics from landscape ecology, various potential options for managing sprawl were inferred. The results suggest that sprawl might best be tackled geographically, by encouraging compact and sustainable clusters of leapfrog development in close proximity. Sprawl on the periphery of these clusters then serves as an in-fill mechanism rather than continuing on the periphery of a larger urban mass in an unsustainable fashion. Moreover, it was determined that road-influenced growth could help to link isolated fragments of sprawl on the urban periphery under certain conditions.

The simulations discussed in this paper were designed to explore geographic dimensions of sprawl, focusing on mimicking the spatial distribution of growth in dynamic contexts. In the literature on sprawl, however, it is clear that there are other important components to the phenomenon that these simulations have not addressed—namely, preference-based drivers at within-neighborhood geographies. Elsewhere, the authors have applied a similar methodology to the modeling of preference-based behavior in an artificial residential submarket, roughly equivalent to a single fixed-infrastructure automaton in the growth-based simulations described in this paper (Torrens forthcoming). This remains a topic of ongoing research.

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