Scale and Urban Growth Models
UGEC and NASA Joint Workshop on Urban Remote Sensing (URS) and Forecasting Urban Growth (FORE), April 1 – 3, 2011

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Analysis of urban systems and urban change must be sensitive to the issue of scale, considering how choices made regarding both spatial and temporal *extent* and *resolution* influence the analyses we conduct and the conclusions we draw (Walsh and Crews-Meyer 2002; Verburg, Schot et al. 2004). Urban systems exhibit any number of hierarchies, or levels at which key processes interact and evolve at similar speeds and over similar spatial extents (Simon 1974). Information may be transferred to levels up or down, but stable, recognizable structures emerge (Holling 2001). These recognizable structures, or scale effects, may constitute evidence of these hierarchical processes at work, but in applied research, we encounter the impacts of scale empirically. We may have to conduct extensive inductive analysis to understand scale-specific patterns in our data, which may make it harder to theorize a priori important scales of influence (Munroe and Müller 2007; Manson 2008).

Thus, identifying and accounting for spatial processes at varying scales is challenging. Scale effects can be intrinsic to the data we use: the remote sensing pixel is an artifact of the device, and not related to either social or environmental processes in a straightforward way (Fisher 1997). More generally, there is not necessarily an obvious way to group data by relevant scales; depending on how the data are measured or aggregated, results can vary (Turner, O'Neill et al. 1989; Cressie 1996).

In the sections below, I explore several critical scale issues we often encounter in data-driven modeling of urban growth. A common theme to all these points is the distinction between pattern and process (Nagendra, Munroe et al. 2004), understanding that we generally know much more empirically about the former than the latter. These models are likely to be spatially and temporally explicit, and thus must accurately represent processes that vary over space and time. Urban growth models may be informed by microeconomic principles: that land values shape (but not necessarily dictate) likely trends and transitions in urban form. Here, I focus my comments primarily on conceptualizing and identifying domains of scale. Ultimately, computational modeling that integrates spatially and temporally dynamic feedbacks is necessary to understand the behavior of urban systems (Irwin, Jayaprakash et al. 2009).

Spatial scale

Urban growth models may have to contend with a variety of scale-dependent processes shaping urban form. We must then consider how key processes underlying urban land-use change express themselves over space. At the most basic level, models of urban land-use change increasingly focus on individual decision-making, attempting to understand how individuals choose to live or work in particular locations of the city given locational attributes and variations in land value.

However, individual decision-making in urban areas is strongly mediated by many processes operating at larger spatial extents. Neighborhood effects are often extremely important; many sorting processes happen at this level (Bayer and Timmins 2007). In the United States, local funding of schools often means that perceived variations in school quality can be a substantial determinant of land value. Other political factors can vary at the neighborhood level, including zoning ordinances, taxes, the distribution of service centers (e.g., commercial sites of opportunities) and natural amenities (Carrion-Flores and Irwin 2004; Walsh 2007; Bayer, Keohane et al. 2009; Klaiber and Phaneuf 2010). Neighborhood-level effects are often endogenous: past land-use changes shape current and future neighborhood possibilities. For example, a declining neighborhood may lose tax revenue and not be able to invest in the maintenance of its amenity base (Anacker 2010). Beyond the neighborhood, local land markets can be tied to larger regional or national trends in the macroeconomic economy, and job and housing markets can be endogenously linked (Partridge and Rickman 2003).

There are several techniques that can be used to capture spatial scale effects. Geostatistical techniques, such as variogram analysis, can be used to identify domains of scale within a particular urban setting (Fleming 1999). In a regression context, locally weighted regression (such as GWR) is often used to explore spatial variation in a continuous variable (e.g., parcel sales price) to identify patterns or derive spatially demarcated discontinuities in the relationship between two or more variables over space. This technique is descriptive, and as such, can be useful for investigating the spatial implications of hypotheses drawn from theory (Griffith 2008). Another promising technique is the use of multi-level statistical models, which allow us to identify trends in one variable conditional on processes operating at different spatial extents (Polsky and Easterling 2001). Finally, Bayesian hierarchical models facilitate a process-based description of spatial-temporal change, along with associated uncertainty estimates (Wikle 2003) that can be very useful in understanding the dynamics of an urban system.

Temporal scale

Time scale effects, or patterns in the sequencing of events, can in some cases be more complicated than spatial scale because time can be linear, periodic, cyclic or infrequent (e.g., large-scale shocks). In modeling urban systems, temporal scales generally matter in two related ways. First, we must consider the variable speed at which processes occur (and change), such as labor markets, land markets, land-use policy, and regional and international migration. Secondly (and indirectly following from the first), we must often consider legacy effects, path-dependency, or long-established structures that influence all subsequent urban changes (Pickett, Cadenasso et al. 2005). Perhaps the classic example in an urban area is that of water: there are almost always upstream and downstream effects in sewage and industrial waste that shape subsequent patterns of industrial, residential and commercial activity (Munroe 2007).

A principal challenging in modeling an urban system is the endogeneity of many of its components (zoning, roads, utilities and other local public goods). The relationship between roads and development is particularly polemical. Infrastructure construction and improvements and subsequent land development can co-evolve in highly complicated patterns. From a policy side, this pattern has been debated to argue either that roads cause or roads follow development. Public investments that indirectly subsidize new construction, such as road building or improvements, may lead to more and more fragmented growth (Pendall 1999). Roads also follow development: decisions about subsequent road construction might be made following land conversion and resulting congestion (Baum-Snow 2007). Because such temporal interdependencies can feed back across space and time, models must be able to represent such feedbacks or inferences may be biased.

A third aspect of temporal scale in studying urban growth is making a case for structural change in a given process over time. Irwin and Bockstael (2007) discuss data and methods needed to determine whether urban fragmentation is increasing over space (distance from metropolitan center) and time (1973 vs. 2000); significant differences in land fragmentation patterns could indicate a qualitative shift in urban form associated with exurbanization, or low-density, fragmented urban-dependent development in formerly rural areas. Aspinall (2004) also explores temporal variations in the drivers of land-use change. Using multi-model inference techniques, he shows that over a multi-decadal time period, various factors such as infrastructure become more or less important in explaining overall land-use change over time.

Data availability is critical here. The retrieval of satellite imagery is often dictated by weather patterns or the orbits of satellites (Lambin 1997). Secondary data may only be collected through a decadal census. In fact, urban analysts are often much more constrained in the amount and access to information over temporal domains rather than spatial. Current major efforts include ways to derive datasets longer in duration and richer in sampling frequency. More process-based modeling of urban systems requires much richer data on underlying processes (e.g., individuals, neighborhood groups, political decisions, etc.) and not just the statistical association of these effects at an aggregated level (Brady and Irwin 2011).

Teleconnections

One issue relating to scale that has received substantially less conceptual and analytical attention is that of teleconnections: functional relationships between often distal locations. Accounting for these teleconnections may fundamentally challenge the ways we currently draw boundaries around processes we measure (i.e., a given scale as a "container" of process). Urban systems are clearly not closed; there are critical processes flowing in and out of cities, often daily or even hourly. However, it is conceptually challenging to think about which processes are most critical to represent in an urban growth model. Particularly when we use satellite data to observe changes in urban pattern, we are focused on the snapshot in space and time. How do we begin to integrate processes happening outside of this region, outside of this time point? For example, urban analysts might be able to measure accurately how many people are moving in and out of a city region (depending on how data are collected), but understanding the various "push and pull factors" relative to other locations may be considerably difficult. Without a precise understanding of these factors and their local effects, however, models of urban process may yield biased and misleading results.

The standard approach in the human dimensions community until now has to been to conceptualize ever-larger, more or less nested, more or less hierarchical sets of spatial and temporal extents (and processes acting on those extents) (Holling 2001). For example, see Gibson et al.'s (2000) nested hierarchy of institutional decision-making. While this framework is insightful and sheds critical insights on how decisions are influenced and structured by any number of processes operating above or below, there are shortcomings of this framework that we may seek to improve upon.

Most importantly, "global" decision-making (i.e., processes that cross two more international borders) does not always happen at a global level. One category of actors shaping land use locally by operating globally would be transnational corporations (TNCs) (Jepson 2006; Geist, Otanez et al. 2008). TNCs often operate through complicated networks of places, but ultimately, have a distinct geography. The involvement of distal actors in processes of urbanization can reflect former colonial ties, investment and banking infrastructure, and particular cultural or ethnic diasporas (Seto and Kaufmann 2003). Therefore, their imprint is certainly not global (in the meaning of *universal*). Cities, in turn, depend on web-like connections to many distal places for everyday flows of people, materials and energy (Decker, Elliott et al. 2000). Depending on the research question, greater elucidation of these linkages may be necessary for a richer understanding of how urban systems function and change.

The difficulty in understanding the role of international non-state actors like firms may be hampered by the land-change science community's conceptual adherence to hierarchies (cf. (Perz and Almeyda 2009)). In order to move beyond this impasse, urban modelers may want to think about networks that connect various forms of decision-making at various places on the globe and across various levels of institutional arrangements. To do so might make us reconsider processes that work across multiple scales. Reconceptualizing urban systems as complex adaptive networks to understand interconnections among decision-makers in multiple locations (in space and time) may be a fruitful endeavor toward this end.

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