Changing Landscapes in the Twin Cities Metropolitan Area

by Steven Manson and Marvin Bauer

Humans have long altered the land by clearing forests, farming, and building settlements. It is increasingly apparent, however, that these transformations have serious social and environmental implications. This is evident in the Twin Cities metropolitan area, a 7,700 square-kilometer seven-county region home to roughly 2.8 million people. The metro area population is forecast to top 3.5 million in 2020, continuing a trend of the region being one of the fastest-growing metropolitan areas in the nation. Urbanization in the Twin Cities and elsewhere in the United States is characterized in large part by suburbanization, or decentralized, low-density residential land use.

Increasingly, the public, researchers, and policy makers recognize that urbanization must be examined and understood at small spatial scales, on the order of individual lots or parcels of land. The severity and nature of the impacts of urban growth are related to the extent to which urbanization occurs through a leapfrog process that intersperses housing with open spaces such as agriculture lands or woodlands. Although the total *amount* of land converted to urban uses is important to determining the impacts of urbanization, its *spatial configuration* also matters a great deal. Decentralized urbanization offers some important benefits, such as freedom of choice and affordable housing; however, it also has negative implications for traffic, atmospheric chemistry, natural habitat, water resources, infrastructure efficiencies, and inner-city viability. A dispersed pattern of urban development makes it more expensive to provide infrastructure such as roads or sewers, for example, because these networks must be spread out and extended to reach every house or business. Similarly, ecosystem functions such as providing natural habitat and water purification require undisturbed expanses of open space, forests, and wetlands. Decentralized development creates a fragmented landscape, one that is a crazy quilt of human and natural land covers. Much of the current research on urbanization examines changes in aggregate measures of urbanization, such as variations in housing density or commuting times among counties. Although this broad view is important to understanding urbanization, it does not capture the patterns and processes of land conversion at fine temporal and spatial scales.

Single-family residential development in Woodbury. Development tends to occur near existing developed land, expanding outward from current urban areas—the so-called "birds of a feather" principle of urban development.

Our research integrates several different approaches to describe and understand the processes of urbanization in the Twin Cities. We started by creating maps of the changing landscape based on satellite imagery, an approach that offers a streamlined method for inventory, monitoring, and analysis of land, vegetation, and water resources. We were interested in two particular kinds of information about the Earth's surface: the kind of land cover found in a given location (e.g., urban, agricultural, or forest) and the percentage of impervious surfaces (such as roads or parking lots) that do not allow water to penetrate into the underlying soil. We can learn much about urbanization in the Twin Cities metro area from these satellite images. We also combined these maps of land cover and impervious surfaces with other data—such as U.S. Census data and physical characteristics of the land—in a geographic information system (GIS), a computer system used to manipulate and analyze spatial data. We used these combined data sets to create computer models to explore the underlying causes of land change and how this change varies from place to place across the Twin Cities.

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Land-Cover Classification and Change Mapping

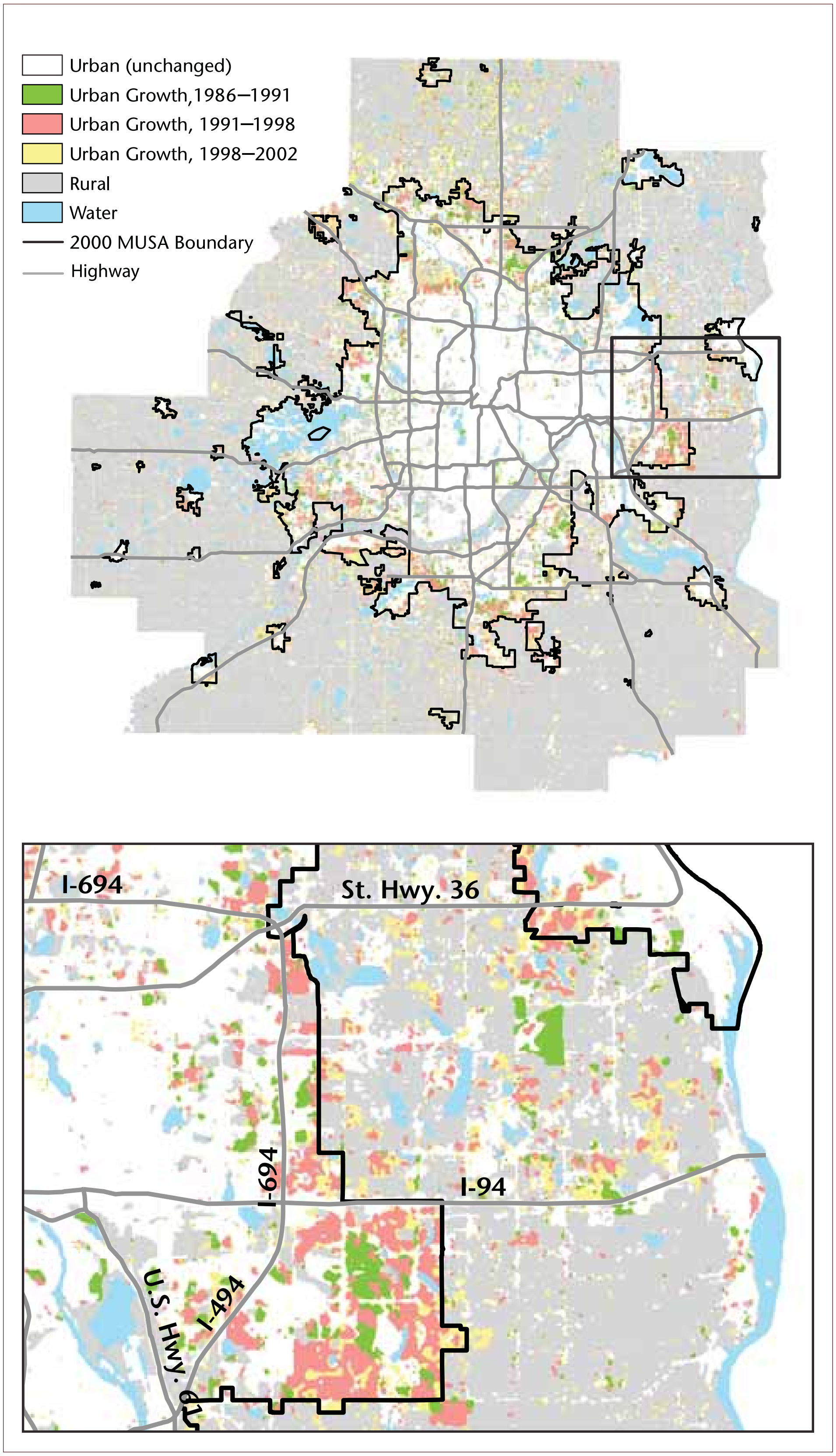
Historically, aerial photography has been an important source of information on land cover (the physical surface and vegetation) and land use (human occupation and applications). The cost of aerial photography acquisition and interpretation of cover types, however, is prohibitively expensive for geographic areas larger than a small city or township. An alternative is to acquire the needed information from digital images of the Earth taken from satellites. This approach has several advantages. First, the broad view of a satellite provides coverage of large, multi-county geographic areas. Second, by comparison with printed photos, the digital form of the data lends itself to more efficient analysis using computers, and the classified data can be used in geographic information systems. Finally, land-cover maps can be generated at considerably less cost than by other methods, such as ground surveys or aerial photography interpretation, which usually require a good deal of human expert knowledge and time.

We used data from a satellite called the Landsat Thematic Mapper (TM) to develop maps of both land cover and impervious surfaces in the Twin Cities metro area for 1986, 1991, 1998, and 2002. The Landsat images resemble those taken with a digital camera, but the satellite senses both visible light (the colors that humans see) and infrared light (wavelengths longer than those our eyes are sensitive to). Each image is composed of millions of picture elements, or *pixels,* each equivalent to a 30-by-30-meter area on the ground, or about one-quarter acre.

Land-Cover Classification. The most common use of remotely sensed imagery is to convert what the satellite sees (visible colors and infrared) into categories of land on the ground. Our land-cover classification system has seven classes: agriculture, forest, grass, urban, water, wetlands, and extraction (i.e., gravel mining). In addition to using the Landsat TM remotely sensed imagery, we collected samples of each land-cover class on the ground to understand what each class looked like from space and to test how well the classification system maps land cover in the real world. We then used specialized statistical methods to classify each pixel in the imagery according to one of the land-cover classes. After classifying imagery for individual years, we mapped changes in land cover for the periods 1986 to 1991, 1991 to 1998, 1998 to 2002, and 1986 to 2002.

Overall, this approach produced very good results. For the four individual years, 94 out of every 100 pixels were classified correctly (94% classification accuracy). We also used high-resolution aerial photography to double-check the maps created from remotely sensed

Figure 1. Urban Growth in the Twin Cities Metropolitan Area, 1986 to 2002



imagery against what was actually on the ground. With few exceptions, the areas identified as having changed from agriculture or rural to urban were identified correctly. It should be noted that we have classified land *cover,* not land *use*. Although they are related and often similar, there are semantic and practical differences between land use and land cover. A single land use such as "urban," for example, can include multiple land-cover types, including buildings, streets, grass, and trees.

We used the classified imagery to create a map of the major land-cover types in the metro area (Figure 1). Between 1986 and 2002, the amount of urban land increased from 23.7% to 32.8% of the total area, whereas rural cover types such as agriculture, forest, and wetland decreased from 69.6% to 60.5%. The majority of these changes are at the periphery of Minneapolis and St. Paul and their first-ring suburbs. Figure 1 illustrates one of the major advantages of satellite data classification: We can produce a map of where land-cover change has occurred.

We used the change map to calculate change statistics across land-cover classes for the four years (Table 1). From 1986 to 2002, urban area increased by 173,000 acres (9.1%), whereas agricultural area decreased 136,000 acres (7.1%), forest area decreased 22,000 acres (1.1%), and wetland area decreased 17,000 acres (1.0%). In relative terms, the amount of urban area in the Twin Cities metro area increased 38.5% from 1986 to 2002, with the greatest increase occurring from 1991 to 1998. During the same period, agriculture, forest, and wetland decreased, respectively, by 15.0%, 7.9%, and 12.4%.

Impervious Surface. In addition to considering changes in different kinds of land cover, it is useful to examine variations within specific classes. One increasingly critical case is the amount of impervious surfaces in the landscape. Impervious surfaces are those that water cannot infiltrate and are primarily associated with building rooftops and transportation infrastructure such as streets, highways, parking lots, and sidewalks.

Our approach to estimating and mapping impervious surface area is based on a strong relationship between the amount of impervious surface in a given area and the amount of "greenness" in satellite images of that area. Greenness is determined largely by the amount of green vegetation on the ground and is therefore inversely related to the amount of impervious surface. We modeled the relationship between greenness and percentage of impervious area using statistical methods to estimate the amount of impervious area in each Landsat TM pixel. In an urban area, there are three major land-cover types: vegetation, impervious surfaces, and water. Each kind of cover looks different to the satellite, enabling accurate estimation of the proportion of each pixel that is impervious. The resulting classification gave us a map that portrays a continuous range of impervious area from 0% to 100% for the entire Twin Cities metro area (Figure 2).

The next step in our investigation was to examine changes in the amount of impervious surface during the period 1986 to 2002. For the entire seven-county metro area, the percentage of impervious area increased from 9.0% in 1986 to 13.0% in 2002 (Figure 3). In general, increases in impervious area were primarily at the periphery of already developed areas. The greatest changes occurred in Anoka and Carver Counties, where the impervious area more than doubled. Conversely, in Ramsey County, the most densely populated county in the state, impervious area increased only slightly after 1991.

An additional advantage of the digital maps available from the Landsat TM classifications is the ability to generate maps and area statistics for smaller areas such as cities or townships. Figure 4 shows the City of Woodbury, a suburb east of St. Paul and one of the most rapidly growing areas in the state during the 1990s, which saw an increase from roughly 8% to 22% impervious surface.

In summary, information from satellite remote sensing can play a useful role in understanding the nature of land change and where it is occurring. Classification of the Landsat TM data also provides a means to map and quantify the degree of impervious surface area, an indicator of environmental quality, for large geographic areas and over time at modest cost. Both kinds of information are essential to planning for development and preserving our natural resources and environment, and are useful to urban planners and citizens. Further information, including maps and statistics from our research, are available at www.land.umn.edu.

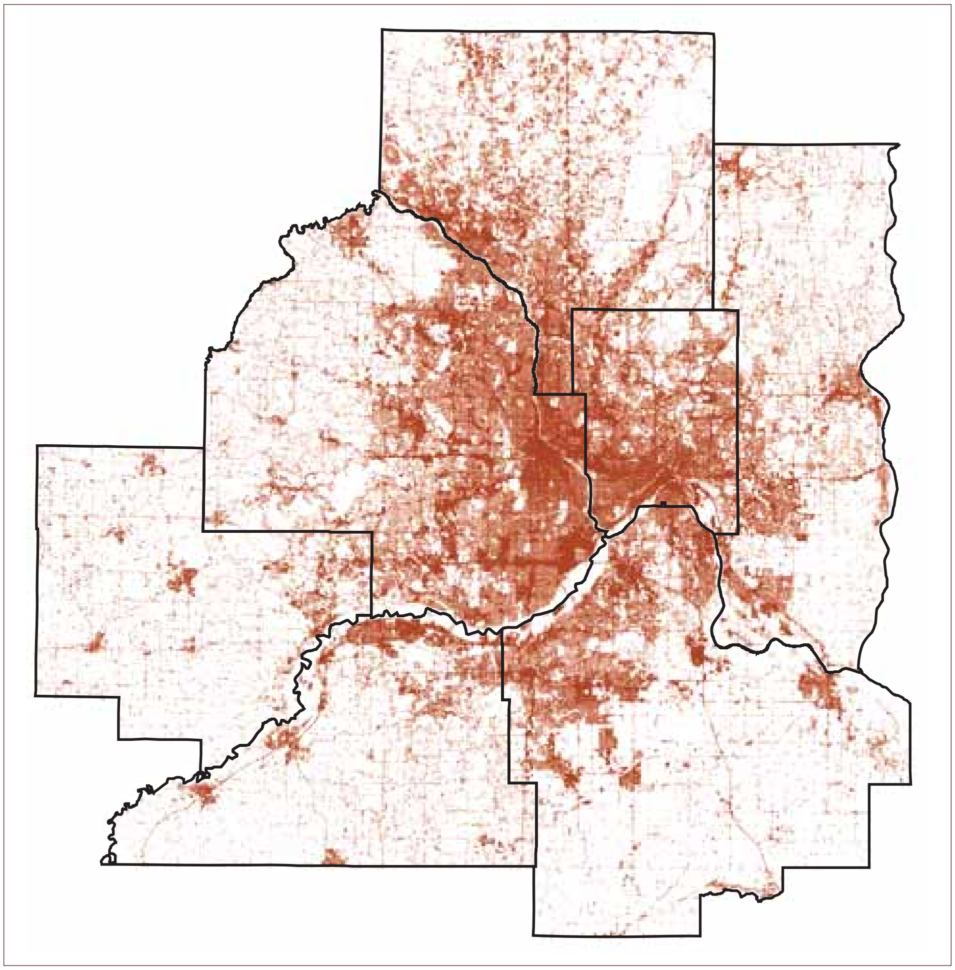
Modeling Changing Urban Landscapes

Our ability to measure, understand, and conceptualize urbanization at very fine spatial scales is evolving with our increasing ability to combine land-change maps from remotely sensed imagery with other kinds of geographic data, such as U.S. Census information. We can combine these various forms of geographic data with computer models to gain insight into the factors that influence urbanization. A perennial challenge for city planners, for example, is determining

Table 1. Summary of Landsat TM Classification Area Statistics for the Twin Cities Metropolitan Area, 1986, 1991, 1998, and 2002

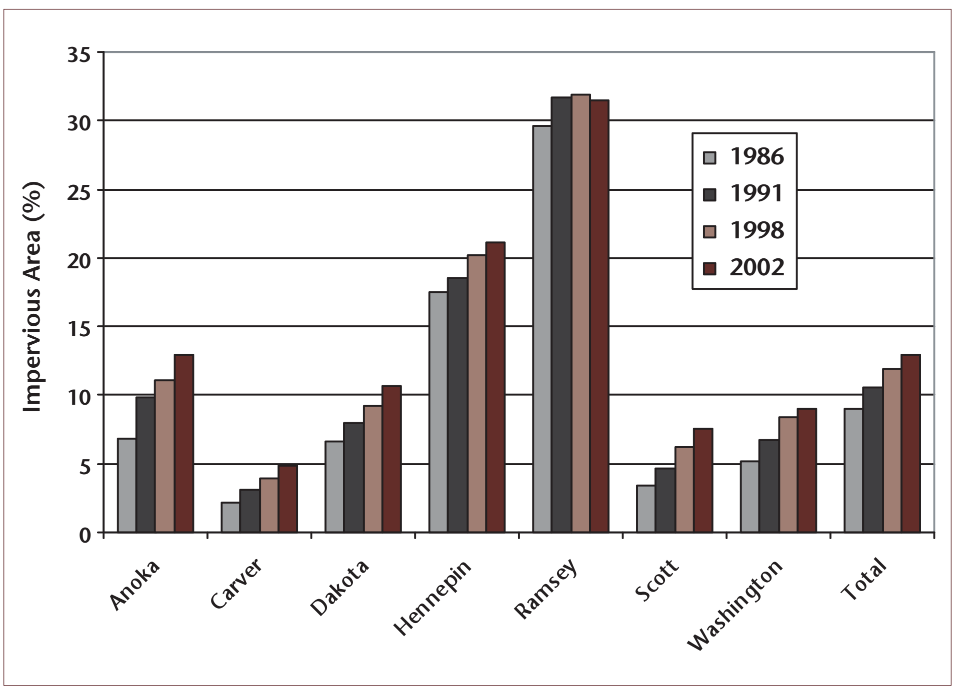
Land-Cover Class	1986		1991		1998		2002		Relative Pct. Change 1986–2002
	Area (acres)	Pct. (%)	Area (acres)	Pct. (%)	Area (acres)	Pct. (%)	Area (acres)	Pct. (%)	
Agriculture	902,000	47.4	838,000	44.1	781,000	41.1	766,000	40.3	–15.0
Urban	452,000	23.7	494,000	26.0	588,000	30.9	625,000	32.8	+38.5
Forest	279,000	14.6	274,000	14.4	262,000	13.7	257,000	13.5	–7.9
Wetland	143,000	7.6	158,000	8.3	136,000	7.1	126,000	6.6	–12.4
Water	104,000	5.5	114,000	6.0	111,000	5.9	106,000	5.6	+3.5
Grass	18,000	1.0	19,000	1.0	17,000	0.9	16,000	0.9	–9.7
Extraction	4,000	0.2	6,000	0.3	7,000	0.4	6,000	0.3	+42.6

Figure 2. Impervious Surface Area Classification for the Seven-County Twin Cities Metropolitan Area, 2002



Note: Impervious surface area is mapped as a continuous variable from 0% to 100%, with darker color denoting a higher degree of impervious surface area.

Figure 3. Changes in the Percentage of Impervious Surface Area from 1986 to 2002, by County



where and how much urban development will occur in the future. Although local and state governments control development in a broad sense through zoning and incentives, individual landowners have much latitude in where and how much property to develop.

We created two stylized models of where (location) and how much (quantity) development is likely to occur in the Twin Cities metro area. We used two related modeling methods, statistical spatial regression and cellular modeling, to explore urbanization in the metro area from 1986 to 1998 to better understand the urban development process and create tools that can be used to predict future land use.

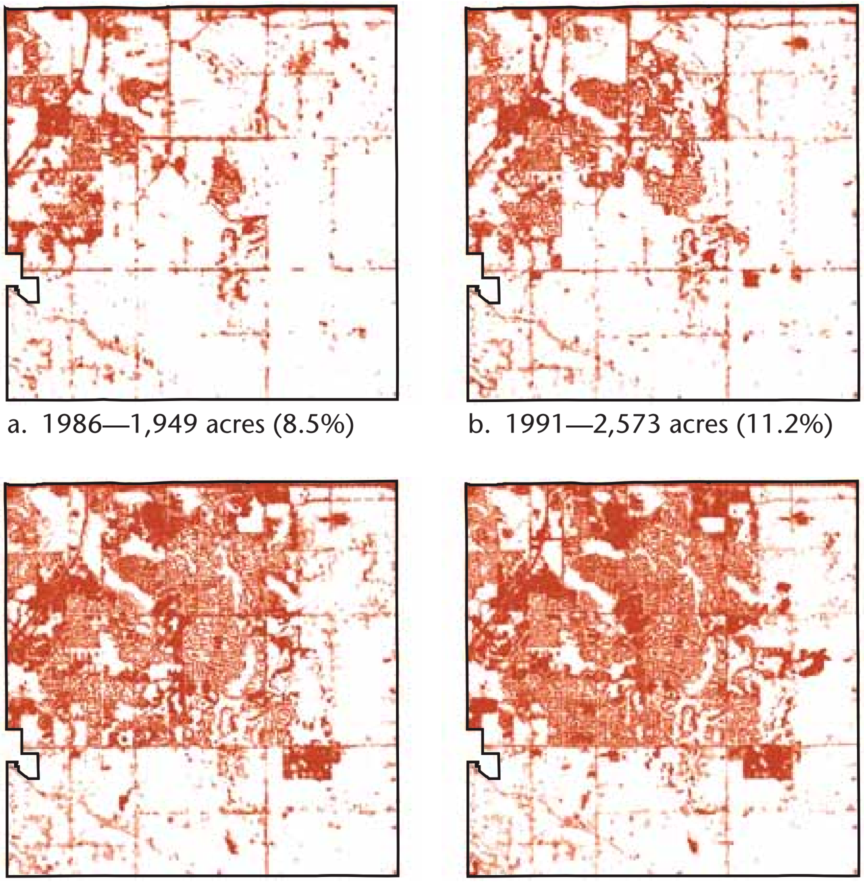
Modeling urbanization is very difficult because it is a complicated process that is contingent on a host of social, political, cultural, economic, and ecological influences. That said, urbanization in the Twin Cities metro area can be conceived of as a "bow wave"[1] of development pushing outward from existing urban areas. This bow wave operates according to two general principles: (1) development expands outward from current urban areas and (2) urbanization is more likely in some places than others depending on a range of social and ecological factors.

The first principle can be termed the "birds of a feather" rule, in that new development tends to occur near existing developed land. Building new properties adjacent to currently developed areas is generally less expensive because infrastructure such as roads and utilities is easier to extend from current infrastructure than it is to build as a stand-alone system. The desirability of a house in a given location is also a function of nearby amenities—such as roads, schools, infrastructure, and shopping—that require a critical mass of people in close proximity. Perhaps most important, many of the factors that influence the siting of development in a given place are usually still in force in adjacent areas, which leads to the second general rule.

The second principle governing the bow wave of development posits that the likelihood of any given parcel of land being developed is a function of socioeconomic and environmental characteristics that vary over the landscape. These include inherent features of a plot of land, such as its size or the

[1] This term originated with Fraser Hart, professor of geography at the University of Minnesota.

Figure 4. Impervious Surface Classification Maps for the City of Woodbury, 1986 to 2002



a. 1986—1,949 acres (8.5%) b. 1991—2,573 acres (11.2%)

c. 1998—4,169 acres (18.2%) d. 2002—4,438 acres (19.4%)

Note: Impervious surface area is mapped as a continuous variable from 0% to 100%, with darker color denoting a higher degree of impervious surface area.

ease with which it may be cleared and leveled for erecting buildings. These characteristics also relate to external factors controlled by the location of the land parcel in the broader spatial organization of the landscape, such as the school district or the distance to important market and employment centers. Therefore, although the bow wave of development flows outward from areas of current development across the landscape, all other things being equal, it occurs earlier in a desirable school district and later in areas with fewer amenities.

Of course, there are exceptions to these two general rules. Counteracting the birds of a feather effect, for example, is the fact that people are willing to pay more for properties that are not hemmed in by development. Similarly, urbanization can fall victim to its own success—for example, when so many homeowners are attracted to an area with less crowding and traffic that they create the crowding and traffic they sought to avoid in the first place. Development also can leapfrog over certain areas entirely, for reasons ranging from restrictive zoning to market speculation, personal situation, or happenstance.

Despite these exceptions, these two general principles serve as a useful way to conceptualize urbanization in the Twin Cities metro area. They also suggest two different, yet related, modeling strategies for understanding urbanization, spatial regression, and cellular modeling. Cellular modeling relies on the first principle, that development expands outward from existing urban areas, whereas spatial regression modeling relies on the second, that development is more likely in some places as a function of a range of social and ecological factors.

Spatial Regression Modeling. We used statistical spatial regression to assess the relationship between urbanization in a location (measured by land cover or impervious surfaces) as a function of social and environmental factors for that location. Although certain factors that influence urbanization—such as "this is a nice neighborhood"—are intangible, we can measure proxies, such as distance to the nearest lake or access to schools that perform well on standardized tests. More important, GIS allows us, for every single location (or every pixel, in this case) in the metro area, to analyze the relationship between the urban land use and various explanatory factors. Spatial regression is designed to use, and deal with the challenges imposed by, geographically referenced data. In aggregate, we can develop an overall view of the importance of these various factors in explaining the incidence of urbanization.

Regression analysis creates a mathematical model of the relationship between some measure, called the *dependent* variable, and a series of *independent* variables. We measured the dependent variable of urbanization in two ways: either by percentage of impervious surface or by the incidence of the urban land class derived from the remotely sensed imagery. We can determine the strength of the apparent relationship between the percentage of impervious surface and the occurrence of urban land as a function of certain factors (the independent variables in our model) that vary across the Twin Cities metro. We identified a number of factors important to urbanization by examining the research literature and speaking with households, policy makers, and developers in the region (Table 2). This list is by no means complete, but instead represents an array of factors that range from whether a particular location falls within an area enrolled in agricultural land protection programs to the test scores of its school district. Furthermore, it is important to bear in mind that this form of analysis determines *correlation,* not *causation,* and these relationships only make sense within a broader discussion of the larger social, economic, and policy contexts of urbanization. Some relationships between urban development and social and environmental factors are seemingly obvious, whereas others are indeterminate.

As expected, there are strong relationships between urban development and areas in the Twin Cities metro targeted by land-use policies. This is evident in the strong negative relationship between urban land use and areas excluded from development by local, state or federal laws (– – –) or areas with high levels of enrollment in state or federal agricultural protection programs (– –). These forms of land protection are explicitly designed to prevent development and they generally work well in the metro area. Conversely, there is a strong positive relationship (+ + +) between development and location within the Metropolitan Urban Services Area (MUSA). The regional planning authority, the Metropolitan Council, implemented MUSA in the 1970s to encourage efficient growth and use of roads, sewers, and transit in the region. As intended, it is difficult to develop land outside of the MUSA because providing essential services such as sewage treatment is expensive.

We found that development varies by county in the metro area. Location in Anoka and Scott Counties has a positive (+ +) or weakly positive (+) relationship with both impervious surfaces and urban land cover, which indicates development was more likely in these regions. Location in Carver, Dakota, and Washington Counties also has a positive, although somewhat weaker, relationship with development. Location in Hennepin County has no apparent relationship with development (•). Ramsey County is the only location with a negative relationship with new development (– –). Although these differences among counties likely relate to a number of features—such as variation in land-use policies or taxes—the key determinant is likely the availability of land. Ultimately, however, the spatial regression analysis only points to further avenues of inquiry, such as considering counties one-by-one in terms of their taxation regime or incentives available to land developers.

In addition to policy considerations as such, we also examined median income as a proxy for socioeconomic variation over the landscape. Income has a strong negative relationship (– – –) with impervious surfaces and a positive relationship with development. Although it is not advisable to generalize too much with such a gross socioeconomic indicator as median income or to generalize across entire cities, residents in the metro area at lower income levels are found primarily in the cities of Minneapolis and St. Paul. Despite the Twin Cities being a very tree-rich region, these heavily developed areas have a greater proportion of land devoted to transportation, commercial, and industrial uses

Table 2. Relationship between Impervious Surface Area or Development State and Selected Social and Environmental Factors in the Twin Cities Metro Area, 2000

Relationship to. . .		
Impervious surface area	**Development state**	**Factor and description**
– – –	– – –	**Excluded areas.** Is the location excluded from development by local, state, or federal law?
– –	– –	**Agricultural protection.** Does the location fall within an area enrolled in an agricultural protection program designed to reduce development?
+ + +	+ +	**MUSA.** Does the location fall within the Metropolitan Urban Services Area?
		County. In which county does the location fall?
+ +	+	Anoka
+	+	Carver
+	+	Dakota
•	•	Hennepin
– –	– –	Ramsey
+ +	+ +	Scott
+	+	Washington
– – –	+ +	**Income.** Median household income in dollars for the location.
+ + +	+ + +	**Twin Cities.** Proximity to the nearest of Minneapolis or St. Paul.
+	+	**Water.** Proximity to the nearest water body greater than three acres in size.
+ +	+ + +	**Park.** Proximity to the nearest park.
+ +	+	**Soil.** Quality of soil for agriculture in the location.
–	•	**Slope.** Slope of the land in that location

Note: Relationships vary from strongly positive (+ + +) to no apparent relationship (•) to strongly negative (– – –). A positive relationship means that the factor is correlated with greater impervious surface or development, whereas a negative relationship means that the factor is correlated with less impervious surface or development.

associated with impervious surfaces. Conversely, higher-income residents can generally be found in areas with larger, more vegetated parcels common to the suburbs. The same income dynamic is at play in the positive relationship between urban land use and development (+ +), given that the bulk of new development is occurring outside the core Twin Cities.

The relationship between urban land use and proximity to the nearest of either Minneapolis or St. Paul is strongly positive (+ + +), which suggests that the likelihood of development increases as a location is closer to either of the Twin Cities. This is in keeping with the expectation that urban land cover is more likely near large market centers, as they are hubs for employment and amenities such as sporting events and the arts. A similar logic holds true for proximity to the nearest water body (+) or to parkland, which shows a strong positive (+ + +) relationship with urban land use and positive (+ +) relationship with impervious surfaces. People like to live near water and parks, and land developers are happy to oblige. It is important to note, however, that in the case of parks, the reverse can also hold true in that we are more likely to situate parks where people live. This highlights once again the caveat that correlation does not necessarily imply causation.

Soil quality and slope are two other, more subtle, environmental features that affect development, although far less in the Twin Cities metro area than in other locales given the relative uniformity of the landscape here. There is a weak negative (–) relationship between slope and impervious surfaces, and no discernable relationship with urban land use. Slope of land is a tricky factor to interpret because although some builders seek out areas with greater slope for their potential to provide scenic views, these areas are also difficult locations on which to build infrastructure given the ruggedness of the terrain. There is a positive (+) relationship between agricultural soil quality and urban development, as these soils are comparatively easy locations on which to build, especially if they have been farmed.

Cellular Modeling. A *cellular model* divides the Earth's surface into very small *cells* or units of land (in our case, pixels from remotely sensed imagery). The purpose of the model is to examine the current land cover in a cell and predict its land cover at a later time. Future land cover is modeled according to two conditions: the land cover that presently exists within the cell and the land cover of neighboring cells. Each of the different land-cover classes determined by classifying the Landsat TM imagery has its own set of rules based on these two conditions.

The first condition, existing land cover, is very important. A cell with water is essentially guaranteed to remain water from one year to the next. A cell that is urban this year is very likely to remain developed next year given the permanence of housing, although there is a very small chance it will revert to undeveloped land through abandonment or reversion to natural uses. In comparison, a cell with forest, extraction, grass, or wetland is less likely to remain the same next year because it can be developed fairly easily. Agricultural cells are the most likely to convert to urban land cover from one year to the next. Finally, there is a remote possibility that a non-urban cover such as agriculture or forest can switch over to another non-urban cover.

The second condition, surrounding land use, takes into account the extent to which a cell is influenced by what is going on around it. All other things being equal, an agricultural cell that is surrounded by other agricultural cells is more likely to remain in its current state than one that is surrounded on all sides by urban land cover. The same holds true to a lesser degree for forest, grass, wetlands, and extraction. Water, as per the first rule, is fairly immune to change as a function of surrounding land cover.

The model we used extracted these rules by examining transitions between different land-cover classes in the Twin Cities for the period from 1986 to 1991. The model then projected forward the process of development to the year 1998. In other words, the model used past experience to predict where (location) and how much (quantity) development would occur in the future.

We determined how well this approach performs by comparing the actual Twin Cites landscape in 1998, as derived from the Landsat TM imagery, to the model projection of the landscape in 1998. It is important to note that the model only had access to land-cover maps from 1986 and 1991 as a basis for predicting what future land cover would look like. Figure 5 shows where the model projected land cover correctly and, more important, incorrectly. The white areas are where the model projected urban cover correctly and the gray areas are where it predicted non-urban land cover correctly (that is to say, agriculture, extraction, forest, grass, water, and wetlands). Overall, the model predicted the majority of urban versus non-urban land cover fairly well, although it makes two kinds of errors. First, the areas in blue are those where the model assumed there would be urban land cover in 1998 when in fact there was no such development. Second, the areas in red are those the model predicted would remain undeveloped when they were actually developed by 1998. The model is far more prone to the second kind of error because it missed the explosive growth of the Twin Cites in the 1990s, which was fueled by population expansion and an increase in house lot sizes compared to development in the earlier 1986 to 1991 period on which the model was based.

The model performed far better when we knew how much growth to expect, but not where to expect it (Figure 6). This situation is analogous to a planner estimating the quantity of future development and having the model predict where this development will likely occur. Here the model used the same rules as before to determine *where* development is likely to occur in 1998, but we knew *how much* land was developed based on our knowledge of actual land cover in 1998. Figure 6 shows that this model predicted with great accuracy where

Figure 5. Comparison of Cellular Model of Twin Cities Urbanization with Actual Urbanization from Landsat TM Imagery based on Estimated Quantity of Urbanization, 1986 to 1998

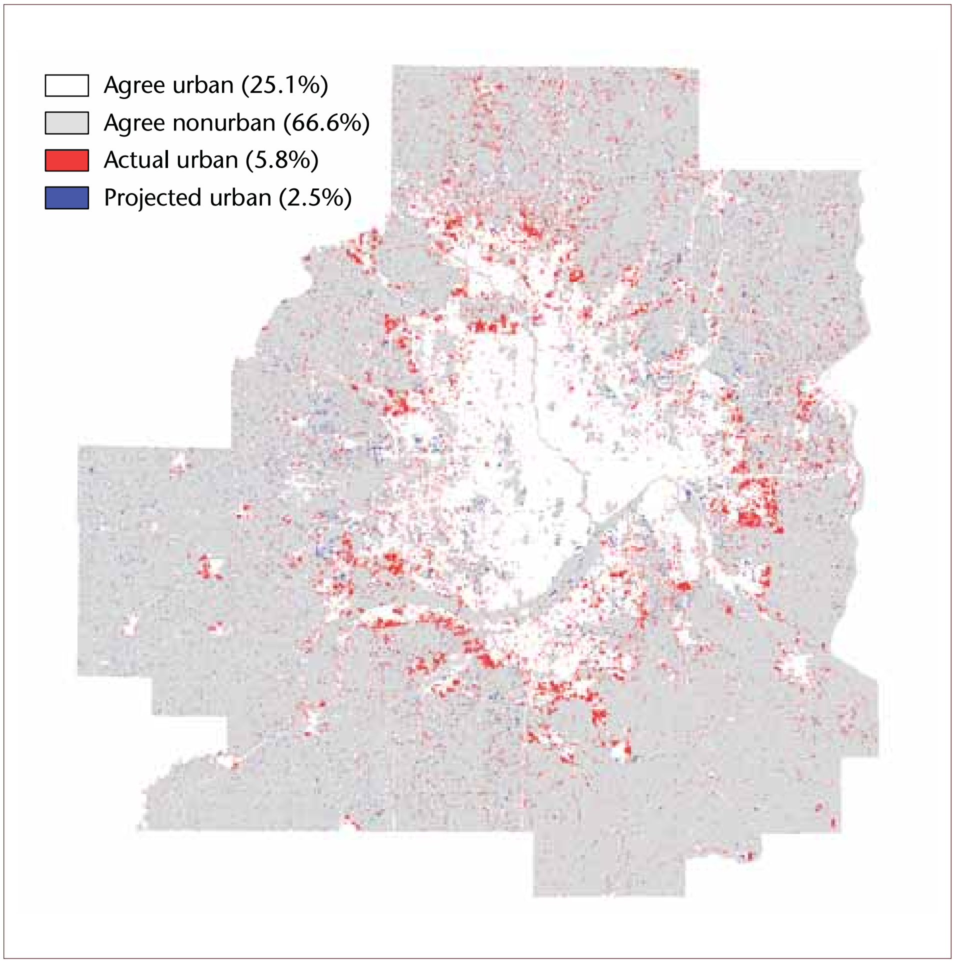
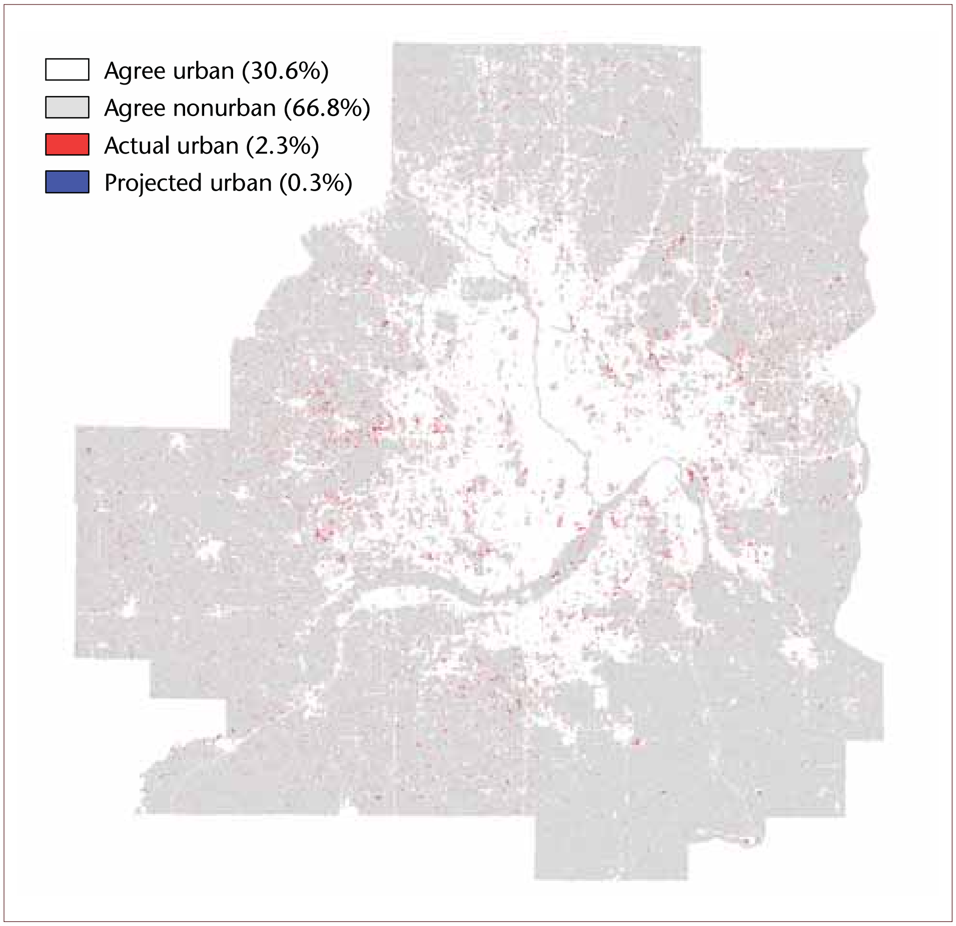


Figure 6. Comparison of Cellular Model of Twin Cities Urbanization with Actual Urbanization from Landsat TM Imagery based on Actual Quantity of Urbanization, 1986 to 1998



development actually occurred in 1998. The incidence of either kind of error (predicting urban areas where there are none, or non-urban areas where there are in fact urban areas) is far lower when we know how much urban development to expect.

Policy Implications

The use of remote sensing, geographic information science, and modeling illustrate the policy implications of land use. Of the various lessons drawn from this research, four in particular stand out for the Twin Cities metro area. First, the region is seeing significant changes in both the quality and quantity of urban and rural land covers. Second, and related to the first, the amount of impervious surface in the metro region is also on the rise in particular sub-areas. Changes in both land cover and impervious surfaces have attendant social and ecological impacts. Third, land and resource policies play a key role in the trajectory of land-cover change. Finally, although it is important to understand the spatial nature of land change, to predict this change it is very important to develop strong estimates of future population growth.

First, based on the results from the classification procedure, the landscape of the Twin Cities metro is increasingly urban at the cost of agricultural land and forest cover. As noted above, urban land cover increased from less than one-quarter to more than one-third of the metro area at the expense of agriculture, forest, and wetlands. In other words, 1 out of 10 rural or natural areas was lost to urbanization in less than two decades, and the rate at which this conversion occurred increased over time. Perhaps more important, in addition to there being significant conversion of agriculture and forest cover to urban land uses (which is an almost necessary precondition to continued growth and vitality of the Twin Cities metro area), the remaining non-urban land cover is increasingly fragmented. We found that although landscape diversity (the number of different types of land cover in a given area, such as a zip code) has remained relatively constant since 1986, fragmentation of this land cover has increased, especially for agricultural land and forest cover. In other words, most areas have the same mix of land cover over time, but the average size of agricultural and forest tracts is decreasing as development chops them up into smaller and smaller pieces. This land-cover fragmentation has a host of socioeconomic and ecological impacts, leading to increased traffic and infrastructure costs, for example, while impairing ecosystem functions such as providing natural habitat and water purification.

Second, impervious surfaces are increasing along with the increase in urban land cover. Imperviousness directly affects the amount of runoff to streams and lakes, and is related to nonpoint source pollution and the water quality of surrounding lakes and streams. It is also related to energy balances and urban heat island effects, where the sun's heat is trapped within a city and then released at night. It also affects the aesthetics of landscapes and leads to habitat degradation and fragmentation. The increasing amount of impervious surface area is directly related to conversion of rural landscapes to urban and suburban land uses, but the linkage is not always clear, as some forms of development produce less impervious surfaces than others.

Residents, developers, and governments must remain mindful of the amount of impervious surface assocated with various kinds of urban land cover. Impervious surface area maps provide one of the best measures of the potential for imperviousness impacts and are useful inputs to urban planning and management activities. A key advantage of the method we used is that although a majority of pixels in urban areas are mixtures of two or more classes (e.g., different housing densities), by using a range from 0% to 100%, we avoid the errors associated with assigning a mixed pixel to one class in a set of discrete classes (e.g., having to distinguish between low- and medium-density housing). Another advantage, and a key difference between our classifications and maps produced in most other ways, is that by mapping impervious area on a scale of 0% to 100%, we have the ability to display the results in various combinations and for other purposes. To describe the relationship between amount of impervious area and environmental quality of watersheds, for example, we could devise a system that identifies protected (0–10% impervious surface), impacted (10–25% impervious surface), and degraded (25–50% impervious surface) watersheds.

Third, policy exerts considerable influence on the trajectory of land-cover change. The spatial regression analysis showed that of the various factors that can influence urbanization, among the most powerful are policy instruments that guide development. Conservation easements and agricultural protection programs provide a strong restraint on urban development. Similarly, the Twin Cities metro area is one of the few large metropolitan regions in the United States with a strong regional planning body, the Metropolitan Council. By controlling the provision of key infrastructure such as sewer service and public transportation, the Metropolitan Council can exert a good deal of pressure on urban form.

More broadly, spatial regression is useful for policy development because it offers a means to unify differing kinds of spatial data with the social and environmental characteristics of the landscape that bear on development. In addition, because it is based on standard statistical methodology, spatial regression gives us a vehicle to test our understanding of various development factors and identify relationships that require further investigation. Spatial regression sheds light on how the importance of these factors can vary over space, in essence adding context to the bow wave conceptualization of urbanization by highlighting how social and environmental forces play out, and again pointing out areas for further investigation.

Finally, although it is important to understand the spatial nature of land change, to predict this change it is very important to develop good estimates of future population growth. Knowing *where* change will occur is important, but so is knowing *how much* change will occur. Cellular modeling illustrates this need well. Although this approach is useful because it requires very little data (two land-cover maps are all that is needed), the model does far better with realistic estimates of the quantity of change. This model does not incorporate much of what is known about urbanization, such as the importance of policy initiatives or economic forces, but it does incorporate spatial relationships by assessing the relationships between neighboring land-cover types and the chances that land will be transformed from one kind of cover to another. It is therefore a straightforward interpretation of a key aspect of the bow wave conceptualization of urbanization—namely the role of incremental growth outward from existing urban areas—but it works best with accurate population estimates.

Conclusions

Our research has a number of immediate policy implications, and it has further ties to the policy community through ongoing consultation with staff at the Metropolitan Council. We have been working with the Metropolitan Council and the Minnesota Pollution Control Agency, as these agencies find the maps of land cover and impervious surfaces to be useful inputs to hydrology and runoff models and planning future development. Satellite remote sensing provides a cost-effective alternative for obtaining such information when the costs of traditional mapping approaches are increasing and budgets are declining. By working with staff at the Metropolitan Council and with past and present documentation produced by the council, we also can identify likely scenarios for future growth, tied to population and socioeconomic forecasts and paying particular attention to the role of policy instruments such as zoning, transportation, and infrastructure provision. We also can identify the scenarios of interest to stakeholders represented by the Metropolitan Council and, similarly, the data and growth models of greatest use to them.

The severity and nature of the impacts of urbanization are intimately related to the pace and spatial configuration of how urban land is developed from rural and natural land cover. Our current form of urbanization, with its emphasis on decentralized land use and development, offers key benefits to the region but with social and ecological costs. The combination of remote sensing, geographic information systems, and spatial modeling offers a powerful and efficient way to describe and understand the processes of urbanization in the Twin Cities. These range from maps of land cover and impervious surfaces to computer models that allow us to explore the underlying causes of land change in the metro area. This research adds to our knowledge of urbanization and, perhaps more important, can help various publics and policy makers find ways to ensure that the Twin Cities metropolitan area remains a sustainable and enjoyable place to live, work, and play.

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