Patterns of Urban Land Use as Assessed by Satellite Imagery: An Application to Cairo, Egypt

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ABSTRACT

Most demographic literature contrasts urban and rural places as though they were always uniquely distinct places. However, as the urban transition progresses, a considerable middle ground has been developing in human settlements. Urban places are socially and environmentally more complex and variable than ever before and rural places are more urban-like than ever before. These transformations suggest that an urban gradient may be more useful for social science research than a dichotomy. In this paper we apply an ecological conceptual framework suggesting that an important component of urban places is the transformation of land into a built environment. The new patterns of land use implied by these land cover changes are routinely ignored in social science literature, but can potentially be incorporated into an analysis of urban areas by combining the classification of data from remotely sensed imagery with census data. We review the processes by which urban land use can be inferred from remotely sensed imagery and then apply the method to Cairo, Egypt by combining the land use measures with underlying population data drawn from census data.

INTRODUCTION

At the beginning of the nineteenth century, almost everyone in the world lived in rural places. Cities like London and Paris were islands of urbanness in a sea of rurality. Even at the beginning of the twentieth century the vast majority (nearly 90 percent) of people lived in rural places. But, at the beginning of the twenty-first century, we find that almost one in two humans is living in an urban place, with the tipping date estimated to be within the first decade of the century (United Nations Population Division 2004). This urban transition—the shift of humans from being predominantly rural to being predominantly urban—is an integral part of the demographic transition and is moving along in concert with the other parts of the demographic transition (see Weeks 2005 for a discussion of the interrelationships). We have in fact reached the point in history where we can envision the end of the urban transition. This is already happening in the more developed nations, where nearly everyone lives in or very close to an urban environment. However, the end of the urban transition does not necessarily signal the end of urban evolution (Pumain 2004). Evolutionary processes include patterns of suburbanization, exurbanization, periurbanization (the shift of urban populations from more dense to less dense regions), multinucleation (the clustering of population around several centers, rather than just one, within the same region) and even counterurbanization (a return of some people back to more urban places —(see, for example, Champion 1989).

There is almost certainly more variability among urban places, and within the populations in urban places, than ever before in human history. This variability has important consequences for the relationship between human populations and the environment, because places (and thus the populations within those places) become urban through the transformation of the land into a built environment, and as urban places evolve, the subsequent changes in the built environment may well have forward-linking influences on human behavior. In concert with Redman (this volume) and Seto (this volume), we posit a fundamental ecological relationship between urban places and human behavior: Humans transform the environment; and are then transformed by the new environment.

Evolutionary ecological processes such as this cannot be captured by the standard distinctions of urban and rural or urban and non-urban. The concept of "urbanness," as we use it here, implies that the rural/urban distinction is a continuum, rather than a dichotomy. Humans increasingly live not simply in urban, but in highly differentiated urban, settings. This means that there is an ever-increasing variability in population-environment interactions because a majority of people live in an environment that is substantially and differentially transformed by human invention and intervention, with the exact nature of that transformation varying considerably from place to place. The ecological perspective suggests that this variability will be associated with variability in human behavior—in how people organize their lives, interact with each other, and utilize the resources of nature. Although we could extend this idea to the entire range of human settlements, in this paper we focus more specifically on the variability <u>within</u> an urban area. As dramatic as human behavioral differences may be between rural and urban areas, there are nonetheless very large intra-urban differences in demographic processes (Weeks *et al.* 2004), and it is probable that these differences will become more important over time as increasing fractions of the world's population come to live in urban places.

Our conceptual framework is thus based on the ecological principle that human behavior is shaped by a combination of the natural, built, and social environments in which people live. Most social science literature that describes the nature and character of urban populations focuses almost exclusively on the measurement of the social environment, often drawing upon census data to describe this milieu. But variations in the social environment depend in part upon variability in the built environment. For example, high population density—an index that is often used as a measure of urbanness--can be achieved with some kinds of physical structures, but not others. In order to put a lot of people in a relatively small amount of space, buildings must be very high above ground or very far below ground or both. The technology to build such structures is relatively new in human history and the expense of doing so limits its uses, adding to the spatial variability in the application of the techniques that permit very high density.

Cities, or urban places more generally, are defined in terms of the way humans have converted the land to largely “unnatural” and non-agricultural uses. But the creation of a built environment that we define as an urban place is itself a representation of the culture of the people living in that place, if we define culture to mean “the manifestation of the way in which we humans solve the problems of everyday life and transmit those solutions to other people and subsequent generations through the teaching/learning process. What do we eat and how do we eat it? How and with what do we protect ourselves from nature and predators? How do we organize our lives to minimize risk and maximize satisfaction?” (Weeks *et al.* 2004:75). But this is not just a one-way street. The built environment, in its turn, can have an influence on the way in which people pattern their social lives. Social science literature is rich with examples of how high-rise apartments and streets crowded with cars create different social worlds for people than do low-rise buildings and spacious pedestrian walkways.

Taken together, the idea that people create an urban place, and then are influenced by the place that has been created, leads us to the hypothesis that an important component of variability in human behavior may be captured in surrogate form by knowledge of the variability of the built environment. In this conceptualization, the built and social environments are intimately entwined, but not completely dependent upon one another. The same built environment can host variation in the social environment, and the same social environment can exist within a range of built environments, but we hypothesize that a relatively narrow range of combined values of the built and social environments would describe a unique set of urban populations.

We typically measure the social environment by the responses to questions on surveys and censuses. Some aspects of the built environment can be captured by census data related to housing characteristics, but one of the difficulties of using only census data to define this aspect of urbanness is that people are almost always enumerated at their place of residence and are asked only about the characteristics of the home in which they live. Little or no information is gathered about the environmental context—do you live next door to the shopping center or to a forest?.

There are a variety of data sources that might be employed to describe (and thus measure the variability in) the urban built environments that humans create for themselves. Censuses if buildings and their uses, cadastral maps that tell what categories of things on a piece of property are being taxed, and even maps of urban infrastructure such as water, sewer, and power lines would be candidates for use. Traffic counts and censuses of businesses can generate data from which can be inferred something about daytime populations. In this research, we propose to use a more universally available set of data—remotely sensed satellite imagery. We suggest that the modification of the physical environment that is characteristic of urban places can be inferred by quantifying data derived from multispectral satellite images.

URBAN PLACE METRICS DERIVED FROM THE IMAGERY

In order to appreciate the value of remotely sensed imagery for analysis of urban places, it is crucial to understand exactly what information can be extracted from such images. The image itself is composed of a two-dimensional array of pixels (picture elements) from which radiant energy has been captured for an area on the ground that is equal to the spatial resolution of the image. A basic premise of remote sensing is that earth surface features and landscapes can be discriminated, categorized, and mapped according to their spectral-radiometric characteristics

(Lillesand and Kiefer 2000). The information recorded for each image depends upon the particular sensor, but the brightness or reflectance within a given band is assigned a digital number. The combination of digital numbers representing relative reflectance across the different bands of light yields the spectral signature of that pixel.

Images are generally characterized according to spatial, spectral, radiometric, and temporal resolution. Spatial resolution refers to the characteristic length of a ground element represented by the image pixel. The highest resolution data available from commercial satellites (such as Quickbird or Ikonos) are, at the time of this writing, 0.6 m for panchromatic and 2.4 m for multispectral imagery. More detailed imagery typically requires the use of airborne platforms such as light aircraft or helicopters to capture aerial digital images. High spatial resolution imagery tends to be quite expensive and so most academic research focuses on moderate resolution data. In the research reported here, we are using Indian Remote Sensing (IRS) images that have a spatial resolution of 5 meters in panchromatic format, and 24 meters in multispectral format. This means that in the multi-spectral bands, one pixel in the imagery covers an area on the ground that is 24 meters square. We also make use of a Landsat Thematic Mapper multispectral image that has a spatial resolution of 30 meters.

As already alluded to, images vary according to the spectral bandwidth of energy captured by the image, ranging from panchromatic (one broad waveband mostly in the visible portion of the spectrum) to multi-spectral (red, green, blue, near-infrared short-wave, and thermal infrared bands). Radiometric resolution pertains to the number of radiant energy levels that can be quantified by a digital remote sensing instrument, which tend to range from 64 to 2048 levels. In general, the greater the number of different bands that are identified, the more finely detailed can numeric distinctions be made about the data in the image. The possible combinations of numbers from 6 bands is geometrically larger than can be derived from 3 bands, and for this reason a more precise spectral signature of something on the ground can be determined with a higher spectral resolution.

Finally, we can note that the repeat imaging capability of a remote sensing system is characterized by its temporal resolution. Satellites that capture images of the same place on the ground several times a year, for example, have higher temporal resolution than satellites capturing data only once a year.

Satellite optical imagery is obviously capable of capturing only what can be seen on the ground, and for this reason the data from the imagery refer to land cover classes, such as vegetation (or even different types of plants), bare soil, water, and impervious surfaces (things that are impervious to water, such as a cement road or parking lot, or a tin or tile roof). It is up to the researcher to infer the land use that is associated with each land cover class, so there is a certain amount of semantic subjectivity in the entire process. We use a semantic classification (such as "impervious surface") to denote a set of spectral signatures that are known to be associated with those kinds of land covers. We then infer land use (e.g., built area) based on the land cover classification, on the assumption that impervious surfaces, for example, are especially likely to be associated with the human transformation of the environment characteristic of roads and buildings and other aspects of the urban area.

The classification of an image is done at the level of the individual pixel, but we are especially interested in the composition and configuration of all of the pixels within a defined geographic region, such as a census tract or enumeration area, because we want to use the data from the imagery in conjunction with census and survey data to better understand the relationship between people (whose characteristics are measured from census and survey data) and the environments in which they live (measured in this instance from the imagery). There are two types of geographic features that are captured by the imagery: continuous features (such as land cover/land use types) and discrete objects (such as buildings) that are distinguishable from the background surface. Continuous features represent the compositional aspect of the scene under investigation, whereas discrete objects represent the configurational aspect. Much more attention has been paid thus far to composition than to configuration (Bian and Xie 2004), and so our ability to quantify composition is superior to our ability to quantify configuration. .

Composition refers to the proportional abundance in a region of particular land cover classes that are of interest to the researcher. In our research, the semantic classification of pixels is guided by Ridd's (1995) V-I-S (vegetation, impervious surface, soil) model. Each pixel is analyzed according to its spectral properties and is assigned to one of three land cover classes (vegetation, impervious surface, or bare soil). Figure 1 illustrates the V-I-S model, which views the urban scene as being composed of combinations of these three distinct land cover classes. An area that is composed entirely of bare soil would be characteristic of desert wilderness, whereas an area composed entirely of vegetation would be dense forest, lawn, or intensive fields of crops. At the top of the pyramid is impervious surface, an abundance of which is characteristic of central business districts, which are conceptualized as the most urban of the built environments. Places that fall between these extremes are, in essence, relatively more or less urban than would be found at the extremes.

FIGURE 1 ABOUT HERE

These compositional metrics build on the qualitative sense that each of us has about what an urban place "looks like." Even today in highly urbanized countries in Europe and North America it is visually very evident when you move from a largely rural to a predominantly urban place and, of course, the change in the built environment is the principal index of that. Even within non-urban areas it is usually quite evident when you have passed from a wilderness area into a largely agriculture area. Once again, it is the composition of the environment that provides the clue. Figure 2 shows this in a schematic way. Wilderness areas can, at the extreme, be expected to be composed especially of bare soil, since deserts tend to be the places least habitable by humans. As the fraction of vegetation increases, there is an implicit increase in the availability of water and where there is sufficient water the possibility of agricultural increases and agriculture creates a signature on the ground that is typically distinct from areas that have not been modified by humans. However, the nature of urban places is that the built environment is dominant, and so cities are distinctly noticeable from the air because vegetation gives way immediately, discontinuously, to impervious surfaces.

FIGURE 2 ABOUT HERE

The most commonly used method of classifying a pixel is what can be called a “hard” classification, in which the entire surface area is assumed to be represented by a single land cover class. However, when using moderate spatial resolution imagery (such as imagery in the 10 to 24 meter range) it is very unlikely that an entire pixel will be completely undifferentiated, especially in urban areas where humans have modified the environment in a variety of ways. Thus, the use of hard classification schemes with moderate resolution data has led to questions about the ability of researchers to accurately discern the characteristics of urban places from such imagery. These problems can be particularly acute in urban settings with considerable amounts of vegetation that may distort the interpretation of the classification of the ground cover underneath the vegetation canopy (Small 2002).

To deal with this problem, the techniques of spectral mixture analysis (SMA) and multiple end-member spectral mixture analysis (MESMA) have been developed that use a procedure somewhat analogous to principal components analysis to "unmix" each pixel into its constituent components of land cover classes. Thus, in a hard classification, the decision might have been made to assign the land cover class "impervious surface" to a particular pixel. However, the SMA or MESMA might lead instead to the decision that 70% of the surface area of that pixel was covered by impervious surface, 20% by vegetation, and 10% by bare soil. We would call this a "soft" classification, and it allows us to infer more about a pixel than is the case with a "hard" classification. The details of these classification methods are described elsewhere (Rashed and Weeks 2003; Rashed *et al.* 2001; Rashed *et al.* 2003; Rashed *et al.* 2005; Roberts *et al.* 1998; Roberts *et al.* 1998; Roberts *et al.* 1998), but the important point is that the soft classification offers a potentially more accurate representation of the surface area covered by each land cover class when the data are aggregated into areal units such as census tracts or enumeration areas. Thus far the accuracy assessments have largely come from comparing the results of spectral mixture analysis of moderate spatial resolution imagery with the classification of data from higher spatial resolution imagery, such as the comparison with Ikonos imagery (Small 2003) or with Quickbird imagery (Stow *et al.* 2004).

We also made one modification to the Ridd V-I-S model by adding another component—shade/water—following the work of Ward, Phinn, and Murray (2000) suggesting that this fourth physical component improves the model in settings outside of the United States. When combined with impervious surfaces in urban areas it becomes a measure of the height of buildings (based on the shadows cast by buildings). Our spectral mixture analysis then permits a soft classification of a pixel into the likely fraction of the pixel that is composed of each of the four physical elements of interest to us: vegetation, impervious surface, soil, and shade. By summing up these fractions over all pixels contained within each area of interest, we have a composite measure of the fraction (the "proportional abundance") of the area that is covered by each of the four land cover types.

The proportional abundance of impervious surface is the baseline measure of urbanness, as suggested by the Ridd model (Figure 1), but shade is also a factor, especially in areas dominated by tall buildings which create shade which is then radiated to the sensor, essentially in the place of the underlying impervious surface. Thus, in areas that are generally urban, such as greater Cairo, the simple addition of the impervious surface and shade fractions should provide an appropriate measure of the proportional abundance of land cover most associated with an urban place.

Measures of proportional abundance capture the land cover composition of the scene that we are analyzing. The other aspect of landscape metrics is the quantification of the spatial configuration of each land cover class. The most widely used measures of configuration employ a fractal approach which examines the spatial relationships among pixels of the same land cover class (Herold, Scepan, and Clarke 2002; Lam and De Cola 1993; McGarigal 2002). We may know that 60 percent of a given area is covered by impervious surface (the measure of composition), but we would also like to know how those pixels are arranged within the area under observation. For example, if the pixels identified as being of impervious surface are clustered together we might infer that we are "seeing" a large building or other large urban surface. A low level of clustering of impervious surface pixels might represent a greater number of smaller buildings in the scene, suggesting a less intensely urban use of the land. Such a measure of spatial configuration should provide a somewhat more nuanced index of urbanness, when folded into the measure of composition.

McGarigal (2002) notes that configuration is much more difficult to assess than composition and although several measures have been developed in an attempt to capture the essence of configuration, it is important to keep in mind that most measures of landscape configuration were developed for the purpose of describing landscape ecology and have only recently been shown to have an adaptation to the measurement of the urban environment (Herold, Scepan, and Clarke 2002). The most specific problem confronting us in the quantification of these measures is that that all such measures require that each pixel in the scene be identified as a member of a single land cover class—a hard classification. This required us to essentially "remix" each pixel from our soft classification back into a hard classification. We did this with an algorithm that assigned each pixel to the land cover class that represented the majority proportional abundance based on the spectral mixture analysis. If no land cover class represented a majority, then the classification was based on an average of the highest proportional abundances among near neighbors.

We have used the Fragstats software (McGarigal 2002) to calculate the contiguity index as a measure of spatial configuration of impervious surfaces within each census area. The contiguity index assesses the spatial connectedness (contiguity) of cells of a given land cover class. A value of 0 indicates that no pixel classified as impervious surface is contiguous to any other pixel classified as impervious surface. At the other extreme, a value of 1 indicates that all pixels classified as impervious surface are contiguous to one another. The contiguity index is blind to the composition of the area with respect to each land cover class—it looks at whatever number of pixels there are of a given class and examines their spatial relationship to one another.

For this reason, this (and the other) measures of configuration do not provide a baseline of urbanness. Rather, they add to our knowledge of urbanness derived from the compositional measures, giving us a more nuanced index.

Our measure of urbanness is thus based first on the proportional abundance of the impervious surface (I) and shade (S) land cover classes. If those percentages are high, an area can be interpreted as being very urban, and if they are low, the area is not very urban. However, for any given proportional abundance of impervious surface and shade, we believe that a high contiguity index (C) will indicate a slightly more urban place (a greater density of urban material) than would a low contiguity index. In general, we would expect that city centers would have the highest abundance of impervious surface and shade and also the highest level of contiguity of that impervious surface. At the other extreme, a place that is not very urban will have a low proportion of impervious surface, but that surface might be highly contiguous (one small building) or only moderately so (three small buildings), but the degree of contiguity would matter less than it would when the proportion of impervious surface is high. This suggests that the configuration of the pixels increases in importance as the proportional abundance of impervious surface increases, implying a conditional relationship such that the value (a coefficient that we will label as ‘a’) assigned to the contiguity index would increase as the sum of I and S increased.

Based on these considerations, our proposed measure of urbanness (U) is the sum of the proportional abundance of impervious surface (I) and shade (S), plus the contiguity index (C) times a coefficient (a). The coefficient (a) should have a value that permits the contiguity index to add no more than 10 percentage points to a measure (U) that would otherwise range between 0 (completely non-urban) and 100 (completely urban). Furthermore, its size should be proportional to the proportional abundance of I and S. Since the contiguity index ranges from 0 to 1, this would imply that the coefficient (a) should be as follows:

$$a = (I + S)/10$$

and the urban index (U) is calculated as:

$$U = (I + S) + (a \times C).$$

APPLYING THE URBAN INDEX

We now apply the urban index to the study site of Cairo, Egypt. The urban area of Greater Cairo represents the governorate of Cairo on the east side of the Nile River as it travels through the metropolitan region, the portion of the governorate of Giza that is along the west bank of the Nile River within the metropolitan region, and the southern tip of the governorate of Qalyubia—which currently represents the northernmost reach of Greater Cairo. The area's location is shown in Figure 3. Nearly one in five Egyptians lives in the Greater Cairo region and for centuries it has been a quintessentially primate city, dominating the social, economic, and political life of the region. The United Nations Population Division lists the population of Cairo to be 10.4 million as of 2000 (the 15th most populous city in the world), with a projected population of 13.1 in 2015 (when it would be the 13th most populous) (United Nations Population Division 2004). Note that these latest data reflect a significant upward revision of the current and projected population of Cairo signaling the importance of knowing more about the dynamics of the region.

FIGURE 3 ABOUT HERE

Two multispectral images have been utilized in this study. The earlier image is a Landsat Thematic Mapper (TM) image acquired in June, 1987 and the more recent is an Indian Remote

Sensing Satellite (IRS) 1C image acquired in August 1996. The acquisition dates correspond as closely as possible to the 1986 and 1996 Egyptian censuses. Both images were acquired at approximately the same time of year (mid-summer) in order to minimize any effects of seasonality. In the interest of brevity, we focus our attention especially on the latter image, which covers three bands in visible the visible ranges of (520-590) and (620-690), and near infrared (770-860 nm) at 23.6 m spatial resolution) and one band in short-wave infrared (1550-1700 nm) at 70.8 m spatial resolution.

Cairo is divided administratively into "shiakhas" which are literally places controlled by a sheikh, but in modern times represent areas controlled by a police station and, more importantly for our purposes, are the bounded areas for which census data are collected by CAPMAS (Central Agency for Public Mobilisation and Statistics). These areas are thus equivalent to a census tract in the US or an enumeration area in the UK. We have census data for 298 shiakhas from the 1986 and 1996 censuses, and the goal is to characterize each of these in terms of their urbanness as measured quantitatively from the imagery.

The urban index as defined above is comprised of two components—the proportional abundance of impervious surface and shade, and the spatial configuration of the pixels identified as representing impervious surface, and the spatial patterning of each of these components is shown in Figures 4 and 5, respectively. Figure 4 shows the percentage of surface area in each shiakha that is comprised of either impervious surface or shade. The pattern is for the older, more central parts of Cairo to the east of the Nile (in the Cairo governorate and in the more industrial governorate of Qalyubia to the north of downtown Cairo) to have higher proportional abundances of these land cover classes, whereas in the more suburban western portion (in the governorate of Giza), the fractions tend to be lower. This is the pattern we would expect to find.

FIGURE 4 ABOUT HERE

Figure 5 shows the spatial pattern in the spatial configuration of pixels that are classified as impervious surface. Low values indicate the such pixels are not highly contiguous to one another in a given shiahka, which we interpret to be characteristic of a lower density, more suburban area; whereas higher values indicate a high degree of contiguity, which we interpret to be more likely to occur in more dense, central city areas—at least when it occurs in the presence of a high proportional abundance of impervious surface. The data appear visually to support this expectation. Note as well that the measures of composition and configuration are not simple overlays of one another—they exhibit somewhat different spatial patterns. This supports our view that configuration provides a more nuanced index of urbanness than we would obtain from using only the composition measure.

FIGURE 5 ABOUT HERE

The combination of composition and configuration comprises our urban index and the spatial pattern of the index in Cairo in 1996 is shown in Figure 6. The pattern is consistent with the qualitative assessment of urbanness in Cairo. The old center is very urban, as is the more industrial area in the northern part of the city. The suburbs of Giza are generally less urban, with the notable exception of the Imbaba area (in the northeastern part of Giza, near the Nile River) which is a well-known high-density slum area.

FIGURE 6 ABOUT HERE

Figure 7 zooms in on several neighborhoods near central Cairo so that the numbers from the urban index for 1996 are displayed at the center of each neighborhood with a high resolution DigitalGlobe Quickbird image in the background. This allows for a qualitative visualization of what the quantification of that neighborhood (the urban index) stands for. In particular, it is easier to see in this figure that the values on the eastern side of the river, in the central part of old Cairo, are higher than in the more suburban areas on the western side of the river in Giza. In the older part of Cairo, buildings are more closely spaced together, whereas in Giza there is somewhat less impervious surface (because there is more vegetation) and the buildings show some spacing between them.

FIGURE 7 ABOUT HERE

Table 1 compares the distribution of the urban index in 1996 (based on the Indian Remote Sensing iamge) with that derived from the 1987 Landsat image. The two images were obtained from different sensors (with similar but not identical spatial and spectral resolution), so some of the observed difference may be due to these technical differences, even though both images were subjected to identical methods of semantically classifying the imagery. The data show that Cairo was, on average, slightly less urban in 1996 than in 1987. That is, in fact, consistent with other evidence that during this time there was a general movement out of the central city and towards the suburbs, accompanied by a pattern of new migrants to the city eschewing the center of the city for the suburbs. The changes in the central city are potentially detectable from the imagery because between 1987 and 1996 the government bull-dozed several slum areas near the central city. And, of course, in the more suburban areas, the expansion of roads and homes was clearly observable and measurable from the imagery. The census data for 1986 show an average density in the Greater Cairo area of 50,000 persons per square kilometer, and that had dropped to an average of 45,000 by 1996. The population of Greater Cairo was increasing during this time from 7.5 million in our study area in 1986 to 8.2 million in 1996. Thus, the drop in density represented a decline in the central city at the same time that there was a rise in the suburbs.

The potential utility of the index lies in its ability to measure some aspect of the physical context in which social lives are being played out. In a previously published analysis of intra-urban fertility in Cairo, Weeks and his colleagues (Weeks *et al.* 2004) demonstrated that a less sophisticated set of measures from the imagery were statistically significantly related to the proportion of young women who were married in a given neighborhood in Cairo, which in turn was the predominant predictor of the neighborhood's total fertility rate. We now substitute the urban index that we have just created into that prior analysis to see the extent to which the total fertility rates in Cairo's neighborhoods are a function of the social environment (measured by variables derived from the census) and the built environment (assessed with these imagery derived variables).

From the censuses in both 1986 and 1996 we were able to derive several variables that measure the social class characteristics of a shiakha. We summarized educational status by calculating the percentage of the population aged 15 and older that had at least an intermediate level of education (equivalent to at least some high school). We calculated these percentages separately for males and females. The participation of women in the paid labor force is a well known correlate of the status of women, and we are able to measure that for women aged 15 and older. Probably the single best measure of social status is the occupational status of the householder. The census does not ask for characteristics specific to the householder, but we know from other sources that in Cairo, as in most places, the householder tends to be male, and we are able to calculate the percentage of economically active males aged 15 and older whose occupation was in the highest occupational status categories, which include technical, professional, administrative, and managerial occupations. Not surprisingly, all of these variables were highly intercorrelated. In 1996, for example, the lowest correlation coefficient among any two of these four variables was .851, and in 1986 it was .888. For this reason, we were able to combine them into a single index using principal components analysis. In both 1986 and 1996 the combined index weights each variable roughly equally into an measure that we call STATUS. This of course refers to a value for the shiakha, not individuals.

We know that neither built nor social environments can have a direct effect on fertility. Rather, they can influence one or more of the proximate determinants of fertility, which include especially age at marriage, breast-feeding, abortion, and contraception (Bongaarts 1982). There is strong evidence from the Demographic and Health Surveys that age at marriage is by far the most important determinant of current fertility trends in Cairo (and possibly in other Arab nations, as well) (Weeks *et al.* 2004), and we were able to derive a proxy for age at marriage from the census data on marital status. This measure calculates the percentage of women aged 15-29 who are single.

Our model suggests that the social environment and the built environment will have independent, but potentially overlapping, effects on the age at marriage within a neighborhood, which in turn will directly affect the neighborhood's total fertility rate. This calls for a structural equation model (path analysis) and the results for 1996 are shown in Figure 8. It can be seen first that the expectation of overlap between the social and built environments is not met. These two variables are almost completely independent of one another, evidenced by the correlation coefficient of .01. This suggests that if we are to understand the behavior of individuals in a neighborhood we are going to have to know something about both the built and social environments, and that different combinations of each will produce unique patterns of social behavior. Of these two factors, the social environment appears not surprisingly to be somewhat more important than the built environment in its influence on the proportion of women who are single. The standardized beta coefficient for social status in 1996 was .66 whereas the coefficient for the urban index was .43. However, both measures are strong and statistically significant predictors and together they explain 63 percent of the variability in the proportion of women who are single which in turn explains 71 percent of the variation in neighborhood fertility rates.

FIGURE 8 ABOUT HERE

The results for 1986 are similar to those for 1996, as can be seen in Figure 9. In 1986 there was only a low correlation between social status and the urban index, but once again these two measures combined to explain a high fraction (69 percent) of the variability in the proportion of young women who were single. And, once again, the status variable was more important a predictor than the urban index, but both variables were strongly correlated with the age at marriage. And, once again, the variability in the proportion of young women who were married explained a high fraction (88 percent) of the variability in neighborhood fertility levels.

FIGURE 9 ABOUT HERE

Finally, we ask whether observed changes in either the social or built environments are related to changes in neighborhood fertility levels. The results in Figure 9 suggest not. There is essentially no impact of changes in either the social status of a neighborhood or its urban index on neighborhood proportions of women who are single. Almost the entire effect comes from the endogenous effect of the fertility level in 1986. In other words, the decline in fertility occurred in those places where fertility was highest in 1986, regardless of what other changes might have been occurring in the neighborhood. On the other hand, we know from Figures 8 and 9 that much of our knowledge of whether fertility was high or low in a neighborhood in 1986 (and again in 1996) was based on information derived about the social environment and the built environment. Neither one of those neighborhood characteristics told us as much individually as did both in combination with each other.

DISCUSSION AND CONCLUSION

The basic premise of this research is that information gleaned from satellite imagery is a proxy for the built environment of urban places, complementing data obtained from a census which represent surrogate measures of the social environment. The underlying theory of our work is that the built environment reflects aspects of the social environment that will be reflected in the attitudes and behaviors of people. The urban environment creates a difference in people's lives by increasing the volume and intensity of social interaction and by increasing the opportunities that exist for educational and occupational specialization and differentiation. By developing a quantitative measure that is potentially comparable over time in the same region, , we should be able to quantify the urban evolution taking place in different contexts throughout the world. Our goal in this paper, then, has been to create and apply an index that could be measured at different time periods to see if the characteristics of places (and thus potentially of the people in those places) are changing over time and/or varying across space. Such an index has the potential to help us assess both the quantum (the amount) and the tempo (the timing) of urban change and evolution, and thus should increase our predictive power and understanding of what is actually happening as nations transition to being largely urban, and as they continue to evolve in their urbanness.

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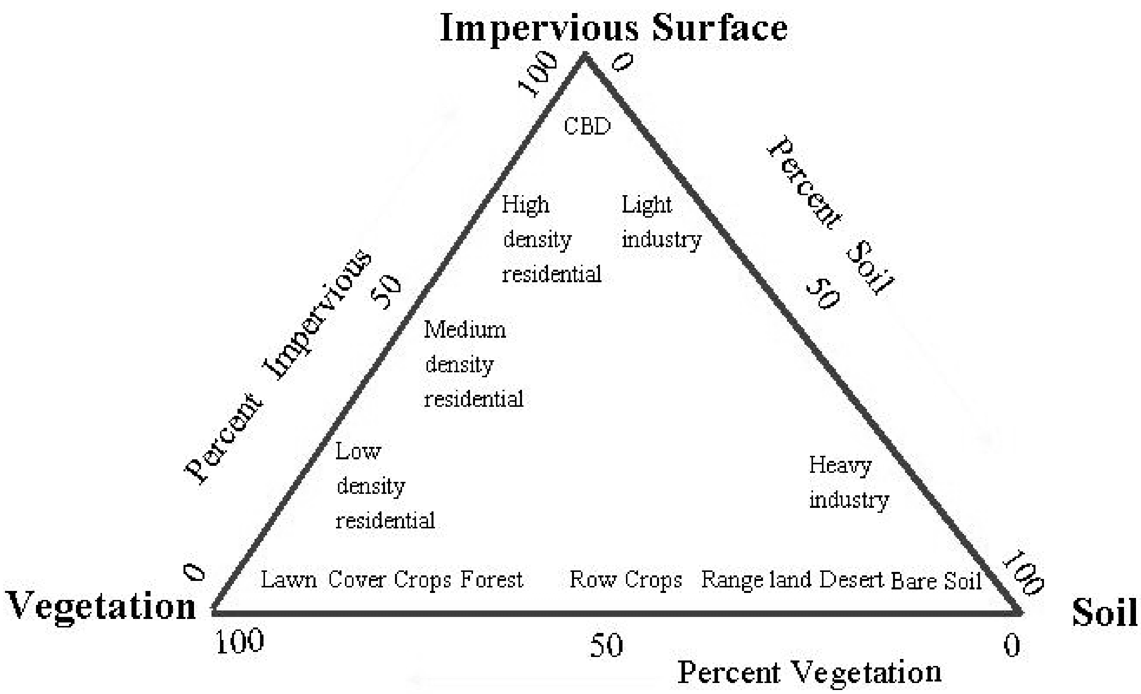
FIGURE 1. RIDD'S V-I-S MODEL OF URBAN ECOLOGY FROM REMOTELY SENSED DATA



Source: M. Ridd, 1995. "Exploring a V-I-S (Vegetation-Impervious Surface-Soil) Model of Urban Ecosystem Analysis Through Remote Sensing: Comparative Anatomy of Cities," *International Journal of Remote Sensing* 16:2165-2185.

FIGURE 2. THE URBAN GRADIENT MAY BE DISCONTINUOUS

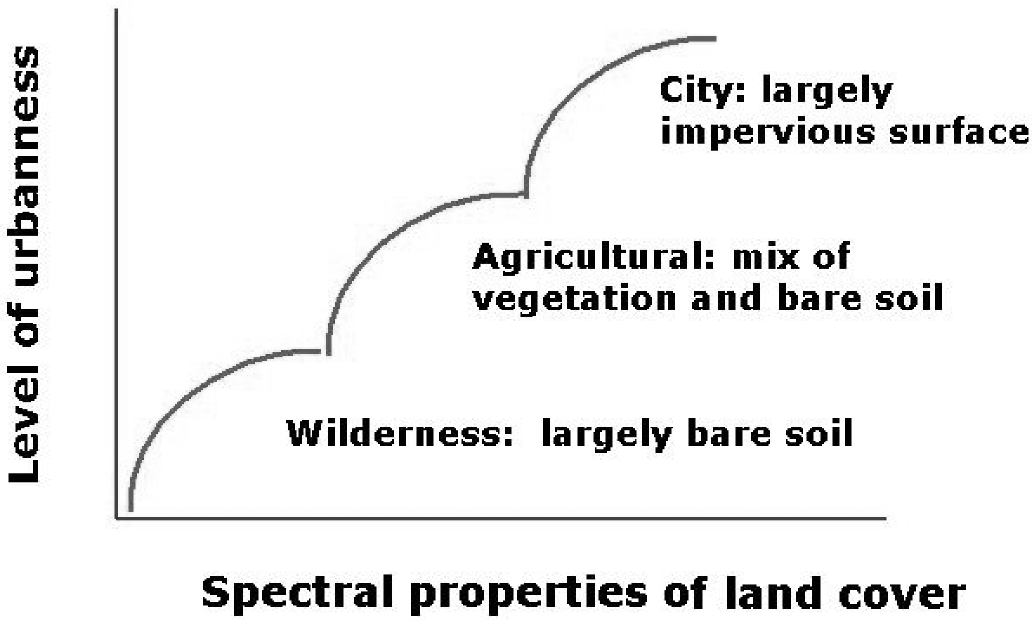


FIGURE 3. THE STUDY SITE OF CAIRO, EGYPT

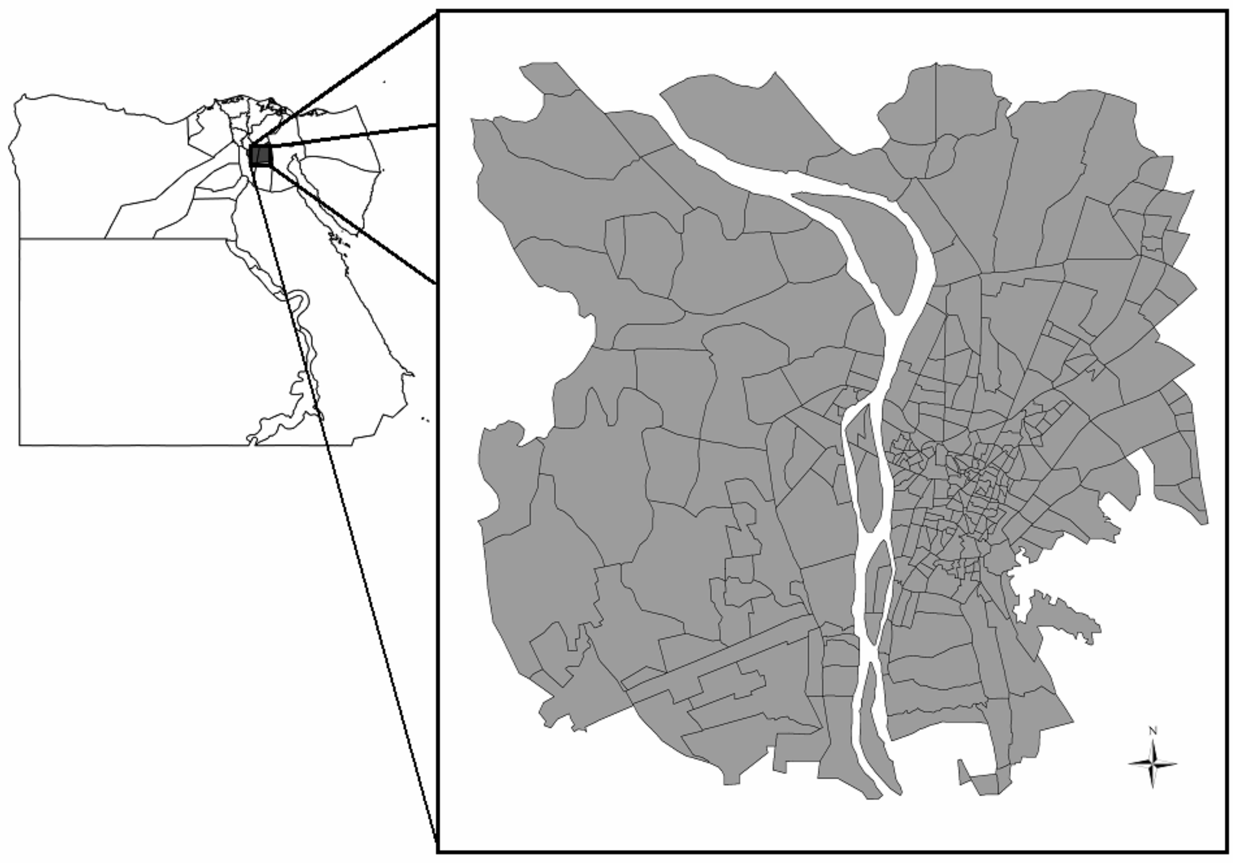


FIGURE 4.PERCENT OF AREA IN EACH SHIAKHA OF GREATER CAIRO THAT IS COMPOSED OF IMPERVIOUS SURFACE OR SHADE: 1996

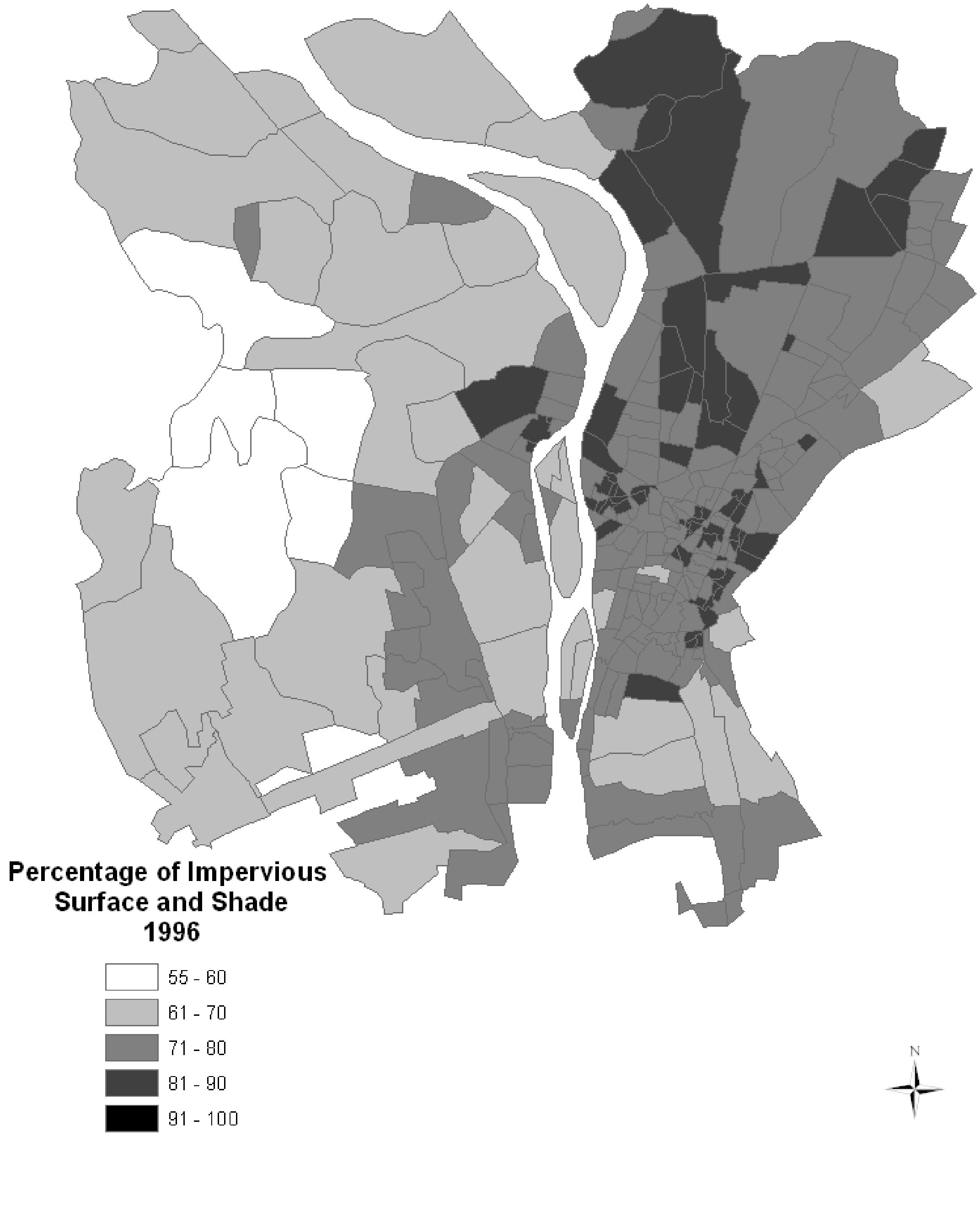


FIGURE 5. CONTIGUITY INDEX MEASURING THE ADJACENCY TO ONE ANOTHER OF PIXELS CLASSIFIED AS BEING IMPERVIOUS SURFACE: 1996

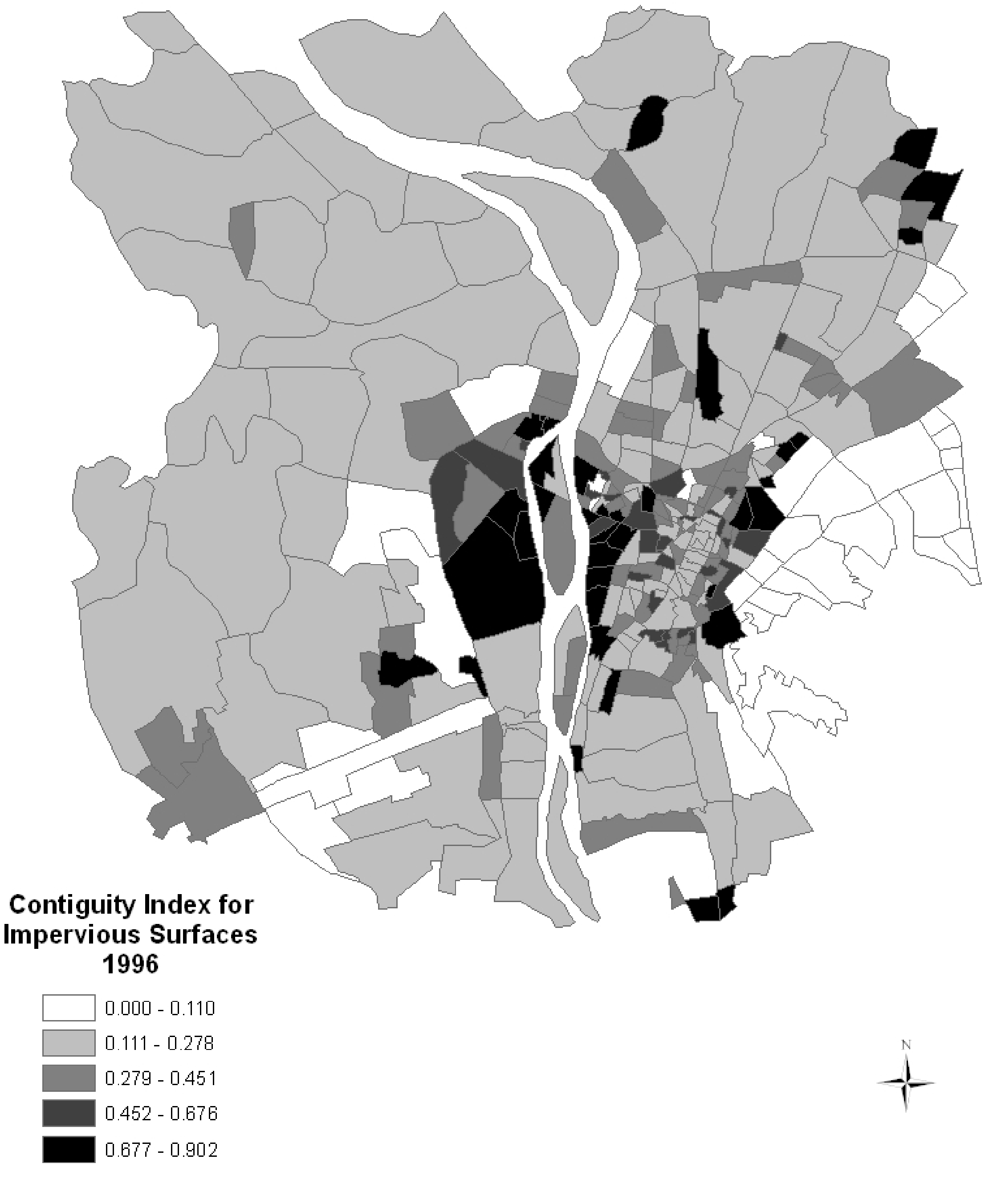


FIGURE 6. URBAN INDEX, CAIRO, 1996

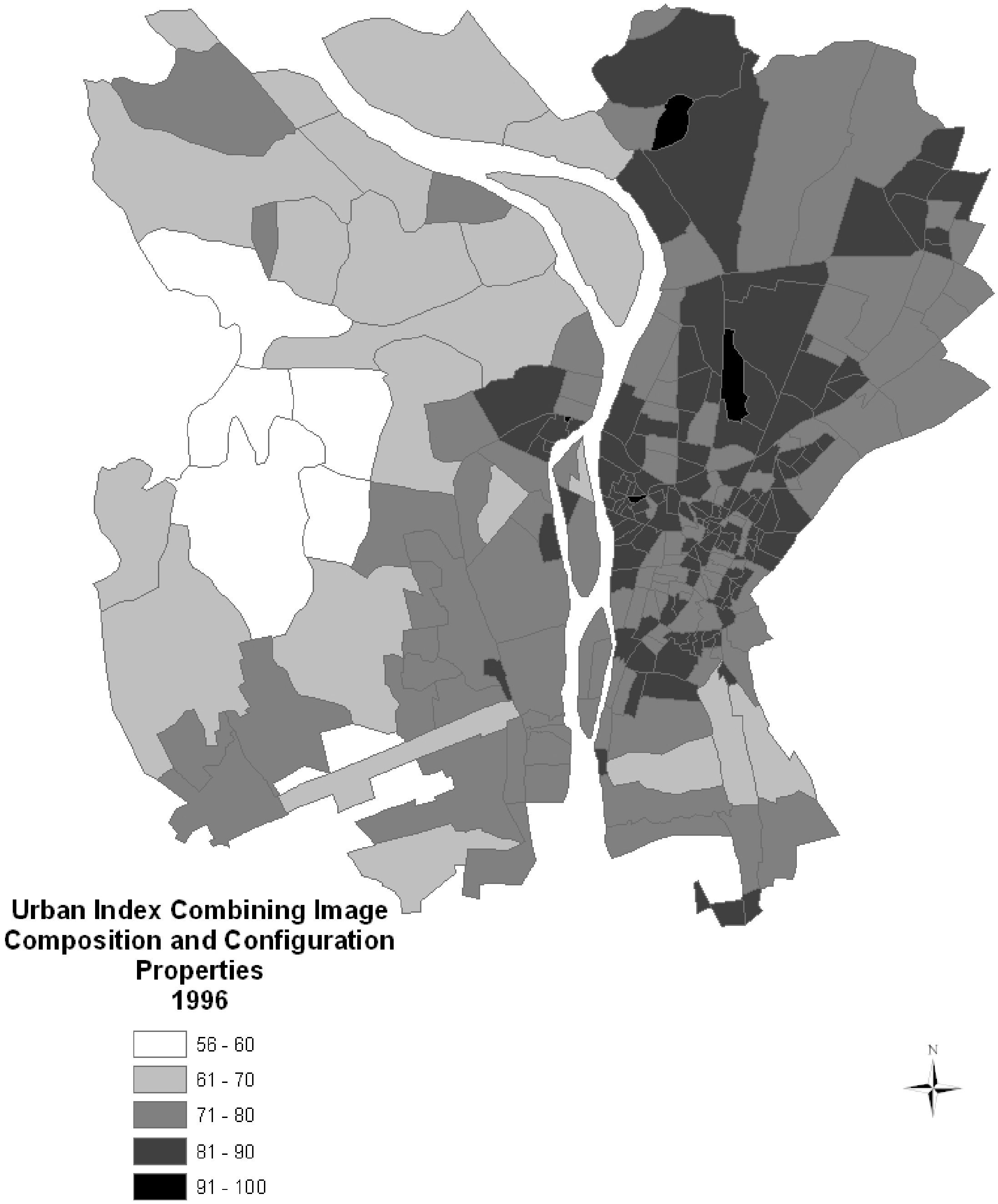


FIGURE 7. THE URBAN INDEX FOR 1996 OVERLAID ON A HIGH-RESOLUTION IMAGE OF CENTRAL CAIRO

TABLE 1. URBAN INDEX FOR CAIRO: 1987 AND 1996

		1987	1996
N of shiakhas		276	276
Mean		80.84	78.81
Median		82.08	80.06
Std. Deviation		8.50	6.30
Kurtosis		0.50	1.08
Minimum		52.94	56.48
Maximum		100.27	91.50
Percentiles:	25	76.37	75.63
	50	82.08	80.06
	75	86.65	82.81

FIGURE 8. PATH MODEL SHOWING THE INDIRECT EFFECTS OF THE SOCIAL AND BUILT ENVIRONMENTS ON NEIGHBORHOOD FERTILITY LEVELS: CAIRO 1996

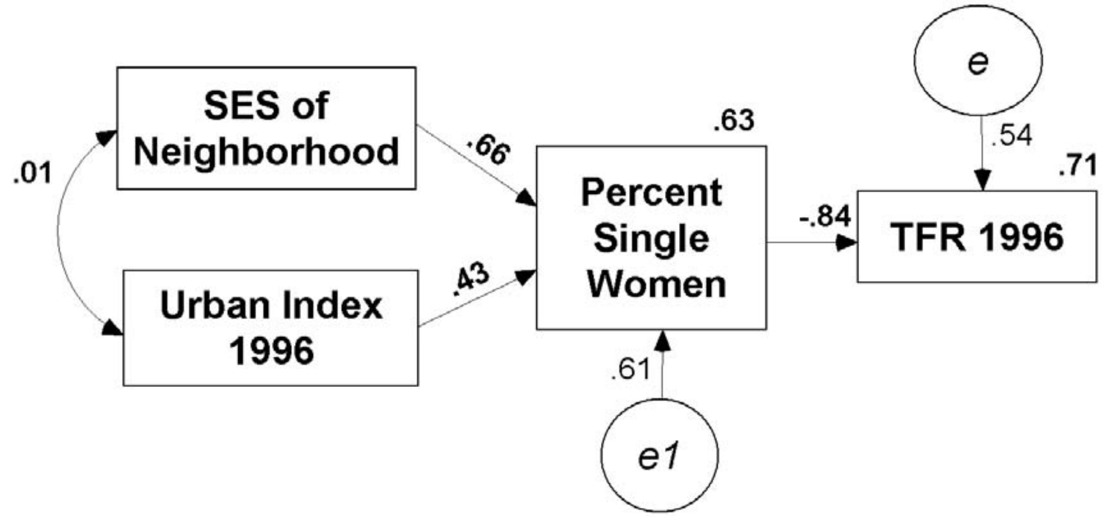


FIGURE 9. PATH MODEL SHOWING THE INDIRECT EFFECTS OF THE SOCIAL AND BUILT ENVIRONMENTS ON NEIGHBORHOOD FERTILITY LEVELS: CAIRO 1986

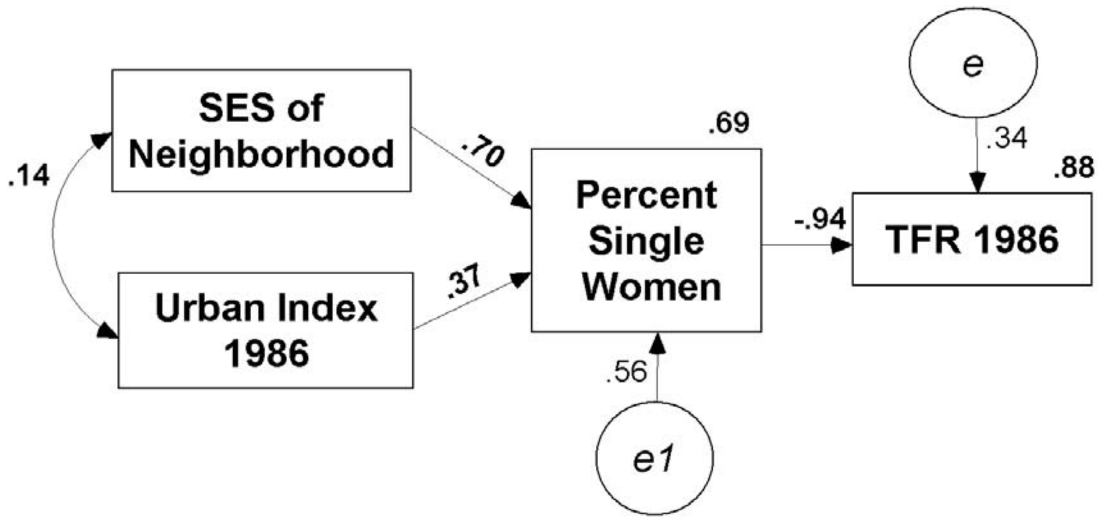


FIGURE 10. PATH MODEL SHOWING THE INDIRECT EFFECTS OF THE CHANGE IN SOCIAL AND BUILT ENVIRONMENTS ON THE CHANGE IN NEIGHBORHOOD FERTILITY LEVELS: CAIRO 1986 TO 1996