Patterns and scale relations among urbanization measures in Stockholm, Sweden

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Abstract

In this study we measure urbanization based on a diverse set of 21 variables ranging from landscape indices to demographic factors such as income and land ownership using data from Stockholm, Sweden. The primary aims were to test how the variables behaved in relation to each other and if these patterns were consistent across scales. The variables were mostly identified from the literature and limited to the kind of data that was readily accessible. We used GIS to sample the variables and then principal component analyses (PCA) to search for patterns among them, repeating the sampling and analysis at four different scales (250 × 250, 750 × 750, 1250 × 1250 and 1750 × 1750, all in meters). At the smallest scale all variables seemed to be roughly structured along two axes, one with landscape indices and one mainly with demographic factors but also impervious surface and coniferous forest. The other land-cover types did not align very well with these two axes. When increasing the scale this pattern was not as obvious, instead the variables separated into several smaller bundles of highly correlated variables. Some pairs or bundles of variables were correlated on all scales and thus interchangeable while other associations changed with scale. This is important to keep in mind when one chooses measures of urbanization, especially if the measures are indices based on several variables. Comparing our results with gradients from other cities, we argue that universal gradients will be difficult to find since city shape and size, as well as available information, differ greatly. We also believe that a multivariate gradient is needed if you wish not only to compare cities but also ask questions about how urbanization influences the ecological character in different parts of a city.

Keywords: urban gradient, scale, landscape metrics, land-cover, demographic variables

Introduction

Urban centers may be viewed as one end of a gradient of human impact on ecosystems. Toward the urban centre, there is a change in several processes, for example altered disturbance regimes, changed predation rates, and suppressed disturbance events (Collins et al. 2000). Gradient analyses (cf. Whittaker 1967) have been promoted as a suitable tool for studies of urban landscapes and analyses of rural-urban gradients have been commonly used to investigate how urbanization changes ecological patterns and processes across landscapes (e.g. McDonnell and Pickett 1990). A multitude of definitions of urbanization has been used, for example, relatively subjectively based on land-use (Blair 1996), transects of distance from urban core or land cover changes (Carreiro et al. 1999; Burton et al. 2005), population density (Bowers and Breland 1996), or housing/building density (Germaine and Wakeling 2001).This makes comparison of the results from different urban gradient studies somewhat complicated. Further, since urban landscapes represent complex socio-ecological systems, it has been suggested that a more comprehensive description of the degree of urbanization should include not only physical geography, demography, and rates of ecological processes (McIntyre et al. 2000), but also history of land-use, management patterns (Dow 2000) and characteristics of the human population occupying a particular area (Kinzig et al. 2005).

Not all effects of urbanization decrease in intensity in a simple linear or concentric pattern from a single centre, nor will all the variables that are relevant measures of urbanization covary (see e.g. Luck and Wu 2002). To capture these nuances of urbanization you need to measure a wide range of variables (Cadenasso et al. 2007). The result will not be a straight-forward gradient ranging from rural to urban, but rather a multi-layered characterization of the cityscape and its parts. Furthermore, the level of urbanization has normally been measured at one spatial scale only, but since the importance of different variables and their relationships vary with scale and question asked, analysis should be done on several scales (e.g. Wiens 1989; Levin 1992; Steffan-Dewenter et al. 2002).

We argue that an urban gradient should include broad measures for comparing different cities, as suggested by McDonnell and Hahs (2008), and provide a basis for assessing and investigating ecological conditions. We analyzed an urban landscape in the Stockholm metropolitan region and measured 21 variables including demographic variables, physical variables and landscape metrics, measured at four different scales, to construct a multi-layered representation of urbanization. Based on the results we discuss the value of using a multivariate instead of a simple gradient. Our main questions were:

1. How do the variables behave in relation to each other?
2. Do correlations between variables change when moving from a small local scale to a larger scale?

Material and methods

Our study was carried out in the city of Stockholm, Sweden’s capital and largest urbanized area, located at 59º20’N latitude and 18º05’E longitude on the eastern coast (Fig. 1). The city core straddles Lake Mälaren’s outlet into the Baltic Sea, and the city is characterized by many waterways and relatively high proportion of green areas. The Stockholm County today houses approximately 1.8 million people (SCB 2006), a figure expected to increase by 200,000 over the next 10 years (RTK 2005). Development has followed several different planning paradigms over time, thus adding to the overall heterogeneity (cf. Elmqvist et al. 2004; Barthel et al. 2005).

<Figure 1>

Creating a land-cover map based on satellite images

Due to lack of a uniform land-cover map over the whole Stockholm Metropolitan area, satellite imagery was used to create a map containing the six dominating land-cover types within the study area. The classification was based on three SPOT 5 satellite images with 10 m resolution. The images are from 3 Aug and 12 Aug 2004 with GRS IDs K/J 061/228, 058/228 and 061/229 respectively (Metria 2006). Since the two paths are from different dates the images from each path were classified independently. A principal component analysis (PCA) was performed, followed by an unsupervised classification in ERDAS 9.0 (Leica Geosystems Geospatial Imaging, USA) generating 50 classes based on the digital numbers (Lillesand et al. 2003). The PCA is a linear ordination method that aims at ordering a large number of variables along preferably two or three axes that are relatively independent and represent the main compositional gradients in the data. Based on maps, aerial photos and ground truthing the 50 classes were manually aggregated in ArcINFO 9.1 (ESRI, USA) into the following 6 classes: Impervious surface, Coniferous forest, Deciduous forest, Open land, Agriculture and Water. The results for the two paths were finally merged and a mean filtering was applied to reduce the noise in the resulting map (single pixels).

Measures of urbanization

Twenty-one measures of urbanization, most of them identified from the scientific literature (e.g. Dow 2000; Hope et al. 2003; Hahs and McDonnell 2006), were used for the analysis. The measures include landscape metrics, demographic and physical variables (Table 1), and were intended to capture both biophysical variation and, albeit indirectly, changes in the nature and intensity of human activities. We included measures of owner and property diversity as other studies (e.g. Andersson et al. 2007) have demonstrated that green areas classified as part of the same land-cover class can differ ecologically depending on their management. These measures could be used as surrogates for land-use and management heterogeneity, variables usually not available at the scales needed for gradient analyses. We also included different vegetation classes and age of buildings as management of urban green areas has previously been shown to change for example tree species composition over time (Jokimaki and Huhta 1996). Acoustic environment was included as it gives an indication of human activity and traffic in the area and is potentially perceived as disturbance by many organisms, e.g. birds (Slabbekorn and Peet 2003; Katti and Warren 2004). Because of the many waterways intersecting Stockholm we also included water as a separate variable.

Demographic information

Measures describing socio-economic factors such as mean income per household, age of buildings, population density etc. were either derived directly from the Statistics Sweden (SCB), or calculated from figures provided by SCB. All demographic information is based on the 2003 census. The information came as averages or totals for 250 × 250 meter grid cells. The census information is biased towards residence rather than work, meaning that industrial or commercial districts can experience high levels of human activity during certain hours without this showing in the statistics.

<Table 1>

Gradient analysis

The choice of variables used for the gradient analysis was based on what had been used previously and the information available (see Table 1). The values for the 21 measures were calculated for 116 sample points within two transects with 1750 × 1750 meter grid cells running north-south and east-west through central Stockholm. Each cell was centered on one of the 250 × 250 meter census grid cells described above. All measures were calculated at 4 nested scales (all in meters), 250 × 250, 750 × 750, 1250 × 1250 and 1750 × 1750. However, the three scales above 250 × 250 were based on buffer zones created around the 250 meter cells, which meant that they got increasingly rounded corners with increasing size (Fig. 2). The variables and metrics were sampled by intersecting the information layers with a vector version of the grid theme in ArcView 3.2 and ArcGis 9.0 (ESRI, USA). Measures were either derived directly, e.g. percentage of the different land-cover types, or computed (see Appendix 1. for the formulae used).

<Figure 2>

Data analysis

To identify the major trends in the 21 measures of urbanization we ran principal component analyses (PCA) at each scale. The data was first standardized using 'center and standardize by species', which is an option suitable for variables that are measured in different units (ter Braak and Smilauer 2002). The data for the four different scales were analyzed separately to find out how the relation between variables would change with increasing spatial scale.

Results

Two main ordination axes were revealed in the PCA using measures of urbanization from the 250 × 250 m grid cells (Fig. 3a). Landscape metrics were mainly associated with the first axis and demographic variables with the second. Physical measures of the landscape were related to both axes. Percentage water and open land, for example, were associated with the first axis while percentage impervious surface and coniferous forest were associated with the second axis and deciduous forest was associated with both (Table 2). When the scale was increased the general pattern along the two axes broke down into several smaller bundles of correlated variables (Fig. 3b-d). Some variables were correlated on all scales while others changed individually. Diversity of owners and properties were always correlated with each other and people, households and impervious surface were also correlated on all scales. Other correlations were scale specific, for example the connection between acoustic environment and road density became clearer when the scale increased. We also found people per unit impervious surface to be scale sensitive; it was strongly correlated to the second axis at the smallest scale and to the first axis at the largest scale, but not correlated to either of the first two axes at mid scales. Mean income, age of development, agriculture and land-cover richness were not strongly correlated with either of the first two axes at any spatial scale. The first two axes explained more or less the same percentage of the variation in the data for the four scales measured (48.1-55.5%). Axes three and four together only explained an additional 14.2-16.9% of the variation in the data and were therefore not included in the results table.

<Figure 3 a, b, c and d>

<Table 2>

Discussion

Which variables or combinations of variables capture the rural-urban gradient? How do they covary?

At the smallest scale most variables seemed to be roughly structured along two axes, one with landscape indices and one mainly with demographic factors but also impervious surface and coniferous forest. The other land-cover types did not align very well with these two axes. When increasing the scale this pattern was not as obvious, instead the variables separated into several smaller bundles of highly correlated variables. Some variables were correlated across all scales and thus interchangeable while others changed individually.

It seems difficult to find patterns or correlations between variables that would apply to cities in general. For example, in contrast to Luck and Wu (2002) we did not find measures of landscape complexity (LSI) to increase with urban land cover (impervious surface), pointing to the importance of the specific landscape context of each city. Further, we found that impervious surface could be used interchangeably with density of people and density of households, whereas in other cities this might not be true. Stockholm has neither many industrial or commercial areas with low density of people but high proportion of impervious surface, nor many buildings such as skyscrapers with very high concentrations of people. The variables not strongly correlated with the first two axes, e.g. mean income, are interesting since they can potentially add information not captured by other variables (see e.g. Hope et al. 2003).

Proportion of impervious surface has often been used to define the level of urbanization (e.g. Ridd 1995; Lu and Weng 2006), and it seems to be relevant also in our study. However, Stockholm with its particular layout where the city centre straddles several islands show us a pattern where the most central parts are covered both by high proportions of both impervious surface and open water. This makes the definition of impervious surfaces somewhat difficult from an ecological perspective as many organisms will perceive water as equivalent to impervious surfaces in terms of habitability. To avoid the potentially confounding effect of water when comparing gradients of urbanization in different cities it might be an idea to use proportion of terrestrial land-cover types per terrestrial surface.

McDonnell and Hahs (2008) argue that a small set of easily measured variables or indices should be used for different cities to make comparison possible. However, in the light of very different cities the relevance of these measures for assessing ecological conditions or the functions of different parts of a city seems rather dubious (cf. ibid). Finding these broad measures, e.g. different indices (Hahs and McDonnell 2006), can be difficult for several reasons. First, combining demographic and landscape information can be problematic. We did not have access to data with the same resolution for all our measurements and data availability and quality are likely to vary a great deal between cities and countries. For some of the variables we have detailed information while for others, e.g. for acoustic environment and mean income, we have used average values. Second, finding a generic classification of land-cover seems unlikely, especially when there are problems with measuring even a class as well-defined as impervious surface (Lu and Weng 2006). We divided the land-cover data into six classes and even though we distinguished between deciduous and coniferous forest it would have been interesting to divide the urban green areas even further, according to management. Third, the availability of data will differ substantially between cities. For example, included among the measures proposed by McDonnell and Hahs (2008) was an index based on information that, at least for Stockholm, was not readily available (e.g. number of males in non-agricultural jobs). One of the ideas with our study was to find variables that were both relevant as measures of urbanization and relatively easy to find information about. Therefore some of the social variables such as local green area management, a variable truly important for many organisms (e.g. Andersson et al. 2007), were not possible to include. Never the less, we believe that a diverse set of variables would allow comparisons as well as practical use in planning.

Spatial scales

The importance and effect of scale will vary between cities; Stockholm is rather small and has through its system of green wedges access to large green areas even close to the city center. The grain and extent on different patterns is generally accepted to influence the analysis (e.g. Wiens 1989; Gustafson 1998; Wu 2004). However, within the growing literature on urban gradients few articles address the variables of urbanization (McDonnell and Hahs 2008), and fewer still test the importance of the analytical scale (Wu et al. 2002). Our set-up explicitly tested the effect of scale and whether the relationship between variables changed with scale. The results suggest that correlations change with scale; some variables can be used interchangeably across scales while other display similar behavior only on certain scales. Thus, scale dependence both in variable behavior and potentially in relative importance call for multi-scaled gradients. McDonnell and Hahs (2008) argue for the use of indices to define urbanization. From looking at our results we see a potential problem in the interpretation of the indices if the variables used for calculation would prove to have scale specific behavior. Also, it is interesting to see that the landscape metrics strongly correlated with axis 1 at the smallest scale change their affiliation to axis 2 at the largest scale, and vice versa for some of the demographic variables.

While measuring several variables we measured all of them across all scales. In our choice of commonly used variables we might have missed variables that are only relevant at certain scales. Landscape studies aimed at understanding patterns of species occurrence in cities have frequently showed that qualitatively different sets of variables are relevant at different scales (e.g. Whited et al. 2000; Melles et al. 2003). However, considering the lack of city wide information on local conditions in terms of e.g. vegetation structure and management activities we see such information as a necessary complement to but not part of future gradient analyses.

Conclusions

Differences between measures used to characterize urbanization were in our case clearest at a small scale, where variable behavior could largely be explained by two general axes. We found that variables covary, but not consistently across scales. This is important to keep in mind when one chooses measures of urbanization, especially if the measures are indices based on several variables. We believe that a multivariate gradient is needed if you wish not only to compare cities but also ask questions about how urbanization influences the ecological character in different parts of a city.

Table 1. Description of the 21 measures of urbanization used to characterize grid cells at all scales in the study area. All variables except those marked with a star were adopted from Hahs & McDonnell (2006). The formulae used to calculate the different measures and information on owners, properties, age and land-cover can be found in Appendix 1.

Measure	***Abbreviations***	***Description***
Demographic variables		
Density of people	People	Total number of inhabitants within a sample area
Density of households	Households	Total number of households within a sample area
People per unit impervious surface	People/I	Number of inhabitants per unit impervious surface
Mean income (per household) *	Income	Mean income per household and year, excluding no-income households
Simpson's diversity, land owners *	Owners	An index of land owner diversity, based on both number of different land owner categories and number of estates, 8 categories
Simpson's diversity, properties *	Properties	An index of land property type diversity, based on both land-use classes and number of estates, 7 classes
Physical variables		
Age of development *	Age	Average age of the buildings, 4 intervals
Impervious surface (%)	I	Fraction of impervious surface, based on land-cover maps
Coniferous forest (%)*	CF	Fraction of coniferous forest, based on land-cover maps
Deciduous forest (%)*	DF	Fraction of deciduous forest, based on land-cover maps
Open land (%)*	OL	Fraction of open land, based on land-cover maps
Agriculture (%)*	A	Fraction of agricultural land, based on land-cover maps
Water (%)	W	Fraction of water, based on land-cover maps
Simpson's diversity, land-cover	Div. land-cov.	An index of land-cover diversity, based on both richness and proportion, 6 classes
Road network density, km per ha	Roads	Length of existing public roads, ranging from local roads to highways
Acoustic environment*	Noise	The relative noise profile within a sample area
Landscape metrics		

Land-cover richness	LCR	Number of land-cover types present in a sample area
Fractal dimension	FD	A measure of patch shape reflecting shape complexity
Number of patches	Patches	Count of the number of patches within a sample area
Largest Patch Index	LPI	Area of the largest patch within a sample area
Landscape shape index	LSI	Index of how irregular the shape of the landscape patches are

*Variables that were not used by Hahs and McDonnell (2006) but that we found informative when defining a rural-urban gradient in general (i.e. acoustic environment, diversity of owners and properties) or in the context of Stockholm in particular (i.e. percentage impervious surface including water, deciduous and coniferous forest, agricultural and open land).

Table 2. Results for the first two components from the PCA with the measurements of urbanization at the four different scales (250 × 250, 750 × 750, 1250 ×1250 and 1750 ×1750 all in meters). Eigenvector coefficients in bold are larger than 0.500 and indicate that the variable contributes considerably to that principal component. The largest eigenvector coefficient for each principal component is underlined.

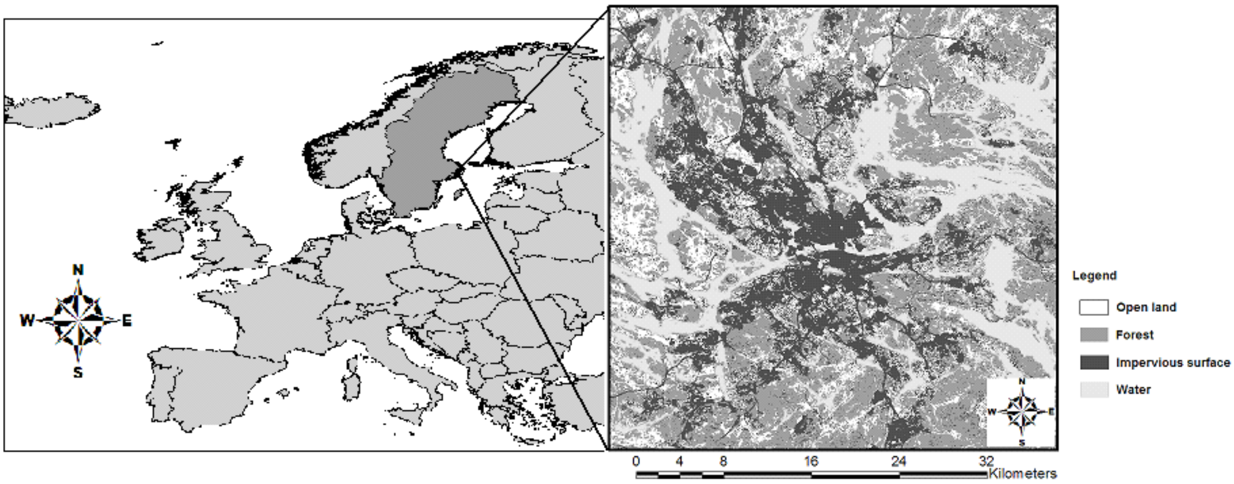
Scale (m)	250×250		750×750		1250×1250		1750×1750	
	PC 1	*PC 2*	*PC 1*	*PC 2*	*PC 1*	*PC 2*	*PC1*	*PC2*
Eigenvalues	0.2867	0.2183	0.2579	0.2229	0.2755	0.2428	0.3142	0.2411
Eigenvector coefficients								
Demographic variables								
Density of people	-0.217	**0.760**	0.198	**0.767**	0.483	**0.677**	**0.832**	-0.362
Density of households	-0.175	**0.762**	0.250	**0.746**	**0.531**	**0.641**	**0.853**	-0.306
People / unit impervious surface	-0.317	**0.504**	-0.040	-0.142	-0.132	0.225	**0.617**	-0.352
Mean income (per household)	-0.387	0.198	-0.258	0.028	-0.166	-0.190	-0.253	-0.022
Simpson’s diversity, land owners	-0.170	**0.733**	0.453	**0.511**	**0.653**	0.340	**0.771**	0.061
Simpson’s diversity, properties	-0.263	**0.686**	0.480	0.414	**0.708**	0.169	**0.681**	0.216
Physical variables								
Age of development	-0.377	0.349	-0.183	-0.034	-0.328	-0.086	-0.469	-0.080
Impervious surface (%)	-0.164	**0.752**	0.090	**0.889**	0.411	**0.830**	**0.772**	-0.516
Coniferous forest (%)	0.024	**-0.546**	-0.136	**-0.647**	-0.366	**-0.566**	**-0.579**	0.314
Deciduous forest (%)	-0.474	**-0.501**	**-0.578**	-0.413	**-0.694**	-0.222	**-0.728**	-0.128
Open land (%)	**-0.554**	-0.055	**-0.644**	0.303	**-0.575**	**0.519**	-0.279	**-0.732**
Agriculture (%)	-0.041	-0.074	-0.091	-0.299	-0.106	-0.327	-0.244	0.256
Water (%)	**0.749**	-0.067	**0.689**	-0.366	**0.503**	**-0.580**	0.140	**0.742**
Simpson’s diversity, land-cover	**-0.834**	-0.442	**-0.808**	-0.200	**-0.769**	-0.076	**-0.722**	-0.149

Road network density, km per ha	-0.336	**0.549**	-0.311	**0.832**	0.066	**0.871**	0.488	**-0.781**
Acoustic environment	-0.408	0.326	-0.312	**0.563**	-0.133	**0.647**	0.207	**-0.663**
Landscape metrics								
Land-cover richness	-0.462	-0.199	-0.132	-0.353	0.116	-0.455	-0.041	0.385
Fractal dimension	**-0.886**	-0.239	**-0.614**	0.143	**-0.579**	0.418	-0.415	**-0.519**
Number of patches	**-0.869**	-0.039	**-0.808**	0.348	**-0.658**	**0.593**	-0.308	**-0.842**
Largest patch index	**0.857**	0.368	**0.897**	0.076	**0.892**	-0.120	**0.745**	0.468
Landscape shape index	**-0.932**	-0.196	**-0.905**	0.258	**-0.787**	**0.538**	-0.460	**-0.842**

Figure 1. Stockholm’s location and general layout.

Figure 2. Study design for the gradient analysis. Two transects with nested concentric sample grids traverse Stockholm from East to West and North to South, respectively. Sample points were located so that the largest (1750 × 1750 meters) cells shared borders but did not overlap.

Figure 3. First two axes of the PCA for the 21 measurements of urbanization at the four different spatial scales **a)** the 250 m × 250 m cells, **b)** the 750 m × 750 m cells, c) the 1250 m × 1250 m cells and d) the 1750 m × 1750 m cells. The first two axes together explain 50.5%, 48.1%, 51.8% and 55.5% of the variation in the data in figure 3a, b, c and d respectively.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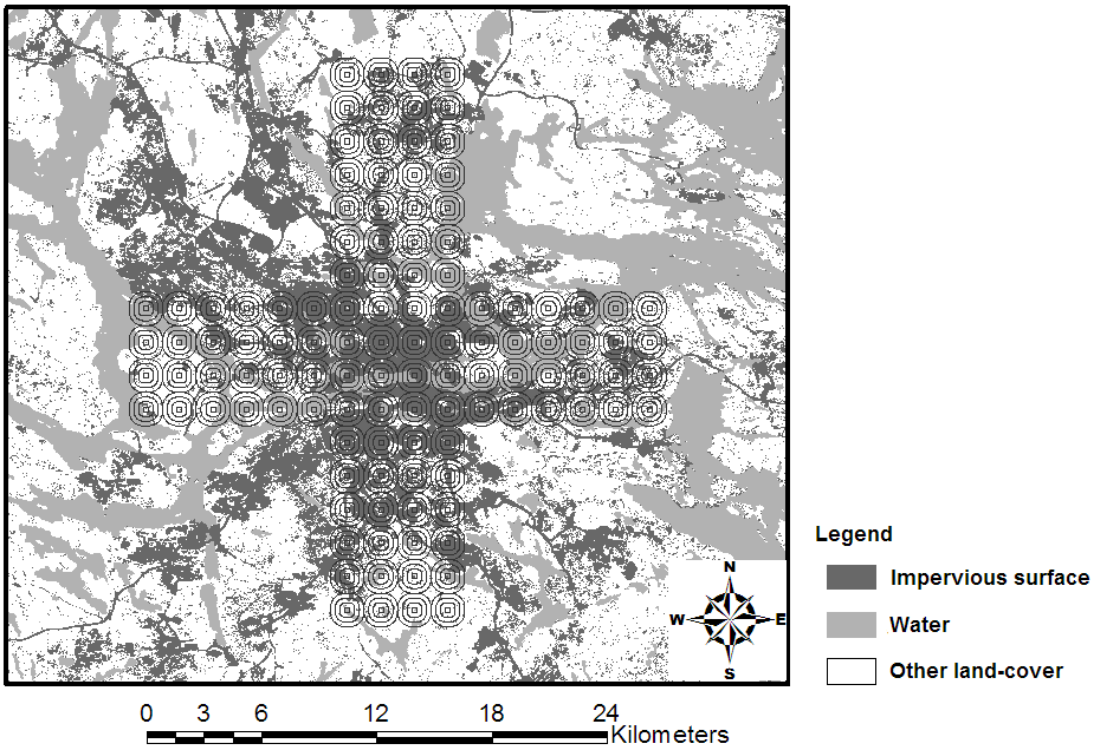
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Impervious surface
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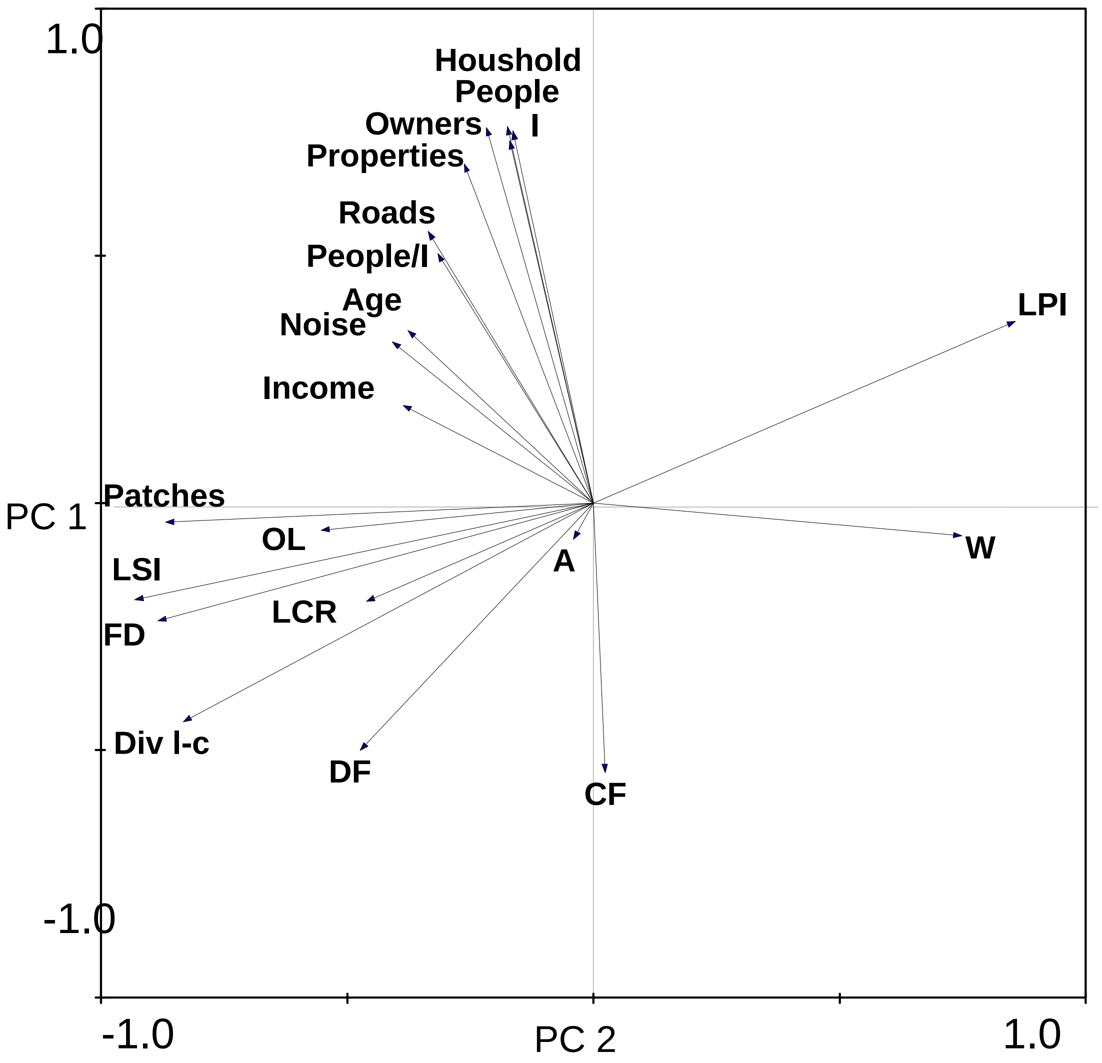
Other land-cover

Figure 2.



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PC 2
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Figure 3a

310

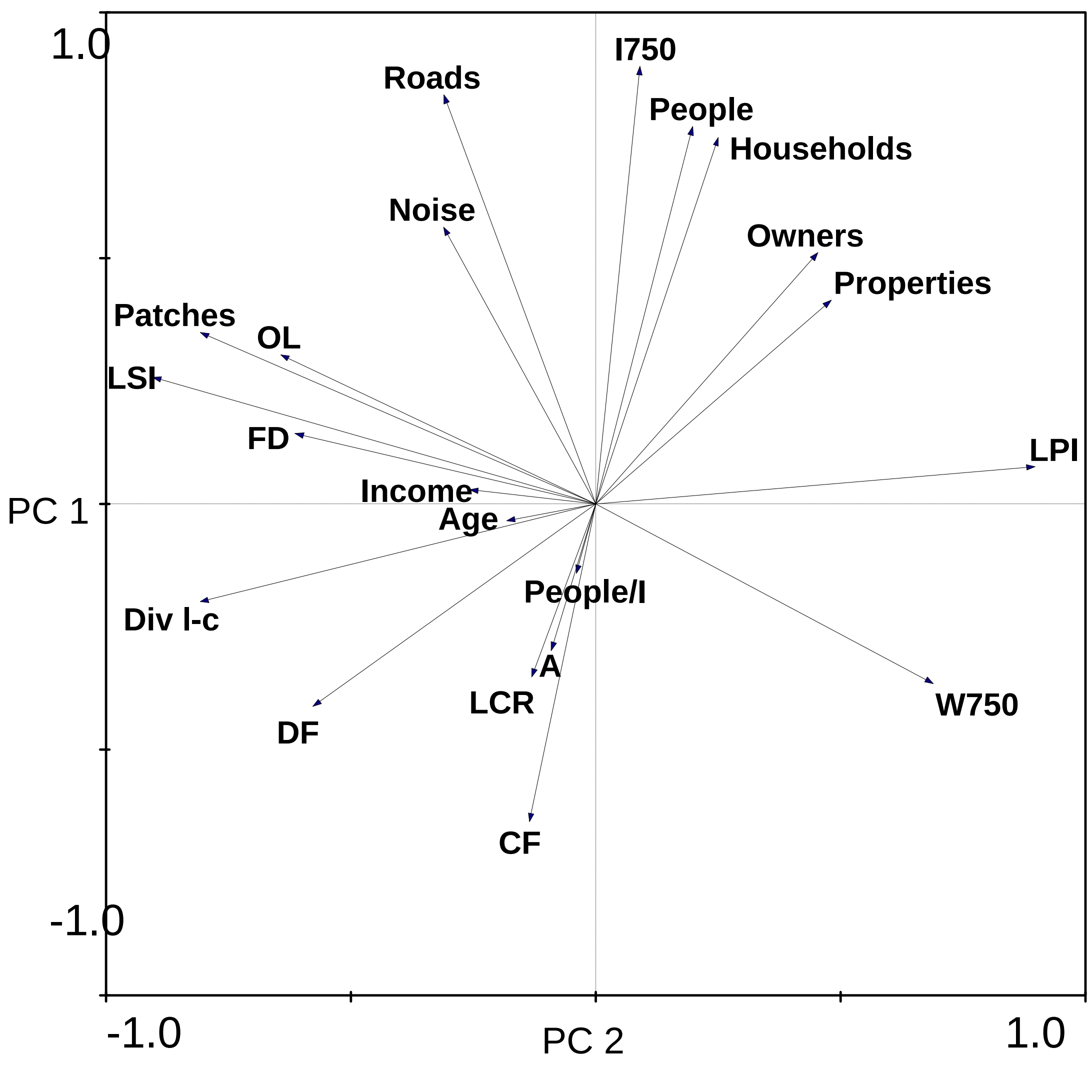
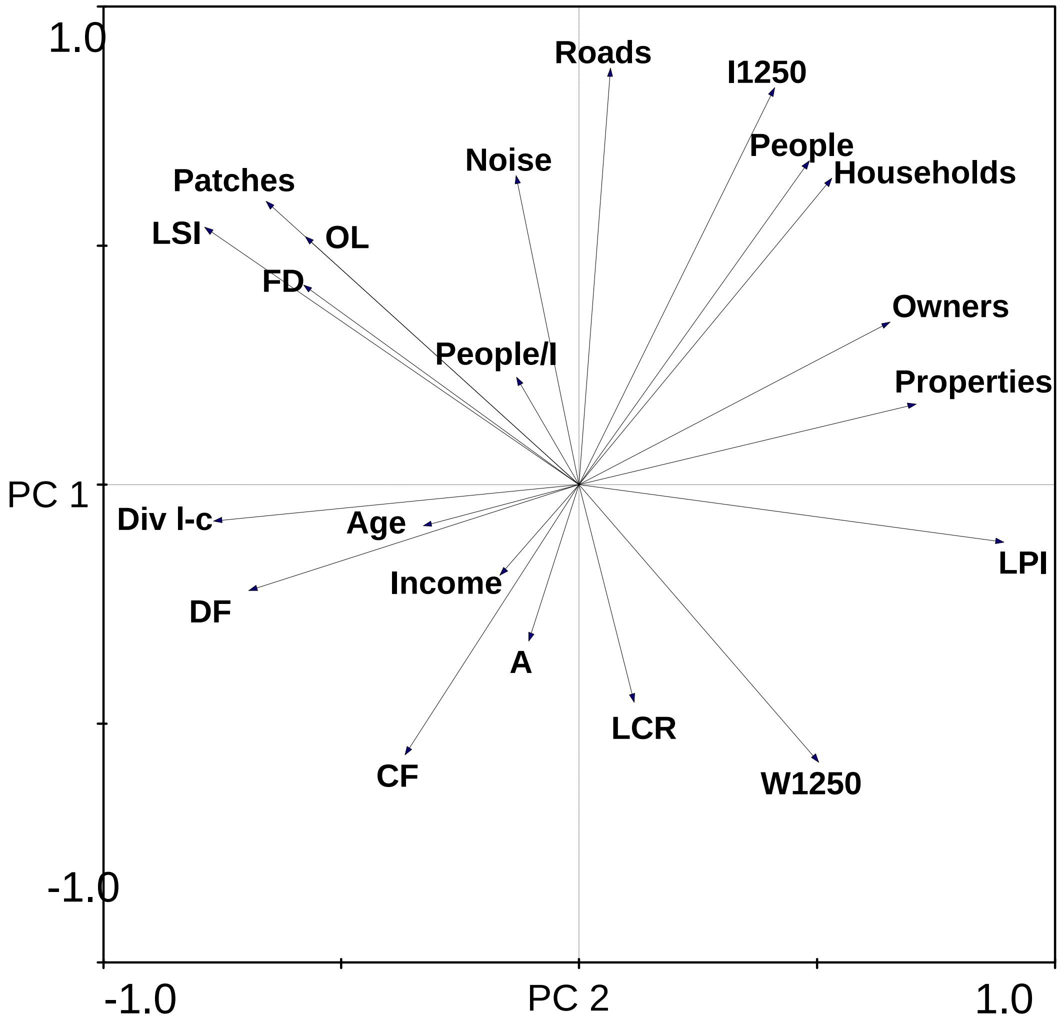
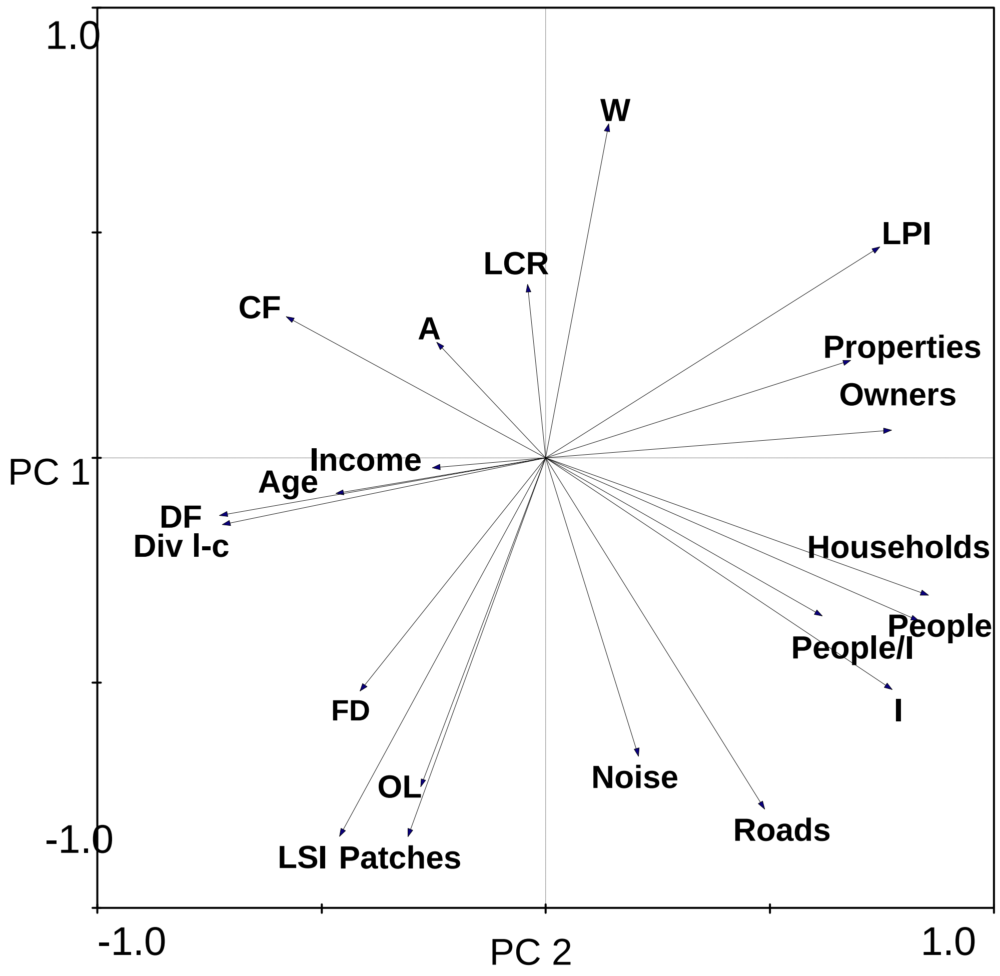


Figure 3b



315

Figure 3c



320 Figure 3d

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Appendix 1. The formulae used to calculate the variables not directly measured or derived.

Variables	***Description and / or formulae***
Demographic variables	
Simpson's diversity (1-D), land owners	Simpson's diversity index calculated as: $1-D=\sum p_i^2$ where $p_i =$ the proportion properties in category *i* within the sampled area. The eight categories were: church or state, municipality or county, private person, estate, corporation, economic association, municipal housing firm, and other.
Simpson's diversity (1-D), properties	Simpson's diversity index calculated as above where $p_i =$ the proportion properties of type *i* within the sampled area. The seven property types were: farm, small houses excluding summer houses, summer houses, business premises, apartment houses, combined business premises and apartment houses, and other.
Physical variables	
Age of development	Median age of the houses. Based on four categories: built before 1940, 1941-1960, 1961-1980, and after 1981.
Simpson's diversity (1-D), land-cover	Simpson's diversity index calculated as above where $p_i =$ is the proportion of the land-cover class *i* within the sampled area. The six land-cover classes were: impervious surface, open land, deciduous forest, coniferous forest, agriculture and open water.
Acoustic environment	An index calculated from the spatial extent of four noise intervals: 0-40, 40-45, 45-55, and 55-65 dB (A).
Landscape metrics	
Fractal dimensions (PAFRAC)[1]	$PAFRAC = 2 \div \left[\left[N\sum_{i=1}^{m}\sum_{j=1}^{n}\left(\ln p_{ij} \times \ln a_{ij}\right) \right] - \left[\left(\sum_{i=1}^{m}\sum_{j=1}^{n}\ln p_{ij}\right) \times \left(\sum_{i=1}^{m}\sum_{j=1}^{n}\ln a_{ij}\right) \right] \right] \div \left[\left(N\sum_{i=1}^{m}\sum_{j=1}^{n}\ln p_{ij}^2 \right) - \left(\sum_{i=1}^{m}\sum_{j=1}^{n}\ln p_{ij} \right)^2 \right]$
	Where $a_{ij} =$ area (m^2) of patch ij, $p_{ij} =$ perimeter (m) of patch ij, and $N =$ the total number of patches in the landscape.

Number of patches (NP)[1]	NP = the total number of patches in the landscape. A patch was defined as one or several adjoining pixels of the same land-cover class.
Landscape shape index (LSI)[1]	$LSI = E \div \min E$ Where E = the total length of edge in the landscape in terms of number of cell surfaces and '$\min E$'= minimum total length of edge possible, which is achieved when the landscape consists of a single patch.
Largest patch index (LPI)[1]	$LPI = (\max(a_{ij}) \div A) \times 100$ Where a_{ij} = area (m^2) of patch ij and A = total landscape area (m^2).

[1]For more information about the landscape metrics see FRAGSTATS documentation of landscape metrics available on homepage: http://www.umass.edu/landeco/research/fragstats/fragstats.html