

Short communication

A multi-scale method of mapping urban influence

Timothy G. Wade^{a,*}, James D. Wickham^a, Nicola Zacarelli^b, Kurt H. Riitters^c

^aUnited States Environmental Protection Agency, MD243-05, Research Triangle Park, NC 27711, USA

^bUniversity of Salento, Department of Biological and Environmental Sciences and Technologies, Landscape Ecology Laboratory, Ecotekne (Campus) Strada per Monteroni, 73100 Lecce, Italy

^cSouthern Research Station, US Forest Service, 3041 Cornwallis Road, Research Triangle Park, NC 27709, USA

ARTICLE INFO

Article history:

Received 11 September 2008

Received in revised form

18 March 2009

Accepted 25 March 2009

Available online 29 April 2009

Keywords:

Urban pattern

Cluster analysis

GIS

Scale

Ecosystem services

ABSTRACT

Urban development can impact environmental quality and ecosystem services well beyond urban extent. Many methods to map urban areas have been developed and used in the past, but most have simply tried to map existing extent of urban development, and all have been single-scale techniques. The method presented here uses a clustering approach to look beyond the extant urban area at multiple scales. The result is a single, synoptic multi-scale map of urban influence that should be useful in urban, regional and environmental planning efforts.

Published by Elsevier Ltd.

1. Introduction

The impacts of urbanization extend over large areas (e.g., Folke et al., 1997) even though the areal percentage of urban land in regional land-cover maps is typically quite small (e.g., Vogelmann et al., 2001; Homer et al., 2007). Many species are 'urban avoiders' (sensu McKinney, 2002), extending environmental impact of the built environment by making otherwise suitable habitat unsuitable because it is near an urban area. Impervious surfaces lead to higher amounts of runoff, increasing sediment and nutrient loads to surface waters, and these effects can be measured well downstream from where the built environment ends (Paul and Meyer, 2001). Industrial and vehicle emissions are carried downwind and deposited in areas remote from their source. The concepts of downstream and downwind indicate that spatial context, gradients (e.g., McDonnell et al., 1997) and scale are important aspects for understanding the influence of urban areas on their surroundings (Dale et al., 2000).

Existing urban development has been mapped in a variety of ways, but most do not attempt to account for the 'halo' of influence imposed by urban areas. The United States Census Bureau delineates urbanized areas (UAs) and urban clusters (UCs) based on

population density. Urbanized areas are defined as densely settled territories that contain 50,000 or more people. Urban clusters are smaller than UAs, with population between 2500 and 50,000 people. Densely settled territory is defined as core census block groups with population densities of 1000 people per square mile or more, and surrounding census blocks with population densities of 500 people per square mile or more (US Census Bureau, 2008a). Housing density has been used to identify low-density suburban and exurban development missed in other mapping techniques (Theobald, 2001). Housing information is available from the Census Bureau, but are only estimates calculated from a random sample. It is collected by census block, which has a minimum size of 0.28 ha and no maximum size (US Census Bureau, 2008b). In general, census blocks are small, bounded by physical features such as streets, roads, and jurisdictional boundaries; however, they may be very large where there are few people (US Census Bureau, 2000).

Satellite data have also been used to map urban areas. A U.S. national ecosystem report used a threshold of 50% developed based on estimates from land-cover maps (Vogelmann et al., 2001) to define urban areas (Heinz Center, 2002). "City Lights" used night time satellite imagery to map urban centers using thresholding to differentiate urban (the brightest pixels) from non-urban (Imhoff et al., 1997). Pixel size was 2.7 km on a side. Landscape Pattern Types (LPTs; Wickham and Norton, 1994; Riitters et al., 2000) used a moving window approach to define dominant (over 60%) and

* Corresponding author. Tel./fax: +1 919 541 4119.
E-mail address: wade.timothy@epa.gov (T.G. Wade).

Table 1

NLCD 2001 Land-cover classes (http://www.mrlc.gov/nlcd_definitions.php). Our re-classification coded NLCD 2001 classes 21 through 24 as urban and all others as non-urban.

| | |
|---|--|
| 11. Open Water | All areas of open water, generally with less than 25 percent cover of vegetation or soil. |
| 12. Perennial Ice/Snow | All areas characterized by a perennial cover of ice and/or snow, generally greater than 25 percent of total cover. |
| 21. Developed, Open Space | Includes areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20 percent of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes. |
| 22. Developed, Low Intensity | Includes areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20–49 percent of total cover. These areas most commonly include single-family housing units. |
| 23. Developed, Medium Intensity | Includes areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50–79 percent of the total cover. These areas most commonly include single-family housing units. |
| 24. Developed, High Intensity | Includes highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses, and commercial/industrial. Impervious surfaces account for 80–100 percent of the total cover. |
| 31. Barren Land (Rock/Sand/Clay) | Barren areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits, and other accumulations of earthen material. Generally, vegetation accounts for less than 15 percent of total cover. |
| 32. Unconsolidated Shore* | Unconsolidated material such as silt, sand, or gravel that is subject to inundation and redistribution due to the action of water. Characterized by substrates lacking vegetation except for pioneering plants that become established during brief periods when growing conditions are favorable. Erosion and deposition by waves and currents produce a number of landforms representing this class. |
| 41. Deciduous Forest | Areas dominated by trees generally greater than 5 m tall, and greater than 20 percent of total vegetation cover. More than 75 percent of the tree species shed foliage simultaneously in response to seasonal change. |
| 42. Evergreen Forest | Areas dominated by trees generally greater than 5 m tall, and greater than 20 percent of total vegetation cover. More than 75 percent of the tree species maintain their leaves all year. Canopy is never without green foliage. |
| 43. Mixed Forest | Areas dominated by trees generally greater than 5 m tall, and greater than 20 percent of total vegetation cover. Neither deciduous nor evergreen species are greater than 75 percent of total tree cover. |
| 51. Dwarf Scrub | Alaska only areas dominated by shrubs less than 20 centimeters tall with shrub canopy typically greater than 20 percent of total vegetation. This type is often co-associated with grasses, sedges, herbs, and non-vascular vegetation. |
| 52. Shrub/Scrub | Areas dominated by shrubs; less than 5 m tall with shrub canopy typically greater than 20 percent of total vegetation. This class includes true shrubs, young trees in an early successional stage, or trees stunted from environmental conditions. |
| 71. Grassland/Herbaceous | Areas dominated by grammanoid or herbaceous vegetation, generally greater than 80 percent of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing. |
| 72. Sedge/Herbaceous | Alaska only areas dominated by sedges and forbs, generally greater than 80 percent of total vegetation. This type can occur with significant other grasses or other grass like plants, and includes sedge tundra, and sedge tussock tundra. |
| 73. Lichens | Alaska only areas dominated by fruticose or foliose lichens generally greater than 80 percent of total vegetation. |
| 74. Moss | Alaska only areas dominated by mosses, generally greater than 80 percent of total vegetation. |
| 81. Pasture/Hay | Areas of grasses, legumes, or grass–legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20 percent of total vegetation. |
| 82. Cultivated Crops | Areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20 percent of total vegetation. This class also includes all land being actively tilled. |
| 90. Woody Wetlands | Areas where forest or shrubland vegetation accounts for greater than 20 percent of vegetative cover and the soil or substrate is periodically saturated with or covered with water. |
| 95. Emergent Herbaceous Wetlands | Areas where perennial herbaceous vegetation accounts for greater than 80 percent of vegetative cover and the soil or substrate is periodically saturated with or covered with water. |

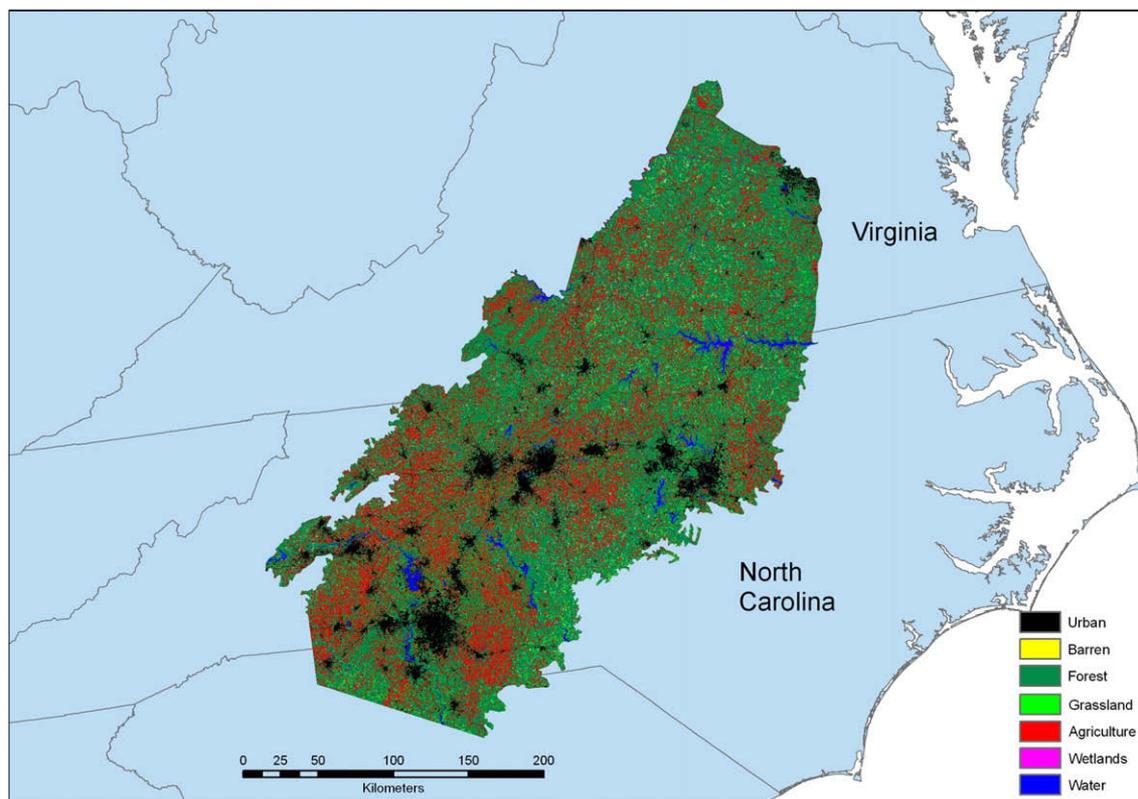


Fig. 1. 2001 land cover in the piedmont study area. Urban centers are Charlotte in the southwest, Greensboro in the central, Raleigh in the east central, and a portion of Richmond in the northeast.

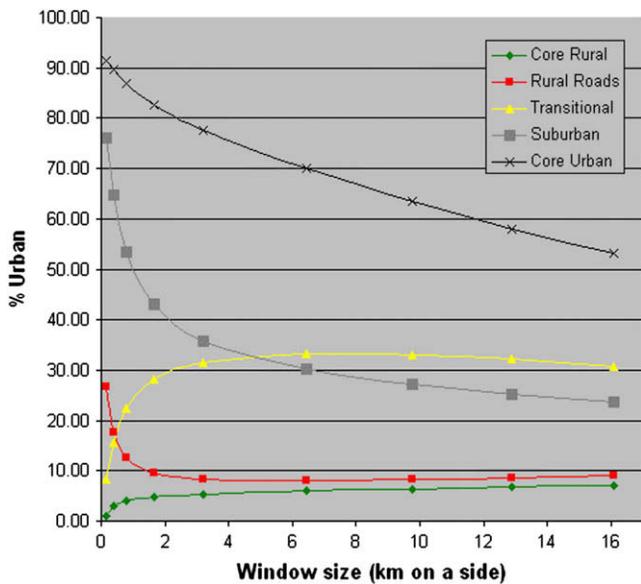


Fig. 2. Cluster means at all scales for the entire study area. Y-axis is percentage of urban land cover and X-axis is window size.

background (10%–60%) land-cover classes at a single, user-defined scale.

Despite the well-established penetrating impacts of urban areas, urban area mapping does not typically incorporate the amount of urban at different lag distances. The likely pervasiveness of the effects of the built environment (see, for example, Riitters and Wickham (2003)) suggests that it would also be worthwhile to develop methods that map entire regions based on the influence of

urban land cover at several scales. Here we provide methodological details and example products (maps) that classify broad regions based on the spatial pervasiveness of urban land-cover at multiple scales.

2. Methods

The only required input for the method, derived from Zurlini et al. (2007), is land cover. In this case, the 30 m National Land Cover Database (NLCD; Homer et al., 2004, 2007) from 2001, is available at www.mrlc.gov. The original 21 classes were reclassified into a binary map of urban and non-urban (Table 1). The study area was in the piedmont region of the southeastern United States (Fig. 1). Moving windows (e.g., Riitters et al., 2000) were used to estimate the percentage of urban land in the surrounding neighborhood (size of the window), assigning that estimate to the neighborhood's center pixel. Water was treated as missing so urbanization was not "diluted" at lake shorelines.

Nine different sizes of moving windows were used. The window sizes were 0.15, 0.39, 0.81, 1.65, 3.21, 6.45, 9.75, 12.87, 16.11 km on a side. The size of an individual window is less important than the use of several window sizes. The window side lengths spanned two orders of magnitude (0.15–16.11 km) to ensure, as best as possible, accurate estimates of the scale-dependent behavior of percentage urban.

The nine rasters were submitted as a stack to a migrating means clustering algorithm (IsoCluster; ESRI, 2008a), to produce statistics for five clusters. Cluster statistics were generated from an 11% sample of 84,717,327 total pixels using 200 iterations of the process. The resultant cluster statistics were used with a maximum likelihood classifier (MLClassify; ESRI, 2008b) to classify the stack of nine urban proportion maps, resulting in a single raster with five classes. Cluster means are shown in Fig. 2, and the five-class cluster maps are shown in Figs. 3 and 4. Intuitive class labels were determined from the cluster distributions in Figs. 2–4. The asymptotic behavior of four of the five classes (Fig. 2) suggests that the scale-dependent pattern of percentage urban was adequately captured with the window sizes used.

3. Discussion

Urban areas typically have high densities at local scales (small windows) that decrease as the window size increases (Fig. 2, core urban and suburban clusters). The converse pattern identifies

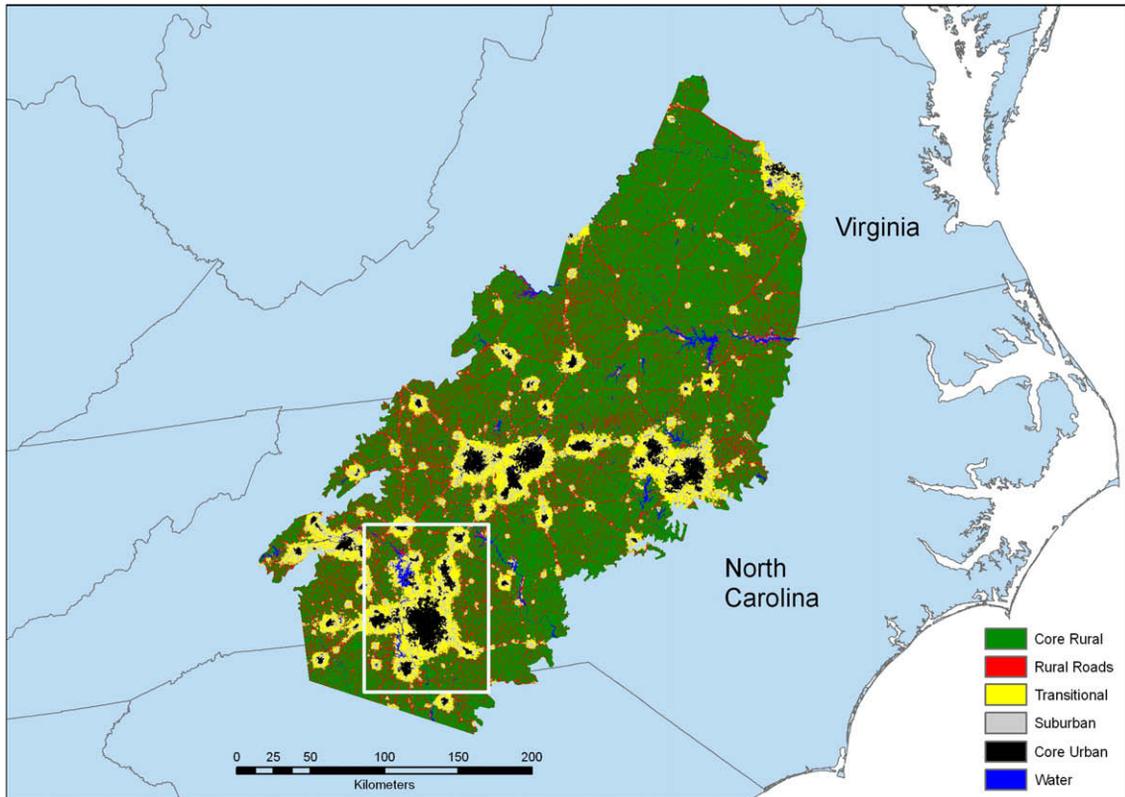


Fig. 3. Cluster map of the entire study area. The white box indicates the area shown in Fig. 4.

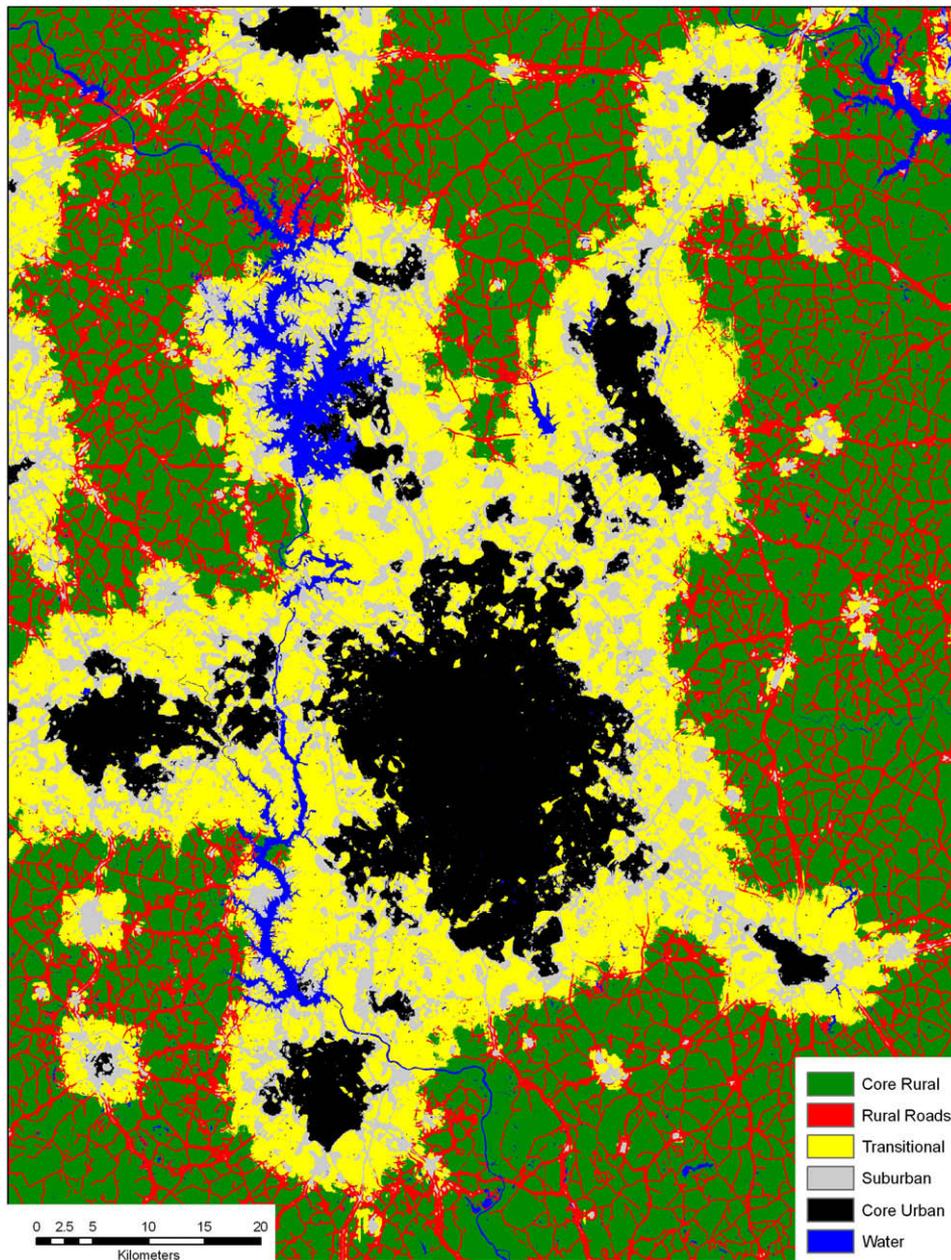


Fig. 4. Cluster map of Charlotte, North Carolina. Visible satellite urban areas are Gastonia (west), Statesville (north), Concord and Kannapolis (northeast), Salisbury (far northeast), Monroe (southeast), and Rock Hill, South Carolina (south).

localities where urban areas are not local, but at the same time are not free from longer-range urban impacts (Fig. 2, transitional and rural roads clusters). The amount of urban land in the 2001 NLCD land-cover map was 11.46% (Fig. 1). In contrast, the core urban, suburban, transitional and rural roads clusters, each of which represents some degree of urban influence, covered 36.72% of the area (Figs. 2 and 3). The amount of land influenced by urban development is three times larger than the urban area itself. Further, the results indicate that urban land is a significant component (i.e., ~5%) of the core rural class at lag distances of 1.65 km and greater, indicating that very little of the study region is entirely free of urban influence when spatial context, gradient, and lag distance are included in the concept of urban.

The combination of common GIS routines (moving windows) and statistical techniques (cluster analysis and maximum likelihood classification) provides an off-the-shelf means to create

a synthetic, multi-scale map showing urban spatial influence across a user-defined number of lag distances (Figs. 3 and 4). These maps should be useful for many land-use planning applications, including issues related to urban sprawl, zoning, restoration and preservation, and for setting up gradients to study the influence of urbanization on ecological resources (e.g., McDonnell et al., 1997). We expect that the mapping techniques reported herein would be useful for most studies where the influence of urban areas is not confined to the strictly defined urban borders.

Acknowledgements

The U.S. Environmental Protection Agency (EPA), through its Office of Research and Development (ORD), funded and performed the research described. This manuscript has been subjected to the EPA's peer and administrative review and has been approved for

publication. We thank Deb Chaloud (US EPA) and Dr. Ari Jolma for their comments and suggestions.

References

- Dale, V.H., Brown, S., Haeber, R.A., Hobbs, N.T., Huntly, N., Naiman, R.J., Riebsame, W.E., Turner, M.G., Valone, T.J., 2000. Ecological principles and guidelines for managing the use of land. *Ecological Applications* 10, 639–670.
- ESRI, 2008a. ArcGIS Help 9.3 – Iso Cluster. URL: http://webhelp.esri.com/arcgisdesktop/9.3/index.cfm?id=5733&pid=5723&topicname=Iso_Cluster.
- ESRI, 2008b. ArcGIS Help 9.3 – MLClassify. URL: <http://webhelp.esri.com/arcgisdesktop/9.3/index.cfm?id=5735&pid=5723&topicname=MLClassify>.
- Folke, C., Jansson, A., Larsson, J., Costanza, R., 1997. Ecosystem appropriation by cities. *Ambio* 26 (3), 167–172.
- Heinz Center, 2002. Technical note for urban and suburban indicator: area of urban/suburban lands. URL: http://www.heinzctr.org/ecosystems/2002report/urban_technotes/urban_area.shtml.
- Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., Wickham, J., 2007. Completion of the 2001 national land cover database for the conterminous United States. *Photogrammetric Engineering and Remote Sensing* 73, 337–341.
- Homer, C., Huang, C., Yang, L., Wylie, B., Coan, M., 2004. Development of a 2001 national land-cover database for the United States. *Photogrammetric Engineering and Remote Sensing* 70, 829–840.
- Imhoff, M.L., Lawrence, W.T., Stutzer, D.C., Elvidge, C.D., 1997. A technique for using composite DMSP/OLS “city lights” satellite data to map urban area. *Remote Sensing of Environment* 61, 361–370.
- McDonnell, M.J., Pickett, S.T.A., Groffman, P., Bohlen, P., Pouyat, R.V., Zipperer, W.C., Parmelee, R.W., Carreiro, M.M., Medley, K., 1997. Ecosystem processes along an urban-to-rural gradient. *Urban Ecosystems* 1, 21–36.
- McKinney, M.L., 2002. Urbanization, biodiversity and conservation. *Bioscience* 52, 883–890.
- Paul, M.J., Meyer, J.L., 2001. Streams in the urban landscape. *Annual Review of Ecology and Systematics* 32, 333–365.
- Riitters, K.H., Wickham, J.D., Vogelmann, J.E., Jones, K.B., 2000. National land-cover pattern data. *Ecology* 81, 604.
- Riitters, K.H., Wickham, J.D., 2003. How far to the nearest road? *Frontiers in Ecology and the Environment* 1, 125–129.
- Theobald, D.M., 2001. Land-use dynamics beyond the urban fringe. *The Geographical Review* 91 (3), 544–564.
- US Census Bureau, 2008a. Census 2000 urban and rural classification. URL: http://www.census.gov/geo/www/ua/ua_2k.html.
- US Census Bureau, 2008b. Geographic areas reference manual, chapter 11. URL: <http://www.census.gov/geo/www/garm.html>.
- US Census Bureau, 2000. Appendix A. Census 2000 geographic terms and concepts. URL: <http://www.census.gov/geo/www/tiger/glossary2.pdf>.
- Vogelmann, J.E., Howard, S.M., Yang, L., Larson, C.R., Wylie, B.K., Van Driel, N., 2001. Completion of the 1990s National Land Cover Data Set for the Conterminous United States from Landsat Thematic Mapper data and ancillary data sources. *Photogrammetric Engineering and Remote Sensing* 67, 650–662.
- Wickham, J.D., Norton, D.J., 1994. Mapping and analyzing landscape patterns. *Landscape Ecology* 9, 7–23.
- Zurlini, G., Riitters, K.H., Zaccarelli, N., Petrosillo, I., 2007. Patterns of disturbance at multiple scales in real and simulated landscapes. *Landscape Ecology* 22, 705–721.