Analyzing Urban Sprawl Spatial Fragmentation Using Multi-temporal Satellite Images

Junmei Tang,[1] Le Wang, and Zhijun Yao
Department of Geography, Texas State University, San Marcos, Texas 78666

Abstract: The landscape pattern of Daqing City, China has undergone a significant change during the last two decades as a result of rapid urbanization. A quantitative analysis describing the spatial fragmentation caused by urban sprawl from satellite images was presented on three dates: 1979, 1990, and 2000. Five landscape indices with supplementary ecological meanings were chosen to facilitate our examination of current fragmentation status and its fragmentation trend. Specifically, the values of mean patch size (MPS) and edge density (ED) indicate a more regular shape in the human-disturbed landscapes than the natural landscapes, while the contagion index (CONT) and mean nearest-neighbor distance (MNND) show a higher fragmentation degree in the natural landscape than the human-disturbed landscape by revealing the contiguity and clumping trends of patches for each class. The different change trends in these fragmentation metrics also reflect the respective change trend and manner of conversion for each class. A GIS-based landscape index, coupled with remote sensing analysis, proved its unique value and effectiveness in assessing landscape patterns and dynamics.

INTRODUCTION

Increasing awareness regarding the importance of urban sustainable development is stimulating the improvement of current methods. This will allow a better understanding of urban landscape evolution, which is the result of complex interactions between physical, biological, and social forces in time and space (Turner, 1987). Remote sensing data, in conjunction with geographical information systems (GIS), has been recognized as an effective tool in quantitatively measuring landscape pattern and its change on a relatively large spatial scale (Nelson, 1983; Isingh, 1989; Metzger and Muller, 1996; Frohn, 1998; Quattrochi and Luvall, 1999; Petit et al. 2001; Roy and Tomar, 2001). Most of this potential, however, has not been realized due to lack of appropriate analytical methodologies to represent and predict the underlying biocomplexity (Michener et al., 2001).

The ability to quantify landscape structure and pattern is a prerequisite to the study of its function and change (McGarigal and Marks, 1994). Currently, most quantification methods begin the analysis by converting classification results to vectors; from this, various spatial indices are derived to summarize the spatial pattern at each given time. Then, a comparison is made on the spatial indices to detect the spatial

[1]Email: jmtang@txstate.edu

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pattern changes over different times (Singh, 1989; Jensen, 1996; Zhao et al., 1996; Zheng et al., 1997; Macleod and Congalton, 1998; Miller et al., 1998; Mas, 1999; Roy and Tomar, 2001; Yang and Lo, 2002). Such metrics, with greater availability of digital spatial data and advanced GIS, offer more opportunities to link the landscape dynamics with ecological and environmental processes for analyzing both the causes and consequences of the change.

During the last two decades, a variety of landscape metrics have been proposed for different purposes. Based on the analysis level, they can be grouped into patch-based indices and spatial heterogeneity indices. The first category characterizes the configuration for the individual landscape class or at the whole landscape base. Indices of patch size and patch shape have been widely used to convey meaningful information on biophysically changed phenomena associated with patch fragmentation on a large scale (Viedma and Melia, 1999; Fuller, 2001). These configuration indices vary as a function of the shape of patches, and they usually correlate with the basic parameter of an individual patch, such as the area, perimeter, or perimeter-area ratio. Consequently, the indices perform poorly in reflecting the spatial location of patches within the landscape (Imbernon and Branthomme, 2001). The spatial heterogeneity indices quantify the spatial structures and organization within the landscape. Based on information theory, O'Neill et al. (1988) first developed dominance and contagion indices to capture major features of spatial pattern throughout the eastern United States. According to Gustafson and Parker (1992), the proximity index quantifies the spatial context of patches in relation to their neighbors. Specifically, the nearest-neighbor distance index (NND) distinguishes isolated distributions of small patches from the complex cluster configuration of larger patches (Turner, 1989). The patch-based and heterogeneity-based indices reflect two aspects of the same spatial pattern and complement each other.

In this paper, we will focus on the analysis and interpretation of environmental fragmentation caused by the urbanization of Daqing City during the last 20 years using remote sensing and GIS. A set of landscape indices was chosen for the comprehensive investigation of the complex and heterogeneous landscape in Daqing. Furthermore, we evaluated these landscape metrics as the quantitative measures of spatial fragmentation caused by ongoing changes in urban sprawl.

STUDY AREA

The study was carried out in the central part of Daqing City, maintaining a variety of landscape types with its unique geology and climate environment. As the largest base for the petrochemical industry in China, Daqing City has undergone rapid economic development as well as environmental deterioration during the last two decades (1980–2000). Centered at 124°15' E Long. and 46°20' N Lat., the study area covers four major urban areas in Daqing City: the Shaertu, Ranghulu, Longfeng, and Honggang districts (Fig. 1). The terrain consists of a relatively flat plain with mean elevations ranging from 126 to 165 m and relief ranging from 10 to 39 m.

The study area exhibits the typical characteristics of a large Mesozoic and Cenozoic terrestrial sediment basin covered mainly with meadow, halophyte, and swamp vegetation. After long geotectonic movements, Daqing ended up with a unique geological structure for the storage of oil. Although Daqing is now diversifying its

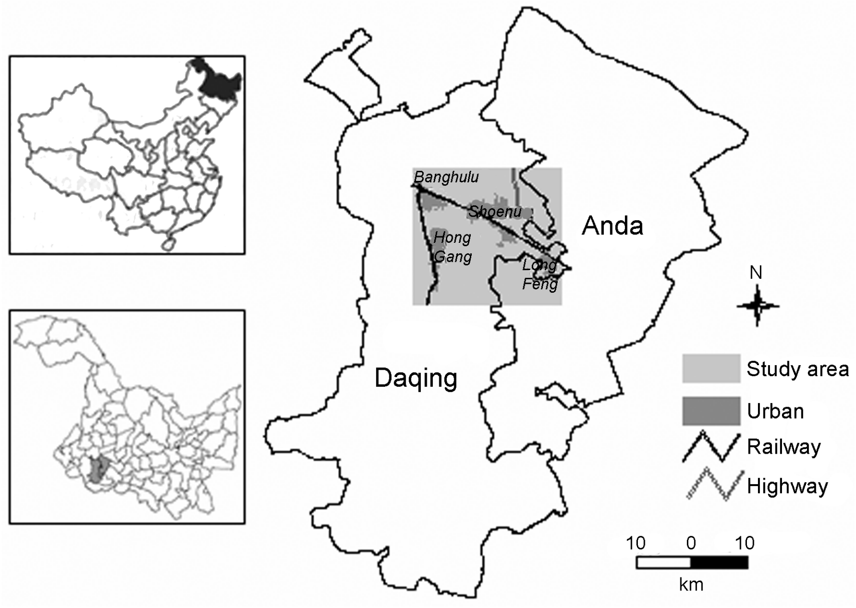

Fig. 1. Study area, Daqing City, China.

energy-oriented economy, the petroleum and petrochemical industries are still the core activities in its economy. Extreme population growth in the Daqing region over the last 50 years has increased the population from 100,000 in 1945 to 2.5 million in 2000 (Statistical Bureau of Daqing, 2001).

Continued development of the region's oil fields has changed the original landscape pattern over the last 20 years. Reduction of swamps, grasslands, and forests has resulted in the deterioration and desertification of the area, potentially affecting the future urban landscape pattern, regional environment, and climate. As a result, the Daqing region, which contains rich landscape types, is subject to rapid changes in landscape pattern.

METHODOLOGY

Data Preparation

Two 1500 × 1500 pixel Landsat Thematic Mapper (TM) and Multispectral Scanner (MSS) satellite images were chosen in this study to detect the spatial fragmentation in Daqing City over the 20-year period 1979–2000. All the images were acquired during the growing season in the Daqing area, from late June to late August. One Landsat MSS was acquired on August 23, 1979 and two Landsat TMs were obtained from July 20, 1990 and June 22, 2000. All images were registered to the UTM map projection, WGS 84, Zone 51, on a SUN workstation using ERDAS™ software, achieving an accuracy of less than 0.5 pixel root mean square error (RMSE) for all images. The MSS was resampled to 30 meters, the same spatial resolution as the TM image.

Table 1. Classification Systems and Definitions Used in Training and Test Samples

Second level	Characteristic in color composite[a]	Code
Agriculture	Primarily for the production of rice and fiber, shows in the image as light or dark red, green with strip texture	1
Urban or build-up	Intensively use by buildings, shows in the image as mixed pixels of light blue.	2
Grassland	Mixed pixels of red, white, and light green.	3
Saline or barren land	White or light, most near to the water	4
Water	Smooth, cyan, blue, and sometimes black	5
Wetland	Dark red and distributed in the northeastern part of city	6
Woodland	Identified on higher elevations; regular shape, red or dark red	7

[a]Bands 3, 4, and 5.

Table 2. Accuracy Assessment of the 1979, 1990, and 2000 Landscape Maps from Landsat Images by ML Classification[a]

	Training sample			Test sample			User accuracy, %			Producer accuracy, %		
Landscape types	79	90	2000	79	90	2000	79	90	2000	79	90	2000
Agriculture	324	332	335	316	324	329	80.66	76.38	66.94	64.92	83.97	91.04
Urban or build-up	313	324	322	312	308	313	94.08	98.78	87.92	92.64	78.9	92.09
Grassland	315	314	307	300	315	314	94.86	80.86	76.69	89.64	83.17	61.78
Saline or Barren land	317	305	302	300	309	322	89.4	79.73	83.24	99.99	95.41	92.6
Water	312	305	306	317	303	333	96.98	99.44	99.53	96.98	99.15	99.05
Wetland	311	310	312	314	310	309	80.73	98.18	80.31	96.27	84.33	97.84
Woodland	303	327	308	303	320	308	69.58	81.56	96.77	84.03	83.28	67.8

[a]Overall accuracy (%): 86.23 (1979), 87.05 (1990), 83.86 (2000); Kappa (%): 83.93 (1979), 84.89 (1990), 81.12 (2000).

The conventional Maximum Likelihood Classification was adopted to obtain four classified maps in our study area. We intended to map seven classes: agriculture, urban/build-up, grass, saline/barren land, water, wetland, and woodland. The selection of separate training and test samples was guided by the characteristic description of each class (Table 1). The number of training and test samples and the classification accuracy are shown in Table 2.

Landscape Fragmentation Analysis

In this paper, we study urban fragmentation from two perspectives—the current fragmental status, which is observed from current or the most recent data; and the potential fragmental trend, which can be derived from short- and mid-term environmental scenarios. One set of landscape indices, which has the least mutual correlation but possesses complementary ecological meanings, was selected for the fragmentation analysis (Table 3). The indices were calculated with the FRAGSTATS (UMASS, 2004) and ARC/INFO software.

Although a wide variety of landscape indices have been applied in describing the spatial composition and configuration of landscape patterns, many of them substantially overlap one another (Giles and Trani, 1999; Tischendorf, 2001). In order to reduce redundancy, two categories of landscape indices were chosen from the perspectives of patch attributes and spatial heterogeneity. The patch-based indices consist of mean patch size (MPS) and edge density (ED), which aims to measure fragmentation caused by the areal distribution and shape of the patches. The spatial heterogeneity-based indices we chose were: the contagion index (CONT), to measure the composition and configuration of landscape; mean nearest-neighbor distance (MMND), to denote the fragmentation degree caused by the isolation; and core area percent of landscape (CPL), to measure the interior fragmentation degree in the landscape.

RESULTS AND DISCUSSION

In this study, the spatial pattern and dynamics of landscape fragmentation caused by urban sprawl were investigated over the 20-year period noted above. The landscape map produced from the image in 2000 only exhibits current landscape patterns, whereas the landscape maps in 1979, 1990, and 2000 (Fig. 2) were used to describe the combined fragmentation process during the last two decades.

Current Fragmentation Status

From the landscape maps in 2000, it can be discerned that most of the urban area lies in the southeast, north-central, and northwest, along the Binzhou and Rangtong railways. Agriculture is the dominant category and has large continuous patches, occupying 788.97 km^2 (39.13%) of the entire study area (Fig. 2, Table 4). This can be attributed to the regional characteristics and historical development of this area. Fertile soil and sufficient rain for agricultural production made agriculture the domainant economic activity in Daqing City before petroleum was discovered in the 1950s. Another dominant landscape is grassland, which occupies 664.89 km^2 (32.97%) of the entire study area (Table 4). Most grasslands exist in the western part of the study area, around the urban area. The wetland and woodland categories are distributed in the northeastern corner of the study area, which is a part of the Longfeng Nature Reserve in Daqing.

Table 3. Definitions of Landscape Metrics for Spatial Fragmentation Analysis

	Landscape metric	Formula	Description
Patch-based	Mean patch size	$MPS = \frac{\sum_{i=1}^{m} [a_i]}{m}$; where a_i is the patch size, and m is the total number for the ith landscape	Mean patch size is considered as the foremost predictor of diversity and the sensitivity to the fragmentation within a patch (Forman and Godron 1981)
	Edge density	$ED = \frac{P_i}{A_i}$ where P_i and A_i are the perimeter and area of the ith landscape	Edge density is a typical index of the degree of fragmentation through the segmentation of an edge to the internal environment
Heterogeneity-based	Contagion index	$CONT{=}1 + \sum_{i=1}^{m}\sum_{j=1}^{n} P_{ij}\ln(P_{ij})/2\ln(n)$ $P_{ij} = P_i P_{j/i}, P_{j/i} = m_{ij}/m_i$ where the P_{ij} is the probability that a patch of ith landscape is found adjacent to a patch of jth landscape, while m is the patch number within one landscape category and n is the number of landscape categories. P_i is the probability that a randomly chosen polygon belongs to patch type i, and $P_{j/i}$ is the conditional probability	A large CONT reflects the clumping of large contiguous patches, whereas a small CONT value reflects a landscape that is dissected into small patches (O'Neill et al. 1988; Turner and Gardner, 1990; Li and Reynolds 1993; Griffith et al. 2002)
	Mean nearest-neighbor distance	$MNND = \frac{\sum_{i=1}^{m} h_i}{m}$ where h_j is distance from each patch to its nearest neighbor, and m is the total number of nearest neighbors to this patch	The MNND measure both the degree of patch isolation and the degree of fragmentation of the corresponding patch type within the specified neighborhood of the focal patch (Gustafson and Parker 1992)
	Core area percentage of landscape	$CPL = \frac{\sum_{i=1}^{m} a_i^c}{A}$ where a_i^c is the core area (the interior habitat as an undisturbed area in the ecological meaning), A is the total class area, and m is the patch number	These edge-to-interior indices provide fragmentation information for the class—i.e., the higher ratio between core area and total area, the less fragmented this class would be (FRAGSTATS * ARC, 2004)

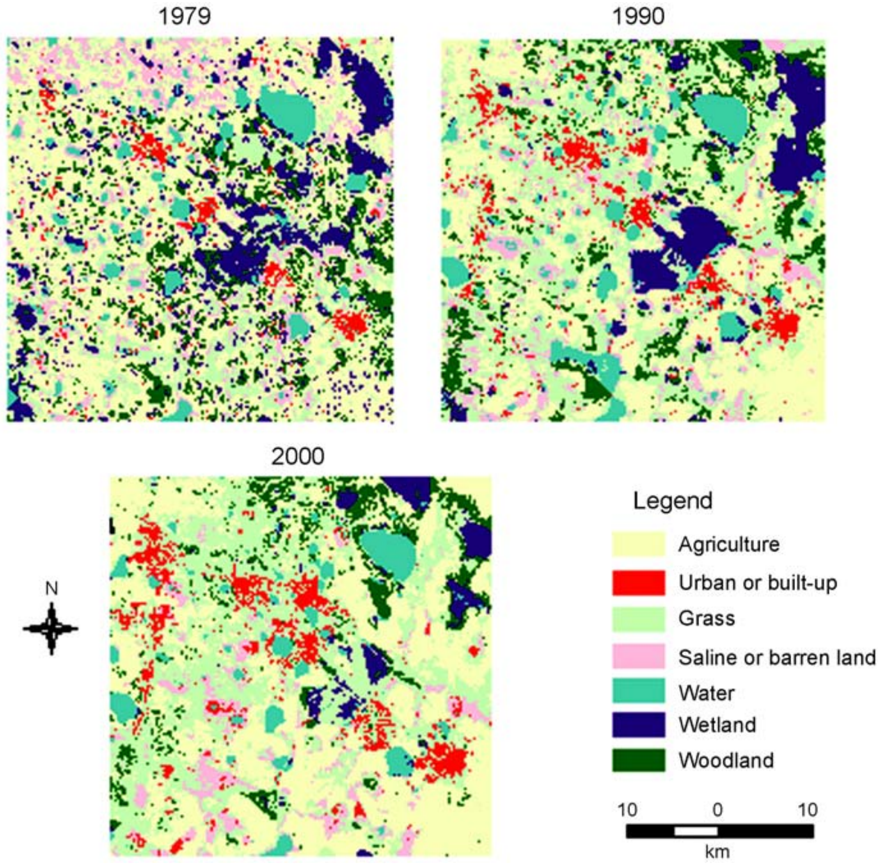

Fig. 2. Sequential maps used in the current landscape fragmentation status and its dynamics.

Table 4. Synoptic Landscape Characteristics of Daqing City, 2000

Classes	Area, km^2	No. of patches	Pct. of total area	Patch size, km^2/patch	Patch density patches/km^2
Agriculture	788.97	307	39.13	2.57	0.39
Urban or build-up	125.73	189	6.23	0.67	1.5
Grassland	664.89	394	32.97	1.69	0.59
Saline or barren land	114.53	178	5.68	0.64	1.55
Water	107.69	101	5.34	1.07	0.94
Wetland	70.73	69	3.51	1.03	0.98
Woodland	143.96	264	7.14	0.55	1.83

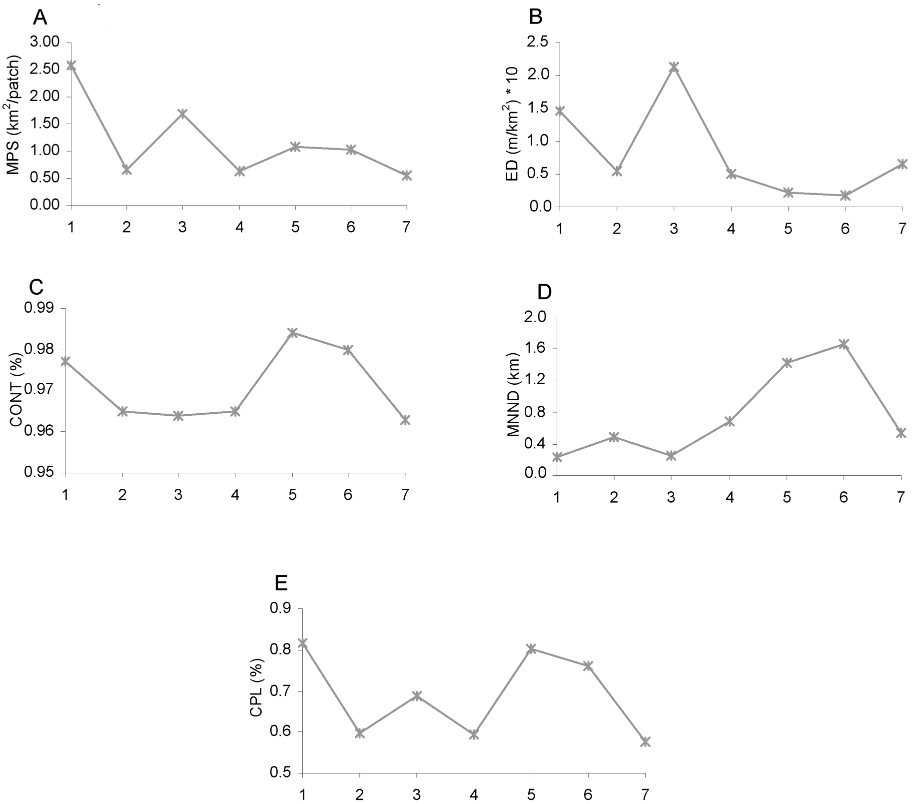

Fig. 3. Comparison of landscape fragmentation metrics between landscapes types. A. Mean patch size. B. Edge density. C. Contagion index. D. Mean nearest-neighbor distance. E. Core area percentage of landscape. Categories: 1 = agriculture; 2 = urban or built-up; 3 = grassland; 4 = saline; 5 = water; 6 = wetland; 7 = woodland.

There were large differences among the landscape types regarding the patch characteristics. The mean patch size (MPS) for the entire landscape is 1.34 km^2/patch, and the mean patch density (PD) is 0.74 patch/km^2. Similar to the landscape areas, agriculture and grass had the highest MPS values: 2.57 km^2/patch and 1.69 km^2/patch, respectively. It suggests that these two dominant classes are the least fragmented in Daqing City. Woodlands, saline, and urban areas have small MPSs and large PDs, indicating a high degree of fragmentation in these three landscape types.

Landscape fragmentation metrics of each landscape type in the study area are shown in Figure 3. As a patch shape index, the edge density (ED) has a significant ecological meaning when studying the landscape change, edge effect, and ecotone. Grass and agriculture have the highest ED, since both have an elongated edge. This is caused by human disturbance along the boundary; however, water and wetland, the typical natural landscape types, have the smallest ED with a relatively straight edge.

In further fragmentation analysis, we compared the contagion index (CONT), mean nearest-neighbor distance (MNND), and core area percent of landscape (CPL)

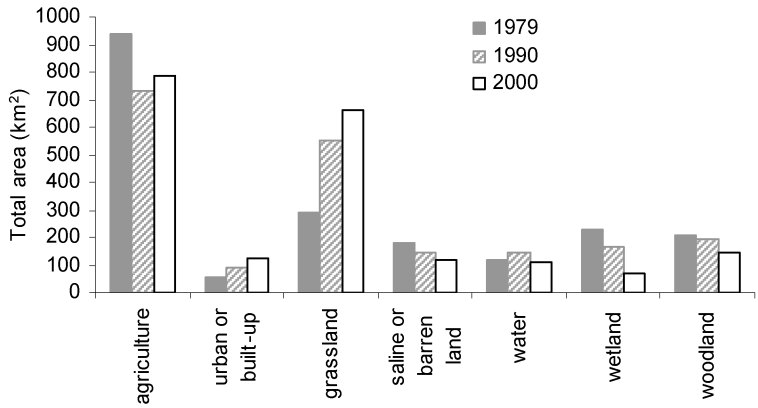

Fig. 4. Landscape area change in each class between 1979 and 2000.

within the landscape types, judging spatial characteristics for all landscape classes. Figure 3C suggests that all the classes have a similar CONT value (ranging from 0.96 to 0.98). Values for natural landscapes are higher than those for human-disturbed landscapes. The large CONTs in water and wetland also suggest the patches within these two landscapes are relatively large and are adjacent to each other. Other human-disturbed landscapes, such as agriculture and grassland, have large MPS values but small CONTs and MNNDs. It indicates that they are fragmented by the small polygons along their edges. Agriculture is clustered in the southeastern corner of the study area, and has the smallest MNND of all landscapes.

CPL shows a different trend from CONT and MNND. The water and wetland have large CPLs, but agriculture, the dominant human-disturbed landscape type, has the largest CPL. Obviously, the agriculture, water, and wetland categories have a larger interior environment than other landscape types. Such results also indicate that CPL is informative for fragmentation analysis. The calculation of its equation calculation involves both the edge area and the interior area of a patch.

The analyses for current fragmentation status (Fig. 3) show that different fragmentation metrics have completely different ecological meanings. Although all of these indices could be used to indicate the fragmentation degree in the landscape types, the MPS and ED focus on the patch characteristics of the patches, such as patch size, patch shape, and edge contour. CONT and MNND allow for a better understanding of the spatial distribution between patches. Concurrently, CPL regards the interior habitat as an undisturbed area, and it considers both patch shape and spatial characteristics.

Potential Fragmental Trend

Our study area has underwent tremendous change during the past 20 years. Figures 4 and 5 show that the landscape area and patch number changed from 1979 to 2000. The total changed area during 1979–1990 and 1990–2000 were 631.35 km^2 and 423.54 km^2, or 31.33% and 21.00% of the entire area, respectively. In the first eleven years (1979–1990), the most significant changes involved the expansion of the urban

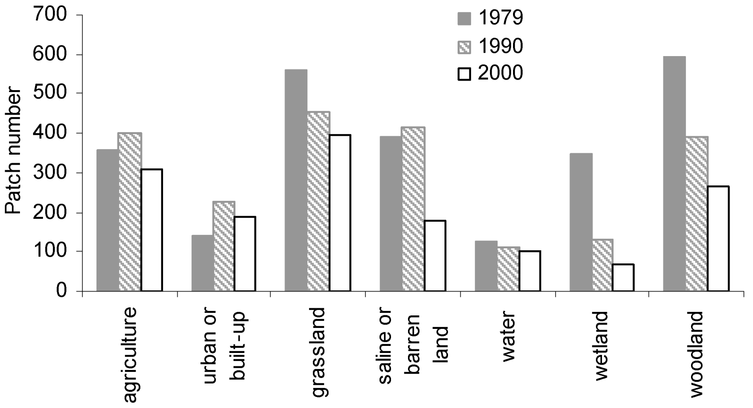

Fig. 5. Landscape patch number change in each class between 1979 and 2000.

and grass categories, and the decrease of agricultural land. This is primarily due to the "nibble" effect of the agriculture landscape on the fringes of the expanding urban area, and the development of new oil production fields. The continual construction of the oil fields in the first 11 years also damaged soil nutrients and soil structure, which caused a large area of agriculture to gradually convert to grassland. During the following 10 years (1990–2000), however, agriculture increased from 31.29% of the total area in 1990 to 39.13% in 2000. This increase is associated with the significant decrease of both wetland and woodland. Therefore, the major change during these two periods can be best summarized as: sprawl of the human-disturbed landscape and shrinkage of the natural landscape.

The changes of patch number, especially in the human-disturbed landscape, differed according to patch area. The patch number of the agriculture and urban categories increased in the beginning and decreased throughout the second period. The increasing patch number in agriculture and urban landscapes was caused by human disturbance. As human disturbance increased, small patches in urban area merged to become larger, continuous patches. The typical natural landscapes, wetland and woodland, decreased in both patch area and patch number. This result indicates a gradual shrinking and fragmentation of these natural landscapes. This shrinkage and fragmentation are found mostly in the wetland landscape in the northeastern part of the study area (Fig. 2).

A complete comparison of the landscape fragmentation dynamics through the fragmentation indices can be found in Table 5. Because water is always affected by precipitation in a particular year, we will not discuss the fragmentation process occurring in water. We will, however, study the fragmentation process based on the three following groups: (1) human-induced landscapes, including agriculture and urban or built-up areas; (2) semi-natural landscapes, including grassland and woodland; and (3) natural landscapes, including saline and wetland areas.

Although both agriculture and urban areas belong to human-induced landscapes, their landscape fragmentation indices showed a completely different, even opposite trend. The most significant difference between them is the ED: over the 20 years, the ED of agricultural landscapes kept decreasing while the ED of urban areas kept increasing. The CONT and CPL of agriculture increased continuously, while the

Table 5. Comparison of Landscape Fragmentation Metrics between 1979 and 2000

	MPS (km^2/patch)			ED (m/km^2)			CONT(%)			MNND(km)			CPL (%)		
Landscape types	79	90	00	79	90	00	79	90	00	79	90	00	79	90	0
Agriculture	3.37	1.76	2.57	0.27	0.17	0.14	96.00	97.10	97.70	0.20	0.29	0.24	71.15	74.51	81.76
Urban or build-up	0.39	0.40	0.67	0.02	0.05	0.05	96.50	95.80	96.50	1.13	0.72	0.50	58.36	53.31	59.65
Grassland	0.39	1.67	1.69	0.16	0.27	0.21	95.10	95.40	96.40	0.31	0.20	0.26	49.10	61.05	68.86
Saline or barren land	0.50	0.37	0.64	0.09	0.09	0.05	95.90	94.90	96.50	0.44	0.45	0.68	52.96	45.44	59.42
Water	0.98	1.31	1.07	0.03	0.03	0.02	98.20	98.40	98.40	1.24	1.08	1.43	77.68	80.34	80.42
Wetland	0.44	1.34	1.03	0.09	0.03	0.02	96.60	98.30	98.00	0.48	0.96	1.66	63.16	81.53	75.98
Woodland	0.37	0.52	0.55	0.10	0.09	0.07	95.80	96.00	96.30	0.37	0.38	0.53	52.82	56.90	55.75

urban CONT and CPL decreased in the first period and increased in the second. During 1990–2000, both agriculture and urban areas increased in the MPS and MNND.

A possible explanation for this difference is their different trend and manner in conversion during these 20 years. The urban area sprawled outward from a central core. This type of growth results in an increase in both MPS and ED, and a decrease in MNND. By contrast, the patch area of agriculture declined in the first period, which made both the MPS and ED decrease. Although agriculture increased during the second period, it did not expand outward from a central core, but rather, grew by gradually merging with small "spots" on its periphery. This makes the shape irregular at first, but becoming regular during the second period.

The MPS, CONT, and CPL of grassland showed an increasing trend, as did its patch area. The ED of grassland showed a significant increase in the first period, followed by a slight decline. The MNND, however, showed an opposite trend: a significant decline followed by a slight increase. Because most of the increasing grassland sprawled outward from its original location, it shows a different change trend with respect to ED and MNND.

The landscape fragmentation indices of wetland and woodland changed in the same manner, except for the MPS. This is caused by their difference in patch size and original shape. Because the forest is more fragmented than the wetland, small patches of forest are likely to be replaced directly by other types. After the small patches merge with other classes, larger woodland patches are fragmented into smaller pieces along the patch edge. This made both the CONT and MNND value increase during the second period. Unlike woodland, wetland was continuous in the beginning. During the second period, it was fragmented along its edge, and then the fragments were replaced by other landscapes. This caused the CONT first to increase and then to decrease.

CONCLUSION

Landscape spatial indices built on the classified vectors were useful in measuring various landscape patterns and changes with different ecological meanings. Based on the patch area, MPS and CPL were found effective in the identification and description of the shapes of landscape types. ED reveals the patch shape and its degree of fragmentation using the perimeter-area ratio of each class. CONT and MNND measure the degree of contiguity and homogeneity by revealing clumping trends and inter-patch distance. Generally, all of these fragmentation indices have great potential to provide useful information on the overall spatial landscape pattern, maintaining both statistical and ecological meaning. By incorporating more biophysical or social-economic factors, this spatial statistical method demonstrates its unique role in the quantitative analysis of landscape ecology.

The quantitative measures in this study showed different sensitivities to different fragmentation processes, such as perforation, nibble, or direct replacement. Although the landscape types have the same change trend in terms of patch area and patch number, they can have different values in the landscape fragmentation metrics. Consequently, one must choose a suitable set of landscape fragmentation metrics based on both the initial fragmentation and the fragmentation trend. These results can be used to further evaluate the fragmentation metrics.

Our current research only emphasizes the spatial fragmentation process caused by urban sprawl over a small region. A natural outgrowth of this study might be to predict the status of landscape fragmentation at some future date, utilizing a suitable spatial model. Furthermore, efforts to move toward obtaining a regional, national, or even global portrait of the urban landscape pattern would require work to develop a more sophisticated and technology and more practical methods for analysis of landscape patterns and their dynamics.

REFERENCES

Forman, R. T. T., and M. Godron, 1981, "Patches and Structural Components for a Landscape Ecology," *BioScience*, 31:733–740.

FRAGSTATS * ARC, 2004, *Fragstats Manual: Definition and Description of Class Metrics*, [www.innovativegis.com/products/fragstatsarc/manual/manclass.htm#Patch%20Size%20Standard%20Deviation%20-%20PSSD], accessed May 12, 2004.

Frohn, R. C. (Ed.), 1998, *Remote Sensing for Landscape Ecology. New Metric Indicators for Monitoring, Modeling, and Assessment of Ecosystems*, Boca Raton, Florida: Lewis Publishers, 10–19.

Fuller, D. O., 2001, "Forest Fragmentation in Loudoun County, Virginia, USA Evaluated with Multitemporal Landsat Imagery," *Landscape Ecology*, 16:627–642.

Giles, R. H. and M. K. Trani, 1999, "Key Elements of Landscape Pattern Measures," *Environmental Management*, 123:477–481.

Griffith, J. A., Trettin, C. C., and R. V. O'Neill, 2002, "A Landscape Ecology Approach to Assessing Development Impacts in the Tropics: A Geothermal Energy Example in Hawaii," *Singapore Journal of Tropical Geography*, 23:1–22.

Gustafson, E. J. and G. R. Parker, 1992, "Relationships between Landcover Proportion and Indices of Landscape Spatial Pattern," *Landscape Ecology*, 7:101–110.

Imbernon, J. and A. Branthomme, 2001, "Characterization of Landscape Patterns of Deforestation in Tropical Rain Forest," *International Journal of Remote Sensing*, 22: 1753–1765.

Jensen, J. R. (Ed.), 1996, *Introductory Digital Image Processing: A Remote Sensing Pperspective*, 2nd ed, Englewood Cliffs, NJ: Prentice Hall, 257–277.

Li, H. and J. F. Reynolds, 1993, "A New Contagion Index to Quantify Spatial Patterns of Landscapes," *Landscape Ecology*, 8:155–162.

Macleod, R. D. and R. G. Congalton, 1998, "A Quantitative Comparison of Change-Detection Algorithms for Monitoring Eelgrass from Remotely Sensed Data," *Photogrammetric Engineering & Remote Sensing*, 64:207–216.

Mas, J.-F., 1999, "Monitoring Land-Cover Changes: A Comparison of Change Detection Techniques," *International Journal of Remote Sensing*, 20:139–152.

Mcgarigal, K. and B. J. Marks, 1994. *FRAGSTATS: Spatial Pattern Analysis Program for Quantifying Landscape Structure*, version 2.0, Corvallis, OR: Oregon State University, Forest Science Department.

Metzger, J. P. and E. Muller, 1996, "Characterizing the Complexity of Landscape Boundaries by Remote sensing. *Landscape Ecology*, 11, 65–77.

Michener, W. K., Baerwald, T. J., Firth, P., Palmer, M. A., Rosenberger, J. L., Sandlin, E. A., and H. Zimmerman, 2001, "Defining and Unraveling Biocomplexity," *Bioscience,* 51:1018–1023.

Miller, A. B., Bryant, E. S., and R. W. Birnie, 1998, "An Analysis of Land Cover Changes in the Northern Forest of New England Using Multitemporal Landsat MSS Data," *International Journal of Remote Sensing*, 19:245–265.

Nelson, R. F, 1983, "Detecting Forest Canopy Change Due to Insect Activity Using Landsat MSS," *Photogrammetric Engineering & Remote Sensing*, 49:1303–1314.

O'Neill, R. V., Krummel, J. R., Gardner, R. H., Sugihara, G., Jackson, B., DeAngelis, D. L., Milne, B. T., Turner, M. G., Zygmunt, B., Christensen, S. W., Dale, V. H., and R. L. Graham, 1988, "Indices of Landscape Pattern," *Landscape Ecology*, 1:153–162.

Petit, C., Scudder, T., and E. Lambin, 2001, "Quantifying Processes of Land-Cover Change by Remote Sensing: Resettlement and Rapid Land-Cover Changes in Southeastern Zambia," *International Journal of Remote Sensing*, 22:3435–3456.

Quattrochi, D. A. and J. C. Luvall, 1999, "Thermal Infrared Remote Sensing for Analysis of Landscape Ecological Processes: Methods and Application," *Landscape Ecology*, 14:577–598.

Roy, P. S. and S. Tomar, 2001, "Landscape Cover Dynamics Pattern in Meghalaya," *International Journal of Remote Sensing*, 22:3813–3825.

Singh, A., 1989, "Digital Change Detection Techniques Using Remotely-Sensed Data," *International Journal of Remote Sensing*, 10:989–1003.

Statistical Bureau of Daqing, 2001, *Daqing Statistical Yearbook in 2001*. Harbin, China: Heilongjiang Statistical Bureau.

Tischendorf, L., 2001, "Can Landscape Indices Predict Ecological Processes Consistently?," *Landscape Ecology*, 16:235–254.

Turner, M. G., 1987, "Spatial Simulation of Landscape Changes in Georgia: A Comparison of Three Transition Models," *Landscape Ecology,* 1:29–36.

Turner, M. G., 1989, "Landscape Ecology: The Effects of Pattern on Process," *Annual Review of Ecology and Systematics*, 20:171–197.

Turner, M. G. and R. H. Gardner, 1990, "Quantitative Method in Landscape Ecology: An Introduction," *Ecological Studies*, 82:3–14.

UMASS, 2004, "Landscape Ecology Program," UMASS online [www.umass.edu/landeco/research/fragstats/documents/Conceptual%20Background/Background%20TOC.htm], accessed May 20, 2004.

Viedma, O. and J. Meliâ, 1999, "Global Change and Plant Diversity: Monitoring Temporal Changes in the Spatial Patterns of a Mediterranean Shrubland Using Landsat^{TM} Images," *Diversity & Distributions*, 5:275–293.

Yang, X. and C. P. Lo, 2002, "Using a Time Series of Satellite Imagery to Detect Land Use and Land Cover Changes in the Atlanta, Georgia Metropolitan Area," *International Journal Remote Sensing*, 23:1775–1798.

Zhao, Y., Liu, Z., and L. Xu, 1996, "Changes of Landscape Pattern and Its Influence on Environment in Dongling District, Shenyang City, China," *Journal of Environmental Sciences*, 8:166–173.

Zheng, D., Wallin, D. O., and Z. Hao, 1997, "Rates and Patterns of Landscape Change between 1972 and 1988 in the Changbai Mountain Area of China and North Korea," *Landscape Ecology*, 12:241–254.