Available online at www.sciencedirect.com
SCIENCE DIRECT®

Landscape and Urban Planning 69 (2004) 335–354

LANDSCAPE AND URBAN PLANNING

This article is also available online at:
www.elsevier.com/locate/landurbplan

Analyzing spatial restructuring of land use patterns in a fast growing region using remote sensing and GIS

Xia Li [a,b,*], Anthony Gar-On Yeh [c]

[a] School of Geography and Planning, Sun Yat-sen University, 135 West Xingang Road, Guangzhou 510275, PR China
[b] Guangzhou Institute of Geography, Guangzhou 510070, PR China
[c] Centre of Urban Planning and Environmental Management, The University of Hong Kong, Pokfulam Road, Hong Kong SAR, China

Received 22 May 2003; received in revised form 18 October 2003; accepted 20 October 2003

Abstract

This study analyzes urban expansion and spatial restructuring of land use patterns in the Pearl River Delta of south China by using remote sensing and GIS. The region has pioneered the nation in economic development and urbanization process. Tremendous land use changes have been witnessed since the economic reform in 1978. Land use changes over two time periods, 1988–1993 and 1993–1997, are analyzed to demonstrate how enforcing land use policies can influence the direction and magnitude of landscape change. The adoption of a market economy has resulted in the internal restructuring of agricultural land use from traditional paddy production to more diversified agricultural activities, such as growing cash crops, fruits and aquaculture. Spatial dependency of land use changes and variations of land development can be identified between the eastern development corridor and the western development corridor. The measurement of spatial patterns is accomplished by using the indicators of compactness index and entropy. This study provides new evidence with spatial details about the uneven land development in the Pearl River Delta.

Keywords: Remote sensing; GIS; Land use changes; Urban forms; Pearl River Delta

1. Introduction

There is a considerable interest in the study of land use changes and their related impacts on environment (Fung and LeDrew, 1987; Eastman and Fulk, 1993; Li and Yeh, 1998). Alig and Healy (1987) examined alternative measures of built-up areas and made long-term national projections of built-up areas under alternative assumptions from 1960 to 1980. The built-up land of the United States was expected to remain below 4% over the next two decades. Burnside et al. (2003) found that the amount of arable land actually increased in the South Downs, United Kingdom in 1971–1991. In contrast, China has much more pressure in preserving its land resources because of the rapid urbanization process. China's recent experience of urbanization is affected by globalization processes (Shen et al., 2002). The rapid urbanization process caused an unprecedented scale and rate of urban expansion in China over the last two decades (Seto and Kaufmann, 2003). It is expected the urban land in China is likely to expand at a very rapid rate because more than 50% of the population will be urban by 2030 according to a UN projection (United Nations, 2001).

* Corresponding author. Present address: School of Geography and Planning, Sun Yat-sen University, 135 West Xingang RD, Guangzhou 510275, PR China.
E-mail addresses: gplx@zsu.edu.cn, lixia@graduate.hku.hk (X. Li).

0169-2046/$20.00
doi:10.1016/j.landurbplan.2003.10.033

China has an inherent problem with a small amount of per-capita land resources far below the world's average (Chang and Kwok, 1990). Prior to 1978, the central government and provincial governments had strict control on land use planning. Growing grains was especially important in China because of its huge population. Peasants were not allowed to change land use types under the planning economy. However, through the 1980s, China gradually shifted from a planning economy to a market economy as the result of economic reform (Lin, 2001). Land and property sectors are under transformation as they begin to play important roles in the economy. The implementation of new land policy has created profound influences on the patterns of land use and land use conversion in China. This has resulted in intensified land use conflicts and rapid depletion of agricultural land resources in many fast growing cities. In 1994, the nation had to implement the 'Ordinance for the Protection of Primary Agricultural Land' (State Council, 1994) to control the over-heated land development. The direction and magnitude of land use changes have been affected by this land policy.

The Pearl River Delta has pioneered the nation in economic growth and urbanization processes since the economic reform in 1978. Unprecedented land use changes were witnessed in the region in the last two decades. Many land-related problems have been identified, including agricultural land loss, water pollution, soil erosion, and an increase in the magnitude and frequency of flooding in recent years (Yeh and Li, 1999). In particular, fast urban expansion has triggered the loss of a large amount of agricultural land in the Pearl River Delta. It is expected the similar land use problems will soon be found in other fast developing areas in China because of the rapid urbanization process.

Remote sensing data can be used to quantify the type, amount, and location of land use conversion (Fung and LeDrew, 1987; Eastman and Fulk, 1993; Jensen and Cowen, 1999). The measurement of urban forms can provide a more systematic analysis of the relationships between forms and processes. Urban scientists are concerned with the change in shape, size, and configuration of the built environment (Webster, 1995; Mesev et al., 1995). Urban morphology is a central element in creating urban sustainability. Banister et al. (1997) found that there are significant relationships principally between energy use in transport and physical characteristics of city, such as density, size, and amount of open space.

This study quantifies the amount and type of land use changes over two time periods, 1988–1993 and 1993–1997, in the Pearl River Delta. The general patterns in land use changes over the two time periods are important for examining the effect of the introduction of the 'Ordinance for the Protection of Primary Agricultural Land' in 1994. This will help to identify how enforcing land use policies can influence the direction and magnitude of landscape change. The internal variation of land use changes in the region are also analyzed for each time period. The study examines the relationship between land use change and a series of distance variables. It also compares the methods of using the compactness index and entropy for measuring the spatial patterns and the process of land development. The method should be applicable to other regions with rapid land use changes.

2. The study

The Pearl River Delta has an area of about 41,157 km^2. It used to be a major agricultural production base in south China before economic reform. The major agricultural land use types include the cultivation of paddy, sugar cane, banana and aquaculture. It experienced rapid economic growth and unprecedented landscape alteration in the last two decades. A large part of agricultural land has been used to satisfy the growing land demand from property development, processing industries and joint ventures. The problems confronted in the Pearl River Delta are not unique because they will soon be found in other rapidly developing regions in China. Similar land use problems can also be found in other fast developing countries (Lambin, 1997; Murdiyarso, 2000).

The region is situated in the central part of Guangdong province. The province has experienced significant economic growth in terms of gross domestic production and export trade output. According to statistical data (Guangdong's Statistical Bureau, 1997), the values of gross domestic production (GDP) and the output of export trade were US$ 98.7 (RMB 731.6) billion and US$ 59.3 billion, respectively in 1997. These figures were significantly larger than those of other provinces in China. The province attracted over half of

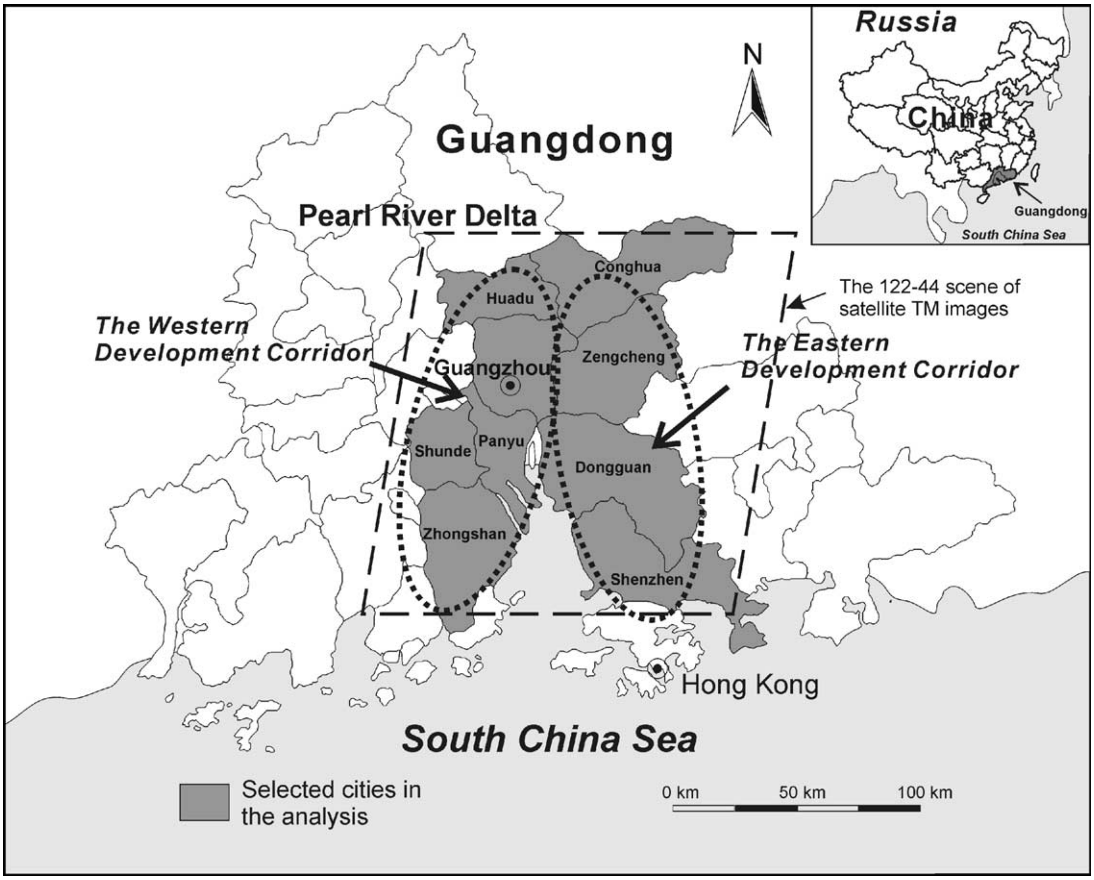

Fig. 1. The study area in the Pearl River Delta.

the nation's foreign investment for processing industries and joint ventures in the whole nation according to the statistical data. However, most of the achievement in the province is attributed to the Pearl River Delta.

The study area represents the core of the Pearl River Delta, including the city proper of Guangzhou, Huadu, Conghua, Zengcheng, Panyu, Shunde, Dongguan, Shenzhen and Zhongshan (Fig. 1). A city corresponds to an administration unit including the city proper and its administrative rural areas under the Chinese context. A single TM scene (No. 122-44 in the Reference System of China Remote Sensing Ground Station) can almost cover the whole part of the above nine cities. Only some minor corners of Conghua, Shenzhen and Zhongshan fall outside the scene. The use of a single scene makes the research technically simpler without involving image mosaic of multiple scenes. Moreover, the image can just cover the eastern and western development corridors of the delta. Table 1 lists the major economic data for the cities in the study area.

3. Methodology

3.1. Change detection

A change detection technique based on principal components analysis (PCA) is used to monitor land development in the Pearl River Delta. The techniques of land use change detection using remote sensing data have been developed for many years. A common problem for these techniques is the over-estimation of

Table 1
Economic data for the cities of the study area in 1997

Cities	Population	Area (km^2)	GDP (US$ millions)	Agricultural output (US$ millions)
Guangzhou	3,956,521	1,444	13,985.68	313.68
Huadu	580,725	961	1,335.59	145.47
Conghua	488,980	1,975	521.39	93.45
Zengcheng	758,533	1,741	1,375.60	230.97
Panyu	880,103	1,314	2,602.54	248.44
Shunde	1,040,301	802	2,699.91	207.71
Dongguan	1,471,220	2,465	3,548.21	361.20
Shenzhen	1,094,571	2,020	13,605.27	190.17
Zhongshan	1,283,625	1,683	2,660.23	277.51
Total	11,554,579	14,405	42,334.43	2,068.60
Total of the Pearl River Delta (%)	52	35	67	44
Total of Guangdong (%)	16	8	48	17

*Note: the above data come from Statistical Yearbook of Guangdong 1997; 100 US$ = 830.57 RMB.

the amount of land use changes (Fung and LeDrew, 1987). The technique of combining PCA with interactive supervised classification has been developed to overcome the over-estimation of the amount of change and reduce the possibilities of creating unlikely change classes (Li and Yeh, 1998). This technique was previously applied to Dongguan, one of the cities in the Pearl River Delta. This study extends the analysis by applying the technique to the whole Pearl River Delta. Moreover, this study takes a new focus on examining the process of spatial restructuring of land use patterns and identifying the temporal and internal variation in land development in the Pearl River Delta.

When two images are used to detect land use changes, the first step of the PCA method is to put the two images into a stack consisting of a total of $2n$ bands. PCA is then carried out to compress these original bands into a number of components. Interactive supervised classification of land use changes is carried out on the compressed components. As the compressed PCA image contains most of the information of the two original images, it should be possible to use the image for the classification of land use changes. It is found that the first four components contain more than 96% of the total variance and the other remaining components have little information about land use changes. Therefore, the first four components are used for change detection. The signature of each class is created by interactive supervised training.

The training samples for supervised classification are identified on the compressed PCA image. First, the two original images are displayed as standard false-color composites. The PCA image is also displayed and live linked to these two original images using the ERDAS IMAGINE software.[1] Then training sites are picked up conveniently on the PCA image using a cursor when these images are live linked. The two original images are just used to assist the identification of training samples in the PCA image. Actually, the training only needs to pick up 'from-to' change classes which are present in the PCA image by comparing these three linked images. Decomposing can be later carried out to obtain land use classes of the two original images. Maximum likelihood classification is performed on the PCA image, producing a thematic image with the information of land use change.

This method was applied to the 1988–1993 and 1993–1997 images to obtain land use change in these two time periods. Landsat TM images in 10 December 1988, 24 December 1993 and 29 August 1997 were used for the classification. It may be better to use the images of the same season for comparison. However, the winter image in 1997 was unavailable. The sequential images can facilitate the analysis of land development processes and highlight the spatial restructuring of land use patterns in 1988–1993 and

[1] ERDAS IMAGINE is a trademark of ERDAS, Inc., Atlanta, GA.

1993–1997. The classification scheme includes nine types of land use—cropland, orchard, forest, built-up areas, development sites, idle land, bare soil, fishpond and water. The built-up areas and the development sites constitute the urban land in the region. Land use conversion matrixes are built to indicate the amounts of land use changes in these periods. Some local experience is required for identifying the training samples. Development sites are a common type of land use in the region. They are in a very bright tone in standard false-color composite images. The idle land is referred to the uncompleted development sites which remain in the same tone longer than the period of 4–5 years. The period is determined according to local practice. Bare soils also have the bright tone, but not as bright as development sites. They are usually situated in mountainous areas.

The accuracy assessment was carried out with reference to land use maps and field investigation. A total of 1000 points were selected to calculate the classification accuracy. GPS were used to assist in the identification of field data on images. The κ coefficient is 0.83, and the total accuracy is 0.87 according to the accuracy assessment.

3.2. Spatial statistics

The next step of this study is to measure the geometry of land development and land use patterns by providing detailed spatial information for land use planning. GIS provides a useful tool to implement the morphological approach with powerful functions and convenient modeling environments. Two indicators, compactness index and entropy, are proposed to facilitate the measurement of urban morphology. The measurement is carried out on classified satellite Landsat TM images by using GIS analysis.

The compactness of land development is estimated according to the average comparison between the perimeter of each developed cluster and that of a circle which has the same area. This comparison is useful for standardizing the data. The index is calculated by using the following equation:

$$\mathrm{CI} = \frac{\sum_j P_j/p_j}{n} = \frac{\sum_j 2\sqrt{(S_j/\pi)}/p_j}{n} \tag{1}$$

where CI is the value of the compactness index, S_j and p_j are the area and perimeter of developed cluster (polygon) j, P_i is the perimeter of a circle with the area of S_j, and n is the total number of clusters. It is obvious that the land development with average narrow shapes will have low values of the index.

The index may be biased towards the large number of small compact patches rather than the large complex ones. The bias can be minimized by normalizing the index using the total number of clusters. The revised compactness index is given as follows:

$$\mathrm{CI}' = \frac{CI}{n} = \frac{\sum_j 2\sqrt{S_j/\pi}/p_j}{n^2} \tag{2}$$

It is convenient to calculate the index because the total area and perimeter of developed clusters can be automatically obtained by using GIS functions, e.g. the *Zonalgeometry* function in ARC/INFO[2] GRID. The total number of clusters can also be conveniently counted in GIS, such as the *Tables* of ARC/INFO. The compactness index can determine whether land development is compact or not. The larger the value of CI is, the more compact the development.

A more sophisticated indicator to measure urban morphology is based on the concept of entropy. The method has advantages in reflecting the orientation and configuration of spatial patterns because it can easily incorporate spatial variables from GIS in the calculation. The measurement is directly carried out within GIS to facilitate the convenient access to GIS spatial databases. It is based on entropy theory, which was originally developed for the measurement of information. Entropy can be related to the concentration or dispersion of a phenomenon. Shannon's entropy (E) can measure the degree of spatial concentration and dispersion exhibited by a geographical variable (x_i). The relative entropy is calculated by using the following equation (Theil, 1967; Thomas, 1981):

$$E = \sum_{i=1}^{n} p_i \log(1/p_i)/\log(n) \tag{3}$$

where $p_i = x_i/\sum_{i=1}^{n} x_i$ and x_i is the observed value in the ith zone in a total of n zones. In this study, the observed value is the area of urban land in each buffer zone. The entropy value ranges from 0 to 1. If the distribution is maximally concentrated in one region,

[2] ARC/INFO is a trademark of Environmental Systems Research Institute, Inc., Redlands, CA.

the lowest value, 0, will be obtained. Conversely, an evenly dispersed distribution across space will give a maximum value of 1.

The buffer zones are created according to the distances to urban centers and roads. This can incorporate spatial variables from GIS to reflect the orientation and configuration of land development. Each buffer zone has a width of 1 km. The amount of urban land in each buffer zone is summed as the spatial variable x_i for the Eq. (3). The entropy method is convenient and effective in identifying whether the patterns of land development are dispersed or compact with regard to centers and roads. Other methods, such as the fractal dimension, cannot identify the differences in orientation and configuration (Shen, 2002).

3.3. Regression analysis

A further aspect of this study is to examine the driving forces that are responsible for land use restructuring. Regression analysis can be applied to examine the relationships between land use changes and spatial variables. Land use changes reflect location behaviors and preferences. The spatial dependency of land use changes can be analyzed by the integration of remote sensing and GIS. In this study, we hypothesize that the probabilities of land use changes are a function of three spatial variables: distance to built-up areas; distance to roads; and distance to Hong Kong. Regression analysis can be undertaken to verify this hypothesis. The analysis is important for a variety of urban models which require selecting appropriate spatial variables for the modeling process. The selection of spatial variables critically influences the performance of urban modeling.

The conversion probability from agricultural land to urban land may be in a distance decay function. Regression analysis can be carried out to establish the relationship. Buffer zones around urban centers are created to calculate the density of agricultural land loss. The relationship between the density of agricultural land loss and the distance to urban centers is expressed by the following equation:

$$\mathrm{DEN}_{\mathrm{agloss}}(x) = \begin{cases} a_1 + b_1 x & (x \le c) \\ a_2\,\mathrm{e}^{-b_2 x} & (x > c) \end{cases} \quad (4)$$

where $\mathrm{DEN}_{\mathrm{agloss}}$ is the density of agricultural land loss in the buffer zone, a_1, b_1, a_2, b_2 and c are coefficients.

4. The analysis and results

4.1. Land use change between 1988 and 1993

The first period of 1988–1993 witnessed rapid land use changes and massive agricultural land loss in the region according to the conversion matrix from the classification (Table 2). The proportion of land that underwent changes was as high as 12.7% among the total land. There were three major types of land use changes—conversion from agricultural land (cropland, orchard, and fishpond) to built-up areas and development sites, conversion from cropland to fishpond, and conversion from cropland to orchard. These three types of land use changes constituted about 88.0% of the total changes in the Pearl River Delta in 1988–1993. Agricultural land loss has the largest figure among different types of changes during the period. The study area lost 98,418 h of agricultural land, which was 7.7% of the total land or 13.1% of the total agricultural land. Smaller areas underwent changes from cropland to bare soil, development sites to idle land or built-up areas, and water to development sites.

Spatial variations in land use changes were identified between cities. The cities experiencing rapid economic development usually have large amounts of land use changes. Shenzhen and Dongguan, situated in the eastern part of the delta with a closer distance to Hong Kong, had the largest percentages of land use changes—21.2 and 16.0% of the total land, respectively (Fig. 2A). These two cities have fast growth of GDP according to the statistical yearbooks. Zhongshan, Panyu and Shunde, which are in the western development corridor, had smaller percentages of land use changes, but the changes still reached as high as 12.9, 13.4 and 11.8% of their total land, respectively. The city proper of Guangzhou is the provincial capital where land development was relatively strictly controlled, with about 11.6% of land use changes. Conghua and Zengcheng, which are mountainous cities in the northern part of the delta, had the lowest amounts of land use changes—7.3 and 9.2%, respectively.

Shenzhen and Dongguan had unusually high percentages of agricultural land loss—26.3 and 18.8% of their total agricultural land, respectively. The amounts of land loss in other cities were also high, with all above 9.2% of their total agricultural land (Fig. 3A).

Table 2
Land use conversion matrix in the Pearl River Delta in 1988–1993 (in ha)

1988	1993									1988 total
	Crop	Orch	Forest	Built	Devt	Idle	Bare	Pond	Water	
Crop	283,504 (72.8%)	11,850 (3.0%)		19,836 (5.1%)	31,882 (8.2%)		5,999 (1.5%)	36,126 (9.3%)		389,196 (100%)
Orch		195,298 (82.8%)		24,066 (10.2%)	16,637 (7.0%)					236,001 (100%)
Forest			352,094 (100%)							352,094 (100%)
Built				82,630 (100%)						82,630 (100%)
Devt				1,077 (12.2%)		11,046 (87.8%)				12,123 (100%)
Idle[a]										0 (100%)
Bare										0 (100%)
Pond								124,364 (100%)		124,364 (100%)
Water					3,711 (5.0%)				70,227 (95.0%)	73,937 (100%)
1993 total	283,504 (100%)	207,148 (100%)	352,094 (100%)	127,609 (100%)	52,230 (100%)	11,045 (100%)	5,999 (100%)	160,490 (100%)	70,227 (100%)	1,270,346

The figures in parentheses refers to proportion of 1988 total for that land use type. *Abbreviations*: Crop, cropland; Orch, orchard; Forest, forest; Built, built-up areas; Devt, development sites; Idle, idle land; Bare, bare soil; Pond, fishpond; Water, water.

[a] Idle land in 1988 cannot be identified unless an additional image 4–5 years before 1988 is used. Therefore, some development sites in 1988 may actually belong to idle land. However, this type of land use was in a very small percentage since a lot of land development only took place in the early 1990s.

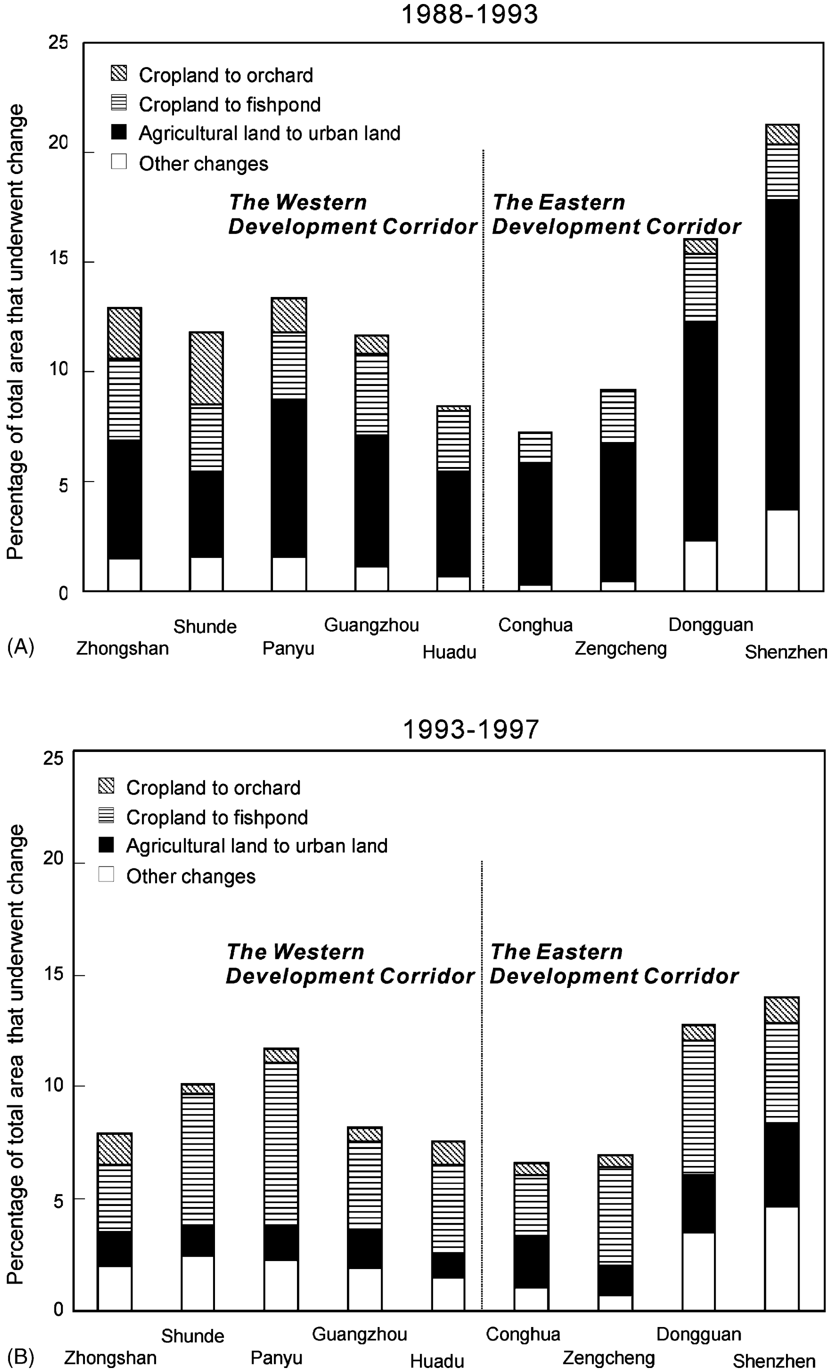

Fig. 2. Major components of land use changes in the Pearl River Delta in 1988–1993 and 1993–1997 by cities.

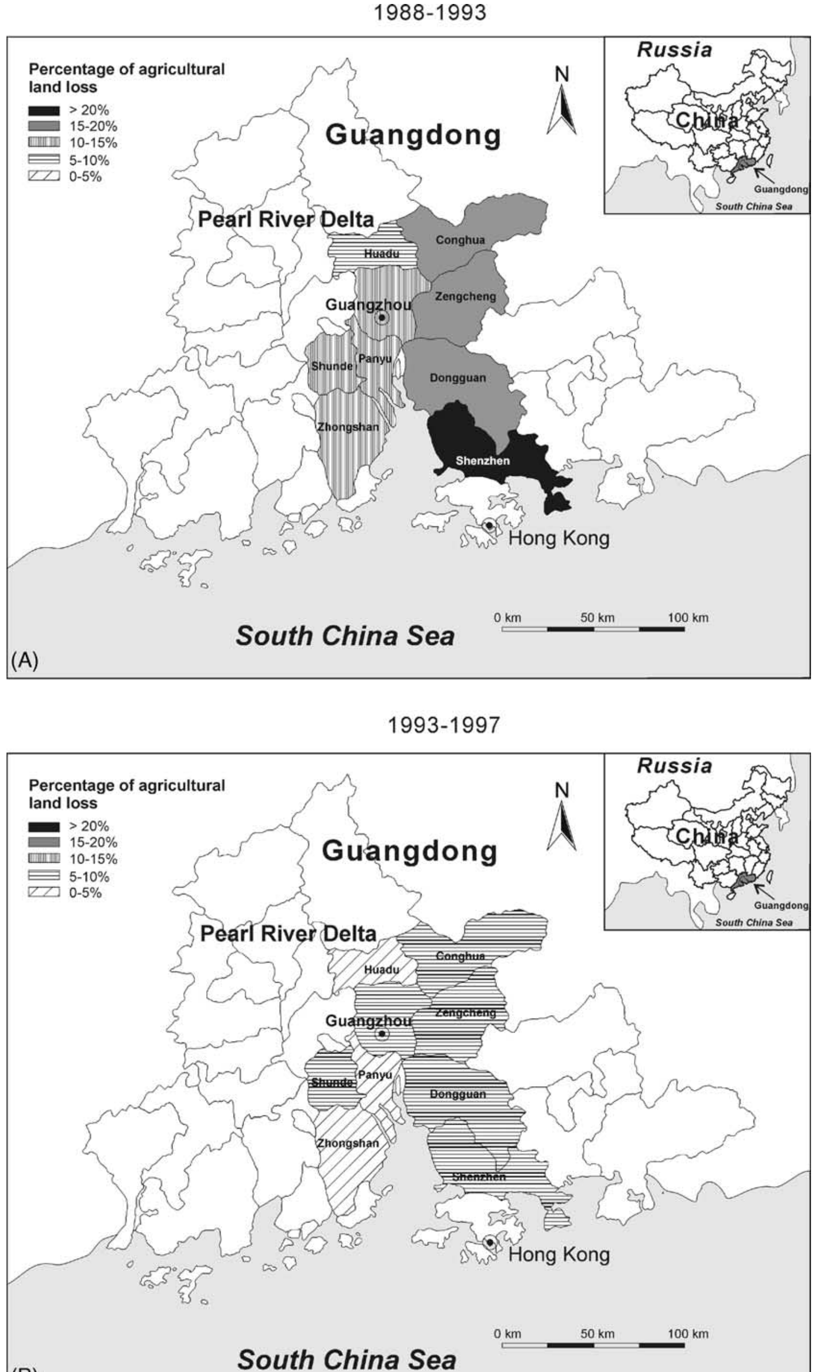

Fig. 3. Spatio-temporal patterns of agricultural land loss in the Pearl River Delta in 1988–1993 and 1993–1997.

Table 3
Land use conversion matrix in the Pearl River Delta in 1993–1997 (in ha)

1993	1997									1993 total
	Crop	Orch	Forest	Built	Devt	Idle	Bare	Pond	Water	
Crop	181,009 (63.9%)	9,467 (3.3%)		8,225 (2.9%)	5,076 (1.8%)		13,325 (4.7%)	66,402 (23.4%)		283,504 (100%)
Orch		196,080 (94.7%)		4,222 (2.0%)	6,846 (3.3%)					207,148 (100%)
Forest			329,816 (93.7%)				22,278 (6.3%)			352,094 (100%)
Built				127,609 (100%)						127,609 (100%)
Devt				3,996 (7.7%)		48,233 (92.3%)				52,230 (100%)
Idle						11,046 (100%)				11,046 (100%)
Bare							5,999 (100%)			5,999 (100%)
Pond								160,490 (100%)		160,490 (100%)
Water					10,554 (15.0%)				59,673 (85.0%)	70,227 (100%)
1997 total	181,009 (100%)	205,547 (100%)	329,816 (100%)	144,052 (100%)	22,476 (100%)	59,279 (100%)	41,602 (100%)	226,892 (100%)	59,673 (100%)	1,270,346

The figures in parentheses refers to proportion of 1993 total for that land use type. Abbreviations are same as in Table 1.

4.2. Land use change between 1993 and 1997

In the second period of 1993–1997, 11.8% of the land was under changes, but agricultural land loss significantly decreased compared to that of the first period. The region had a total of 37,694 ha of agricultural land loss in 1993–1997, which was 3.0% of the total land or 5.8% of the total agricultural land. The amount of land lost in 1993–1997 greatly reduced to approximately 38.3% of that in 1988–1993. However, agricultural land loss did not stop completely, but took place at a smaller scale, compared with that in the property boom period of 1992–1993.

The reason is the implementation of the 'Ordinance for the Protection of Primary Agricultural Land' (State Council, 1994) in 1994. The two cities, Shenzhen and Dongguan still had the largest percentages of land use changes, which were 14.0 and 12.8% of their total land, respectively (Fig. 2B and Table 3). The spatial patterns and the changes of agricultural land loss are shown in Fig. 3B.

A particular phenomenon was the existence of a large amount of idle land in the whole region during the period of 1993–1997. Only a small proportion of the development sites in the early 1990s was further developed into built-up areas while the rest was left idle. The conversion of excessive agricultural land was obvious because of the widespread existence of idle development sites.

4.3. Spatial patterns of urban land use

Fig. 4 shows that urban land is mainly located along major roads in the Pearl River Delta, highlighting

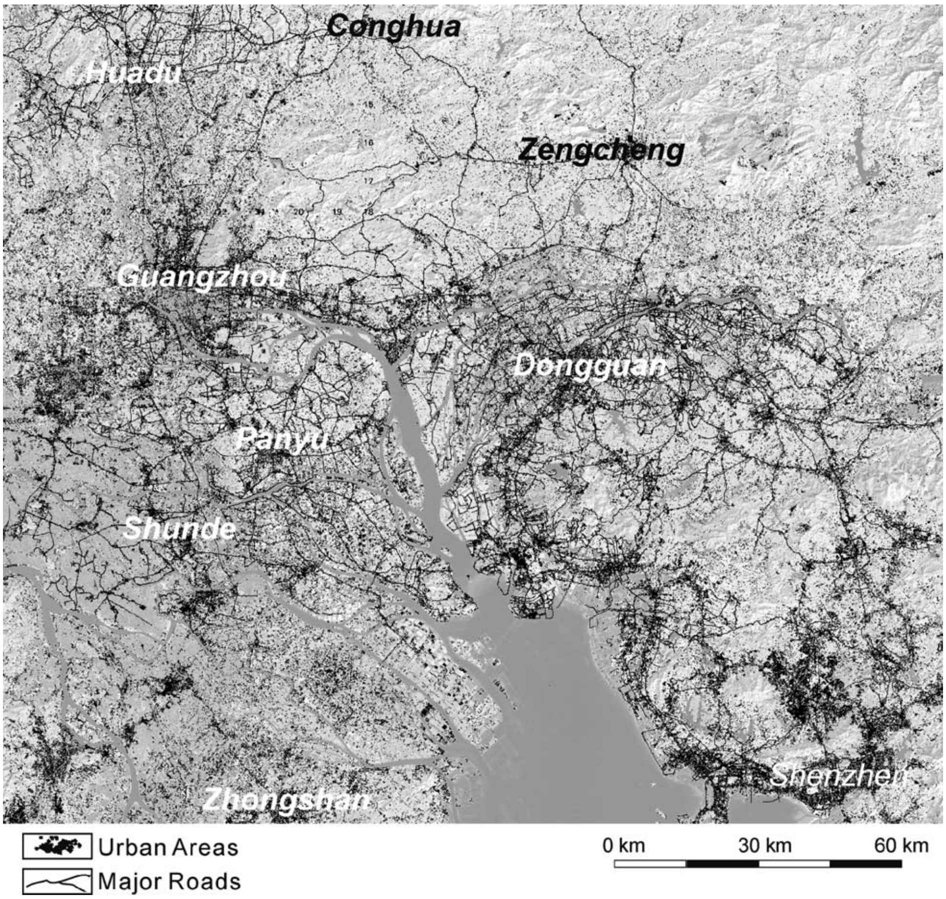

Fig. 4. Urban sprawl along roads in the Pearl River Delta from the 1997 TM image.

dispersed development patterns. The spatio-temporal variations of agricultural land loss can be identified at the aggregated level by cities (Fig. 3). This can help urban planners identify which cities or towns have severe land use problems. There were higher percentages of agricultural land loss in the cities in the eastern development corridor of the Pearl River Delta during 1988–1993 and 1993–1997.

The first measurement of urban sprawl was carried out using the compactness index according to Eq. (2). The cities (e.g. Dongguan) in the eastern development corridor all have lower values of the compactness index (Fig. 5). This indicates that these cities are associated with the most dispersed development patterns. However, the cities of Huadu, Shunde and Panyu in the western development corridor had higher values of the index, which indicate relatively concentrated development patterns. The reason is that the cities in the eastern development corridor are closer to Hong Kong. The spatial patterns are more subject to the influences of investment from Hong Kong. Local governments are very eager to attract investment by relaxing control on land use development. This has caused dispersed development patterns in the eastern development corridor. The index is useful for land use planning because it can quantitatively identify which cities or towns have more compact development forms.

Fig. 6 shows the changes of entropy values for each city in 1988, 1993 and 1997. A larger entropy value is associated with more dispersed development. The cities in the eastern development corridor are more dispersed than those in the western development corridor according to the entropy analysis. This coincides with the analysis using the compactness index.

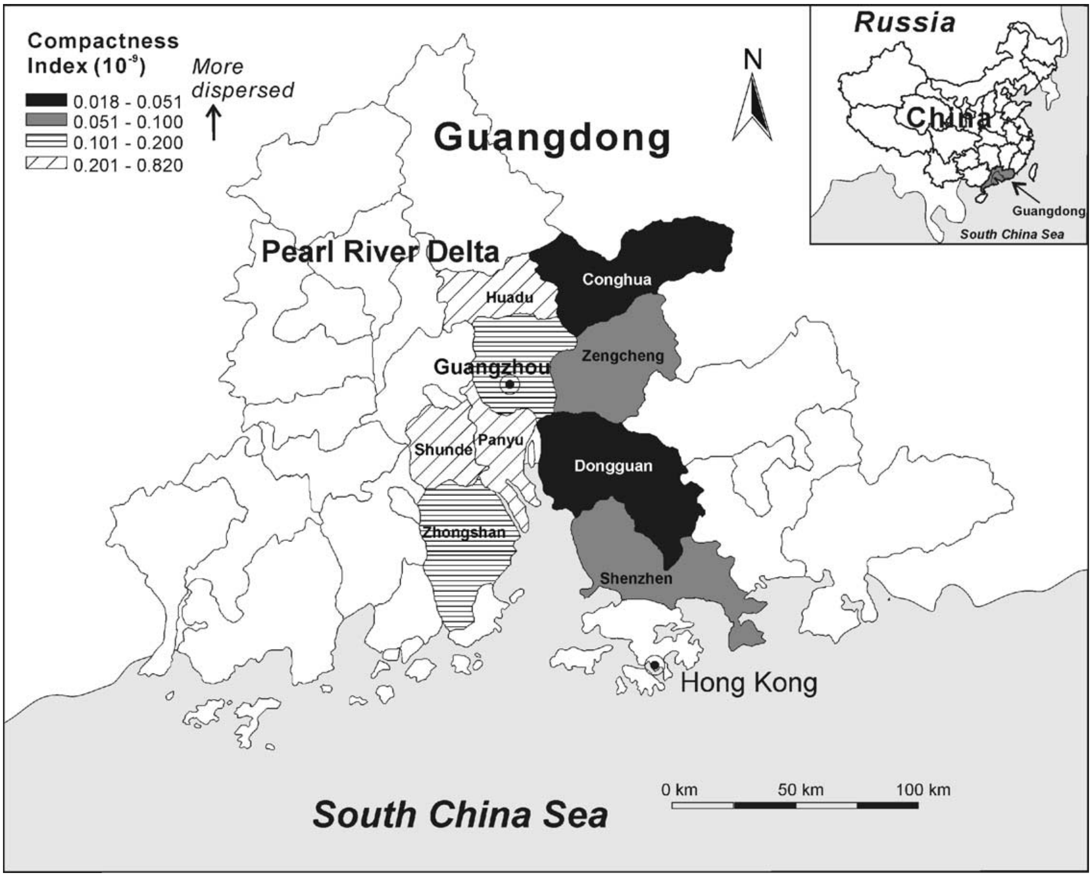

Fig. 5. The compactness of land development in the cities of the Pearl River Delta in 1988–1997.

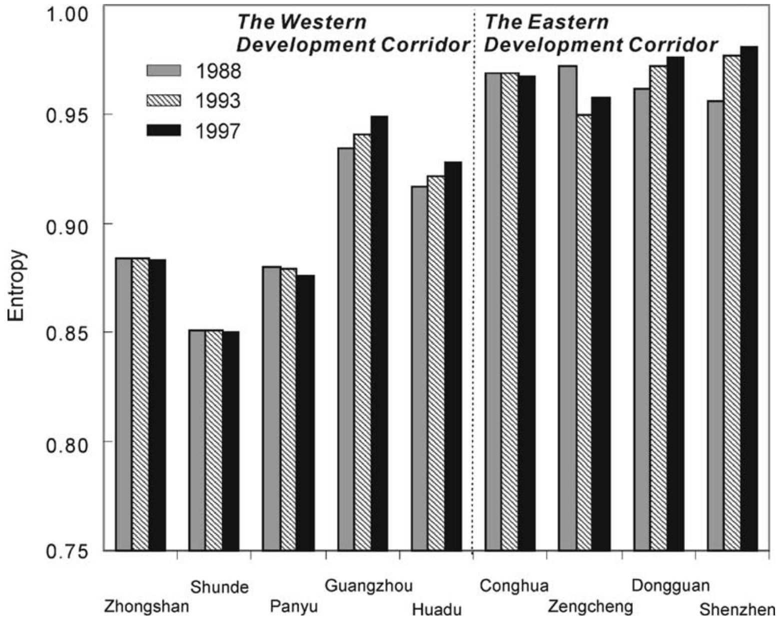

Fig. 6. Measuring urban sprawl in the Pearl River Delta in 1988, 1993 and 1997 by entropy.

The figure clearly reveals the differences of urban expansion process among the cities in the Pearl River Delta. The larger cities, such as Shenzhen, Dongguan and Guangzhou tended to be more dispersed as highlighted by the increase of entropy values during the period of 1988–1997. Shenzhen had the greatest increase in entropy over this period. The sprawl patterns of the city can be confirmed visually from satellite images.

4.4. Spatial dependency of land use patterns

The analysis indicates a strong spatial dependency of land use changes. Fig. 7 shows the relationships between the major types of land use changes and the average distance to urban centers. There is a strong distance decay function affecting the conversion probability from agricultural land use to urban land use. It is obvious that a high proportion of land use changes occurs near urban areas. The relationship is stronger for the period of 1988–1993 than for the period of 1993–1997.

Table 4 shows the regression results for the spatial dependency of agricultural land loss by cities according to Eq. (4). The average R^2 is 0.86 from the regression analysis. The relationship consists of two parts: (1) The density of agricultural land loss rapidly reaches the peak in a short distance from urban centers; (2) Then it declines in an exponential decay function. The first part of the relationship is controlled by the parameters of a_1 and b_1, and the second part is controlled by the parameters of a_2 and b_2. Difference settings of these values reflect the variations of land development by cities.

It is found that the patterns of agricultural land loss are quite different among these cities as can be re-

Table 4
The relationships between the percentages of agricultural land loss and the distance to urban centers

	a_1	b_1	a_2	b_2	c (km)
Western development corridor					
Zhongshan	0.516	0.387	2.163	0.073	2.6
Shunde	−0.124	0.165	0.486	0.018	4.8
Panyu	−0.631	2.636	2.389	0.071	2.6
Guangzhou	−0.022	0.046	2.223	0.045	19.2
Huadu	−0.261	0.437	1.176	0.027	2.4
Eastern development corridor					
Conghua	−0.325	0.986	0.732	0.017	1.7
Zengcheng	−1.731	8.376	7.212	0.733	1.5
Dongguan	−1.672	1.821	11.520	0.910	3.8
Shenzhen	−1.142	0.658	14.777	0.336	15.8

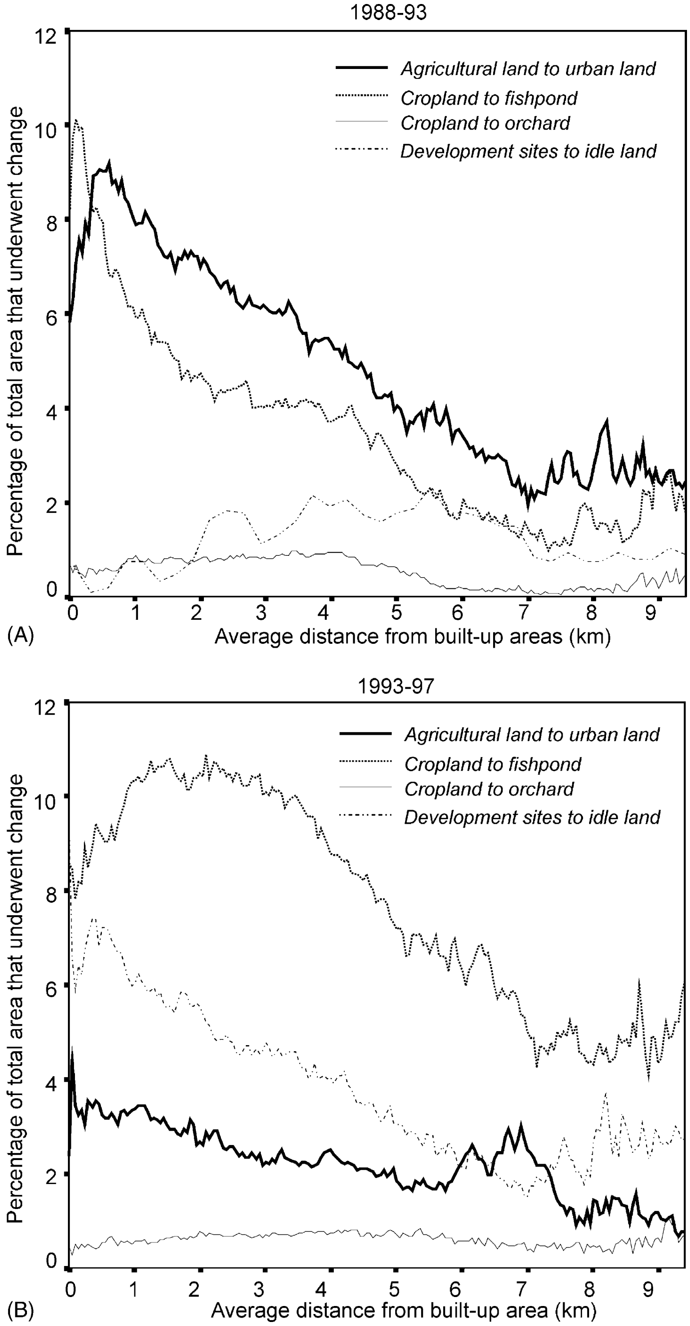

Fig. 7. Spatial dependency of land use change from urban centers over two time periods: (A) 1988–1993 and (B) 1993–1997.

flected by these parameter values. The parameter of a_1 is the intercept for the first part of the relationship. However, it only has virtual meanings since the urban (town) centers have not got agricultural land loss. The parameter of b_1 indicates how rapidly the density increases to the peak from the centers to the outwards. Larger cities usually have the lower values of the increase, such as Guangzhou (0.046). The small cities have the higher values of the increase, such as Zhengcheng (8.376).

In the second part of the relationship, the value of a_2 corresponds to the maximum density of agricultural land loss. It is obvious that the cities in the eastern development corridor have the higher densities of agricultural land loss. For example, the value of a_2 are 11.520 and 14.777 for Dongguan and Shenzhen, respectively, but they become only 0.486 and 1.176 for Shunde and Huadu, respectively. The parameter of b_2 indicates how fast the density decreases from the peak to the outwards. Larger cities also have the lower values of the decrease, such as Guangzhou (0.045). The small cities have the higher values of the decrease, such as Zhengcheng (0.733).

The density of agricultural land loss decreases away from existing built-up areas although there are still some small peaks in the outer areas. This indicates that agricultural land near existing built-up areas is more likely to be converted into urban land uses. The small peaks reflect the trends of urban sprawl and chaotic development patterns.

The conversion probability from cropland into fishpond is also in a distance decay function from urban centers. This means that agricultural land near urban areas is more likely to be converted into fishpond for better economic returns. The conversion is much more significant in the period of 1993–1997. The figure also shows that the conversion probability from development sites to idle land is in a distance decay function only in the period of 1993–1997. No patterns are found for the change from cropland to orchard.

Fig. 8 shows the relationships between major types of land use changes and the proximity to roads. The distance decay function for development probability only exists within a very short distance of about 2–3 km. The conversion probability from development sites to idle land also fits distance decay functions in both periods. However, the conversion probability from cropland to fishpond is not in a distance decay function. It is because the distribution of fishpond from roads is in a heterogeneous pattern in the region. This category of change does not fit the distance decay function from roads.

Fig. 9 is the patterns of land use changes associated with the proximity to Hong Kong. The density of land loss in 1988–1993 obviously fits the distance decay function as more land loss took place in the locations near Hong Kong. The conversion probability from development sites to idle land also roughly fits distance decay functions in both periods. Other categories of changes do not fit distance decay functions. It is because investment from Hong Kong only influences property development. The patterns of land use changes associated with the proximity to Guangzhou should be the same with those associated wit the proximity to Hong Kong. It is because the distance to Guangzhou just reverses that to Hong Kong.

5. Discussion

Although various studies have been carried out to explore the methods of measuring urban forms, there is no consensus on which indicator is more appropriate in capturing the characteristics of urban sprawl. These methods, which are just developed in the context of image analysis or fractal theory (Batty and Longley, 1994; Webster, 1995), may have some limitations. For example, Shen (2002) finds that fractal dimension cannot capture orientation and configuration of a physical urban form. Different urban forms may have virtually the same fractal dimension value because of its aggregate effects. The proposed indicators, compactness index and entropy, seem to be effective in discriminating development patterns according to this study.

Interesting results were obtained by differentiating the land development patterns among cities in the Pearl River Delta. Substantial deviation of land development patterns exist because of the variations in government behavior and geographical properties. Although the policies from the central government are the same, local governments usually implement them in a modified way to get more benefits. They may looser the controls on land development to have a better competitive position to attract foreign investment. This usually results in the excessive loss of agricultural land and serious fragmentation of land use. The cities with good

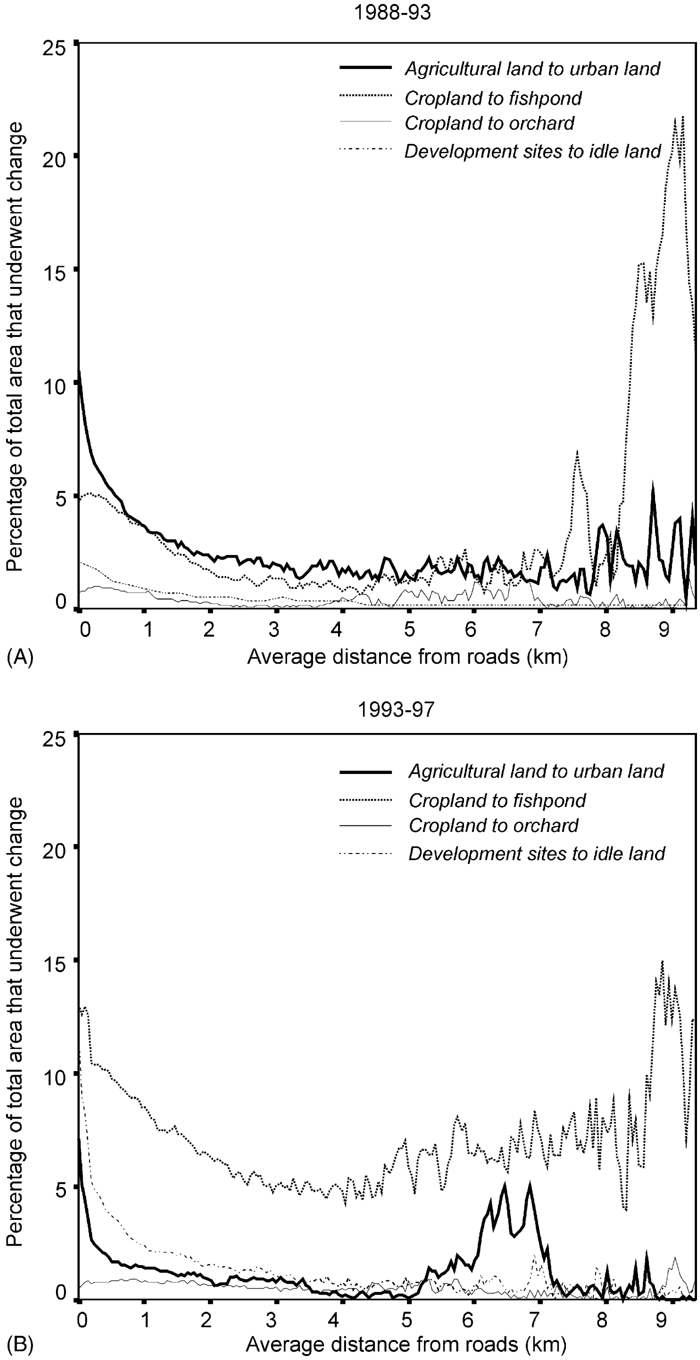

Fig. 8. Spatial dependency of land use change from roads over two time periods: (A) 1988–1993 and (B) 1993–1997.

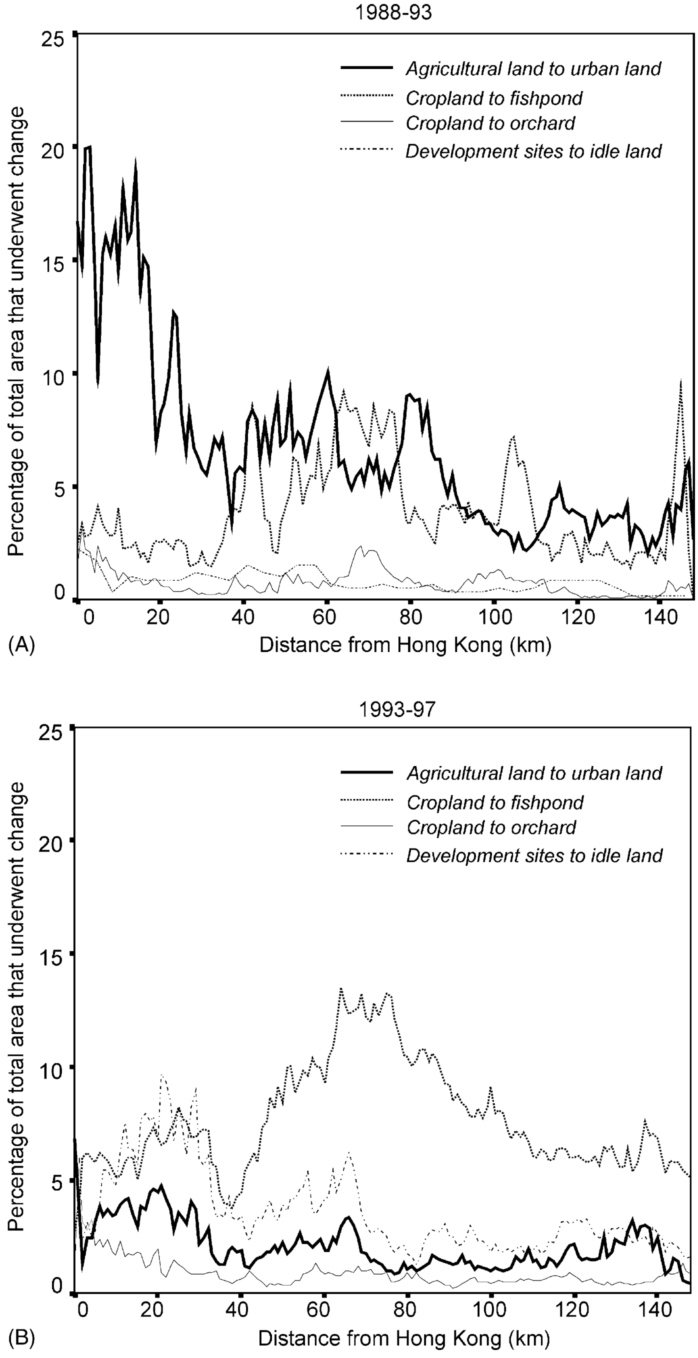

Fig. 9. Spatial dependency of land use change from Hong Kong over two time periods: (A) 1988–1993 and (B) 1993–1997.

accessibility may have higher probabilities of losing agricultural land. Spatial disparity of land use can be identified from satellite images. There was much fluctuation of land use changes and agricultural land loss in the Pearl River Delta in the two periods.

Since 1994, the conversion of agricultural land into urban land has been under strict control because the central government became concerned about the problem of excessive land loss. Agricultural land loss was significantly reduced in the period of 1993–1997. The intervention had the effect of alleviating the severe encroachment on agricultural land by adopting top-down policies. The monitoring indicates that the major components of land use changes in this period were different from those in the first period. The different patterns of land use changes had reflected the change of national development strategies and policies.

The spatial patterns of land development in the eastern corridor are not in compact forms according to the measurement from the compact index and the entropy indicator. This has raised a lot of land use conflicts and related environmental issues. The promotion of compact development is an important way to save land resources and avoid a series of environmental problems. It can help to reduce the consumption of agricultural land during the urbanization process. Otherwise severe environmental consequences may occur in this densely populated region with the depletion of its limited agricultural land assets. This is hazardous to both agricultural and ecological systems. The study is useful for providing detailed spatial information for local planners to tackle land use problems.

Bruijn (1994) indicates that the factors influencing land suitability and hence development probabilities often have a strong ‘distance decay function’. Usually, the influences are not in a linear form. For example, the influences from a road or existing built-up areas diminish quickly for land development. Other empirical models include the applications of fractal theory to explain the distributions of various land use types by means of an inverse power function (Batty and Longley, 1994). We have observed such function in the Pearl River Delta by using remote sensing data. However, the parameter values of the function can fluctuate from place to place because of different development patterns. There is a major difference for the parameter values between the western development corridor and the eastern development corridor.

Land use restructuring has taken place in response to economic development. Internal structural changes of agricultural land use can be observed from classified remote sensing imagery. There was a significant decrease in the amounts of paddy fields and other types of agricultural land use in the early 1990s. Many paddy fields were converted into other types of agricultural land use for better revenue under the influences of market mechanism. A major change is to convert paddy fields into orchards and fishponds, which produce much higher income. As a result, the conversion from paddy fields to orchards and fishponds was intense in the early 1990s. The change detection reveals that 3.0 and 9.3% of the paddy fields were converted into orchards and fishponds, respectively in the study area during 1988–1993.

The region lost 13.1% of the agricultural land just within 1988–1993. The built-up land amounts to 11.3% of its total area in 1997. These figures are much higher than international standards. For example, in the study on the amount of encroachment on rural land in the United States, Hart (1976) concluded that the amount of rural land which would likely be converted to urban use from 1976 to 2000 only accounted to 4% of the nation’s total land area. Alig and Healy (1987) also predicted that physical occupation of built-up land remained below 4% over the next two decades. In New Zealand, it was found that the urban growth since European settlement represented only 4% of its highly productive land (Leamy, 1974). In Canada, the same situation was also found in the study by Smit and Cocklin (1981) on the extent of future rural-to-urban land use conversion for each of the 30 Ontario counties for the period 1976–2001. Four future urban growth scenarios were associated with the conversion, but only less than 2% of the prime agricultural land of Ontario would be lost even under the “worst” scenario. In England and Wales, the same conclusions were reached with regard to the impacts from land conversion (Edwards, 1969).

The above analyses reveal the spatio-temporal variations and restructuring of land use patterns, which reflect the dynamics and complexity of economic and physical factors in the region. It is obvious that the cities or towns of fast economic development are consuming more land resources. More rapid land use changes are mainly concentrated along the eastern development corridor between Guangzhou and Hong

Kong. Within the corridor, the cities of Shenzhen and Dongguan have unusually high percentages of land use changes and agricultural land loss. The disparity of using land resources coincides with the findings of other studies that indicate the emerging regional polarization of economic development in the region (Gu et al., 2001). Based on statistical data of industrial and agricultural output and foreign investment, Fan (1995) also indicated that polarization was the most important source of rising spatial inequality within the province. China has made efforts to remove regional inequity so that the gap between rich and poor areas will be gradually reduced. However, it is believed that recent economic development in China can bring about a new pattern of uneven regional development (Fan, 1995). This study provides new evidence with spatial details about the uneven land development in the Pearl River Delta. The measurement of development patterns has important implications for urban planning and management.

Acknowledgements

This study is supported by the funding from the National Natural Science Foundation of China (NSFC). We are grateful to two anonymous referrers whose comments are very useful for improving this paper.

References

Alig, R.J., Healy, R.G., 1987. Urban and built-up land area changes in the United States: an empirical investigation of determinants. Land. Econ. 63, 215–226.

Banister, D., Watson, S., Wood, C., 1997. Sustainable cities: transport, energy, and urban form. Environ. Plann. B 24, 125–143.

Batty, M., Longley, P.A., 1994. Fractal Cities: A Geometry of Form and Function. Academic Press, London, p. 394.

Bruijn, C.A., 1994. Spatial factors in urban growth: toward GIS models for cities in development countries. ITC J. 4, 221–231.

Burnside, N.G., Smith, R.F., Waite, S., 2003. Recent historical land use change on the South Downs, United Kingdom. Environ. Conserv. 30, 52–60.

Chang, S.D., Kwok, Y.W., 1990. The urbanization of rural china. In: Kwok, R.Y.W., Parish, W., Yeh, A.G.O., Xu, X.Q. (Eds.), Chinese Urban Reform: What Model Now? M.E. Sharpe, London, pp. 140–157.

Eastman, J.R., Fulk, M., 1993. Long sequence time series evaluation using standardized principle components. Photogramm. Eng. Rem. S. 59 (6), 991–996.

Edwards, A.M., 1969. Land requirement for UK agriculture by the year 2000: a preliminary statement. Town Country Plann. 37, 108–150.

Fan, C.C., 1995. Of belts and ladders: state policy and uneven regional development in post-Mao China. Ann. Assoc. Am. Geogr. 85 (3), 421–449.

Fung, T., LeDrew, E., 1987. Application of principal components analysis change detection. Photogramm. Eng. Rem. S. 53 (12), 1649–1658.

Gu, C.L., Shen, J.F., Wong, K.Y., Zhen, F., 2001. Regional polarization under the socialist–market system since 1978: a case study of Guangdong province in south China. Environ. Plann. A 33, 97–119.

Guangdong's Statistical Bureau, 1997. Guangdong's Statistical Yearbook. Chinese Statistical Press, Beijing, China (in Chinese).

Hart, J.F., 1976. Urban encroachment on rural-areas. Geogr. Rev. 66 (1), 3–17.

Jensen, J.R., Cowen, D.C., 1999. Remote sensing of urban suburban infrastructure and socio-economic attributes. Photogramm. Eng. Rem. S. 65 (5), 611–622.

Lambin, E.F., 1997. Modelling and monitoring land-cover change processes in tropical regions. Prog. Phys. Geog. 21 (3), 375–393.

Leamy, M.L., 1974. Resources of highly productive land. New Zealand Agric. Sci. 8, 187–191.

Li, X., Yeh, A.G.O., 1998. Principal component analysis of stacked multi-temporal images for the monitoring of rapid urban expansion in the Pearl River Delta. Int. J. Remote Sens. 19 (8), 1501–1518.

Lin, G.C.S., 2001. Metropolitan development in a transitional socialist economy: spatial restructuring in the Pearl River Delta, China. Urban Stud. 38 (3), 383–406.

Mesev, T.V., Longley, P.A., Batty, M., Xie, Y., 1995. Morphology from imagery: detecting and measuring the density of urban land use. Environ. Plann. A 27, 759–780.

Murdiyarso, D., 2000. Adaptation to climatic variability and change: Asian perspectives on agriculture and food security. Environ. Monit. Assess. 61 (1), 123–131.

Seto, K.C., Kaufmann, R.K., 2003. Modelling the drivers of urban land use change in the Pearl River Delta, China: integrating remote sensing with socioeconomic data. Land. Econ. 79, 106–121.

Shen, G., 2002. Fractal dimension and fractal growth of urbanized areas. Int. J. Geogr. Inf. Sci. 16 (5), 419–437.

Shen, J.F., Wong, K.Y., Feng, Z.Q., 2002. State-sponsored and spontaneous urbanization in the Pearl River Delta of south China, 1980–1998. Urban Geogr. 23, 674–694.

Smit, B.E., Cocklin, C., 1981. Future urban growth and agricultural land: alternatives for Ontario. Ontario Geogr. 18, 47–55.

State Council, 1994. Ordinance for the Protection of Primary Agricultural Land, State Council, Beijing, China, p. 12 (in Chinese).

Theil, H., 1967. Economics and Information Theory. North-Holland, Amsterdam, p. 488.

Thomas, R.W., 1981. Information Statistics in Geography. W.H. Hutchins & Sons, Norwich, p. 42.

United Nations, 2001. World Population Prospects: The 2000 Revision. New York (http://www.un.org/esa/population/pubsarchive/pubsarchive.htm).

Webster, C.J., 1995. Urban morphological fingerprints. Environ. Plann. B 22, 279–297.

Yeh, A.G.O., Li, X., 1999. Economic development and agricultural land loss in the Pearl River Delta, China. Habitat. Int. 23 (3), 373–390.

Xia Li is distinguished professor of the School of Geography and Planning, Sun Yat-sen University. He is undertaking research in the Centre of Urban Planning and Environmental Management, The University of Hong Kong SAR, China.

Anthony Gar-On Yeh is chair professor of the Centre of Urban Planning and Environmental Management and Director of the GIS Research Centre, The University of Hong Kong, Hong Kong SAR, China.