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Fractal characteristic analysis of urban land use evolution with remote sensing images in Shenzhen City

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ABSTRACT

Changes in urban land use/land cover (LULC) are the result of national policy and the economic activities of the urban population. Determining the spatial pattern of land cover types in cities is of particular significance for sustainable regional development. To achieve a better understand the spatiotemporal patterns of land cover types, this study uses the fractal dimension of spatial distributions as an index of the complex evolution of urban land-use. A long-term sequences LULC datasets are collected to do analysis, which covers the period 1988-2015 by employing Landsat TM/ETM+/OLI. Last but not least, a granularity analysis is adopted to study the structural changes of each land cover. Over this period, the fractal dimension of grassland, waterbody, and bare land exhibited bi-fractal dimensionality, but grassland, and bare land showed a consistently increasing bi-fractal trend, while the waterbody bi-fractals trend is weakened. The development of urban land saw a process of a multi-scale differential development with a hierarchical spatial system, and information entropy indicates that the urban land-use structure was unevenly distributed. These findings offer a scientific references for regional planning decisions on the evolution of urban land use in Shenzhen.

Background & Summary

With the acceleration of China's urbanisation process and the rapid growth of its urban space, changes in urban spatial patterns are taking place everyday. And the contradiction between the functional organization of urban interior space and the uneven use of urban land, is becoming increasingly serious, which affecting the sustained and healthy development of the urban economy and society¹⁻³. To mitigate the contradictions and support the sustained and healthy development of urban space, it is important to first understand the current functional organization of urban interior spaces. As land is the carrier of urban development, land-use patterns reflect the expansion of cities⁴⁻⁸, and the study of urban land-use structure can better reveal the situation of urban land use, this paper will therefore focus on the evolution of land use patterns to develop insight into the process of urbanization⁹⁻¹¹.

Complexity is a necessary feature of city systems⁵, and the uneven distribution of land use can make it hard to grasp the spatial organization of urban patterns. If a city land-use structure is too simple, it becomes over-planned or under-structured and may fail to evolve successfully or even cease to functioning¹². This realization helps in formulating general guidelines for urban planning policies. Nevertheless, a complex urban form can evolve from only a few developed parcels, showing a process of organic growth as more urbanized blocks are added¹³. Due to free-scale patterns in the urban internal structure and city size distributions, traditional probability theory and statistics are not suitable for such an analysis. The internal evolution process of cities is part of a complex system. Fractal geometry, meanwhile, is already used in geography and has been an effective tool for analyzing the complex systems of cities^{14,15}. The fractal geometry is a frontier multidisciplinary research field (geoinformation) and an effective tool for studying complex urban systems^{16,17}. A research object's fractured, irregular, or complex geometry can be regarded as fractal^{18,19}. Utilizing the fractal geometry, whether the seemingly irregular research objects have self-similar fractal characteristics can be discriminated, it can reveal the evolution of urban development. Usually, the fractal dimension is used as the fractal feature²⁰⁻²².

Many studies have explored the evolution of urban development using different datasets and methods²³, which can be divided into two categories:

a. Model-based research on the evolution of change.

For example, Wang et al²⁴ proposed a cellular automaton to do research on urban land-use patterns, in which cell states represent land uses, and transition rules express the transformation probability. An patch-logistic-CA model was later developed

to consider the spatial evolution of land-use patches to achieve urban growth, and this achieved better performance for Hangzhou (2005-2012)²⁵. Besides, simulation model of different urban growth patterns, called SMDUGP²⁶, was proposed to explain the reasons and processes of urban expansion, and this better simulated infilling, edge expansion, outlying growth patterns, and the structure of the actual urban development model.

b. Knowledge of morphology based characterization for urban interior space.

Many scholars have focused on urban individuals, including the study of urban form, structure, growth, transportation, and evolutionary mechanisms²⁷⁻²⁹. Irwin et al³⁰, discussed the evolution of urban sprawl in terms of spatial heterogeneity and land fragmentation, while, Nie et al³¹, used fractal theory to study the complexity of the spatiotemporal changes of the impervious urban surface. Other scholars have also analyzed the urban form, structure, urban network, land-use, and method research methods³². Chen et al³³, considered the city as a multifractal system and used the local and global parameters in the multifractal to analyze changes urban development.

Although, existing methods have made some progress in the study of urban expansion and changes in urban structure, they have not focused on the changes in the morphological characteristics of the structure of each type of land use. Besides, no long-term sequence was adopted to study the structure of urban land-use types in detail. Since research studies have usually been short and limited, it has been impossible to characterize the regular changes of a city from formation to stable development, and the complex characteristics of urban land-use evolution can thus not be objectively reflected⁸. In addition, as a city is an open and complex system, its evolution in time and space has characteristics of discontinuity and even jumping, the evolutionary processes are thus a result of natural, social, economic, and various sudden factors³¹.

Traditional mathematical methods and quantitative analysis are based on typical scale, which is often termed characteristic length. However, spatial patterns of cities has no characteristic scale and cannot be effectively described by conventional measure such as length and area. In this scale, the concept of characteristic scales should be substituted with scaling ideas. Owing to scale-free properties of urban form, the conventional measures should be replaced by fractal parameters. The box-counting method in this paper is employed for estimating the fractal dimension of urban form of study regions in Shenzhen from 1988 to 2015. It has become a method widely applied by many researchers (such as Mandelbrot³⁴; Batty and Longley²⁷; Benguigui et al.¹⁶; Chen and Wang³⁵; Ni et al.³⁶) to measure the fractal dimension in 2-dimensional images.

To effectively analyze the change in the morphological characteristics, this study will be based on fractal theory using a long-term sequence, in which the change in the fractal dimension represents a change in scale, and the fractal can thus reveal the nonlinear characteristics of the urban structure³⁷. The fractal dimension describes the urban land's morphological characteristics and represents an optimal structure that can optimize space. Researchers have shown that cities have fractal features and that fractal dimensions can describe fractal features well²². Urban spatial form can be considered the external manifestation of the spatial structure formed by various spatial activities under the influence of different factors. As the spatial pattern of a city changes, a set of indicators, including population, infrastructure and economy also changes^{38,39}, and the resulting scale law can interpret the inherent laws of the urban structure change. To make the evolutionary processes of urban land use clear an to improve the analysis of the urban land-use structure changes, a grid-based fractal analysis method will be used to calculate and analyze the fractal dimension of each land-use type.

In this paper, multitemporal LULC remote sensing data were used to investigate the fractal dimension characteristics for a modern coastal city, Shenzhen, China, including 1988, 1993, 1999, 2001, 2005, 2008, 2011, 2013, 2015. Then, the fractal dimension of different land use was calculated by using LULC data to carry out the evolution of urban land use analysis, which can reveal the spatial form changes of Shenzhen in the past 30 years. The paper aims to analyze the urban land use structure changes from 1988 to 2015 based on the theory of fractal geometry and combined with long-term sequences of land use data obtained by calculation. Then combined with the calculation result of fractal dimension and the urban development policy, it shows that the change of urban form is controlled by the policy, and puts forward suggestions for the current situation.

Materials and methods

Study area

Shenzhen, a coastal city situated at the southern edge of Guangdong Province, South of China, is adjacent to Hong Kong, and covers an area of 1997.47 km², shown in Fig. 1 (a) and (b), consisting of nine districts with a total resident population of 13.0266 million. It is located at a lower latitude, south of the Tropic of Cancer (113°43' E to 114°38' E, and 22°24' N to 22°52' N). The landforms in Shenzhen are mainly low mountains, flat platform, and terraced hills. It has a subtropical marine climate with a mean annual temperature of 22.4°. Activate as China's first fully urbanized city and one of the most economically efficient cities in China, Shenzhen has witnessed rapid land expansion and urbanization in the past 30 years. There are 6 land cover classes in Shenzhen shown in Fig. 1(c), including forest, grassland, waterbody, bare land, build-up area, and cultivated land.

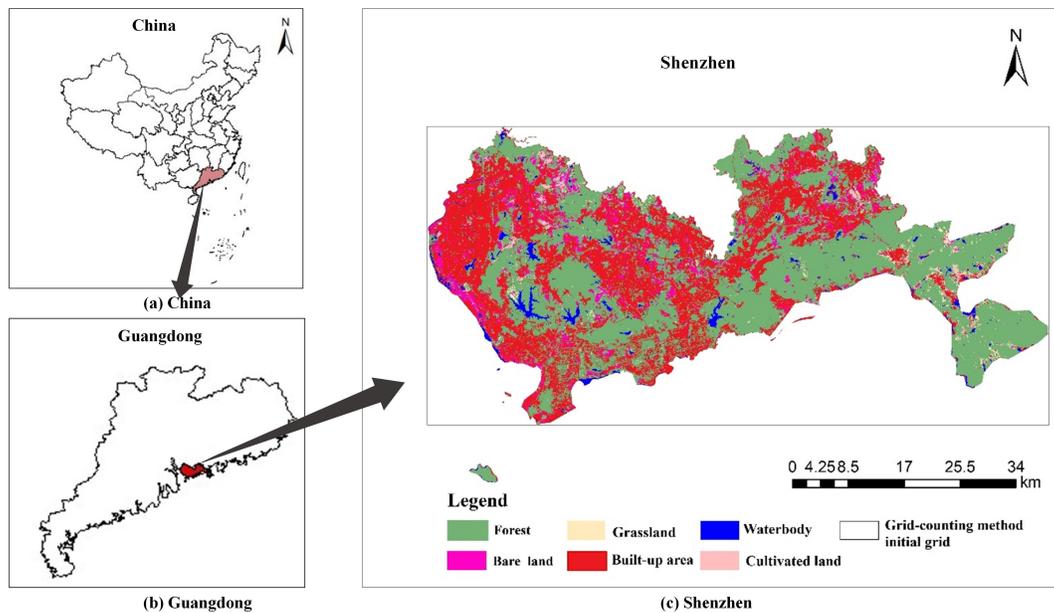


Figure 1. Location of the study area: (a) Location map of China, (b) Location map of Guangdong, (c) Location map of Shenzhen. The boundary map of China comes from China Natural Resources Bureau. The boundaries map of Guangdong province and Shenzhen city come from Guangdong Natural Resources Bureau. The map was completed with the ArcGIS (version 10.5) software, which can be download on <https://www.esri.com>.

Data sources

In this paper, land use and land cover (LULC) data and traditional census data will be analyzed. In recent decades, increasing numbers of classification algorithms based on remote sensing data have been proposed and applied to land use and land cover, of those, ensemble learning using multiple classifiers to find solutions performs well⁴⁰. By obtaining rich decisions from multiple component classifiers, ensemble classification methods can achieve better performance than traditional single classifiers⁴¹. In this work, more than 15 years of remote sensing imagery, including 1988,1993,1999,2001,2005,2008,2011,2013, and 2015, are used for analysis of the evolution of Shenzhen city land use. (see Table 1). The C4.5-based AdaBoost hierarchical classification algorithm proposed by Dou et al⁴² was adopted for land use classification of cloudless Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI (shown in Fig. 1 (c)), the dataset is available from the Figshare website (<https://figshare.com/>). The C4.5 tree-based AdaBoost was used to train the base classifiers for AdaBoost, specifically, seven AdaBoost classification models based on C4.5 were used in the hierarchical classifier. A manual comparison of earlier and later land-use classification results was conducted to identify unreasonable land-use conversions. Traditional census data are also collected for final analysis of the evolutionary process of city land use, which were downloaded from the official website of the Shenzhen Municipal Statistics Bureau.

Table 1. Remote sensing data

Parameter	1988	1993	1999	2001	2005	2008	2011	2013	2015
Platform	Landsat 5	Landsat 5	Landsat 5	Landsat 7	Landsat 5	Landsat 5	Landsat 5	Landsat 8	Landsat 8
Sensor	TM	TM	TM	ETM+	TM	TM	TM	OLI	OLI
Spatial resolution(m)	30	30	30	30	30	30	30	30	30

Data preprocessing

The study area for this work is in the central of Shenzhen, and the long-term sequences covers the period from 1988 to 2015. The LULC data was in the form of raster files, and ArcGIS (version 10.5) software was used to convert them to shape files. ArcGIS software was then used for data registration and region extraction, and the ENVI 4.8 platform was used to classify these registered Shenzhen datasets, and to obtain a series of classification images. Finally, ArcGIS was used to convert the classification maps from raster format file into shape files to prepared for counting of the different land cover areas.

Methods

Bourne et al.⁴³ divides the urban change of city systems into three components: random, predictable, and controlled. The urban self-organization process impacts the random and predictable components, but this can be affected by the control of government policy planning. Studies show that China's urban development is a self-organizing process⁴⁴, and the spatial fractal pattern of the urban structure is important quantitative evidence process^{45,46}. Information entropy can also reflect the urban land-use structure, so this study combines fractal geometry with information entropy to examine the mechanism of urban land use structure change.

The Calculation of the Fractal Dimension of Urban Land-Use Structure

Fractal dimension is often used to indicate the degree of complexity and stability of a city. The calculations of fractal dimension varies, depending on the purpose, research focus, or research techniques, and the measurement of a fractal dimension is widely used in medicine, soil mechanics, geography and technical analysis. To measure urban land-use by certain r scale, there is a measure M in the corresponding scale, when the scale r is changed, the measure $M(r)$ is also changed, which can be described as Eq. (1)

$$M(\lambda r) \propto \lambda^D M(r) \quad (1)$$

where the λ denotes scalling ratio, D represents scalling exponent. If the urban land-use structure pattern with fractal feature, the scale (r) and measure (M) follows scale invariance. The power-law relationship between r and M can be expressed as:

$$M(r) \propto r^{-D} \quad (2)$$

, calculated by transforming Eq. (1). The urban fractal is generally a random pre-fractal, rather than a strictly mathematical regular fractal, and it is not possible to achieve optimal coverage of an urban fractal dimension in the process of measuring it, only to approximate.

In this paper, grid-based fractal analysis is used to extract spatial information and calculate the fractal dimensions, which is an efficient approach for estimating the fractal parameters of the urban form⁴⁷. The principle of the grid dimension is as follows: The process start with covering the whole research area with grids of different scales; the fitting relationship between the number of non-empty grid and the grid scale is determined statistically. This fitting relationship is used as a measure of the urban fractal dimensions. If the urban land-use pattern has fractal characteristics, the corresponding relationship from the grid-counting method can be represented, according to Eq. (2), which is as follows:

$$N(r) \propto r^{-D_0} \quad (3)$$

D_0 denotes the capacity dimension, which is an important parameter of the fractal dimension, and $N(r)$ is the number of the non-empty grid of scale r . Converting the Eq. (3) to logarithmic form is shown as follows:

$$\ln N(r) = \ln(N_0) + D_0 \ln\left(\frac{1}{r}\right) \quad (4)$$

where N_0 denotes the proportional coefficient. Formally, the grid-counting method in geospatial analysis can be processed using the grid method to obtain the grid dimension, which represents the capacity dimension of fractal. The capacity dimension of fractal is the space filling index, which represents a kind of space information. In this paper, the capacity dimension is treated as an important parameter of the fractal dimension in the analysis.

The fractal parameters were computed as part of a grid-counting method using the least-squares method, and the concrete process is shown as follows:

a. Initialize the rectangular grid of the grid method. To make the study comparable, a fractal dimension method for the fixed region was defined. The selection of the initial rectangle to extract the digital map of the urban structure was mainly based on the urban administrative boundaries. The urban land-use in 2015 encompassed the scope of the urban land-use for the previous eight years. Thus, the minimum outsourcing rectangular area of the Shenzhen administrative district is defined on the 2015 urban structure map. The four sides of the rectangular area are consistent with the north, east, south, and west sides of the urban boundary. The resulting rectangle covers the entire urban area, which is indicated by the solid box in Fig. 1(c). The object measured by the grid-counting method is the land within the outermost grid and is located in the administrative division (excluding the land within the maximum frame range that does not belong to the administrative division).

b. Generate the grid. The ArcGIS (version 10.5) tool is used to generate 10 rectangular grids from

$$r_0 = \left(\frac{1}{2}\right)^0 \quad (5)$$

to

$$r_9 = \left(\frac{1}{2}\right)^9 \quad (6)$$

Taking the remote sensing imagery of 2015 as an example, Table 2 shows the multi-scale patch data. Based on the image resolution, the grid is divided into 10 levels (first column), corresponding to the different grid side length, regional spatial recognition levels and grid sizes (second, third and fourth columns, respectively).

Table 2. Multi-scale patch data

		2015			
Data level	r	Region spatial level	Grid size(m) (width*height)	Grid count	Number of nonempty grid
0	1	District/country level	91290.43*54436.84	1	1
1	1/2	District level	45645.22*27218.42	4	4
2	1/4	District level	22822.61*13609.21	15	14
3	1/8	Sub-district level	11411.30*6804.60	63	44
4	1/16	Sub-district level	5705.65*3402.30	255	144
5	1/32	Block level	2852.83*1701.15	991	850
6	1/64	Road level	1426.41*850.58	3842	1798
7	1/128	Residential compount level	713.21*425.29	15249	6761
8	1/512	Comunity level	356.60*212.64	27924	26113
9	1/1024	Comunity level	178.30*106.32	281744	102535

c. Extract the spatial data. The urban land-use vector data are intersected with the grid file generated by each equal division. The number of non-empty grids, $N(r)$, in each intersecting file and the area of the different types of land in each small grid are counted.

d. Caculate the grid dimension. With the $\ln(\frac{1}{r}) - \ln N(r)$ log-log plot, trends can be observed, and a log-log arithmetic linear fitting is performed to obtain the regression model for the nine years. With the results of the grid dimension, the fractal characteristics of the land-use structure in Shenzhen can be obtained.

The Caculation of Information Entropy for Urban Land Use Structure

In this paper, the Information Entropy is used to assess the structural characteristics of urban land-use⁴⁸. Urban land cover can be divided into different types according to function. To conduct a systematic analysis of urban structure, geographers put forward the concept of urban land-use balance based on the Shannon information to better reveal the structural characteristics of urban land-use^{49,50}.

The Shannon information function of urban land-use is defined as Eq. 7. Assuming that a city has a land area of A , the city's land can be divided into N types according to the type of coverage. The area of each function types is $A_i (i = 1, 2, \dots, N)$.

$$A = \sum_{i=1}^N A_i \quad (7)$$

According to the equation, the percentage of land area available is as follows:

$$P_i = A_i/A = A_i / \sum_{i=1}^N A_i \quad (8)$$

The P_i is equivalent to the probability of the event, so that the information of the land use structure is defined as follows according to the Shannon formulation:

$$H = \sum_i^N P_i \log P_i \quad (9)$$

Here, H is the information entropy. The level of information entropy can reflect the degree of balance of the urban land-use. With higher information entropy, there are more types of land-use functions, smaller area difference for each function type, and a more balanced land distribution⁵¹.

Results

The LULC are obtained based on the collected TM/ETM+/OLI images spanning 27 years: 1988, 1993, 1999, 2001, 2005, 2008, 2011 and 2015. From the Table 2, both the urban form and land use structure of Shenzhen obey the power law defined by Eq. 3, and the statistical self-similarity is very clear. Therefore, Shenzhen is fractal and qualitative in the sense of time and space. For all the study areas, the RMSE values are less than 0.015, which indicate the reliable results of fractal estimation. Fig. 2 also shows the change in land use distributions among the four images, revealing the spatial and temporal evolution process of land use patterns during the study period. Overall, the spatial growth follows a land use change pattern of modern coastal cities during the study period generally. And the area of land cover types changed significantly during 2000-2015.

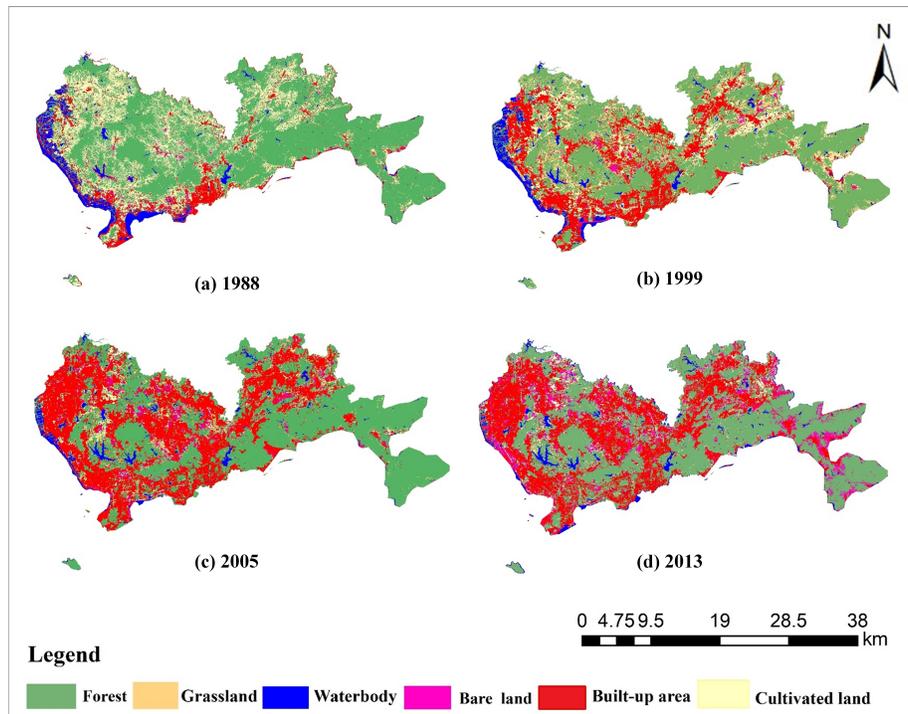


Figure 2. LULC classification data: (a) 1988, (b) 1999, (c) 2005, (d) 2013. The boundaries of the map come from Guangdong Natural Resources Bureau. The maps were completed with the support of ArcGIS (version 10.5) software, which can be download on <https://www.esri.com>.

Fractal Characteristics of Urban Land-Use

In this work, the fractal dimension of Shenzhen land-use structure is calculated, which is shown in Table 3. It can be seen from the results that the fractal dimensions (D) and the goodness of fit (R^2) of forestland, cultivated land and built-up area are higher than the others, forming an apparent fractal shape and indicating that their evolution was relatively stable. The fractal dimension of cultivated land and grassland can be seen decreasing year on year, while that of waterbody is increasing, illustrating that modern industry, transportation and town development have occupied part of the cultivated land and grassland area during rapid urbanization, resulting in low self-organization and the fragmentation of the cultivated land and grassland. In addition, it can also be noticed that the R^2 values of grassland, bare land, and waterbody are lower than 0.996, meaning that they are influenced by the urbanization development and shows a low filling degree of urban space. However, the overall structure of forestland in the city is relatively stable, with no significant changes.

To more clearly show the trends in the fractal dimension changes of the land-use types, the log-log fitting curve of the six land-use types is shown in Fig. 3. Significant bi-fractals can be seen in the fractal dimensions of the different land-use types, and these implies a self-affine characteristic that unsynchronized fractals develop in different directions, scales, and regions⁵. Theoretically, healthy urban development of urban should be a self-organizing optimization process, which would be reflected in the evolution of fractal features from double-index self-affine fractal to single-scale similarity fractal⁹. Therefore, self-similarity is the optimal structure of urban systems in an ideal relationship between structure and function in a city.

Table 3. Fractal dimension of Shenzhen land use types based on fractional grid-based methods

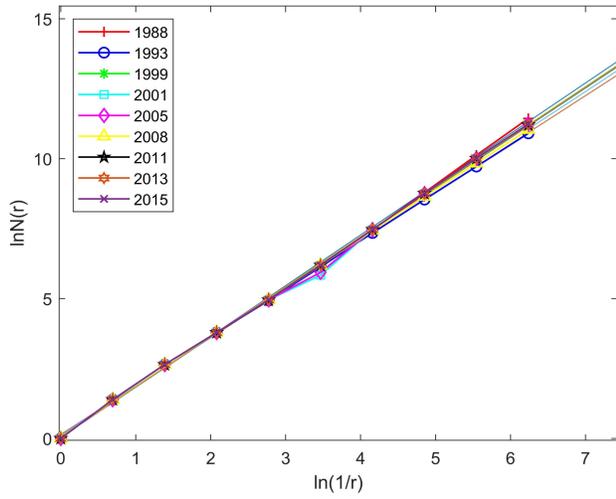
Year	Parameters	Land use					
		Forest land	Grass land	Cultivated land	Build-up land	Bare land	Water body
1988	D	1.8104	1.5321	1.7459	1.6387	1.4715	1.3951
	R^2	0.9995	0.9898	0.9997	0.9971	0.9905	0.9853
1993	D	1.7297	1.0853	1.7554	1.6845	1.4573	1.4483
	R^2	0.9997	0.9872	0.9998	0.9993	0.9914	0.9944
1999	D	1.7838	1.5602	1.6515	1.6699	1.462	1.3219
	R^2	0.9998	0.9982	0.9982	0.9992	0.9897	0.983
2001	D	1.7772	1.6652	1.682	1.6539	1.4367	1.5503
	R^2	0.9922	0.9935	0.9992	0.9993	0.989	0.9926
2005	D	1.7668	1.6018	1.4992	1.7302	1.3821	1.4641
	R^2	0.9998	0.9967	0.9942	0.9997	0.9854	0.9919
2008	D	1.7545	1.445	1.6884	1.7144	1.3905	1.5545
	R^2	0.9998	0.987	0.9987	0.9996	0.9851	0.9933
2011	D	1.7248	1.2655	1.6975	1.723	1.3649	1.5691
	R^2	0.9997	0.9848	0.9993	0.9997	0.9838	0.9956
2013	D	1.7849	1.4672	1.5891	1.7215	1.4253	1.6419
	R^2	0.9997	0.9888	0.9962	0.9997	0.985	0.9975
2015	D	1.7869	1.3104	1.4236	1.7379	1.36	1.6052
	R^2	0.9997	0.9789	0.986	0.9997	0.9816	0.9967

Compared with the other land-use types, the trend of the scatter fitting line of forest land is roughly stable between 1988 and 2015 (Fig. 3 (a)). The fractal dimension of forest land fluctuates at around 1.77, with the deviation not exceeding 0.05 (Table 3). However, the variation of grassland (Fig. 3 (b)) fractal dimension is more considerable, with the largest fractal dimension seen in 2001 ($D = 1.66$) (the cyan line with squares) and the smallest in 1993 ($D = 1.08$) (the blue line with circles). Surprisingly, the log-log plots of grassland, cultivated land, bare land, and waterbody showed a sudden change. Both ends of the mutation point showed an approximately linear relationship, consistent with the bi-fractal feature. Fig. 3 (c) show that the difference in the fractal dimension of cultivated land increases every year and that the bi-fractals trend is increasing. Fig. 3 (d) show that the fractal dimension of the build-up area is increasing every year, and the goodness of fit R^2 is also increasing (close to 0.996), indicating that its fractal characteristics are more prominent. Similar to the changing trend of the cultivated land, the difference in the fractal dimension of waterbody (Fig. 3 (e)) land increases every year. This means that the development patterns of cultivated land and bare land in Shenzhen show the fractal characteristics of anisotropic expansion. The fractal dimension of the waterbody (Fig. 3 (f)) decrease every year, and the bi-fractals tend gradually toward a single fractal, which means that the development and evolution probability of different regions is quite different. From the whole Fig. 3, it can be concluded that the anisotropic self-affine feature gradually weakens and that the isotropic self-similarity feature gradually strengthens.

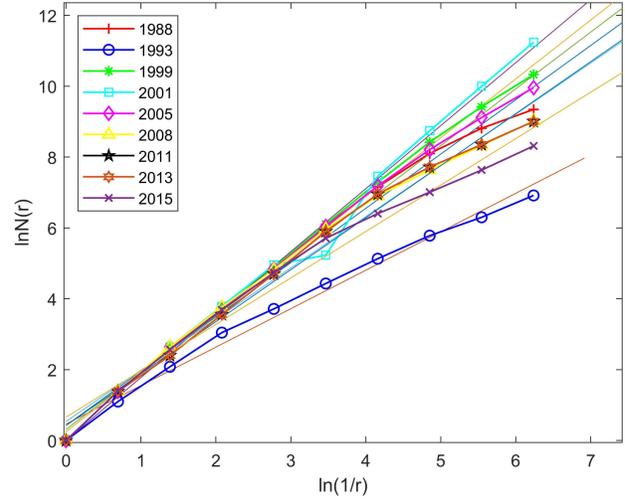
Information Entropy Characteristics of Urban Land-use

The information entropy of the composition of land functions was calculated using the Shannon entropy formula to determine the ratios of each land-use area to the total land area each year. According to the mathematical definition of information entropy, the information entropy of the land-use composition in the Shenzhen was calculated from 1988 to 2015. As shown in Fig. 4, the information entropy increased from 1.17 in 1988 to a peak at 1.38 in 2011, then decreased gradually there after to a low of 1.12 in 2015. The peak information entropy around 2011 indicates that the area gap between each land-use type was small and the distribution of the various land-uses relatively balanced, consistent with China's "Eleventh Five-Year Plan", which advocated comprehensive, coordinated, and sustainable development.

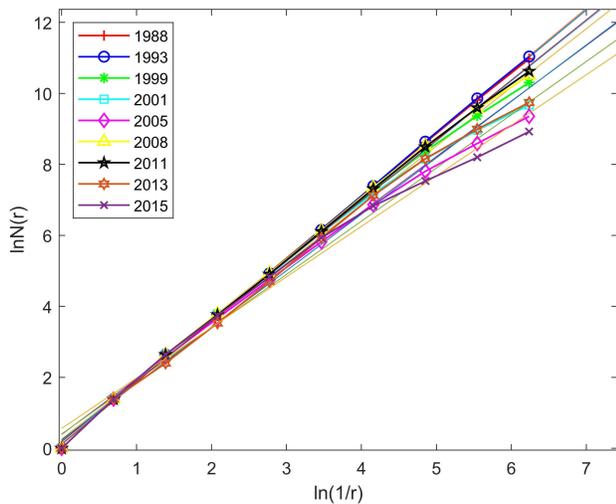
Notably, the information entropy declined year on year from 2000 to 2005, reaching trough in 2005, coincident with the continuous expansion and development of the Shenzhen Special Economic Zone from around 2000, which led to an imbalance in land-use types with different functions and an imbalance inland distribution. The State Council of China issued the "Decision of the State Council on Deepening the Reform of Land Management" in 2004, which required improvements in the land-use consolidation, urban construction, and the implementation and management of village and township planning. This policy had a significant impact on the evolution of the land-use structure in Shenzhen. The information entropy increased year by year after 2005 and reached the highest in 2011, which has made the land use structure more diverse and increasingly balanced state. This demonstrates that the evolution of urban land-use structure can be seriously affected by land policy.



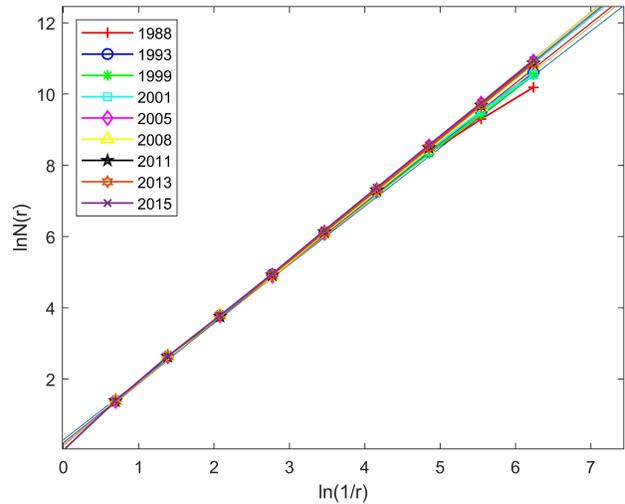
(a)



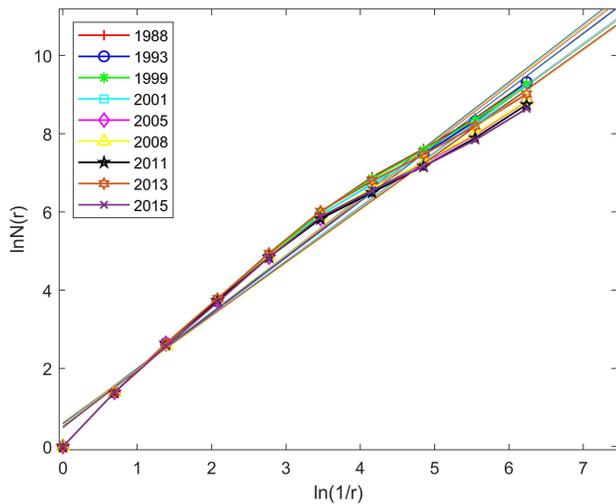
(b)



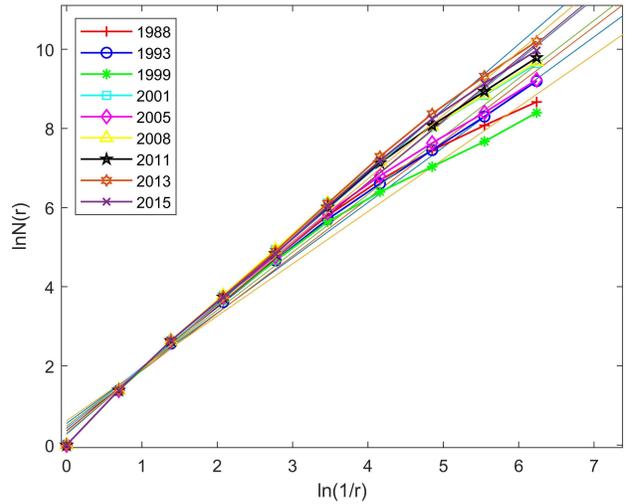
(c)



(d)



(e)



(f)

Figure 3. Example of log-log plots of scaling relations of urban land use in Shenzhen for 1988-2015: (a)forest land; (b)grassland; (c)cultivated land; (d)build-up area; (e)bare land; (f)waterbody.

Fig. 5 shows the changes in the area of the six land-use types. The differences in the areas of the various land-use types are most considerable in 1988 and 2015, which indicates that the internal distribution of urban land is hugely uneven. From 1993 to 2011, the different types of land gaps become smaller gradually. The build-up area had increased every year, and the cultivated area was most extensive in 1993 and then decreasing every year. Relatively, the grassland, bare land, and waterbody area were relatively small.

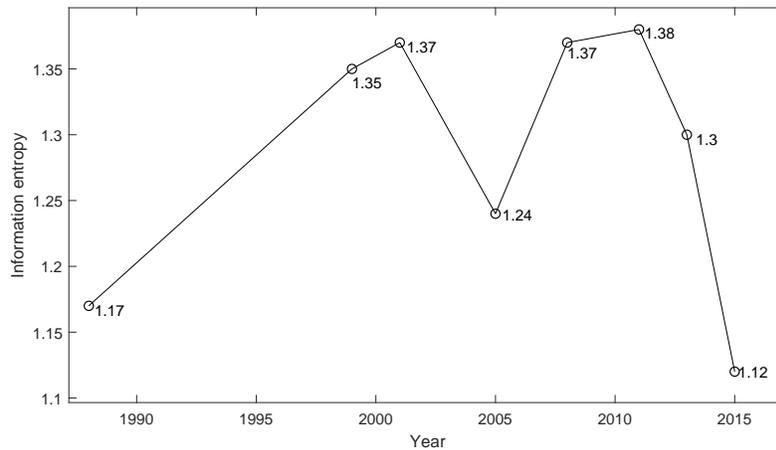


Figure 4. The information entropy of the land-use structure in Shenzhen from 1988-2015.

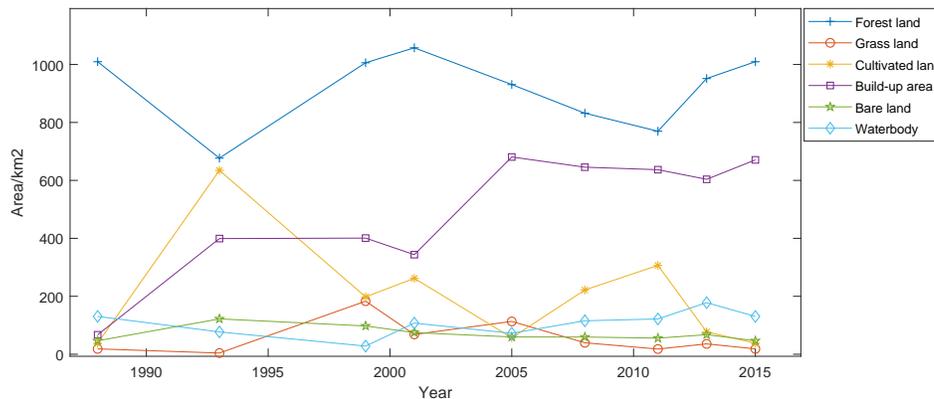


Figure 5. Area change of different land use types of Shenzhen during the period 1988-2015.

Discussion

Characteristics of Fractal Dimension in Urban Areas

The fractal dimension of various urban land-use types remains relatively high, indicating that urban land-use is not apparent enough, making the city in a state of disorder and weakening its functional strength^{12,52}. Therefore, the fractal dimension of various land-use types in the city should be up and down to maintain its regular operation⁵³. From Table 3, forest land always maintains a stable fractal pattern. The fractal dimension of cultivated land and grassland shows a downward trend, while the build-up area and waterbody show an upward trend. The fractal dimension of these land-use types are different gradually. As the urban development has entered a stable period and its self-organization characteristics, the fractal pattern of build-up area and waterbody have enhanced gradually, indicating that the urban land-use has become more and more obvious.

Combined with the fractal dimension of land-use, the annual entropy of urban land information, and the results of land use type change, the results reveal that different land-use structures have changed because of the increasing urbanization in

Shenzhen. Benguigui¹⁶ examined the view of urban fractal evolution and found that the self-similarity feature of the city appears in a time-space range. He proposed the statistical criterion of an urban fractal: when the standard error of dimension D is less than the critical value of 0.04, it is equivalent to the goodness of fit R^2 being less than or equal to 0.996. For realistic fractal objects such as cities, the measurement results in log-log plots as a significant straight line segment, as the scale is too large or too small to appear as a curve³⁵.

The results showed that the fractal structure has prominent evolutionary characteristics, whether looking at the entire urban area, built-up area, or various land-use types. The evolutionary characteristic are mainly manifest in two ways. The first is that the structure of urban land-use fractal form is gradually improving. From Table 3, it can be seen that the goodness of fit r^2 has an overall upward trend, while the standard error has a downward trend. The structure of each land-use type is relatively complicated. The second is the fractal dimensions of various land-use types in Shenzhen city have been rising and falling over the past thirty years. Specifically, the fractal dimension of the built-up area distribution is always greater than that of other lands, indicating the complexity of the intertwined penetration of the building areas. The green space dimension undergoes dramatic changes in 2005, mainly because of the economic construction-focused strategy of urban development after that date, which was a result of the government paying more attention to the ecological environment and the human settlement environment. The distribution of land in the built-up area is in a relatively balanced state. The grid dimension of the land is at a high level, while the bare land and public green space is small, reflecting the uneven distribution of urban green space and bare land and the low green space sharing rate. The fractal structure of the waterbody in Shenzhen has evolved from a self-affine structure to a self-similar structure, indicating that the trend toward integration of the waterbody space structure is gradually strengthening.

Analysis of Factors Associated with Land-use evolution

Shenzhen is one of the pilot cities during China's reform and opening-up, and its a symbol of the rapid development of the times. The spatial pattern of cities is driven by natural, economic, and political factors, with the fractal characteristics of spatial patterns of land cover types being the result of urbanization, and the various influences, economic factors and policy have played particularly important roles in the Shenzhen's urbanization. Shenzhen developed from 1988, with the establishment of a special economic zone, to a state of urban expansion in 2015. In the 1990s, a system of paid use of urban land was implemented, resulting in changes in land use in the suburbs. The built-up area is the economic, political, and cultural center of residents' lives, and the rapid growth of the city created a new trend of localized urbanization. The size of the built-up area has also been increasing, but its fractal dimension is relatively stable, indicating that the city is undergoing steady and orderly expansion. However, the fragmentation and agglomeration of grassland and bare land in the city is becoming increasingly apparent, the fractal dimension are decreasing, indicating that the distribution is becoming increasingly fragmented. Simultaneously, the bi-fractal characteristics weakened and gradually evolved into single fractals during the fragmentation process. The spatial shape of the entire grassland developed from anisotropy to isotropy, meaning that the aggregation of the grassland decreasing.

The land in the built-up area is used to protect residential land and public infrastructure construction. The increase in land area is obviously caused by urban development, and the fractal dimension of the built-up area is between 1.6 and 1.7, which is relatively stable. When combined with the entropy information and land area change, this allows the change in urban area form to be discussed in terms of space-filling, spatial balance, and space complexity.

a. Space-filling

The process of urban growth is necessarily accompanied with the process of filling the interior space. Fractals can reflect the system's ability to fill space. The higher the space-filling of urban land-use is, the higher the fractal dimension is, and vice versa. The fractal dimension of the various land-use in Shenzhen has shown an increasing trend, reflecting the process of filling the inner space of the city. The area and fractal dimension of built-up areas are increasing, demonstrating that the construction of built-up areas occupies a major factor in the process of urban filling, compared with other land use types. In recent years, the urban land-use structure of Shenzhen has developed into a balanced state. The area gap of various land-use types has gradually decreased, and the homogeneity of the urban land structure has increased.

b. Spatial balance

In the case of urban systems, the more uniform the urban spatial distribution is, the higher the fractal dimension is, and vice versa. The distribution of the built-up area is in a relatively balanced state, and the fractal dimension of the land is also at a high level. While the fractal dimension of bare land and public green space is small, which reflects the uneven distribution of urban green space and bare land, as well as the low sharing rate of the green space. After 30 years of development in Shenzhen, the fractal dimension of grassland has not increased but decreased. Therefore, it is worth thinking about Shenzhen's urban construction processes over the years. The difference in the proportion of land use is becoming larger, and the information entropy is decreasing. From the Fig. 4, it can be noticed that the information entropy of land use was increasing at first and then decreasing, which shows that the current urban land is also in a relatively stable state. However, the small part of the changes in the structure of cultivated land and bare land shows an anisotropic expansion trend compared with other land use structures.

The difference in information entropy and fractal dimension of land use can be jointly proved that the distribution of land in the built-up area is concentrated with a large proportion, while the grassland is concentrated with a smaller proportion.

c. Space complexity

It can be observed that the types of land-use structures are relatively complex in Shenzhen. In the past 30 years, the standard deviation of area of the various types of land has declined, indicating that the growth of Shenzhen has a trend of self-organization optimization.

From the above analysis, it can be concluded that Shenzhen ensemble display a spatial evolution that follow a fractal pattern. The fractal ideas can enable humans to make reasonable use of limited geographical space resource¹². During this period studies, the overall fractal dimension of land-use fluctuated, indicating that urban land-use has been both changing and reasonable, reflecting the judicious control of urban planning over the regional landscape. Overall, the land-use structure in Shenzhen is relatively reasonable, but the government should adjust relevant land policies to address the fragmented distribution of grassland, bare land, and cultivated land, in order to better control land development.

Conclusions

This paper has examined the law of urban land use evolution, which is a critical mission for urbanization development. Empirically speaking, the fractal dimension of a healthy city will increase steadily with the growth and development of the city. The urban form of Shenzhen city has prominent fractal characteristics, reflecting the growing complexity of building the infrastructure to accommodate the enormous complexity of a growing population involved in increasingly diverse and complex activities. Combining Shenzhen's economic development and the changes in land-use structure over the past 30 years shows that its fractal dimension was relatively low when the city was in an economic downturn, but, as the city develops more rapidly, its fractal dimension rose. We have presented a novel study of the urban land-use evolution characteristics based on a LULC dataset with a long-term sequence for Shenzhen. Multitemporal LULC remote sensing data was also used to investigate the fractal dimension and information entropy characteristics of a modern coastal city, Shenzhen, China. The land-use patterns dramatically changed as the city and surroundings were urbanized, and areas of Shenzhen maintained expansion along with the development from 1988 to 2015. The fractal dimension grid-counting method revealed that the spatial patterns show scale invariance during the study period. There were also some problems in Shenzhen's urbanization process of Shenzhen. The degree of spatial filling in the city is increasing, but its spatial balance is weakening, while overall spatial complexity is growing. The increased bi-fractals features of the bare land indicates that the grassland, bare land, and farmland in the city are becoming more fragmented.

This study suggests that the government should promote the efficient use of urban land by limiting its unreasonable expansion, and effectively controlling the self-organizing regulatory mechanism of urban evolution to promote healthier urbanization management. For future work, more impact factors, such as population flow, can be examined to provide further detail about urban evolution. Furthermore, although the fractal dimension can measure the characteristics of land use structure well, there is no standard for evaluating the fractal dimension of each land-use type in a particular city. There are often fractals in the fractals, forming a composite structure and dependence of multiple fractals, which does not make a good partition. Nevertheless, fractal theory can be used to examine long-term data for fast-developing cities, conduct fine-grained research on urban land use patterns, and qualitatively characterize urban internal space patterns.

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Author contributions

L.C. (Luxiao Cheng) initiated the concept of the study and drafted manuscript. R.F. (Ruyi Feng) and L.C. (Luxiao Cheng) designed the research. L.C. (Luxiao Cheng) and J.L. (Jiabao Li) conducted the analysis. J.L. (Jiabao Li) and J.H. (Jijun He) revised the manuscript. J.H. (Jijun He) and L.W. (Lizhe Wang) contributed to the mathematical methods. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Figures

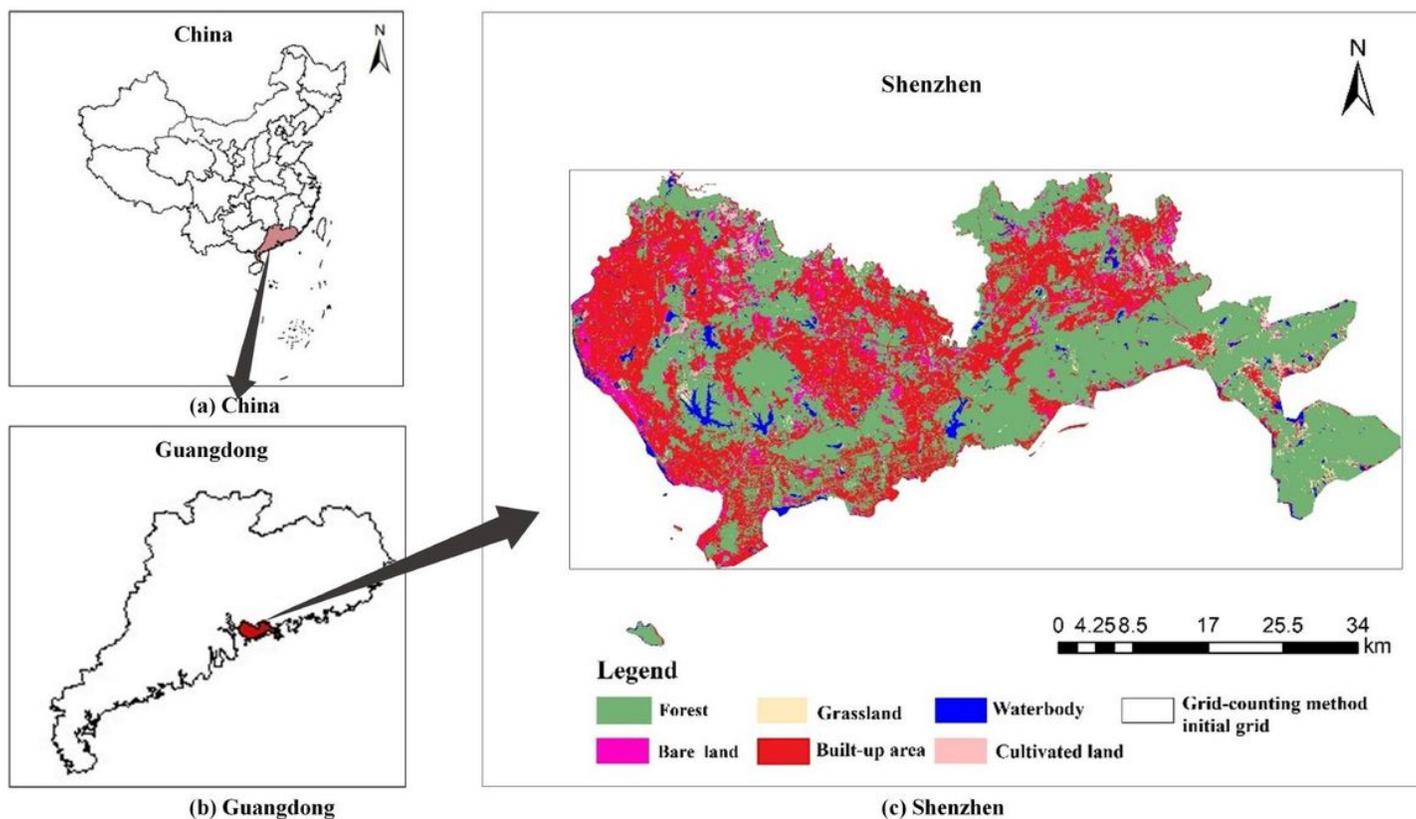


Figure 1

Location of the study area: (a) Location map of China, (b) Location map of Guangdong, (c) Location map of Shenzhen. The boundary map of China comes from China Natural Resources Bureau. The boundaries map of Guangdong province and Shenzhen city come from Guangdong Natural Resources Bureau. The map was completed with the ArcGIS (version 10.5) software, which can be download on <https://www.esri.com>. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

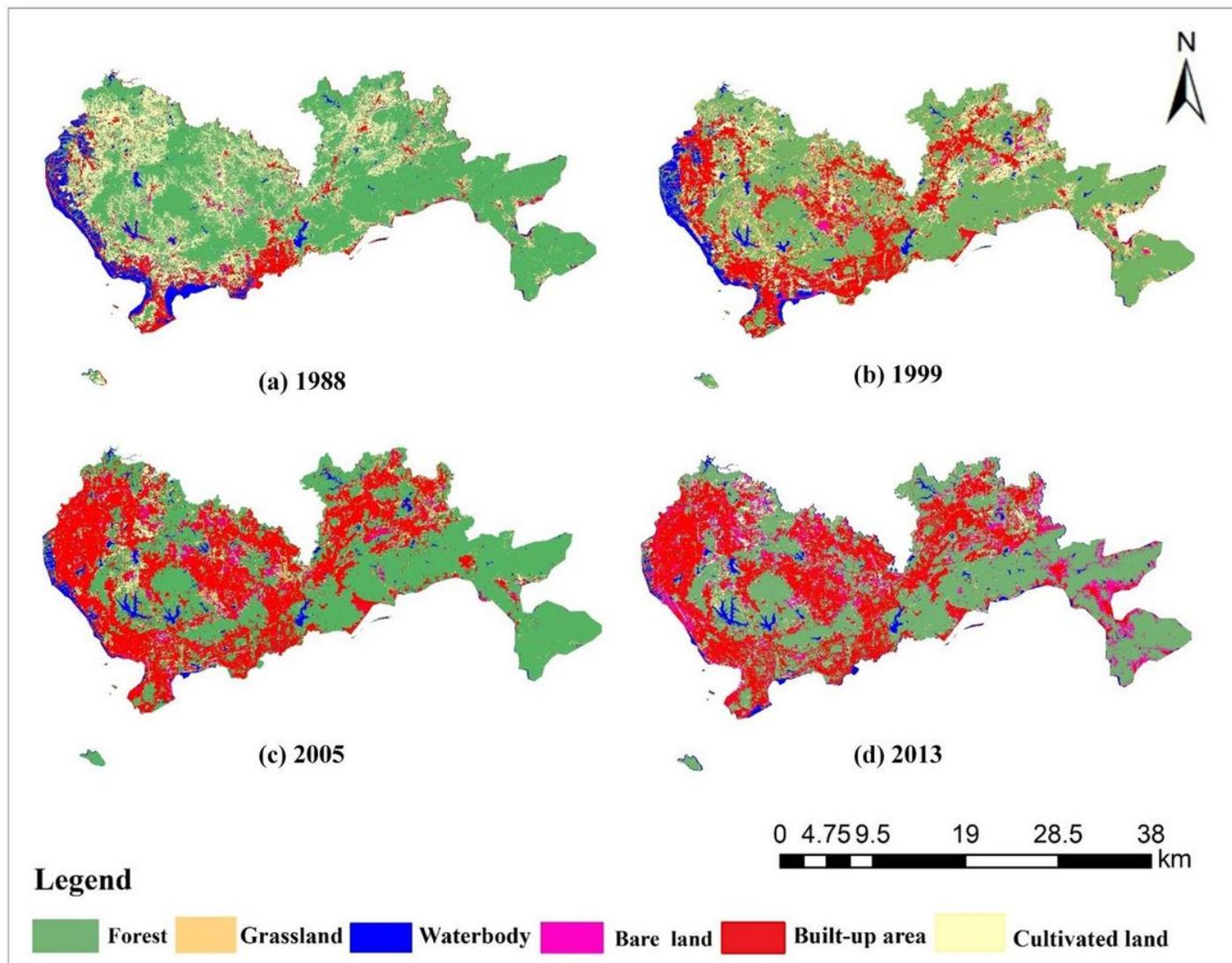


Figure 2

LULC classification data: (a) 1988, (b) 1999, (c) 2005, (d) 2013. The boundaries of the map come from Guangdong Natural Resources Bureau. The maps were completed with the support of ArcGIS (version 10.5) software, which can be download on <https://www.esri.com>. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

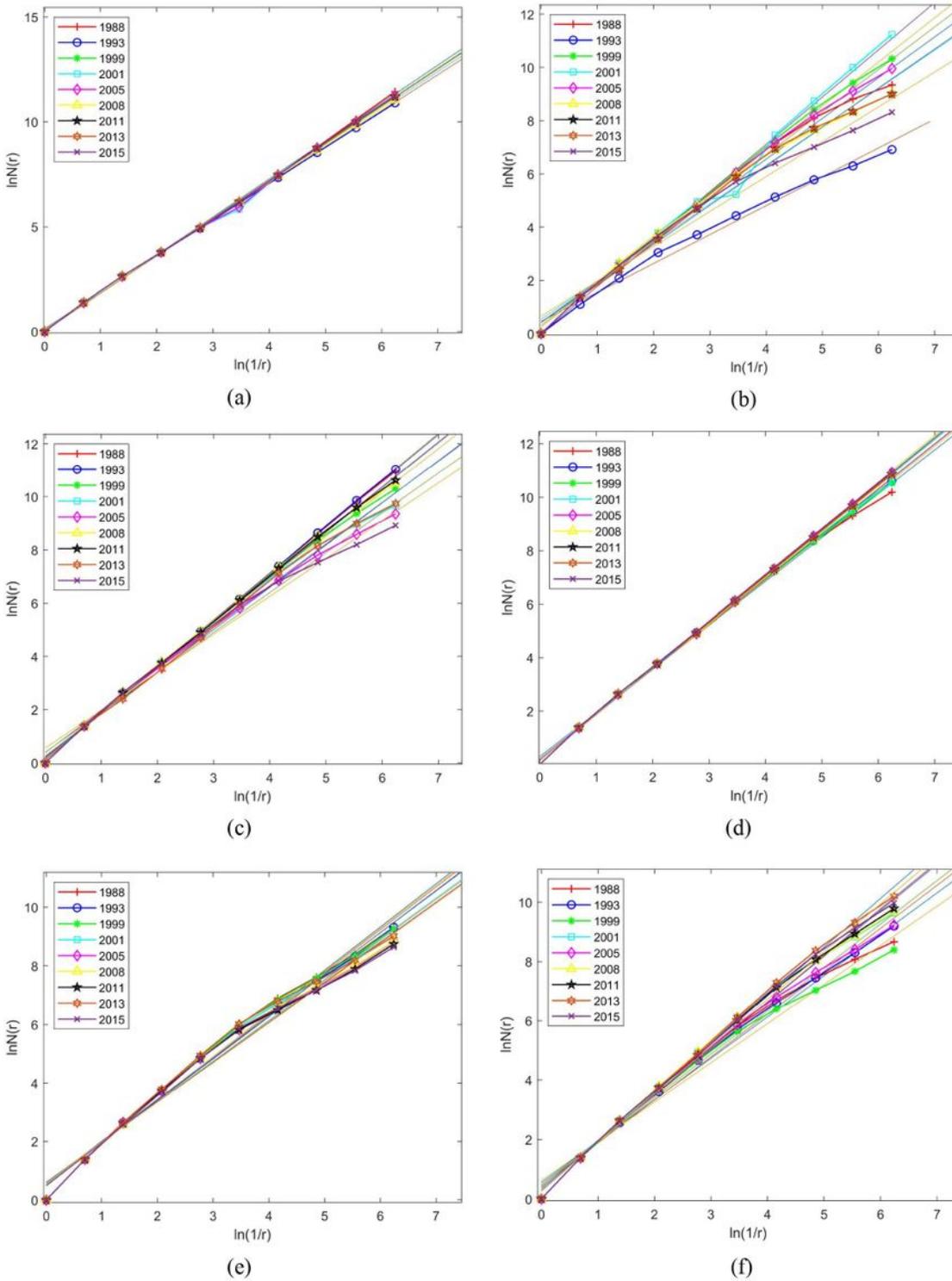


Figure 3

Example of log-log plots of scaling relations of urban land use in Shenzhen for 1988-2015: (a) forest land; (b) grassland; (c) cultivated land; (d) build-up area; (e) bare land; (f) waterbody.

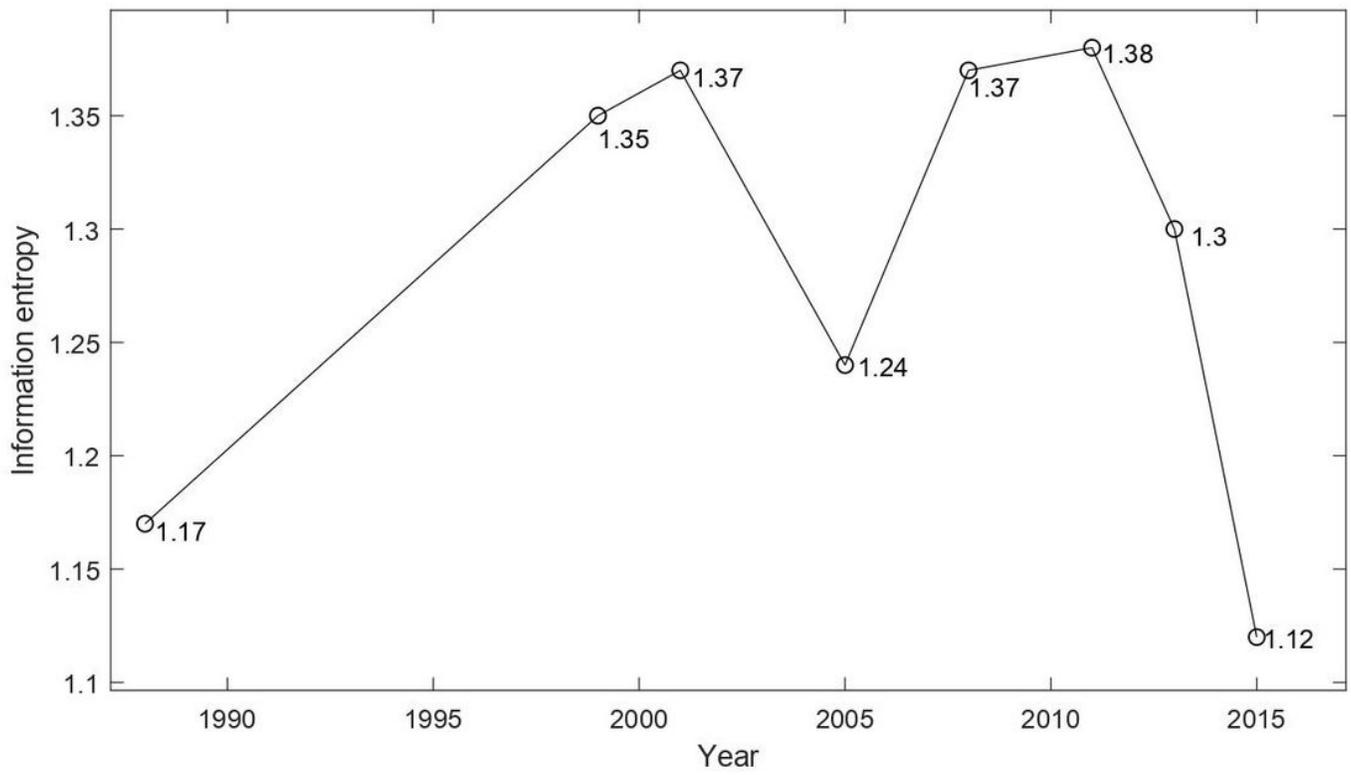


Figure 4

The information entropy of the land-use structure in Shenzhen from 1988-2015.

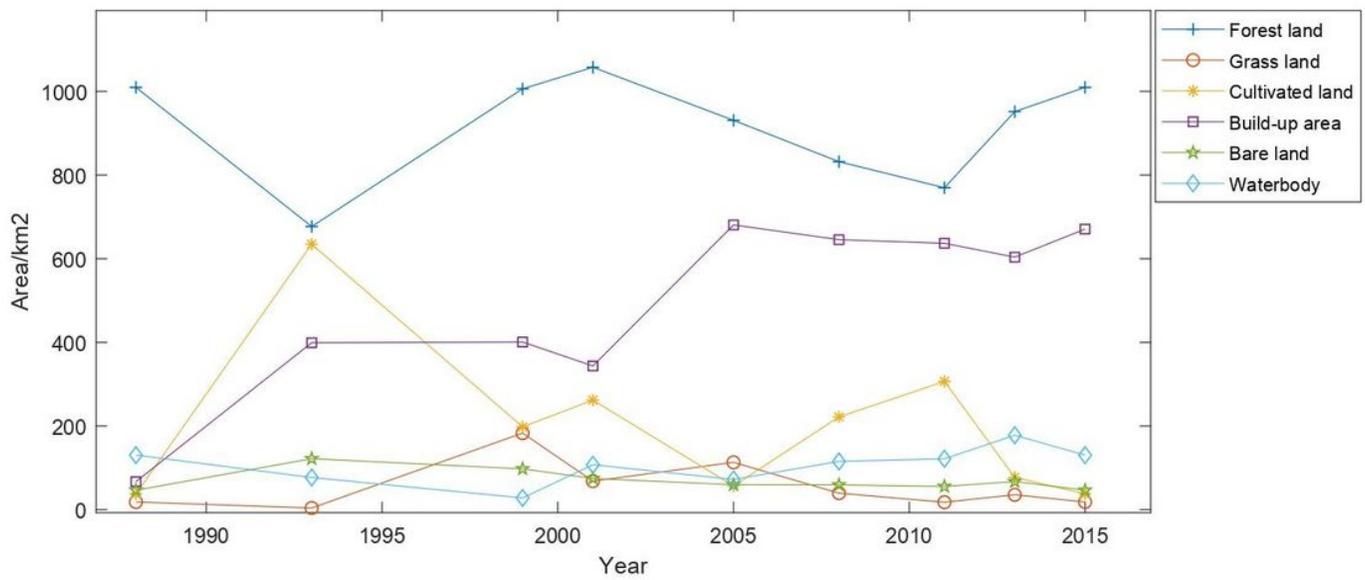


Figure 5

Area change of different land use types of Shenzhen during the period 1988-2015.