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Rencai Dong^a, Mingfang Tang^a, Kang Zhou^a, Siyuan Li^a & Gang Wu^a

^a State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, 100085, China
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Study on the modified quadrat sampling method for urban ecosystem network monitoring

Rencai Dong, Mingfang Tang, Kang Zhou, Siyuan Li and Gang Wu*

State Key Laboratory of Urban and Regional Ecology Research Center for Eco-Environmental Sciences,
Chinese Academy of Sciences, Beijing 100085, China

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Rapid urbanisation and developments in urban ecosystem research have increased attention on the spatial and temporal rules of urban land expansion, changes to the urban interior spatial structure and improvements to urban ecosystem functioning. There is an urgent need for a scientific method which uses remote sensing (RS), global positioning system (GPS), geographical information system (GIS) and ground surveys to quickly, constantly and accurately monitor urban spatial patterns, ecological processes and environmental changes. This study proposes a method to establish urban plots for a Long-term Ecosystem Research Station. The five procedures to determine the 24 plots were (1) analysis of city geography, (2) expert screening, (3) index analysis of urban land use in the plot, (4) coupled analysis of plot characteristics and overall urban development and (5) verifying that plot distribution was suitable for long-term monitoring of the spatial pattern of urban expansion.

Keywords: quadrat sampling; urban ecosystem; long-term monitoring; cluster analysis; urban–rural gradient; quadrat-based assessment

1. Introduction

The world entered the urban society age in 2008 (Zhao et al. 2010). Although urban areas cover a small fraction of the world's land surface, their rapid expansion has significantly altered the natural landscape and created enormous environmental, ecosystem and social impacts (Berling-Wolff and Wu 2004; Li et al. 2009). Rapid industrialisation and urbanisation require the initiation and promotion of the study of the urban environment, to find a way to integrate or couple urban development and eco-environment processes for sustainable cities (Zhao et al. 2008). Urban ecosystem research has drawn attention to the spatial–temporal rules of urban land expansion, the urban interior spatial structure and improvements to urban ecosystem functions.

Urban expansion often occurs in distinct stages, gradually transforming from ‘single-core expansion’, which is relatively simple and based on the city centre and surrounding area, to a more complex ‘multi-core extension’ and ‘point-axis’ expansion, including the central city, satellite towns, suburban towns and main traffic lines (Li et al. 2003). Long-term monitoring of the urban ecosystem, which can accurately analyse and portray the spatial details of landscape pattern changes during the urbanisation process, is used to examine the nature of urban land-use expansion in a large body of literature. However, to analyse the spatial pattern of urban expansion, the first question is: ‘How do the spatial structures of socio-economic, ecological and physical factors in an urban area relate to one another, and how do they change through time?’ To address

this question, the socio-economic, ecological and physical patches within the study area must be defined (Baltimore Ecosystem Study 2012). Urban environmental researchers need to select a special spatial unit for detailed descriptive analysis and field investigation. Hence, studying the spatial and temporal trends of urban ecosystem changes might require the establishment of permanent monitoring stations.

A grid-based approach to sampling plots takes local sub-regions which represent urban development characteristics as a basic unit of the spatial heterogeneity of urban land expansion, and then calculates a spatial measure index. When Estrabou et al. (2011) used lichens as bio-indicators of air quality in Central Argentina, he conducted systematic sampling, and a land-use map was used to choose locations for 576 sample stations. A grid of 1 km² cells was designed, a radius of 200 m around the central point of each plot was determined and three environmental factors were selected in each cell. Li et al. (2003) studied the patterns of urban land-use growth in Shanghai, and the spatial sampling method and GIS analysis were used to calculate the growth rate of the whole study area. Both the authors hypothesised quadrat sampling as fixed calculate unit, allowing for high-efficiency analysis and portrayal of the spatial details of land expansion during the urbanisation process. As a result, the quadrat sampling method has been used to examine the behaviour of urban land expansion in many studies. However, the method used in each study was usually developed for a particular city, individual project, temporary data source or special point of interest, and after

*Corresponding author. Email: wug@rcees.ac.cn

the study work or project was completed, the sampling stations or plots were disappeared.

Various interactions between developed areas and ecological processes in urban ecosystems have been discussed in several studies. Developing a thorough understanding of the evolution of city landscape patterns and mechanisms, and constructing a suitable quantitative evaluation model for city spatial morphology, has a profound and far reaching significance for sustainable urban development and for the reasonable use and protection of the regional ecological environment in China. This can also be used to design long-term urban ecological monitoring. The long-term urban ecosystem research plan should be universal, effective and coordinated to reflect the regular spatial-temporal pattern of urban expansion. This method should combine new technologies, such as RS, GPS, GIS and ground surveys, to monitor urban spatial patterns, ecological processes and environmental changes quickly and accurately over a long period. This paper provides an empirical framework that applies spatial statistical methods to assess the relationship between changes in the geographical clustering of firms and the emergence of urban form.

2. Background and methods

2.1. Long-term ecosystem research station in Xiamen

In 2006, Professor Jingzhu Zhao, former director of the Institute of Urban Environment (IUE), Chinese Academy of Sciences, decided to establish a Long-term Urban Ecosystem Observation and Research Station in Xiamen (Xiamen LUERS), where the Institute is located. It was also decided to build an Environmental Internet of Things (EIoT) with a central platform for long-term observation and comprehensive study of Xiamen's urban environment. The EIoT is explained in detail in Zhao et al. (2013) and Wang et al. (2013). A database with a unified and standardised data format will be created for future studies of China's urbanisation and urban environmental problems, and through networking will include other major cities. This will enable the city centre, suburban and rural areas to be treated as a complex urban ecological system that includes people and their activities. However, choosing the best locations for long-term ecosystem research plots is of vital importance.

2.2. Study area

Xiamen is a coastal city in southeast Fujian Province. The municipal area includes Xiamen Island, the much smaller Gulang Island and the coastal area to the north side of the Jiulong River, with a total land area of 1565 km² and a sea area of 390 km². From the 1920s to the 1970s, Xiamen experienced a slow urbanisation process. After the establishment of the People's Republic of China in 1949, the urban master plan defined Xiamen as a harbour city, an industrial base, a place for convalescence and a military defence city (Zhao et al. 2010). However,

since 1980, Xiamen has experienced rapid urbanisation. In 2008, the permanent resident population of Xiamen reached 2.49 million, and 70% of the total city population lived within the urban built-up area from 35.5% in 1981. In 2003, the administrative area was expanded to include Siming, Huli, Jimei, Haicang, Tong'an and Xiang'an districts (Figure 3). The urban built-up area is mainly on Xiamen Island (Siming and Huli districts), while the off-island districts are mostly peri-urban. During the past three decades, rapid industrial development and population growth have led to significant increases in environmental pollution and decreases in ecological services. The rapid urbanisation process has triggered profound changes in land use and land cover, which have caused the landscape pattern to change greatly. Xiamen's rapid urbanisation and impacts on local ecosystems have concerned many experts in the fields of ecology, economics and sociology.

2.3. Methods

2.3.1. Analysing topographic and evolving characteristics of the target city

Functional regions of a city usually include residential area, commercial and business areas, industrial and manufacturing areas, cultural area, administrative area and green space and public open areas. Phenomena such as peri-urbanisation or sub-urbanisation have changed the urban landscape, modifying the distribution of socio-economic features within the city and between the city and surrounding countryside. In addition, Xiamen city has a complex morphological structure and extends radially along the axis of urban expansion and main roads, including bridges.

In the opinion of local experts, Xiamen entered the late phase of urbanisation in 2003, and the original construction centred around Zhongshan Street has developed into a modern city (Yin et al. 2010). From the establishment of Xiamen Special Economic Zone to the early 1990s, urbanisation rate progressed at a steady pace, growing by only 6% between 1981 and 1993. However, the urban population surpassed the rural population for the first time in 2000 when the urbanisation rate first exceeded 50%.

2.3.2. Nomination of sites by local specialists

Before establishing the Xiamen LUERS, we invited nine local specialists to discuss the project in detail on several occasions. Some specialists had lived in Xiamen for a long time and were very familiar with the urbanisation trends and environmental problems, while the others had conducted several research projects in the city, including studies of ecosystem evolution and environmental quality. First, we asked the local specialists to 24 nominate potential plots for long-term urban environmental monitoring. Sampling plots were chosen a priori, based on available maps, to represent as much of the spatial extent of the municipal administration area as possible. All nominated plots in urban and rural areas were selected based on

satellite images and field reconnaissance to represent the entire range of conditions found in the city.

2.3.3. Extracting the test index from nominated plots

To test the plan to establish urban plots for the Xiamen LUERS, we needed to measure the key index from nominated plots, such as built-up rate, landscape pattern and so on. Then, we needed to validate whether or not those indexes are in accord with the expand trend of urbanisation.

Generally, urban areas have a central downtown area, which concentrate population, energy and materials, industrial and commercial activities, buildings and infrastructure. Many spatial data sources were available for the Xiamen urban area including high-resolution remote-sensing images, and 1:5000 relief maps were also used in the analysis of urban ecosystem characteristics.

The SPOT 5 (Système Probatoire d'Observation de la Terre 5) satellite images (resolution 2.5 m) were used to conduct visual interpretation in all plots. The classification system complied with China's national standard 'Code for classification of urban land use and planning standards of development land', implemented in 2012 (Ministry of House and Urban-Rural Development 2011). We divided town and country non-development land (E) into waters (E1), agricultural and forest lands (E2) and other non-development land (E9). Urban development land (H) was divided into the following eight categories: residential (R), administration and public services (A), commercial and business facilities (B), industry and manufacturing (M), logistics and warehousing (W), road, street and transportation (S), municipal utilities (U) and green space and public squares (G).

All plots were 500 m × 500 m quadrats with four accurately positioned coordinates of the X, Y and Z vertices, using in situ GPS. In all the plots, we counted the built-up area excluding green space and took this as a key index for plot cluster analysis.

2.3.4. Cluster analysis

After obtaining the percent area for all plots, SPSS 16.0 was used to conduct hierarchical cluster analysis, using the between-groups linkage method with Euclidean distance.

3. Results and discussion

3.1. Similarity S-curve generated 24 sampling plots

Table 1 describes the parameters of each nominated plot, including plot IDs, description, built-up rate and cluster analysis results. This shows that the built-up area percent of all plots ranged from 0.01% to 48.80%, as can be seen by the graph in Figure 1. The range of built-up area percent corresponds to the phased features of the urbanisation process, and the entire urbanisation process from early to late phase appears like a tightly stretched inverted S-curve

(Yin et al. 2010). Northam's urbanisation S-curve is one of the most important classical theories in urban geography, and the current built-up area percent of our nominated plots approximately fits this S-curve.

3.2. Cluster analysis

Cluster analysis results showed that the 24 nominated plots can be divided into six groups according their built-up rate: Cluster A > 46%, Cluster B 40–44%, Cluster C 22–25%, Cluster D 17–21%, Cluster E 9–11% and Cluster F < 9%. We found that Clusters A, B, C, D and E belonged to urbanised areas, and Cluster F was located in non-developed areas with little urban construction (Figure 2).

In Cluster A, both JX_16 and RD_14 are residential areas with a built-up rate of 49.36% and 48.17%, respectively, while GN_17 had a built-up rate of 48.80%. This indicates that the built-up area was highest in the old residential and old industrial areas. Because the urban land use and planning standards set the upper bound at 35–45% (Ministry of House and Urban-Rural Development 2011), the built-up area rate in these plots was excessive. The cover rate in Cluster B was almost 40% and included older areas mostly inhabited by long-term residents as well as downtown green space. Clusters C and D included more new residential areas where the built-up rate was moderate. Cluster E included more park and scenic areas with low built-up area. In Cluster F, SDR_24 and BTR_23 are drinking water reservoirs where development is forbidden.

Cluster A therefore represents the highest urbanisation, Cluster B higher urbanisation, Cluster C high, Cluster D medium, Cluster E lowest and Cluster F includes background areas for comparison. Some snapshots are shown in Figure 3 to illustrate this conclusion, which is also clear from the visual imagery.

3.3. Relationship between sampling group and ecosystem type

After comparing the six groups, we found that they corresponded to functional areas: the old town business district, industrial district, mature residential area, green space, urban-rural area and outskirts green area. The goal of the long-term urban ecosystem research was broadly defined as monitoring ecosystem status, environmental quality and urbanisation trends. The selected plots can effectively represent the spatial framework of Xiamen City that consists of Gulang Island, Xiamen Island and the mainland and can be used to describe different patterns of urbanisation. This means that the monitoring data from these plots can perceive the changes in the undeveloped land, developed land and subclasses through time.

A key aspect of efficient and effective environmental monitoring is the establishment of a set of clear conservation objectives, which can be evaluated by measurable attributes. The Xiamen ecosystem has been affected by the conversion of agricultural land to built-up area. Using our quadrat sampling method can promote links between

Table 1. Attributes of each nominated plot.

ID	Descriptions	Rate of build-up (%)	Patch amount	Group
JX_16	Jingxian residential area	49.36	122	Cluster A
GN_17	Guannan old industrial area	48.80	94	
RD_14	Ridong park-side residential area	48.17	131	
HX_22	Houxi river junction	47.46	249	Cluster B
LC_3	Laocheng, the old town for long-term residents	41.11	297	
ZSP_6	Zhongshan park, downtown green space	43.00	239	
WY_11	Wuyuanwan bay	24.25	72	Cluster C
JY_18	Jingyuan, a downtown village	24.69	155	
MD_8	Mudan residential area	22.35	68	
HS_2	Haishang garden, a five-star hotel	17.19	114	Cluster D
WT_13	Wutong dock for yachts	17.18	242	
RJ_7	The second software industry park	17.29	34	
XY_10	Xianyue mountain	16.67	57	Cluster E
STR_21	Shantang reservoir and forest	18.31	96	
HBR_9	Hubing city reservoir	20.09	81	
XYP_12	Xingyu park	19.81	71	Cluster F
DP_4	Dongping, a mountain in the downtown area	10.51	173	
YWP_5	Yangweishan, ecosystem services park	10.14	108	
RG_1	Riguangyuan scenic area	9.01	108	Cluster F
YBY_15	Garden Expo Park seashore	0.04	1	
SDR_24	Upper tributaries of Shidou reservoir	0.01	0	
BX_20	Bixi bridge	0.22	2	Cluster F
SD_19	Shangdian new port	0.75	15	
BTR_23	The water gate of Bantou reservoir	3.28	27

Figure 1. Built-up area percent curve of our plots, overlapping the S-curve of urbanisation in Xiamen (from Yin et al. 2010).

long-term urban ecosystem research and the urban planning and management department, by improved understanding of area and ecosystem characteristics during different stages of urbanisation. This coupled analysis can deepen understanding of the validity and relevance of long-term urban ecosystem monitoring plots.

3.4. Monitoring feasibility

As an efficient but low-cost, adaptable method with a strictly statistical foundation, our sampling method has great potential for application in long-term monitoring of the Xiamen urban ecosystem. First, our 24 sampling plots represent the land-use pattern of the city of Xiamen, including the old business and industrial districts, mature

communities, green space, the urban–rural fringe and rural outskirts. Secondly, our sampling sites can be used to analyse the speed of urbanisation, and distinguish between the fastest, average, slowest and non-urbanising areas. Finally, the plots are easily measured, and our tests indicate that the annual integrated environmental survey of each plot for Xiamen LUERS could be completed in 2–3 days by two or three people. They are suitable for long-term dynamic monitoring of many factors, including ecology, water quality, soil pollution, wind, noise pollution, solid waste and atmosphere.

Figure 4 shows monitoring factors designed to measure dynamic changes in the urban ecosystem. Plots in the inner circle are mainly in the old town business district, plots in the second circle are mainly in the industrial district, plots

Figure 2. Re-scaled distance cluster combine.

Figure 3. Location of the 24 study sites selected by local specialists (left) and snapshots of urbanisation cluster groups (right).

in the third circle are mainly in the mature residential area, plots in the fourth circle are mainly in the urban green areas and plots in the fifth circle are mainly in the urban–rural area or city outskirts.

4. Conclusions

Understanding the urban ecosystem by environment monitoring is widely recognised to be critical to wise urban

decision-making, and monitoring programmes must be as efficient as possible. Our experimental method to establish permanent sampling stations aimed to maximise monitoring efficiency and to improve the likelihood of producing statistically significant results.

Our study showed that the 24 sampling plots of the Xiamen LUERS will allow us to evaluate the interactive effects of urban land use and urban environment quality. The method not only effectively represented urbanisation

Figure 4. The monitoring factor and urbanisation gradient with plots.

characteristics and ecosystem processes but also ensured that all plots could be connected by the inherent relationship of environmental factor. In addition, it was demonstrated that quadrat sampling could be used as the spatial unit for studying the variation in environmental factors during different stages of urban development.

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