Methodology for classifying and detecting intra-urban land use change:

A case study of Changchun city during the last 100 years

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Abstract: Urban internal function and structure which is represented by intra-urban land use information is important spatial-explicitly information in urban geography research and urban planning or management; however, its extraction of fine-scale spatial information is still a difficult question in geographic information science (GIS). To overcome the difficulty in detecting intra-urban land use types using remotely sensed data alone and the positioning errors of mismatch in overlaying multi-temporal images, we have developed a digital reconstructing method to classify and detect intra-urban land use change through combining the "hierarchical classification" and "object-oriented segmentation" methods. This paper traces back to the historical developing process of Changchun city based on the above methods to classify and detect the detail intra-urban land use types including residential land, commercial land, industrial land, roads, water body and urban green space. The study has resolved the key problems on accurate spatial positioning from multi-scale and different data sources, classifying intra-urban land from function characteristics and detecting historical developing process of metropolis. Furthermore, we combined the SPOT5 imagery, 1:10000 topographic maps, historical maps, urban planning map and other auxiliary data of Changchun City to classify and detect its intra-urban land use change from 1905 to 2003. The results indicate that the methods are significant and effective in classifying and detecting urban land use spatial information through combining the human-computer interactive interpretation with the expert-based knowledge from different source data. The methods can not only enhance the accuracy of urban land use classification, but also improve spatial information extraction efficiency and positioning accuracy of multi-temporal spatial overlaying analysis.

Key words: classifying and detecting intra-urban land use change, hierarchical classifying method, object-oriented segmenting method

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1 INTRODUCTION

The world is experiencing a fast urbanization process, 2/3 of its population will live in the city by 2050. Developing countries, especially those in Asia, are facing with a transitional period of fast urbanization, which brings about a series of serious environmental problems. Land use/land cover change in urban and its surrounding area is now becoming one of the most important factors influencing urban ecosystem and global environmental change. Urban ecologists advocate solving this increasingly serious problem through cross-subject methods with urban geographers, urban planners and urban economists (Grimm *et al*., 2008; Montgomey *et al*., 2008). Remote sensing provides a useful and effective means in detecting and monitoring urban land use change. Remote sensing (RS) records the detailed spectral characteristics of land surface, which is closely related with land use and land cover information. It is difficult to detect urban land use types that reflect urban internal spatial structure directly from remote sensing imagery; however, it is available to extract land use information coupled with human-computer interactive visualized interpretation, geo-based knowledge rules and integration of auxiliary data (Chilar *et al*., 2001; Treitz *et al*., 2004). At present, most studies mainly focus on monitoring urban expansion processes using remote sensing (Liu *et al*., 2005; Wang *et al*., 2005; Kuang *et al*., 2005; Mou *et al*., 2007). However, little has been studied on the intra-urban land use structure at higher-resolution spatial information in finer scale. Mei *et al.* (2004) established electronic land use

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maps of the center City of Shanghai from 1947 to 2000, specifically categorizing further intra-urban land use types. The result was applied to analyze the information entropy of intra-urban land use change (Zhao *et al.*, 2004) and evolution of spatial structure of residential land (Liao *et al.*, 2004). But the acquisition of spatial information on urban land use types has not yet been discussed and analyzed in their studies in detail.

Accurate geographic data play an important role in analyzing and conducting quantitatively scientific questions. Therefore, the reliability and quality of the acquainted data have a direct impact on drawn results and specific conclusion. Research on land use change processes at both regional and national scales provides scientific basis for the studies of land use and land cover change and its related environmental construction and preservation (Liu *et al*., 2002). As a focus of human activity, urbanization area has been the hotspot in urban geographic study. At the same time, due to requirement of higher spatial resolution data in urban geographic research and difficulty in interpreting of urban land use change from topography maps and remote sensing imagery, urban land use classification has been a scientific problem in urban geographic information science and urban planning or management. Consequently, research on classifying and detecting methods on intra-urban land use information based on remote sensing and GIS will not only take an example for interpretation of higher resolution urban land use information at a finer scale, but also provide the important spatial information to understand spatial-temporal patterns and mechanisms of urban land use evolution in Changchun City as a historical developing process of one hundred years.

2 METHODS

2.1 Urban spatial information interpretation and land use classification system

Information on the intra-urban land use structure is a reflection of all kinds of economic and cultural factors of a specific historical period on the urban spatial configuration, and is also important spatial information in urban geographic research. However, it is difficult to separate residential and commercial land due to the feature of space-based high-precision positioning and the complexity of social attributes. Changchun City experienced different stages of urban development over the past 100 years in multiple and varied social, political and economical backgrounds. Land use structure changed drastically with fast sprawling of residential and industrial lands showing a characteristic of a transition from industrial land to residential land and moving out of industrial land. In the late 1970s, a large number of urban green spaces were occupied by residential land, which is a typical land use characteristic of large old industrial cities.

Based on the "regulations and rules of cadastral survey in urban" from Ministry of Land and Resources, and through integrating land use evolution characteristics in Changchun City, the probability of urban land use digital reconstruction for historical periods, urban landscape heterogeneity, as well as land use purposes and functions, we classified urban land use into 9 categories: commercial, industrial (including storage land), infrastructure, public building, residential, road, urban green space, water body and bare ground.

2.2 Intra-urban land use classification

Urban land use classification does not only include the categories of natural land coverage such as water body, vegetation, etc., but also takes into account the characteristics and functions of urban build-up land. Therefore, it is difficult to capture the dynamic of land information directly through remote sensing imagery. However, it is feasible to capture and extract land use information with a "hierarchical classification method" though systematically integrating remote sensing interpretation, object recognition, auxiliary information and urban land survey. The hierarchical classification method decomposes the complex urban landscape and phenomena into more simple nodes based on certain regulations. In intermediate nodes of classification trees with fewer objects, it is preferable to take targeted approach or combine with some auxiliary data to classify lower level nodes after making a composite treatment. This method has advantages of flexibility and convenience, which will facilitate the integration of remote sensing and geosciences knowledge (Zhao *et al.*, 2003). We will first classify the land use types for those objects that can be directly classified from remote sensing images with the hierarchical classification method, and then, detailed information will be detected and captured with further interpretation with reference to expert knowledge and other auxiliary information. Thus, the hierarchical classification method has a particular and predominant advantage over other methods in intra-urban land use classification.

In this study, based on SPOT5 imagery, we classified the intra-urban land use types in terms of color, shadow, size, shape, texture, pattern, location and spatial organization of objects. Object feature interpretation is primarily referred to urban topography maps and the names of different land units in multi-temporal periods. Auxiliary information is primarily referred to urban planning and functional maps of different time periods to identify each specific land use boundary in an urban unit with mixed land use types. Meanwhile, the main purpose of urban land use survey is to systematically understand the characteristics of intra-urban spatial structure and verify land use types that are hard to identify.

In sum, the hierarchical classification of intra-urban land use types on spatial information integrated all the information extracting methods mentioned above. Firstly, it is a prerequisite to update urban road maps derived from 1:10000 scale topography based on SPOT5 images and divide urban blocks, which forms the basic framework of the intra-urban land use structure. The concentric rings of roads, which are scattered and radiated obviously in SPOT5 images, surround the center of urban. The color of urban roads in true color images of SPOT5 is indigo or indigo mingled with Modena. Secondly, the urban green space and water body, which are easier to differentiate, will be classified. We found that the water body in Changchun City is mainly concentrated in Yitong River and some parks. The appearance of water body in SPOT5 images looks like a stripped or nearly round shape with a homogeneous texture showing a color of dark blue or blue. In contrast, urban green space is primarily distributed along roads and rivers or within parks. The appearance of urban green space in SPOT5 images looks like a stripped appearance or a large patch with mosaic water bodies in it, showing a color of green, or yellowish green or dark green with a texture of soft nap.

On the basis of development of urban roads framework and classification of natural land cover types (water body and green space), the hierarchical classification is further applied to classification in comparing new and old urban areas. The characteristics of new developed urban areas are more obvious due to relatively independent land use structure and function in the new developed urban. Taking SPOT5 for example, land use classification was detected with help of remote sensing interpretation, auxiliary information and urban land survey. Results showed that a large number of industrial and residential lands occupied the new city, of which industrial land are distributed mostly around the urban fringes, directly connected with the main roads, and clustered distribution showing a white, yellow, or purple color and a homogeneous texture. In fact, the concentrated industrial land can be directly classified from the images; while, for the scattered industrial land, it needs combining other feature characteristics to classify. Residential land can be distributed from the center to the fringe of a city, displaying a shape of regular squares with white and blue patches and regular crude texture. Bare ground and cropland at the urban fringes can also be detected directly through feature attributes.

Commercial land, residential land, infrastructure and public buildings are mingled each other in the old city; therefore, it is difficult to identify the specific land use information. So, we made a further classification by feature characteristics and auxiliary information in urban commercial and residential land mingled with each other while together with uncertainty of boundary between public land and residential land. Infrastructure and public buildings distribute evenly in the old city. Infrastructure buildings are directly connected with the main roads, displaying like a circle or a regular shape with complex structure; Public buildings are also related to main roads and usually mosaic with regular buildings, displaying brown patches with blue in it. Based on the methods mentioned above, we successfully classify and detect the spatial information of intra-urban land use change after applying hierarchical classifying methods in the new and old city step by step.

2.3 Digital information reconstruction of the intra-urban land use structure

Digital reconstruction of urban land use information is based on the 'object-oriented segmentation' classification method, which uses 'sub-street block' as the segmentation unit, through tracing back to the history of each object entity to monitor the spatial behaviors of a urban land use type to deduce spatial evolution of it. Through comparing the land use information at the previous time period with that at the current time period, evolutional behaviors of the object-oriented segmentation is divided into 4 different types: unchanged object, segmented object, attribute-changed object, and entity-expanded object. Therefore, the extraction of each piece of spatial information is accomplished by segregating objects based on previous spatial information until the smallest segmentation (S_i) unit is having been produced. The spatial topological relations between segmentation units should meet:

$$\bigcup_{i=1}^{k} S_i = \Omega, S_i \cap S_j = \phi$$

(i=1,2,…,k; j=1,2,…,k; $i \neq j$) Of which, each smallest segmentation unit has six attribute fields to mark its land use type at different time periods. Another layer of maps will be used as reference to conduct the human-computer interactive interpretation combining with the 'relative position method' under the help of expert knowledge. After spatial computations, six phases of urban land evolution information in Changchun city are obtained eventually (Fig. 1).

Fig. 1 Object-oriented Segmenting Method on urban land types

The important task is to trace the urban land use change information with multiple stages during the urban land digital reconstruction at different historical periods. The change modes of urban land use can be concluded into two types: extended expansion and internal structure transformation. Combining with the historical urban land use maps and functional zoning maps, urban land change information will be derived. In terms of urban evolution of Changchun City, urban extended expansion mainly focused on the expansion of industrial and residential lands, and urban internal structure transformation mostly occurred in the urban center with conversion from residential land to commercial land and replacement of green space by residential land, or substitution industrial land for residential land. Through successfully identifying the land use types at current and previous time periods, digital reconstruction of urban land use information can be achieved based on the methods mentioned above.

2.4 Extraction of the intra-urban land use information

Extraction of urban land use spatial information was achieved by manual digitization. Firstly, SPOT5 images were digitized as reference layers to extract urban main roads and basic road framework by integrating1: 500 and 1:10000 topography maps and field survey data. After that, the minor roads were delimited in terms of various streets composed of urban main roads, and then, different urban blocks were divided based on this information. Land use types within different blocks were identified and for blocks mixed with different land use types were continued being classified with the hierarchical classification method until a single land use type within a segmentation unit was identified. In the meanwhile, attribute codes were assigned for segmentation units, and we generated the user-oriented intra-urban land use information after topological information was established.

To accomplish digital reconstruction of historical urban land use information, we need first to achieve interactive extraction of urban boundary and to establish attribute tables (Fig. 1) with the ARCVIEW 3.3 software. Under the constraint of urban boundary of 2003, land use types were classified and classification codes were input into the field UL-2003 of the attribute tables until each segmentation unit represents only one land use type. And then, we overlaid the urban land use vector map of 2003 derived according to the boundary of 1990 with the 1:10000 topography map of 1990 to monitor the land use change within each segmentation unit. The changes occurred within each segmentation unit were recorded with different codes and written into the attribute tables. For extended expansion areas from 1990 to 2003, a code value of 999 in the field UL-1990 of the attribute tables was assigned, while for entity expansion areas, the land use code for the new land use type was assigned if all the land entities within the segmentation unit were changed. If only parts of the segmentation unit were changed, then we further divided the entities within the segmentation unit in terms of topography of 1990. The unchanged part was assigned the code value from the previous land use map; while, the changed part was assigned the code value from the new land use map. In this way, each land segmentation unit could be detected for its spatial change in land use types at different time periods. Based on the methods mentioned above, urban land segmentation units were divided backtracking from 2003 to 1905, and the spatial land use and urban evolution information of Changchun City was reconstructed for the past 100 years (Fig. 2).

The steps for extracting the intra-urban land use information are described in Fig 2. Firstly, with the help of Arc/info 9.0, the 'shape' format data is converted into 'coverage' format and six

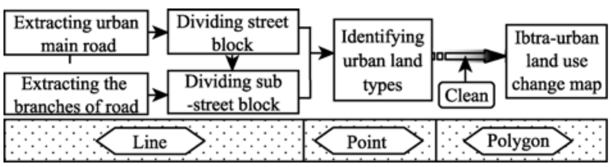

Fig. 2 Flowchart of extracting urban land information

time periods (1905, 1932, 1954, 1976, 1990, and 2003) of land use maps are generated after conducting calculation of 'cal COVER-ID = UL-2003, UL-1990'. The neighbor segmentation units that have identical attribute are merged using the 'dissolve' command, and then, we rebuild the topology information for these maps. Comparing with other traditional methods, 'object-oriented segmentation' can not only increase positioning accuracy in spatial analysis of multi-phases urban land use maps and reduce the 'spatial error' during spatial information extraction then enhance accuracy of information extraction, but also improve extraction efficiency. In this way, six time periods (1905, 1932, 1954, 1976, 1990, and 2003) of intra-urban land use maps are reconstructed, respectively.

3 RESULTS AND ANALYSIS

Many large-scale historical land use maps, topography maps, and documentaries with high-resolution land use information during the past 100 years provide important spatial information for this research. These data were organized as different scale topography, high resolution remote sensing, historical land use, and urban planning maps. In our study, we used a 1∶10000 scale controlling network and a map controlling configuration frame as the first-grade network for urban geographical positioning. The 1∶10000 topographic map was projected using Gauss-Kruger Transverse shear conformal cylindrical projection and was divided into different zones at a spatial resolution of 3 minutes. Changchun City is located at the 42nd zone of. Then, based on the projected 1∶10000 topography map, we generated 1∶100000 and 1:50000 controlling networks and 1:1000, 1:500 controlling configuration maps. These network maps were converted into multi-grade controlling networks with a unified coordinate system after projection transformation and coordinate translation.

The remote sensing images at different scales were combined to extract intra-urban land use types. Urban land use classification in 1905, 1932, 1954, 1976, 1990, and 2003 was referred to the skeleton maps of 1905 for the old city, the land use map of 1932 for the new city, city cadastre map of 1941 and 1∶100000 topographic map of 1954, 1∶10000 topographic map of 1976, 1:10000 topographic map of 1990, and SPOT5 images of 2003 and other thematic spatial information, respectively. Based on the 'object-oriented segmentation' method, land use maps of Changchun City for 1905, 1932, 1954, 1976, 1990 and 2003 were generated (Fig. 3).

Changchun City has a very special history and it has experienced different urbanization processes. Most of the changes in urban land use during 1905—1931 primarily occurred in the Kuanchengzi and Jiuchengzi districts, showing a characteristic of increasing residential lands, roads and reserved urban space. Large numbers of roads and reserved urban space provided enough space for urban development at the late time periods. With residential land expanded greatly with urban development during 1932—1954. After economy transformation from the old

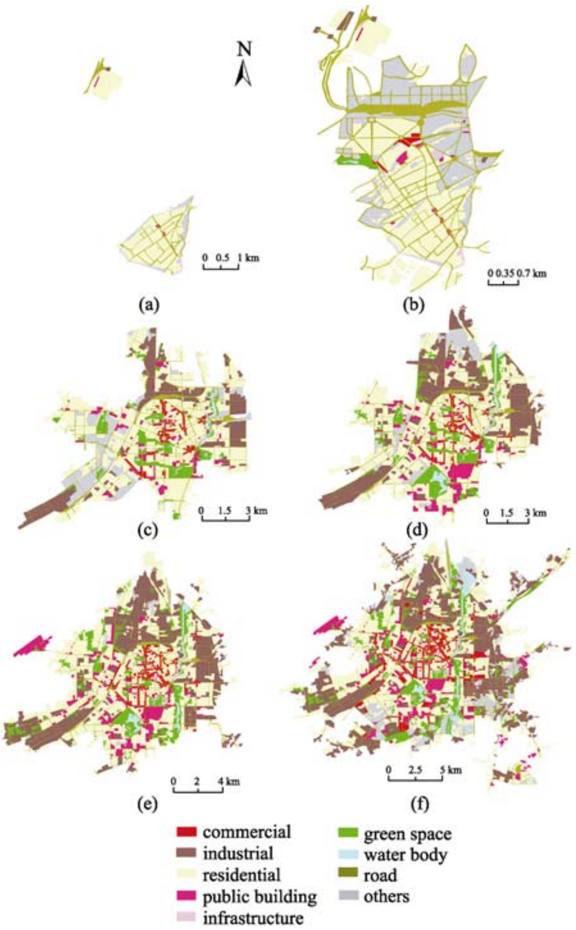

Fig. 3 Classified results of urban land use maps
(a) 1905 year; (b) 1932 year; (c) 1954 year; (d) 1976 year; (e) 1990 year; (f) 2003 year

era under colonization to the new era under post-liberation China administration, four major living communities: Chaoyang, Nanguan, Erdaohezi, Kuancheng were formed. During 1954—1976, industrial land increased very fast and dominated the land use change processes. The modern urban pattern was formed during 1976—1990: commercial center: Nanguan and Chaoyang districts which are located at the center of city and industrial; residential land center: Luyuan, Northern Kuancheng and Northeast Erdao districts. From 1976 to 1990, high-tech development area, economic development area and Jingyuetan development area were gradually emerged. The urban areas during 1990—2003 increased faster than other time periods, showing the most obvious characteristic in increased areas at all kinds of development area.

4 VALIDATIONS AND ACCURACY ASSESSMENT

Spatial data errors include spatial position error and attribute error. In this study, interpretation of urban land use spatial information was based on the 'object-oriented segmentation' method, and other time periods of land use information were captured according to the urban land use boundary map of 2003; therefore, it could meet the accuracy requirement of urban land use classification for 2003. In order to validate the classification accuracy, we sampled 122 points using both point and line survey methods with a 204.5 km × 204.5 km sampling coverage in and around Changchun City. The sampled points covered all the land use types showing in Changchun City. The survey items included: land use types, building height, road type and width, land use types of new development area and urban boundary, infrastructure conditions, major jobs of local residents. We marked spatial location, recorded attributes and took photographs based on current urban traffic maps. We also evaluated the accuracy of classified land use types in 2003 in terms of the urban land use survey and sampling points from aerial photos. The land use area for each specific land use type during 1905—1990, which were generated in this study, was also validated against statistical data.

Accuracy test was conducted through the comparison of the land use information form aerial photographs and field sampling with the corresponding land use information generated in this study (Table 1). We found that the average accuracy of this classification was over 95% and all the produced land use maps could meet the accuracy requirement at a spatial scale of 1:25000. Except the lower accuracy for public buildings and infrastructure, the accuracy for other land use types was very high. We found that our classification accuracy was over 92% when compared the historical statistical land area data with our classified area for a specific land use type. Then, 5 blocks were selected to compare and analyze the classification accuracy from the traditional hierarchical extraction and 'object-oriented segmentation' methods. The results showed that the 'object-oriented segmentation' could increase classification accuracy by 5.9%, and area accuracy by 4.3%. We also found that the extraction efficiency for all the 6 time periods images generated by the 'object-oriented segmentation' method could be 62% higher than that by the traditional hierarchical extraction method and the spatial location accuracy of the 'object-oriented segmentation' method can be up to 98% during overlay analysis.

Table 1 Precision analysis from different land use information

Urban land type	Numbers of samples	Correct samples	Accuracy / %
Commercial land	17	16	94.12
Industrial land	20	19	95.00
Residential land	44	43	97.73
Infrastructure	4	3	75.00
Public building	18	16	88.89
Road	5	5	100.00
Green space	6	6	100.00
Water body	3	3	100.00
Others	5	5	100.00
Total	122	116	95.08

5 DISCUSSIONS AND CONCLUSIONS

This study developed a method combining 'hierarchical classification' and 'object-oriented segmentation' methods to integrate space-based multiple sources of information and to extract high-accuracy and high-resolution urban land use information and its dynamic changes over time. Using ‘sub-street block’ as the basic segmentation unit and through backtracking of each object entity, we monitored the spatial behaviors of urban land use and identified its spatial evolution information in Changchun City. It is highly applicable to achieve the extraction of high-precision urban land use spatial information combining the participation of expert knowledge with human-computer interaction. This method can not only increase the classification accuracy of urban land use types, but also increase the extraction efficiency of spatial information and spatial location accuracy of multi-phase spatial data in overlay analysis.

Classification of intra-urban land use types is very important for urban planning and management, and urban sustainable development. However, its low accuracy can not satisfy the requirement of large-scale topographic maps, limiting its application; therefore, high-accuracy image interpretation methods are required during urban land use classification, which include the right choice of data sources, image correction methods, and spatial information extraction method and so on. This study attempted to develop an intra-urban land use classification method based on all kinds of data sources including remote sensing images, historical statistical maps, topography maps, urban planning and management data, and survey data. This method was demonstrated to be suitable for land use classification in large cities with relatively independent functions, as well as metropolitan cities.

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城市用地空间信息分类与数字重建
——以长春百年城市内部用地变化为例

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摘 要： 针对单一应用遥感影像难以进行城市内部用地结构分类以及高精度城市内部用地多期空间数据叠置分析中位置误差问题建立了基于“分层分类”与“对象分割”的城市内部用地空间信息数字重建方法。实现对特大城市产业用地(住宅、商业、工业等)以及交通、水系、生态绿地等不同功能结构用地的高精度监测以及历史演变过程的重建。综合集成 SPOT5, 1∶1 万地形图、历史地图及城市规划图等辅助信息对长春城市 1905 年以来城市用地信息进行分类。研究表明，在专家知识参与下人—机交互解译，集成多源空间信息对实现高精度城市用地空间信息重建具有较高的应用价值，该方法不仅能提高城市用地分类精度而且能提高城市用地空间信息提取效率以及多期空间数据叠置分析的定位精度。

关键词： 城市用地，数字重建，分层分类，对象分割

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1 引 言

世界正处于快速的城市化过程，到 2050 年将有 2/3 的人口居住在城市。发展中国家，特别是中国正处于快速城市化过程的转型时期。快速的城市化带来一系列的环境问题，城市及周边地区土地利用/土地覆盖变化成为城市生态系统与全球环境变化重要的影响因素之一。面对全球变化带来的威胁，城市生态学家呼吁与城市地理学家、城市规划者、城市经济学家通过学科交叉等方式致力于解决城市化对全球环境变化带来的严重影响这一科学难题(Grimm 等, 2008; Montgomey 等, 2008)。遥感为监测城市土地利用变化提供了重要的手段。遥感记录了地表的光谱特征，与土地覆盖密切相关，通过可视化解译，地学知识的参与，辅助数据的集成等方式可实现土地利用信息的获取(Chilar 等, 2001; Treitz 等, 2004)。目前研究主要集中于对城市扩张过程进行遥感监测(Liu 等, 2005; 王新生等, 2005; 匡文慧等, 2005; 牟凤云等, 2007)。对于更高精度的城市内部用地结构遥感监测相关研究相对较少，梅安新等制作了 1947—2000 年上海市中心城区土地利用电子地图，对城市内部用地结构进行了详细分类，应用分类结果对城市土地利用信息熵进行分析(赵晶等, 2004)。在此基础上，针对居民地空间结构演变方面开展深入研究(廖邦固等, 2008)。但是尚未对城市土地利用空间信息的获取方法进行深入分析。

精准的地理数据是定量化描述和研究问题的基础。数据的可靠性与获取数据质量直接影响分析结果。区域或国家尺度土地利用现代过程重建为土地利用/覆盖变化研究以及生态环境建设与整治提供了科学基础(刘纪远等, 2002)。城市作为人类活动的焦点地区，由于城市地理研究需要更高精度的空间

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数据，且城市用地结构分类难以从地形图或遥感影像等数据源直接提取。因此，城市用地分类一直是城市地理信息科学以及城市规划管理中面临的难题。基于遥感与 GIS 研究城市内部用地重建方法不仅为局地尺度上城市高精度用地空间信息提取方法提供技术示范，而且为长春城市用地演化时空模式与机理的认识提供重要的空间信息。

2 城市用地分类与数字重建方法

2.1 城市用地空间信息特征与分类系统

城市内部用地结构信息是城市在特定社会背景下的各种经济、文化因素在城市地域空间上的反映，是城市地理学研究所需的重要空间信息。城市用地空间信息具有高精度的空间定位基准而且城市住宅、商业等用地反映的社会属性特征难以直接通过遥感影像进行区分。长春近百年来城市发展经历了多重社会政治与经济背景，城市用地结构演变表现为住宅、工业用地的外延式增长以及工业用地不断外迁，城市建设后期大面积绿地被住宅用地建设所侵占等老工业城市比较典型的特征。

本研究在参考国土资源部《城镇地籍调查规程》中城市用地分类系统的基础上，综合考虑长春 100 年来城市用地演化特征的表征，以及历史时期城市用地数字重建的可实现性，城市景观异质性以及土地用途、功能的不同将城市用地分为 9 个类型，分别为商业用地、工业用地(包括仓储用地)、公共设施用地、公共建筑用地、住宅用地、道路用地、城市绿地、水域以及裸地等其他城市用地。

2.2 城市内部用地空间信息分类

城市用地分类不仅包括对城市水域、城市植被等地表自然状态进行分类，而且要根据城市人工建筑用地的性质与用地功能进行分类。因此，难以直接通过遥感信息进行提取，本研究综合了遥感解译、地物名称判别、辅助信息参考和城市土地调查，通过遥感信息的分层分类法对地物类型进行提取。遥感分层分类法把复杂景观或现象按照一定原则作了层层分解，使他们的关系简单化，在分类树的各个中间节点上，面对较少的分类对象采取针对性的方法，或与一些辅助数据进行复合处理，对更低层节点进行分类，该方法在知识的参与下灵活方便，便于遥感与地学知识的复合(赵英时等, 2003)。针对城市用地特点，利用分层分类法对直接可以从遥感影像上识别的城市用地进行分类，通过参考其他信息与专家知识对遥感影像上难以识别的城市用地类型通过层层深入的方法进行分类。

基于 SPOT5 遥感影像，根据图像的色调、阴影、大小、形状、纹理、图案、位置以及空间组合状况进行城市用地分类。地物名称判别主要参考地形图及历史地图上城市各用地单位名称的标注识别用地类型。辅助信息参考主要利用不同时段城市规划图以及历史时期城市功能区规划图，以确定难以识别的同一个街坊内混合用地类型的边界。城市土地调查主要目的是对城市内部空间结构特征的深入认识以及对难以确定的用地类型进行验证。

城市用地空间信息分层分类方法综合上述信息获取方法，首先根据SPOT5遥感影像对1∶1万大比例尺地形图提取的城市道路进行更新，对城市街区进行划分，形成城市用地结构分区的“骨架”。城市道路在SPOT5遥感影像上表现为从城市中央呈散射状分布，表现为圆型广场相连的条带状网状分布等特征，真彩色影像呈现紫蓝色、夹杂深紫色。基于SPOT5遥感影像对城市绿地和水域比较容易识别的自然覆盖类型进行分类，城市水域主要以伊通河、公园水域为主，在影像上呈现带状、自然近圆形态，表现为深蓝色、蓝色，影像结构细腻均匀；城市绿地主要分布于道路两侧、公园内部、河流两侧，影像呈现带状分布、大块状与水域镶嵌分布，颜色呈现绿色、黄绿色、深绿色，有立绒状纹理。

在构建城市道路用地“骨架”与自然覆盖分类基础上，对城市新旧城区分别进行下一层次分类。新城区用地类型功能结构相对独立，在影像上特征相对比较明显，仍以 SPOT5 遥感影像为主，结合地物名称判别的方法，对于旧城区各种功能用地类型混杂，相对难以进行用地类型的判别，主要应用地物名称判别、辅助信息的参考与城市土地调查为主来实现。新城区内大面积工业用地与居住用地分布，工业用地主要集聚分布于城市边缘区与城市主干道直接相连，呈规则的块状分布，颜色呈白色、黄色、紫色交错分布，块状结构、纹理均匀，工业用地集中分布区可以通过影像直接判读，对于零星片状分布区需要结合地物名称来识别。住宅用地在城市中间圈层到边缘均有分布，呈现规则的方格状排列，颜色为白色斑状、白蓝色夹杂，纹理呈现规则的排列、结构粗糙。位于新城边缘区的裸土与农田可以通过遥感影像标志直接判读。

城市旧城区内商业用地、高层住宅用地、公共设施、公共建筑用地混杂分布，难以从遥感影像上直接判别，主要通过地物名称判别、城市规划图等

辅助信息参考，如城市中心区商业用地与居住用地的混合、公共用地与住宅用地的混合边界难以确定时通过城市规划图辅助信息加以识别。公共设施、公共建筑用地在新旧城区均衡分布，公共设施与主干道直接相连，呈圆形或规则排列，无阴影，结构复杂；公共建筑用地与主干道连接、部分带有圈状跑道与规则方格建筑镶嵌分布，颜色呈现棕黄色斑状、蓝色夹杂。基于上述方法对新旧城区不同类型功能用地采用层层深入的“分层分类”方法实现城市内部用地的信息提取。

2.3　城市内部用地结构演化信息数字重建

长春百年城市用地信息数字重建应用面向“对象分割”的分类方法实现，该方法以“街坊”为分割单元，通过逆序监测每一对象实体的空间行为来推演城市土地利用空间演变过程。比较前后两期城市用地信息，将对象分割体演变行为分为：对象不变型、对象分割型、对象属性改变型、对象实体扩张型。每期空间数据的提取是在前一期空间数据上进行对象的分割，直到产生最小分割体(S_i)，图形空间拓扑关系满足：

$$\bigcup_{i=1}^{k} S_i = \Omega, S_i \cap S_j = \phi$$

(i=1,2,…,k; j=1,2,…,k; $i \neq j$)，每个最小分割体有6个属性字段标识不同时期城市土地利用的类型，在专家知识的参与下将另一图层作为参考利用“相对位置法”人—机交互提取变化信息，最后进行一定的空间运算后可以获得6期城市用地演变信息(图1)。

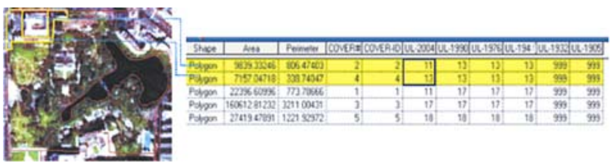

图1　城市用地提取的“对象分割”方法

历史时期的城市用地数字重建中最为重要的内容是分阶段对城市用地变化信息的跟踪，城市用地变化主要表现为城市外延式扩张与内部结构转换两种变化模式。根据历史时期城市现状图、功能分区图等信息对城市用地变化信息分别跟踪监测，城市外延式扩张主要以工业用地与居住用地的扩张为主，根据长春近百年来城市演化特征，城市内部结构调整表现为中心城区居住用地被商业用地置换，城市绿地被居住等建设用地置换，工业用地外迁后被居住用地置换等特征，通过变化前后用地类型的识别，应用上述方法实现城市用地信息的数字重建。

2.4　城市内部用地数字重建的信息提取

城市用地空间信息提取采用人工数字化方法实现，首先将SPOT5作为数字化参考图层，结合1∶1万地形图以及实地调查数据对城市主干道进行提取，画出城市基本道路框架，在城市主干道形成的各个街区内划定各城市次干道进而划分城市各街坊，通过分层分类的方法分别对街坊进行用地类型识别或针对街坊内的混合类型继续分割直到产生单一用地类型为止，分别赋予属性代码，经过拓扑建立后生成最终用户需求的城市用地分类结果。

历史时期的城市用地数字重建的实现首先在ARCVIEW 3.3的支持下交互提取城市边界并建立图1所示的属性表。在2003年城市边界信息的控制下进行用地分类，将分类代码写入属性表的UL-2003字段，直到分割到每个单元只表示一种类型。在1990年边界信息的控制下提取2003年城市用地矢量图叠置在1990年1∶1万地形图上，监测每个用地实体单元的变化情况，并将其分类，1990—2003年城市扩展部分在属性表UL-1990字段赋值999，用地实体单元单纯的用地转型在属性表UL-1990字段赋值转换后的类型代码，如果只是城市用地实体单元的一部分发生用地类型转换，依据1990年地形图对实体单元进行分割，将分割后用地类型不变部分在UL-1990字段赋予原类型代码，变化部分赋予变化后类型代码，依次对1990年逐个用地实体单元监测其空间变化情况。如上述方法逆序直到完成1905年城市用地对象分割，重建百年来城市用地演化空间信息(图2)。

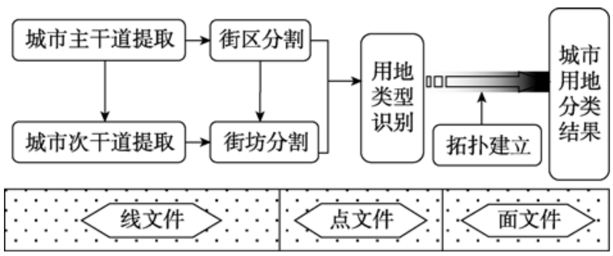

图2　城市用地空间信息提取方法

在Arc/info 9.0的支持下将ARCVIEW 3.3的shp格式转换成coverage格式，通过cal COVER-ID = UL-2003，UL-1990等生成6期城市用地数据，通过dissolve命令去除相邻具有相同属性值的用地实体单元，然后重建拓扑(clean)可以获得所需的城市用地数据。“对象分割”方法较传统的提取方法不仅可以解决多期城市用地空间分析中的定位精度问题，减小空间信息提取的“空间误差”，从而提高信息

提取的精度，特别是空间定位精度；同时“对象分割”方法还可以提高城市用地空间信息提取的效率。基于“对象分割”提取方法重建长春 1905 年、1932 年、1954 年、1976 年、1990 年、2003 年共 6 期城市用地空间信息。

3 结果与分析

长春近 100 年来保存了丰富的大比例尺历史地图、地形图、历史记载资料等高分辨率城市内部用地信息，为该研究提供了重要的信息源。空间数据涉及不同比例尺地形图，高分辨率遥感数据、历史地图、城市规划图等不同来源、不同性质的空间数据。本研究在 GIS 的支持下建立 1∶1 万方里网与图幅控制框作为城市地理空间定位基础的基本一级控制网，1∶1 万地形图投影采用 3°分带，长春市位于第 42 个带，采用高斯-克吕格横轴等角切圆柱投影。建立 1∶10 万、1∶5 万、1∶1 万方里网与包括 1∶1000 和 1∶500 在内的图幅控制框，将多级控制网以 1∶1 万地形图投影标准为基础，进行投影变化与坐标平移整合生成具有统一坐标系统的多级控制网。

综合多种城市用地空间信息提取城市内部用地类型，参考 1905 年城市旧城区轮廓图、1932 年新京(现长春市)城市现状图、1941 年城市地籍图与 1954 年 1∶10 万长春地形图，1976 年 1∶1 万地形图，1990 年 1∶1 万地形图和 2003 年 SPOT5 遥感影像并综合城市其他专题空间信息。基于“对象分割”方法提取长春 1905 年、1932 年、1954 年、1976 年、1990 年、2003 年共 6 期城市用地分类结果如图 3。

长春城市具有独特的历史，在近 100 年来经历了不同社会制度背景下的城市化过程。1905—1932 年城市土地利用增长主要集中于宽城子和旧城子，以住宅用地、道路用地以及城区空地为主，形成了城市建设的基础，大面积的道路建设和预留空地为城市发展提供了广阔的空间。1932—1954 年随着城市扩张住宅用地大面积增加。城市建设形成了朝阳、南关(旧城)、二道河子、宽城 4 个生活区。1954—1976 年以工业用地大面积增加为主。1976 年后城市现代格局基本形成，南关区与朝阳区位于城市中部形成基本的商业中心区，绿园区、北部的宽城区、东北部的二道区各自形成城市的工业和居住中心。1976—1990 年高新开发区、经济开发区与净月潭开发区工业、住宅用地也开始出现。1990—2003 年城市进入快速扩张时期，这一时段城市土地利用突出特点是高新开发区、经济开发区与净月潭旅游开发区各类用地大面积增加。

图 3 长春百年城市用地分类结果

4 结果验证与精度评价

空间数据误差主要包括空间位置误差和属性误差两类，由于历史城市用地分类空间信息是基于“对象分割”方法提取的，其他时段城市用地分类信息是在 2003 年城市用地信息各图斑边界控制基础上获取的，能够满足 2003 年城市用地信息精度要求。为提高城市用地分类精度，通过点、线结合方式对长春城市进行调查，包括长春市区及近郊区内总路线长度 204.5km，共计采集样点 122 个，调查包括城市各类用地类型，楼层高度，道路类型与宽度，新开发用地情况，城乡边界区土地利用、基础设施状况、居民职业状况，调查以城市交通图为基础进行空间位置标注、属性记录与实地拍照方式记录。根据城市土地调查以及 2003 年航片的采样用地类型为标准，对 2003 年城市用地分类进行精度评价。1905—1990 年城市用地数据通过统计进行相对精度验证。

通过航片与实地采样调查进行精度检验，各期图形能够满足 1∶2.5 万制图精度要求，2003 年平均分类精度达 95%以上，除公共建筑用地与设施用地

相对分类精度较低外，其他用地分类精度较高(表1)。通过将历史数据与其他时段面积进行对比验证，其分类精度达 92%以上。选择城市中心的 5 个街区对传统的分层提取方法与“对象分割”方法进行比较分析，发现“对象分割”方法能够在分类精度上提高 5.9%，面积精度提高 4.3%，6 期城市用地分类信息提取效率提高 62%，多期空间数据叠置分析中定位精度达到 98%。

表 1 不同用地类型信息提取精度分析

用地类型	样点数	正确数	分类精度/%
商业用地	17	16	94.12
工业用地	20	19	95.00
住宅用地	44	43	97.73
公共设施用地	4	3	75.00
公共建筑用地	18	16	88.89
道路用地	5	5	100.00
城市绿地	6	6	100.00
水域	3	3	100.00
其他用地	5	5	100.00
总计	122	116	95.08

5 结论与讨论

研究发展了一种“分层分类”与“对象分割”的基于多源空间信息集成下的高分辨率多期城市用地分类与动态空间信息提取方法与技术，以“街坊”为分割单元，通过逆序监测每一对象实体的空间行为推演城市土地利用空间演变过程。在专家知识参与下人－机交互解译，集成多源空间信息对于实现高精度城市用地空间信息提取具有较高的应用价值，该方法不仅提高城市用地分类精度，而且提高城市用地空间信息提取效率以及多期空间数据叠置分析中空间定位精度。

城市内部用地分类对于城市规划与管理、区域可持续发展研究是重要的空间信息，但是，由于城市用地分类需要满足要求较高的大比例尺制图精度，包括数据源的选择、图像纠正、空间信息提取方法等。本研究试图在城市扩张遥感监测基础上，发展内部用地分类方法，该方法适合于城市用地功能相对独立的大城市以及特大城市用地分类。

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