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Construction of an analytical framework for polygon-based land use transition analyses

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ABSTRACT

Polygon representation is important for characterizing land uses and the relationships among them. This study aims to establish an analytical framework for polygon-based land use transitions to understand the processes of change regarding types of land uses and their shapes. The polygon event and polygon state help to reveal continuity both spatially and temporally. A polygon event represents a combination of changes in both the type of land use and its shape through a transition process. A polygon state reflects homogeneity during the transition process. Two indices, the stability index and the compactness, were used to enhance the understanding of the transition process. The stability index evaluates the succession of an attribute, while compactness recognizes the geometrical characteristics of a polygon. A case study on Tsukuba City, Japan, was evaluated to demonstrate the feasibility of the approach that is presented here. The proposed analytical framework supports the clarification of land use transition patterns and is effective in explaining the spatiotemporal land use transition process.

1. Introduction

Land use transitions are directly influenced by human activities. Urban sprawl and deforestation, which are aspects of land use transitions, damage society and the environment. Many researchers have struggled to understand land use transitions to find a solution for sustainable development. The determination of the state attributes (time, location, shape, and land use type) at a certain time and the comparison between different time periods are fundamental to understanding land use transitions. Many indices (e.g., the average polygon area, perimeter, and total number of polygons) have been developed to grasp spatial characteristics at a specific time. A comparison of these index values at different time periods can be used for detecting temporal changes (Matsushita, Xu, & Fukushima, 2006; Thapa & Murayama, 2009). This comparison method using index performs spatiotemporal analysis using timestamps, even though earlier works have noted the lack of a precise temporal consideration (Langran, 1992; O'Sullivan, 2005). These methods have been developed for both raster- and polygon-based vector data. Raster-based methods are well developed because of data accessibility and the ease of maintaining locational consistency among different timestamps. Unfortunately, it is difficult to extend existing methods for raster-based data to polygon-based data because of the differences between these two data models (Robertson, Nelson, Boots, & Wulder, 2007). There is a critical conceptual difference between the raster-based raster format and the polygon-based vector format (Fig. 1). In raster-based land use data, each pixel has an individual digital value and is discrete pixel by pixel. This is quantitative approach and gives descriptive information. In polygon-based land use data, homogeneous space is signified as one polygon. This is qualitative approach. For example, a zoning map for city planning will show an equal regulation area in the same color and an irregular boundary. Land use is also identified by the boundary with differing adjacent land use types. Most of the homogeneous geographical spaces have irregular boundaries. Vector-based modeling takes advantages to represent the shape of geographical feature notably in micro-scale analysis. An irregular polygon in vector-format is a more feasible to representation of the boundary of a geographical feature than a regular cell representation in raster-format. Additionally, road networks or river channels, which have linear geometries, can be represented in vector-based data without interruption. These characteristics allow for detailed spatial analysis (e.g., adjacency relationships between polygons, adjacent polygons with road network, and others). The shape of a polygon is an important attribute for land use, as is the land use category (Williams & Wentz, 2008). Understanding comprehensive land use transitions requires analytical tools to explore the shapes and types of the land use. Polygon-based vector data analysis allows for a better detection of the inherent spatial structure of landscape patterns as compared with raster data analysis (Castilla & Hay, 2007; McGarigal, Cushman, Neel, & Ene, 2002; Stow, 2010; Wachowicz, 1999). The intersection of timestamps,

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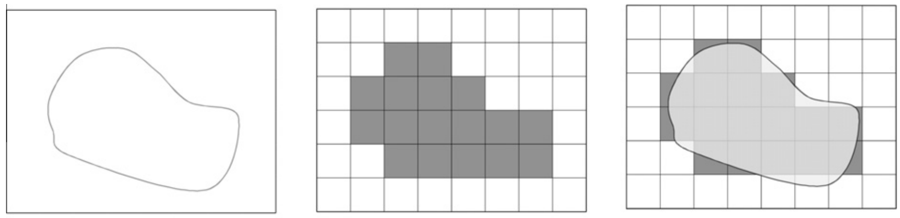

Fig. 1. Difference between raster-based representation and vector-based polygon representation.

which is fundamental to detecting land use changed areas, is based on the location and shape of geographical features. However, all the land use data should have a consistent map scale to detect actual land use changes. If land use data with inconsistent map scale are used, the results of intersection includes actual land use changes and sliver polygons. The location of geographical features is key to tracking them at different time slices and extracting changes in their shapes and attributes (Samtaney, Silver, Zabusky, & Cao, 1994). Polygon-based land use data reflect these geometric identifiers for spatiotemporal analysis. Because polygon-based land use data are popular and will continue to be in use in the near future (Stow, 2010), the development of polygon-based methods requires more attention.

This study aims to establish an analytical framework for polygon-based land use transitions that considers the types and shapes of the land use. This study defines type as an attribute, such as farmland or residential land. Each land use polygon has a single land use type. Shape is defined as the geometric characteristics of a polygon boundary that has defined dimensions.

The remainder of this paper is structured as follows: Section 2 describes how change is detected from polygon-based land use data. Section 3 introduces the definition of a polygon event and a polygon state and the indices for geometric characteristics. Section 4 illustrates the results that were derived from the proposed approach, which is to integrate polygon events and states as well as their indices, to understand the land use transition process. A discussion and conclusions are presented in Section 5.

2. Previous studies on polygon-based land use changes

According to arguments regarding the use of raster or vector formats, geographical information scientists have discussed spatiotemporal databases and their ability to capture the topological dynamics of geographical features (O'Sullivan, 2005; Peuquet, 2001; Prince, 1989). The focus of change detection has evolved from entity-based, relational-based, and object-based to event-based concepts (Hornsby & Egenhofer, 2000; Peuquet & Duan, 1995; Worboys, 2005; Worboys & Duckham, 2004). This evolution indicates the significance of the temporal process for representing the spatiotemporal process and its impact on the methodology of spatiotemporal analysis. Theoretically, object-based data acquisition is more effective than ground scanning methods, such as remote sensing, for detecting the changes of geographical features. For example, the cadastral data system has been taken into consideration for identity-based systems (Chen & Jiang, 2000; Meyer, 2004). The tracking of land ownership registration can clearly account for the significance of taxing for public projects, but it is much more expensive than the usual timestamp databases. Except for a specific case such as the cadastral system, there is a certain limitation to tracking changes in general land use when constructing an identity-based database. In addition, raster-based land use data fail to represent irregularly shaped geographical features.

Furthermore, the geographical research perspective has been separated from time and is devoted more to spatial process analysis (Fotheringham et al., 2000; Gregory & Healey, 2007; O'Sullivan, 2005). Even though the framework for the spatiotemporal processing of geographical features as data information has been constructed, most existing land use data follow the snapshot concept. Therefore, at the analytical phase, it is difficult to consider the spatiotemporal continuity, which demonstrates the gap between the conceptual framework and the hands-on approach. To resolve this problem, some authors have developed spatiotemporal analytical methods based on the intersection concept (Robertson et al., 2007; Sadahiro & Umemura, 2001; Xie & Ye, 2007). These methods consider both qualitative and quantitative approaches for analyzing spatiotemporal aspects using a land use timestamp, which is also represented in the polygon and spatiotemporal continuity. These considerations of the existing methods are supported by polygon-based representations, which can identify geographical features by their shape through the transition process. Ordinary polygon-based land use data fill the space completely at a certain time without overlapping or creating gaps between different polygons of alternative land use types. The land use type of each polygon can be changed to other land use types at the same location during the transition process, which indicates that both the disappearance of existing features and the appearance of new features occur at the same location and at the same time. The existing methods, which focus on a specific polygon attribute, fail to avoid redundancy, thus complicating the spatiotemporal analysis of the land use transition process. For example, Sadahiro and Umemura (2001) chose two primitive events, *generation* and *disappearance*, from Claramunt and Theriault (1996) and added four new primitive events, *expansion, shrink, union*, and *division*, to analyze the polygon distribution. Robertson et al. (2007) set four events to describe geometric changes in polygons: *generation, disappearance, expansion*, and *contraction*. Their methods assume that polygons have a single attribute. Land use change (e.g., from farmland to residential land) falls outside of these premises. A polygon, therefore, could appear and disappear in these methods.

The current study develops four polygon events and six polygon states to describe land use transition processes. A polygon event represents a primitive event that occurs within a polygon. The polygon state covers whole transition patterns. By combining polygon event and state, model redundancy can be avoided, as in the case of the disappearance and generation of polygons at the same location and same time period using timestamp land use data. This study enhances these points for land use transition process analysis.

3. Methodology

3.1. Conceptual framework

When compared with the raster representation, the vector representation is more appropriate for characterizing discrete features