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

Chiaki Mizutani *

*Division of Spatial Information Science, Graduate School of Life and Environmental Sciences, University of Tsukuba, Ibaraki, Japan*

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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,

* Permanent address: 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8572, Japan. Tel.: +81 29 853 5694; fax: +81 29 853 6879.

*E-mail addresses:* mizutani.sis@gmail.com, mizutani@geoenv.tsukuba.ac.jp

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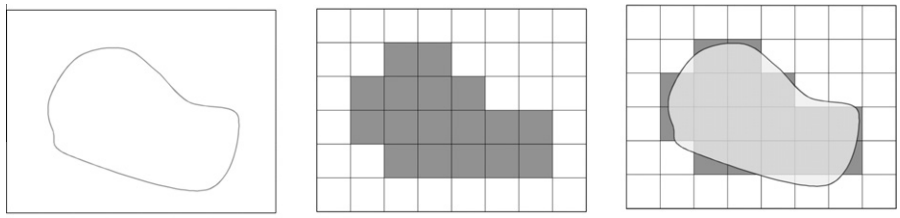



**Fig. 1.** Difference between raster-based representation and vector-based polygon representation.

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

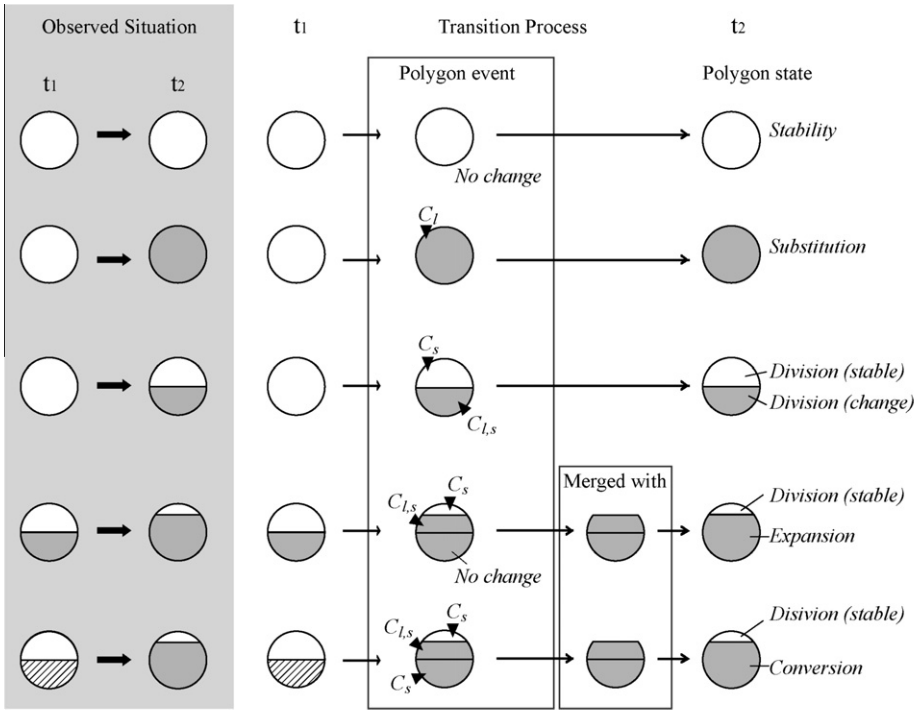



**Fig. 2.** Land use transition process considering polygon events and polygon state. *Notes*: In polygon event, *C* represents "change". The suffixes: $_l$ and $_s$ are abbreviations of "land use type" and "shape", respectively. "Merged with" represents merging the boundary of adjacent polygon event which have same attribute. *Conversion* in polygon state includes ($C_l$ or $C_{l,s}$) as polygon event.

**Table 1**
Definition of polygon event.

| Change in land use type | Change in shape | Polygon event |
|---|---|---|
| | | *No change* |
| ✓ | | $C_l$ |
| | ✓ | $C_s$ |
| ✓ | ✓ | $C_{l,s}$ |

*Notes*: Polygon event has formulated concept based on intersected polygons with land use of $t_i$ and $t_{i+1}$.

and the relationships among the features because it can consider polygon adjacency and topological relationships (French & Li, 2010). Specifically, polygon representation can consider the changes in both the type of shape and the attributes as characteristics of transition processes. The target phenomenon of this study is the land use transition process. Land use fills the whole surface of the study area (if there is no exact category, then the area is classified as unclassified). In the transition process, there are some locations in which disappearance and generation occur simultaneously. A process description should be made in a minimal and simple way (Sadahiro & Umemura, 2001). Following the theory, this study takes polygon event and polygon state to model the transition process. The event and state are the fundamental concepts of the spatiotemporal process (Langran, 1992). The polygon event focuses on the changes in shape and attributes. The polygon state considers the spatial continuity and the adjacency during the transition process.

### 3.1.1. Polygon event

Polygon event characterizes transition patterns that are based on a combination of shapes and attributes from time 1 ($t_1$) through time 2 ($t_2$) (Mizutani, 2009a,b). Usually, a land use transition is analyzed using timestamps of land uses at $t_1, t_2, \ldots, t_n$. If there are timestamps of $t_1$ and $t_2$, then these timestamps can detect differences throughout the investigated period. It is crucial to track the land use history (Meyer, 2004). Vector-based land use data can represent the boundaries of continuous land use types. Both the land use type and the shape of the polygon indicate the characteristics of land use transitions. Polygon event has four categories, which are based on combinations of changes in the shape and land uses: *No change*, $C_s$, $C_l$, and $C_{l,s}$ (Fig. 2 and Table 1). *C* represents "change". The suffixes *l* and *s* are abbreviations of "land use type" and "shape", respectively. For example, $C_{l,s}$ indicates that the polygon was divided, and the land use type was changed at the intersection of two timestamps.

### 3.1.2. Polygon state

Polygon state expresses the homogeneity of an attribute. The polygon state has six categories based on the boundary of $t_2$; some polygons consist of multi-polygon event boundaries (Table 2). If the polygon consists of a single polygon event, then there are choices that are classified into one of four polygon states. A single polygon inherits the state of four polygon events, i.e., *stability, substitution, division* (*stable*), and *division* (*change*) (Fig. 2).

If a polygon consists of multi-polygon events, then there are two choices. The merged polygon will be classified into one of two categories: *expansion* or *conversion*. If the land use type is different from all of the components of the merged polygons at $t_1$, then the polygon is categorized as *conversion*. A *conversion* polygon shows a new land use, from one of $t_1$ uses. If there is an area that has the same land use type as $t_1$, then the polygon is categorized as *expansion* (Table 3).

## 3.2. Indices for transition process

Polygon-based land use data accept the application of shape measurements for individual geographical features. The polygon shape is an inherent aspect of polygon-based land use data. There are many indices that are based on the shape of a geographical feature (Boyce & Clark, 1964; Wentz, 2000; Williams & Wentz,

**Table 2**
Definition of polygon state.

| Intersected polygons with land use of $t_i$ and $t_{i+1}$ | Components of polygon event | Land use of $t_{i+1}$ Polygon state |
|---|---|---|
| Single | *No change* | *Stability* |
| | $C_l$ | *Substitution* |
| | $C_s$ | *Division* (*stable*) |
| | $C_{l,s}$ | *Division* (*change*) |
| Merged | Combination of stable land use polygon and/or changed land use polygon | *Expansion* |
| | Combination of changed land use polygons | *Conversion* |

*Notes*: Polygon state has formulated concept based on geometry of $t_{i+1}$ and land use comparison between $t_1$ and $t_{i+1}$.

**Table 3**
Pair of polygon event in "*expansion*" and "*conversion*".

| Polygon event | *No change* | $C_l$ | $C_s$ | $C_{l,s}$ |
|---|---|---|---|---|
| *No change* | – | E | – | E |
| $C_l$ | | Co | E | Co |
| $C_s$ | | | – | E |
| $C_{l,s}$ | | | | Co |

*Notes*: E is abbreviation of "*expansion*", and Co is abbreviation of "*conversion*"; Blank columns have same category at the diagonal position; "–" shows "not applicable"; If more three types of polygon event are included in one polygon at $t_2$, polygon state is classified as "*expansion*". Because it means combination of stable land use polygon and changed land use polygon.

2008). In accordance with the use of polygon states for understanding the transition process, two indices (the stability index and compactness) are selected. In this study, the stability index evaluates the continuity of the land use through the process and considers the consistency of a polygon state. The compactness is indicative of the homogeneity within a boundary, which is recognized from other polygons. The purpose of applying shape measurements in this study is to grasp the relationships between land use transition and the geometrical character of polygon.

### 3.2.1. Stability index

Stability is a land use characteristics that depend on the rate of land use changes (Kim, Mizuno, & Kobayashi, 2002). The stability index (SI) represents the occupancy of a polygon that keeps its land use type during the land use transition process (Eq. (1)). The numerator $A_{i,t_1 \sim t_2}$ represents the succession area from $t_1$ to $t_2$ for land use type (i). The denominator $A_{i,t_2}$ represents the total area of land use type (i) at $t_2$.

$$\mathrm{SI}_i = A_{i,t_1 \sim t_2} / A_{i,t_2} \tag{1}$$

According to Eq. (1), the numerator is the sum of *no change* and $C_s$ at $t_2$. The numerator shows the succession area as land use type (i) during the land use transition process at the same location. A low SI value indicates that the land use type acquires more new area than the succession area as a result of land use transitions. According to the definition of the polygon state, an SI value of 1.0 indicates *stability* or *division* (*stable*). A value of 0.0 indicates *substitution*, *division* (*change*), or *conversion*. Only *expansion* includes the range of SI values from 0.0 to 1.0.

### 3.2.2. Compactness

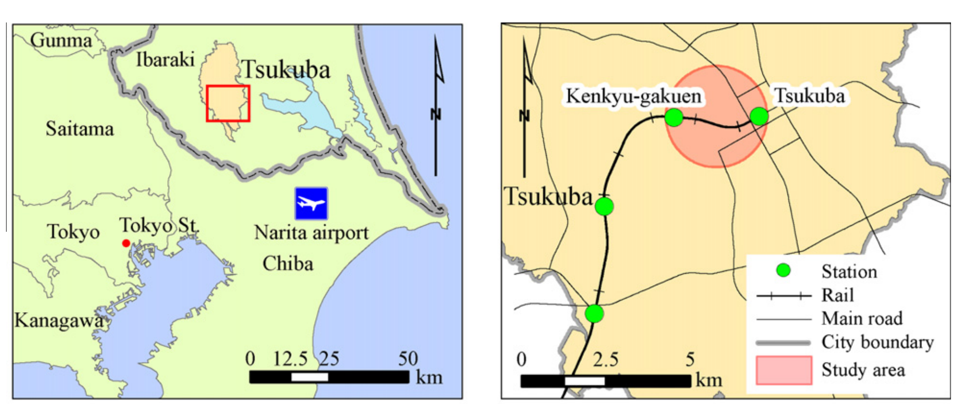
Geographical features represented in polygon-based formats have geometric properties that may vary from feature to feature (French & Li, 2010). Compactness is a relevant factor in the description of geographic shapes (Maceachren, 1985). In this study, compactness is a primitive index that uses the area and perimeter, as follows (Eq. (2)):

$$\text{Compactness} = \sqrt{\text{Area}}/(0.282 \times \text{Perimeter}) \tag{2}$$

The value ranges between 0.0 and 1.0. The value 1.0 indicates that the shape of the polygon is a circle as ideal geometry. The value of a square is 0.89. Except for a circle or square, the index value is not unique. Several researchers have reported the accuracy limit of the index (Shirabe, 2005), but the purpose of measuring the compactness in this study is to measure the geometrical similarity with squares based on a fundamental assumption that the polygon resembles a rectangle land shape. This suffices the needs as this study is not using compactness to detect change in polygon shapes.

## 3.3. Study area and data used

The study area that was selected to apply polygon-based analysis is a central part of Tsukuba City, Ibaraki, Japan (Fig. 3). This study area is delineated with a 1.5 km radius that covers two major train stations, Tsukuba and Kenkyu-gakuen. A new train system (Tsukuba Express, TX) was established in 2005. Rapid land development related to the new train system has occurred since 2000,




(a) Tsukuba City (b) Study area

**Fig. 3.** Study area-Tsukuba City, Japan.

and it has been speculated that the opening of this system impacted the land use in the surrounding area before and after 2005. Land use data for the years 2000, 2005, and 2008 were used to conceptualize land use transition processes. The 2000 land use map was published by the Geographical Survey Institute (GSI) Japan (2007). Polygons with areas of less than 6.5 $m^2$ are ignored at the digital map scale level that was used. Land use data for 2005 and 2008, which have consistent map scale as land use of the year of 2000, were updated using ortho-photos (2005 and 2008), Zmap Town II (2005 and 2008), fundamental geospatial data (GSI, 2008), and field surveys. The consistency of map scale guarantees that any changes in polygon shape are due to changes in land use. The intersected land use polygons of different time periods (2000–2005 and 2005–2008) are classified into four polygon events and six polygon states. To investigate the relationships between the geometrical character and the transition process, SI was used for each period while compactness was used for the 3 years.

**Table 4**
Land use structure in percentage.

| | Land use type | 2000 | 2005 | 2008 |
|---|---|---|---|---|
| 1. | Forest/wasteland | 13.5 | 9.0 | 5.8 |
| 2. | Paddy field | 7.8 | 5.0 | 3.0 |
| 3. | Dry field/other farmlands | 22.1 | 17.2 | 13.9 |
| 4. | Land under construction | 1.6 | 9.8 | 11.9 |
| 5. | Vacant land | 3.7 | 4.6 | 6.6 |
| 6. | Industrial land | 0.4 | 0.4 | 0.4 |
| 7. | Low-storey residential land | 11.0 | 11.7 | 13.3 |
| 8. | Densely developed low-storey residential land | 0.1 | 0.1 | 0.1 |
| 9. | Medium and high-storey residential land | 3.2 | 3.7 | 4.1 |
| 10 | Commercial land | 12.0 | 12.4 | 13.1 |
| 11. | Road | 12.0 | 13.0 | 14.0 |
| 12. | Park/green space | 3.1 | 3.0 | 3.0 |
| 13. | Public facility | 9.0 | 9.4 | 10.3 |
| 14. | Water | 0.7 | 0.8 | 0.5 |
| Total | | 100.0 | 100.0 | 100.0 |

## 4. Results

### 4.1. Land use change

Dry field/other farmlands, forest/wasteland, commercial land, road, and residential land shared more than 10.0% of the total land use in 2000 (Table 4). The placement for each land use type was segregated by road. Land under construction increased significantly in 2005, especially near Kenkyu-gakuen station and along the TX railroad in 2005. The main land resources for development were forest/wasteland. In 2008, roads exhibited the highest coverage of land in this area (14.0%). The transition trend of land development during the period from 2000 to 2005 was stronger than in the period from 2005 to 2008. The Land under construction was converted into vacant land, roads, commercial land, and public facility. At the same time, land under construction increased the land by forest/wasteland, dry field/other farmlands, and other land use types. Land under construction increased from 1.6% to 11.9% during the entire study period. Finally, dry field/other farmlands, residential land, and commercial land exhibited a similar occupancy of approximately 13.1% in 2008.

The shapes of the roads in the polygon data have distinctive features: connectivity and linear shapes. Although the roads are often represented by linear representations, when a road is represented in a polygon that includes road width, the total area occupied more than 12.0% of the land throughout the study period. Land use transition separated roads from other land uses because of the linear feature. Fig. 4b and c shows the area of changed land use from $t_1$ to $t_2$. The increase in land under construction mainly occurred in the surroundings of Kenkyu-gakuen station and along the newly developed road during the first period: 2000–2005 (Fig. 4b). A large commercial land area was also constructed at this time. Residential, vacant, and other land uses are scattered throughout the whole study area. Fig. 4c shows the progress of land development around Kenkyu-gakuen station. Residential land, park/green space, and commercial land were built around the station. New dry field/other farmlands appeared in the southeast region of the previous developing land. The vacant land along the road were mostly converted into commercial land.

### 4.2. Land use event

Fig. 4a and b shows the distribution of polygon events. *No change* occupied approximately 50% of the study area for each period. A large development area exists mainly for $C_s$ and $C_{l,s}$ in the surroundings of Kenkyu-gakuen station (Fig. 4a and b). Compared with Fig. 3b and c, the aggregated land of $C_{l,s}$ and $C_s$ moved to the fringe of the changed area in the first period, but in the second period in 2008, newly developed roads divided the forest/wasteland or land under construction into small lots (Fig. 5b). There are large lots of $C_l$ shown in Fig. 5a and b, which mainly include land under construction or commercial land as a land use type (Fig. 5b). $C_s$ is the second occupancy category, while $C_{l,s}$ is the third. Even though the polygons are divided, two-thirds of them maintain their original land use type. The fourth occupancy category is $C_l$, which only changed the land use type. When land use change occurred, most of the polygon shapes also changed at the same time. Application of the polygon event showed the importance of the consideration of geometrical change for understanding the transition process.

### 4.3. Land use state

In Fig. 5a and b, $C_s$ and $C_{l,s}$ changed into *expansion* or *conversion*, respectively (Fig. 4c and d). The largest *conversion* area was located in the surroundings of Kenkyu-gakuen station, as shown in Fig. 5c. In Fig. 5d, the *conversion* polygons were divided, and the land use categories changed. The locations of *conversion* polygons moved to the fringes of the previous locations of *conversion* polygons. In Fig. 3d and e, these *conversion* polygons show public facilities at the surroundings of Kenkyu-gakuen station and forest/wasteland, land under construction, and vacant land at the fringe of changed land use areas. This scenario indicates a shifting of land use transitions and the progress of land development.

The order of occupancy was as follows: *stability*, *expansion*, *division* (*stable*), *conversion*, *division* (*change*), and *substitution*. Most of the $C_s$ are involved in *expansion*, which is why the order of *division* (*stable*) shifted to the third occupancy category. $C_{l,s}$ was involved in both *expansion* and *conversion*. The comparison of the contents of *expansion* and *conversion* shows that the combination of $C_l$ and $C_{l,s}$ has similar areas in each period (Fig. 6). The proportion of $C_s$ and *no change* has two-thirds of the total area of *expansion*. This result means that the *expansion* expresses the neighborhood condition as a category.

### 4.4. Land use stability

According to the definition of the polygon state, *expansion* is the only category that has the diversity of an SI value from 0 to 1. Fig. 7 represents SI values of *expansion* for each land use type in 2005. A land use type that has less than five polygons is ignored to ensure the diversity of the SI values. The values were distributed gradually from 0.32 to 0.99. Approximately four-fifths of the total *expansion* polygons (116 of 149) had an SI value of greater than 0.50. This result indicates that when *expansion* occurred, the succession land

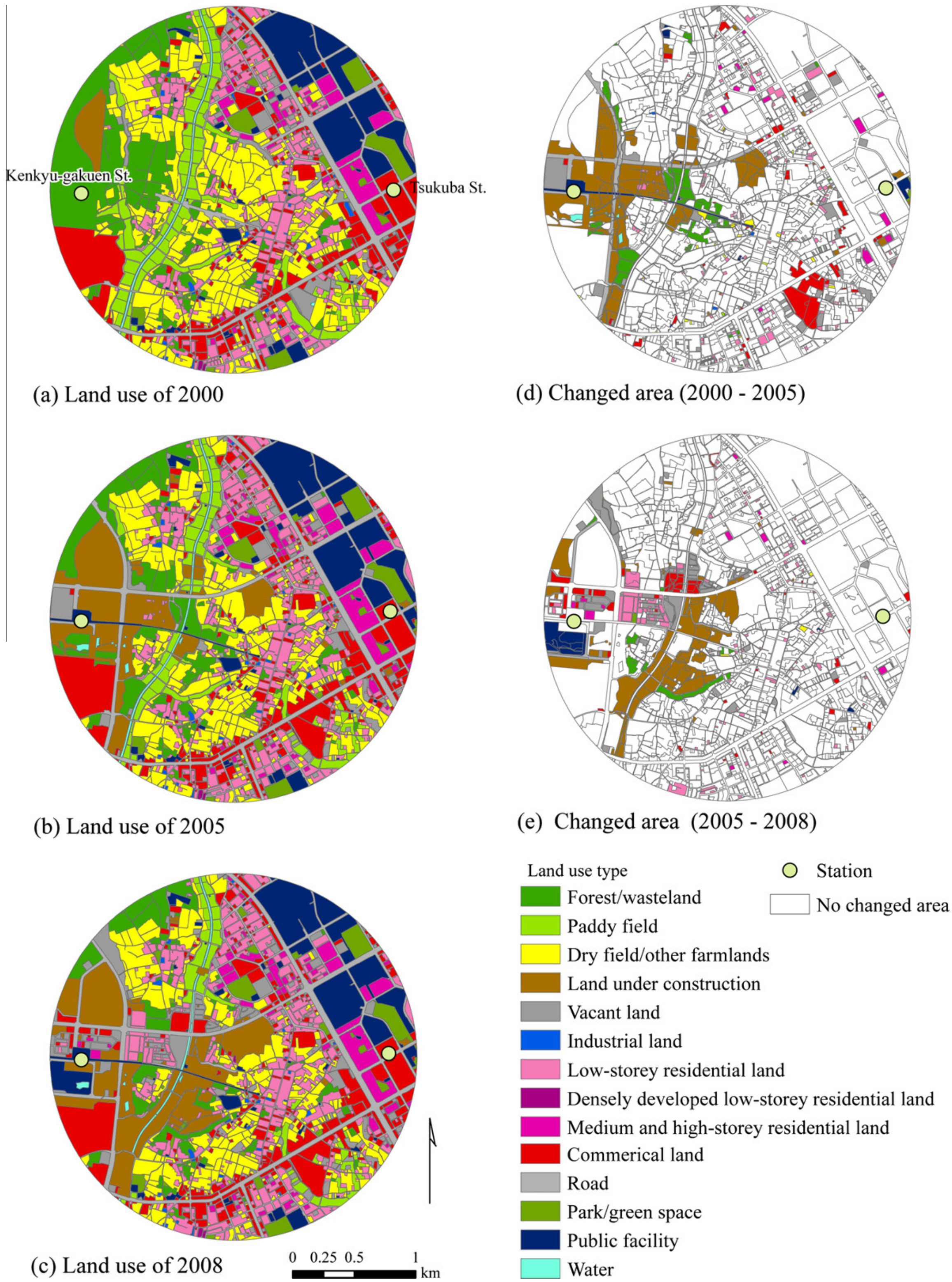



**Fig. 4.** Land use and land use changed area.

use type among the merging polygons affects the neighborhood polygons. A polygon in $t_1$ was affected by an adjacent polygon that has the same land use type, from $t_1$ to $t_2$; then, land use change and/or division of the area occurred. From this perspective, *expansion* mirrors adjacency because polygon presentation reflects not only the homogeneity of the land use type but also its spatial continuity.

*4.5. Land use compactness*

The histogram of compactness shows a similar trend among the three periods (Fig. 8). The highest frequency is shown in the range from 0.89 to 0.90. The values show that the major polygon shape is similar to the squares. Using the Jenks natural breaks classification (Slocum, 1998), the compactness is classified into three types with

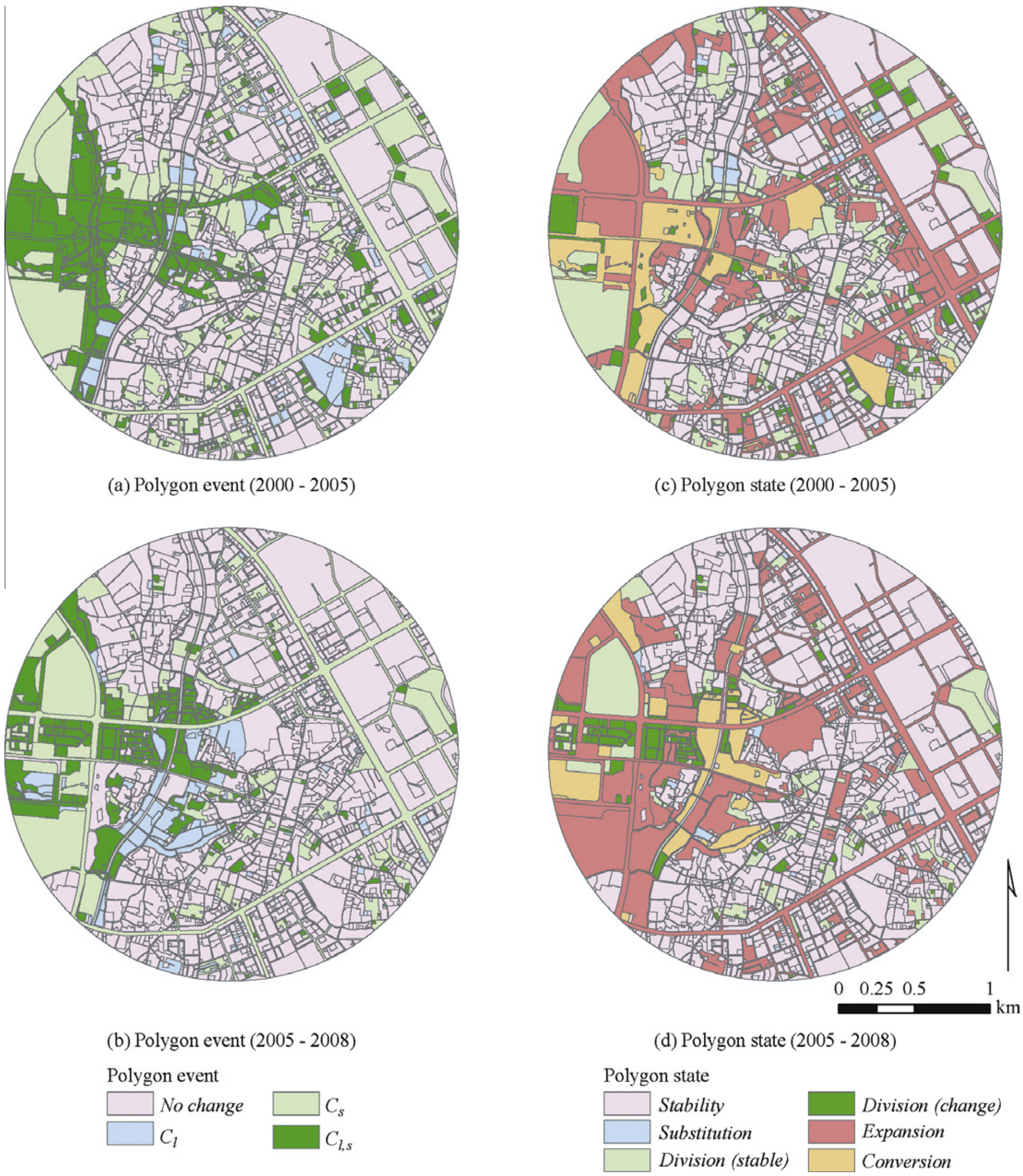



**Fig. 5.** Distribution of polygon event and polygon state.

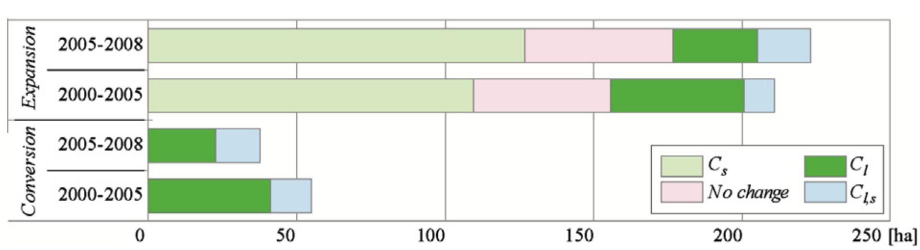



**Fig. 6.** Contents of "*expansion*" and "*conversion*".

approximate ranges as follows: 0.0–0.58 (group 1), 0.59–0.77 (group 2), and 0.78–1.0 (group 3).

Comparing the compactness and the map for each year, each group has a typical shape, as follows. The typical shape of group 1 is a line-style polygon, or a complicated concave polygon. Road and water are the distinguishing land use types. Some polygons have several holes inside their areas. For example, a large vacant area was broken up by several individual residential areas. These holes make the perimeter longer, decreasing the compactness. Group 2 includes many concave polygons, and some of their shapes appear to be C-shaped or U-shaped. The proportion of the long sides to the short sides of the rectangular polygons was more than three to one. Polygons of group 2 are often adjacent to group 3 polygons. These polygons consisted of residential parcels that were

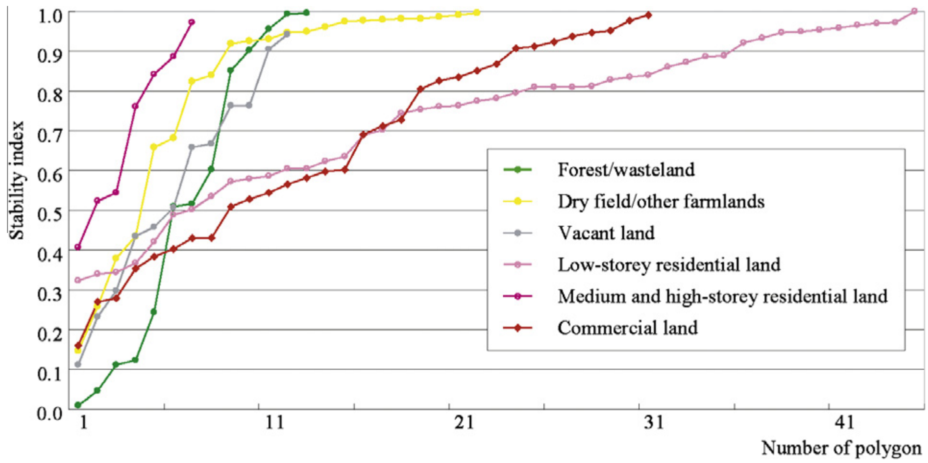



**Fig. 7.** Diversity of SI in "*expansion*" polygon state for each land use type.

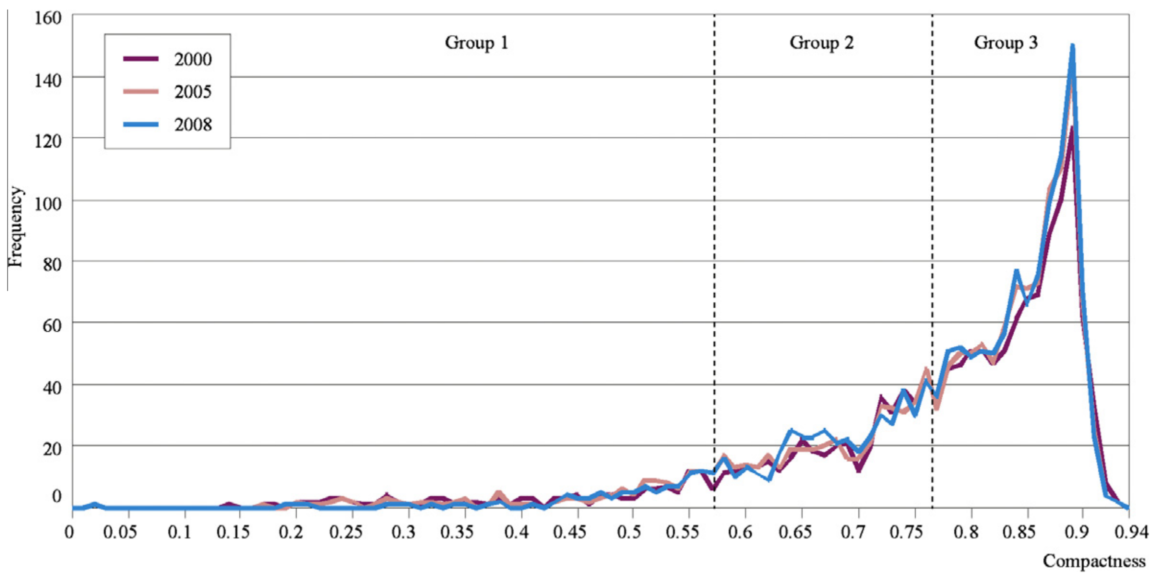



**Fig. 8.** Histogram of compactness. *Notes*: There is no frequency at more than 0.94 class.

divided by roads. The typical shape of group 3 included convex polygons and rectangles in which the proportion of the short side to the long side was approximately two to one. These areas become more compact than other types. Some of the polygons in group 3, which were categorized as concave, have an L-shape. Even when a concave polygon had more vertexes, their interior angles were approximately 90 or 270 degrees.

### 4.6. Land use transition and geometric characteristics

To investigate the relationships between geometrical characteristics and the transition process, first the SI for each land use type is selected as an index that shows the succession of an attribute. The combination of change in the total area and SI values can be categorized into four classes (Fig. 9). The first class (land under construction, vacant land, commercial land, and road) increased both in its total area and SI values throughout the study period. Although the total area increased, the growth rate decreased. The increase in the succession area increased the area of *stability* during the second period. Most notably, land under construction and vacant land rapidly increased during 2000–2005, which made these SI values lower than for the other land use types in 2005. The SI values of these two land use types were still 0.5 in 2008, even though the SI values increased. The second class (forest/wasteland) was characterized by both a total area that was decreased with an increase in the SI, i.e., the total area decreased, and the conversion process slowed down. While the total area of forest/wasteland decreased, there were some gains from other land use types during the first period, but the increase in these areas was much less than for the stable land. As a transition process, the gain of forest/wasteland was converted into land under construction and vacant land in the next period. The total area not only decreased but the gain from other land uses during the second period also decreased. As a result, the land use stability increased. Specifically, the third class (low-storey residential land and public facility) was represented by a total area that increased, with similar values for the SI. These land use types show a high SI value in the first period. During the transition process, most of these land use type polygons remained as the same land use type. SI values were maintained at a certain level. The fourth class (paddy field and dry field/other farmlands) showed both a total area and an SI values that decreased. The loss area of these classes is not small, but the structure of the polygon events reflects the stability of the existing area.

Second, compactness is selected for discussing the polygon state. Tables 5 show the structure of the polygon states in the three compactness groups. A comparison of Table 5a (polygon state in

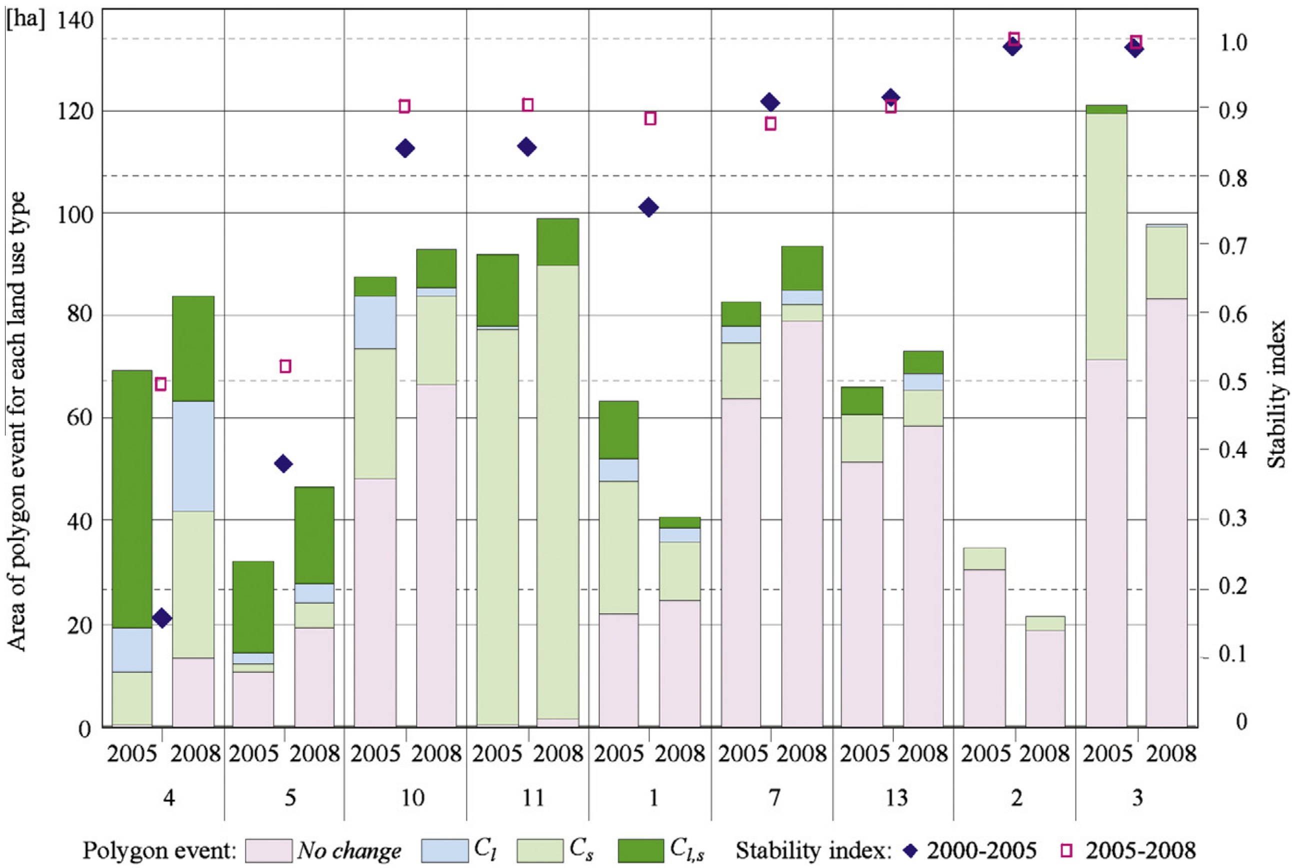



**Fig. 9.** Area of polygon event for each land use type and stability index. *Notes*: Land use type: 4 Land under construction, 5 Vacant land, 10 Commercial land, 11 Road, 1 Forest/wasteland, 2 Paddy field, 3 Dry field/other farmlands, 7 Low-storey residential land, 13 Public facility.

**Table 5a**
Temporal characteristics of compactness and polygon state (2000–2005).

| Polygon state | Group 1 | Group 2 | Group 3 | Sum | N |
|---|---|---|---|---|---|
| *Stability* | 5.08 | 16.52 | 39.46 | 61.05 | 950 |
| *Substitution* | 0 | 0.19 | 1.29 | 1.48 | 23 |
| *Division (stable)* | 1.93 | 4.43 | 6.62 | 12.98 | 202 |
| *Division (change)* | 0.64 | 2.76 | 8.87 | 12.28 | 19 |
| *Expansion* | 2.06 | 4.24 | 3.28 | 9.58 | 149 |
| *Conversion* | 0.77 | 0.77 | 1.09 | 2.63 | 41 |
| Sum | 10.48 | 28.92 | 60.60 | 100.00 | 1556 |

*Notes*: All the unit of value is in percentage except "*N*". "*N*" represents "number of polygon". Compactness of each group is calculated based on land use in 2005.

**Table 5b**
Temporal characteristics of compactness and polygon state (2005–2008).

| Polygon state | Group 1 | Group 2 | Group 3 | Sum | N |
|---|---|---|---|---|---|
| *Stability* | 7.46 | 22.27 | 45.17 | 74.9 | 1164 |
| *Substitution* | 0.06 | 0.32 | 1.42 | 1.8 | 28 |
| *Division (stable)* | 1.48 | 1.99 | 2.12 | 5.6 | 87 |
| *Division (change)* | 0.26 | 2.51 | 5.6 | 8.37 | 130 |
| *Expansion* | 1.93 | 2.9 | 2.45 | 7.27 | 113 |
| *Conversion* | 0.19 | 0.64 | 1.22 | 2.06 | 32 |
| Sum | 11.39 | 30.63 | 57.98 | 100 | 1554 |

*Notes*: All the unit of value is in percentage except "*N*". "*N*" represents "number of polygon". Compactness of each group is calculated based on land use in 2008.

2005) with Table 5b (polygon state in 2008) shows how the compactness changed through the land use transition process. The percentage of *stability* increased from 2005 to 2008 in Tables 5. This increase means that polygons classified as the other polygon states, except for *stability* from 2000 to 2005, have not changed in land use and shape. In other words, polygons that changed in land use or shape for the first period kept the state and were classified as *stability*. The percentage of *stability* increased in later periods for all three groups. Focusing on groups 2 and 3, land use transition during the first period made the shape of many polygons diffuse while the transition during 2005–2008 made them relatively compact. Fig. 6 shows that the decrease of $C_l$ and $C_{l,s}$ in the structure of *expansion* during the two periods and the SI value they represent went up because of a lower ratio of land use changed area in *expansion*. A decrease in new land use changed area in *expansion* reflected a lower impact on the shape of the polygon, which did not change the land use. Then, low compactness *expansion* polygons decreased. Thus, stabilization of the transition process impacts the shapes of the polygons. During the study period, the proportion of *stability* increased, and the proportions of both *division* (*stable*) and *division* (*change*) decreased. Through the land use transition process, some polygons became partially integrated to create a large site and were divided into several individual small polygons. As a whole, most polygon states, except for *expansion* and *conversion* in the first period, showed similar distribution patterns for compactness among the three groups.

## 5. Discussion and conclusions

Spatiotemporal analysis for polygon-based land use is important to understand land use transition processes. This study established approaches for polygon-based land use transition analysis that considered the types of land use and their shapes. The polygon event and polygon state were developed to perform a spatiotemporal analysis of the geographical features, which is distinguished from other work and is based on the shape and attributes of a polygon. A land use event indicates that most of the polygon shapes changed at the same time when the land use change occurred. *Expansion* considered the neighborhood conditions and adjacency because $C_s$ and *no change* showed a high proportion of the total area of *expansion*. The adjacency of land use polygons, which is represented in *expansion*, corresponds to specific spatial relationships with nearby features in the vector data, as was suggested by French and Li (2010). The results of using polygon event and polygon state mirror the nature of land use, as it fully fills the study area with land use polygons without overlapping or leaving gaps between polygons and uses several land use types. When new land use is generated, the designation of the location should be changed from the old land use type to the new land use type. At that time, it is rare to have the changes in land use which occur at exactly the same location and with the same boundary as the old land use (this type of change is classified as $C_l$ in the polygon event and *substitution* in the polygon state). In many cases, the shape of the land use also changes. When we use timestamps on the land use, the location is the absolute identifier, and each land use polygon has a single land use type. These points should be considered with respect to the feature of polygon-based land use data for land use transition analysis. The stability index evaluates the succession of an attribute. Thus, the polygon state and SI represented spatiotemporal continuity during the land use transition process. Additionally, compactness recognizes convex polygons and clarifies the characteristics of polygon states from the geometric point of view. The comparison between two time periods using the developed method shows the characteristics of land use transition and the changes in shape. Aggregation of land makes many polygons with low compactness values during the land development phase. On the other hand, increasingly compact polygons shows the stable trend of a transition process regarding changes in the land use type. But, even though the area of changed land use type is small, aggregation of land has occurred. The shape of a land use polygon is more frequently changing than the land use type. All those aspects make it obvious that polygon-based approaches are better at grasping the relationships between land use transition and the geometrical character of polygon for land use transition analysis than do raster-based approaches.

The present study examined how a polygon-based analytical framework works in land use transition analysis. For example, a tool (STAMP) developed by Robertson et al. (2007) enhanced spatiotemporal analysis, which was developed in the works of Sadahiro and his colleagues (Sadahiro, 2001; Sadahiro & Umemura, 2001). An application of STAMP presented an analysis of the spreading of wildfire (i.e., the outbreak, movement, and extinction of the wildfire) and the distribution of beetle-attacked trees (Robertson, Nelson, Jelinski, Wulder, & Boots, 2009). These examples imply that the target polygon shows either the existence or non-existence of a focusing attribute. The methodology helps to simplify and model the real world using a qualitative approach. Robertson et al. (2007) pointed out the necessity of an analytical method based on the attributes of the boundary; thus, a qualitative approach is as important as a spatial analysis for understanding the mechanisms of real-world representations with polygons. Land use, which is the subject of this study, results in boundaries that are based on differences in the types of land use. As a result, all of the polygons constructed in the study area show the existence of a land use type that is distinguished from others. For this case, the proposed approach helps to understand continuity both spatially and temporally. These findings represent fundamental examples of transition processes that employ polygon-based data. The patterns and processes that are identified are location specific; thus, the results provide a reference for other sites that have been developed by planning, such as in the study area. The approaches based on the results of the intersection operation and the measuring of the geometric features, which are included in standard GIS software, can be adopted for many uses.

The spatiotemporal analysis in this study was conducted using a multiple bi-temporal analysis method. Huang, Li, and Wu (2009) pointed out the lack of temporal continuity aspects in previous spatiotemporal analyses and analyzed spatiotemporal characteristics for successive timestamps. Advancing spatiotemporal analysis requires developing a method for multi-temporal analysis. Another area that requires attention is the availability of data in a polygon-based land use data set, which is limited compared with a raster-based data set. Further improvements of both the spatiotemporal analytical method and spatiotemporal data management are critical. In addition, future studies should analyze individual polygons to gain a deeper understanding of the transition process. The approach developed in this study is shown to be effective for understanding the spatiotemporal land use transition process. This approach will aid in the evaluation of polygon-based land use data and demonstrates the importance of the spatiotemporal perspective, which is necessary to consider when planning for the future based on real-world conditions.

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