Addressing urban expansion using feature-oriented spatial data in a peripheral area of Ulaanbaatar, Mongolia

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Abstract

Because of the lack of time-series spatial data on urban components, urban expansion in developing countries has usually been studied using a pixel-based approach, despite the coarse spatial resolution associated with this technique. To understand the residential-scale processes involved in urban expansion, we developed feature-oriented GIS data extracted from very high spatial resolution satellite images (IKONOS for 2000 and Quickbird for 2006 and 2008). We selected a fringe area of Ulaanbaatar, the capital municipality of Mongolia, as a case study. Residential plots in this area have developed in an unplanned manner owing to the poor execution of land reform policy. This study facilitated the residential-scale delineation of the significantly expanding area occupied by private land plots in time series. It also permitted the identification of geographical factors driving the expansion. Using a logistic regression model, we found that such expansion is related to social infrastructure rather than to natural landforms. In particular, new plots of private land tended to be built near pre-existing plots and in proximity to roads and water kiosks (which provide essential drinking water for residents). These findings and the probability map predicted by the model have implications for urban planners and decision makers.

Keywords:
Urban expansion; Feature-oriented GIS data; Logistic regression model; Ger area; Ulaanbaatar

Highlights:

- Urban expansion processes are depicted realistically by feature-oriented GIS data.
- Implementation of land privatization policy has disrupted land management.
- Social infrastructure is strongly related to urban expansion.

1. Introduction

Cities all over the world have been expanding, driven by the concentration of the global population in urban areas (Seto et al., 2011). More than half of the global population now lives in urban areas (United Nations, 2014) and there are currently approximately 400 cities all over the world that contain over a million residents, although only 16 cities were found at the beginning of the 20th century (Cohen, 2004). As seen that 70% of those 400 cities are located in developing countries (Agunbiade et al., 2012), the urban expansion is an ongoing phenomenon there. Urban areas in developing countries in 2030 are projected to be triple as they were in 2000 and these urban agglomerations are often found in the capital cities (Agunbiade et al., 2012; Angel et al., 2005). This spatiotemporal phenomenon occurs in an unstructured manner, with the failure of guiding development in more desirable directions (Angel et al., 2011; Vaz & Nijkamp, 2015). Urban planners and policy makers struggle with this issue to achieve sustainable urban management, however, in many cases, these attempts fail and result in uncontrolled developments especially on urban fringes around developed city centers.

When such expansion occurs, the surrounding grasslands, forests, and agricultural land are transformed into residential, industrial, and commercial land (Ji et al., 2006). Such changes can induce a range of environmental and social consequences. These include the loss of natural resources (DeFries et al., 2010; Hasse & Lathrop, 2003), the threat of biodiversity loss (Mcdonald et al., 2008; Rojas et al., 2013), and inequality in living standards due to the development of informal settlements (Dubovyk et al., 2011; UN-Habitat, 2003). In particular, because of rapid, unplanned, and uncontrolled development in urban fringes, there is often a lack of basic infrastructure such as sewerage, electricity, garbage disposal, roads, and shops. This lack of infrastructure can inflate the costs of urban management (Frenkel & Ashkenazi, 2008; Hasse & Lathrop, 2003). Thus, it is essential to monitor and manage urban growth.

Urban expansion processes are not uniform in their occurrence (Catal et al., 2008). Thus, in any investigation of urban expansion, the specific geographical, social, and political context must be considered. However, this phenomenon has typically been studied using spatial grids at the city or metropolitan area scale using satellite images with coarse spatial resolution, such as MODIS, Landsat, and SPOT (Cheng & Masser, 2003; Fang et al., 2005; Gimblett et al., 2001; Ji et al., 2006; Martinuzzi et al., 2007; Sudhira et al., 2004; Tsutsumida et al., 2013; Weber, 2003). While these sensors are able to observe urban surfaces frequently, the coarse spatial resolution of these images is not sufficient to explore urban expansion because of the mixed pixel problem. Accordingly, it has proven difficult to observe changes in urban components directly and precisely, particularly because there is a lack of feature-oriented information relating to individual land use. An alternative way to capture urban expansion involves the use of very high spatial resolution (VHR) imagery such as aerial and satellite images. Although aerial images have been in use for many years, it is expensive to take photographs, and time consuming to prepare the data for GIS applications (Yuan et al., 2008). On the other hand, the decreasing costs and increasing availability of VHR satellite imagery have led to an enhanced ability to observe urban surfaces precisely (Yuan & Bauer, 2006). VHR satellite images have excellent potential. They can extend satellite remote sensing beyond what is possible with aerial photography or with satellite technologies with coarse spatial resolution. They should, therefore, be of interest to resource managers as a way to assess land resources in a timely and reliable manner (Sawaya, 2003). The main advantage of the use of VHR satellite imagery is the fine-scale observation as a snapshot. Thus, the use of such data enables the depiction of land use for each urban component in a time series and can help characterize the spatio-temporal dynamics of urban expansion. When building a spatial information database, one is often hampered by the lack of temporal data, even on developed cities. This issue means that it is still difficult to follow time-series changes in land cover caused by rapid urban expansion. This has generally prevented us from analyzing urban expansion when using existing spatial data.

Here, we describe an investigation into the detailed residential-scale processes of urban expansion in a fringe area of Ulaanbaatar, the capital municipality of Mongolia. We chose this area because of the unplanned proliferation of residential plots that has dominated development here; in parallel with an increase in population, this has caused critical development issues over the past several decades. If the government is to address developmental problems, it will be essential to understand when, where, and how urban expansion happens and to clarify the real factors causing the expansion. Such knowledge would also be beneficial for urban planners and policy makers, allowing them to manage urban expansion in future. Therefore, the present study aims primarily to portray residential-scale urban expansion processes by delineating time-series changes in urban components and to identify the geographical factors contributing to urban expansion.

2. Study area

In the present study, we focused on a fringe of Ulaanbaatar in which residential areas have expanded throughout the last decade (Fig. 1). This study area is located in the western part of Ulaanbaatar, in an area spanning 106°43′−106°52′E and 47°54′–47°56′N and covering approximately 33 km^2. One of the main roads, Enkhtaivan Avenue, is oriented east–west along the southern edge of the study area. Residential plots in this area is primarily on the flat land and hillsides located on the north side of Enkhtaivan Avenue. The area on the south side of the road is part of the city center and includes some apartments and commercial facilities. The study area also includes other land use types—factories, schools, and governmental facilities. The open land consists of grasslands and bare ground. However, these natural land cover types have been affected extensively (i.e., degraded) by anthropogenic activity.

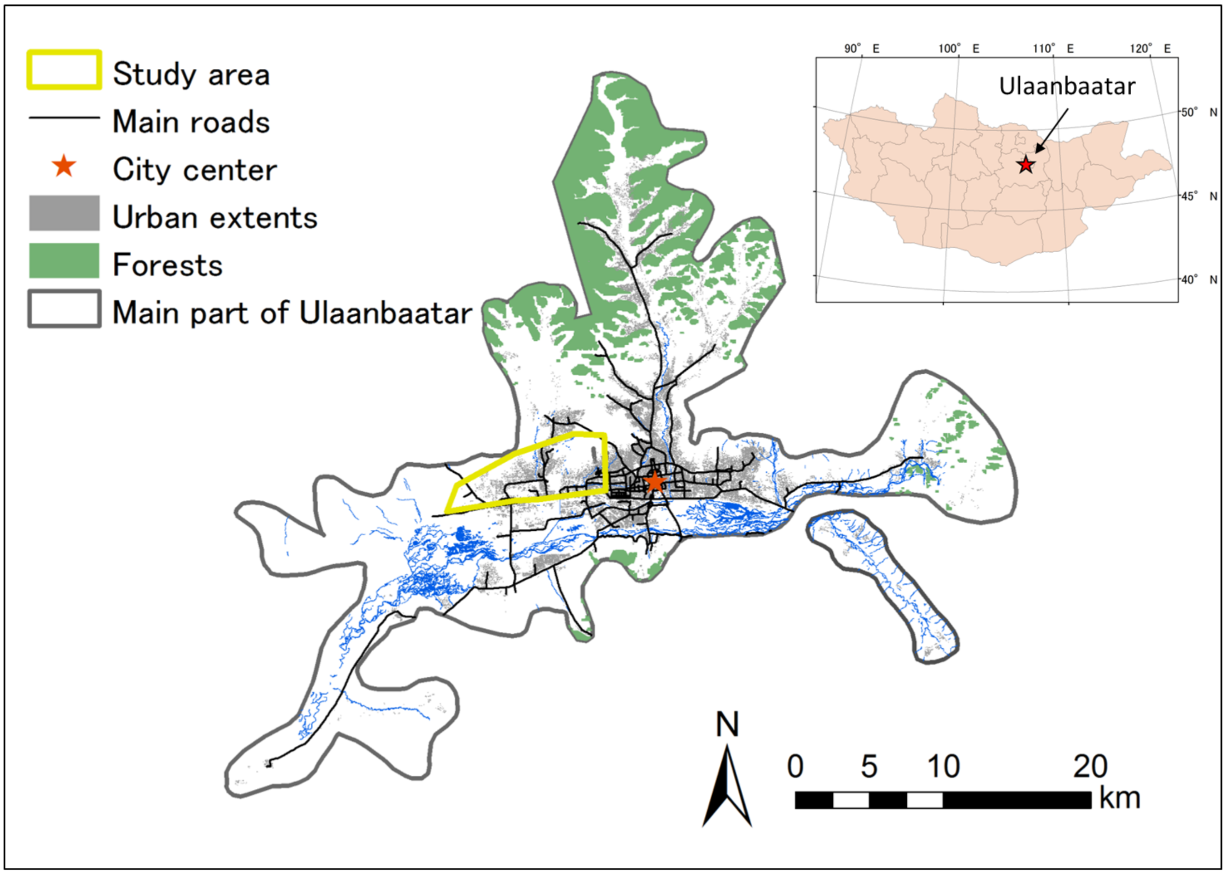

Fig. 1. The location of study area in Ulaanbaatar.

3. Overview of Ulaanbaatar

3.1. Urban expansion in Ulaanbaatar

Ulaanbaatar is the cultural, economic, political, and religious center of Mongolia (Byambadorj et al., 2011). Its population grew from 0.77 million in 2000 to 1 million in 2008 (Fig. 2). This population increase was due in part to the dramatic transition of Mongolia from a planned economy within the former Soviet-backed regime to an independent state with a free market economy (Sneath, 2003). Mongolians were freed from restrictions on internal migration and job selection; consequently, many rural Mongolians migrated into urban areas to seek jobs and education (Algaa, 2007; Byambadorj et al., 2011). Rural Mongolian, especially nomadic people, typically lives in a *ger*, which is a traditional Mongolian dwelling designed for a nomadic lifestyle in grassland (Dore & Nagpal, 2006). The *ger* is a circular tent-like structure consisting of a wooden framework and is covered with a felt made from wool of sheep, goats, or yaks, having sufficient living space for a Mongolian household. As it is mobile, lightweight, and portable, making it well suited for easy movement, the *ger* is an ideal living solution for nomadic people and well adapted to the nomadic life in a sustainable way (Dore & Nagpal, 2006; Kamata et al., 2010). Considering the advantage of such portability, migrants relocate to the city often by disassembling their *ger*, loading it and its contents onto a truck, and reassembling it in peripheral areas (Badarch et al., 2003). In this manner, migrants claim open land, build *khashaas* (wooden fences) marking property boundaries, and build a *ger* or a detached house on the enclosed land (Kamata et al., 2010). Such structures are typically seen in urban fringes known as *ger* areas (Fig. 3), which are typically composed of both formal and informal residential plots. Currently, about 60% of the population of Ulaanbaatar lives in *ger* areas (Byambadorj et al., 2011; Kamata et al., 2010; UN-Habitat, 2010a).

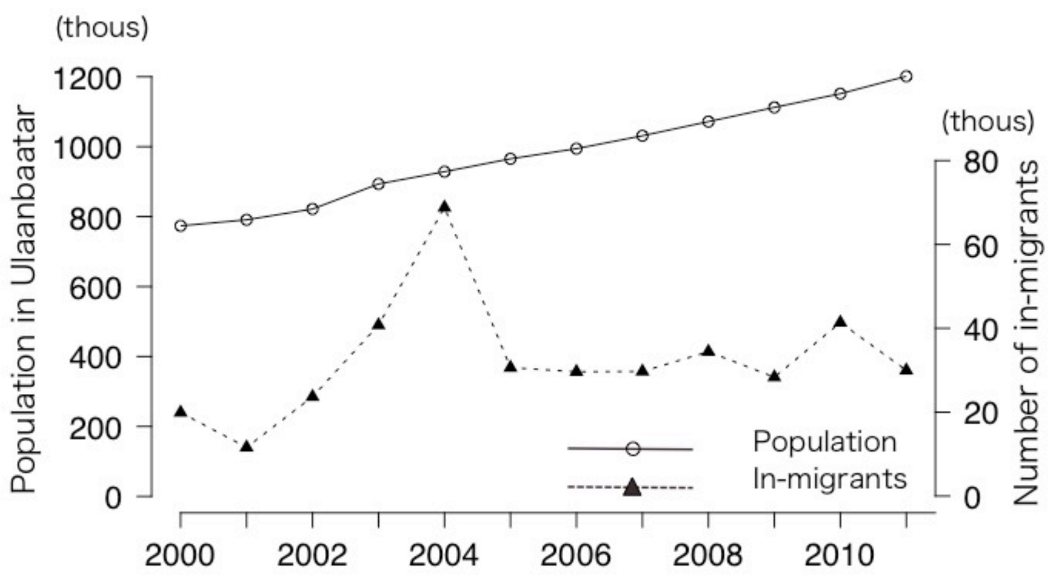

Fig. 2. Population and immigration volumes for Ulaanbaatar.

Fig. 3. A typical landscape in *ger* areas.

The expansion of *ger* areas within the fringes of Ulaanbaatar may have negative impacts on the natural environment and on living conditions (UN-Habitat, 2010b). For example, in winter, air pollution caused by the emissions from household stoves used for heating is one of the critical environmental problems facing Ulaanbaatar. Residents in *ger* areas usually use raw coal and wood as fuels, whereas residents living in apartments typically use central heating. *Ger* areas lack basic infrastructure, including piped water systems, sanitation facilities, paved roads, public transportation, and heating systems (Kamata et al., 2010). Accordingly, issues such as social and spatial inequality, water supply and sanitation, waste management, and air pollution have become urgent. International donor-funded projects are helping address such issues by assisting with the development of much-needed infrastructure (Kamata et al., 2010; UN-Habitat, 2010a). In particular, because the residential plots in *ger* areas are not connected to the public water supply system, water kiosks are being constructed using funding from international donors to meet the basic human need for water (Sigel et al., 2011). Most of these kiosks are managed by the Water Supply and Sewerage Authority of Ulaanbaatar City (USUG).

3.2. Land reform policy and master plan

The Mongolian government has implemented land reforms in the form of the "Law on Allocation of Land to Mongolian Citizens for Ownership" in 2003. These reforms were intended to accelerate the development of the free market economy (Bruun & Odgaard, 1996; Byambadorj et al., 2011; Kamata et al., 2010). This law has allowed Mongolians to own land for the first time in Mongolia's history (Asian Development Bank, 2003; Batbileg, 2007; Kamata et al., 2010). The new land tenure system introduced Mongolians to a combination of three land rights: "ownership," for which only Mongolian citizens are eligible; "possession rights" for up to 60 years, with possible extension, available to Mongolian citizens and joint ventures; and "land use rights," valid for up to five years with possible extension, for which foreigners are also eligible (Kamata et al., 2010). Land ownership is tied to the land fee system, which the government introduced in 1997 under the "Law of Mongolia on Land Fees" (Kamata et al., 2010). However, the "Law on Allocation of Land to Mongolian Citizens for Ownership" stipulates that each household is entitled to own up to 700 m^2 in Ulaanbaatar. The associated land fee was set at a low level: about 90% of the land up to 700 m^2 was originally exempt (Kamata et al., 2010). After some minor revisions, the land reform policy eventually came to stipulate that each Mongolian citizen be allowed to privatize and own one plot of land at no cost until 2018.

In general, a proper urban plan based on up-to-date and reliable spatial information is essential when dealing with urban expansion (Novack & Kux, 2010). Four urban plans formulated at a Russian urban planning institute were implemented between 1954 and 1986, while Mongolians developed the current urban plan for Ulaanbaatar in 2002. This was the first time that Mongolians had developed their own plan for Ulaanbaatar. However, the current urban plan has not helped control urban expansion owing to the lack of regulation and the loose association between the plan and land reform policy (Byambadorj et al., 2011). Byambadorj et al. (2011) noted that the urban plan was presented only on paper and that the authority given to direct its implementation was insufficient. Land reform seeks to grant *ger* areas a formal and permanent legal status, whereas the urban plan has sought to oppose the legitimacy and permanency of these areas because they are considered to represent temporary land use (Kamata et al., 2010). Thus, the current urban plan does not address the issue of urban expansion in Ulaanbaatar adequately.

In recent years, new and clearer policy directions have helped remedy this situation. These policies have helped control spatial expansion and have promoted the development of high-density residential zones (Kamata et al., 2010). For example, the Japan International

Cooperation Agency (JICA), which has been assisting the Mongolian government since 2002, helped in the development of the "Compact City" concept of the UB Master Plan 2030 (a revision of the current urban plan) (JICA, 2009). This new plan is expected to restructure and improve *ger* areas (JICA, 2009). Among other directives, this project proposes a land use zoning strategy that controls unsustainable development relating to urbanization and conserves existing natural networks such as forests, waterways, and green areas (JICA, 2009). The activities associated with this project include new attempts to reduce urban expansion. However, an improved scientific understanding of urban expansion in Ulaanbaatar is also essential, particularly because knowledge of the spatial dynamics of rapidly developing *ger* areas remains limited. Although the conversion of *ger* areas into apartment buildings and the gradual improvement of urban services for existing *ger* areas are addressed in the plan (JICA, 2009; Kamata et al., 2010), it is still essential that the government monitor urban expansion. This is particularly so because encroachments on open land in peripheral areas continue.

4. Materials and Methods

4.1 Data acquisition and processing

Feature-oriented GIS data on urban components were constructed from VHR satellite imagery to explore the process of urban expansion. GIS data relating to private land, buildings, roads, main roads, and other land uses (e.g., factories, schools, and governmental facilities) were constructed from a IKONOS image for 2000 and Quickbird images for 2006 and 2008. IKONOS has a spatial resolution of 1.0 to 4.0 m^2 and was launched in 1999, and Quickbird has a spatial resolution of 0.6 to 2.8 m^2 and was launched in 2001. Both satellites can observe buildings, houses, and roads in detail and have been utilized for such urban component mappings (Helder et al., 2003; Volpe & Rossi, 2003; Weng, 2012).

We included images for 2000 and 2006 to compare the characteristics of the study area before and after the implementation of the land reform policy of 2003. The image for 2008 was selected to assess the continuing effect of the policy. We identified individual packages of private land based on the enclosing *khashaas* and digitized them manually in a vector format along with other land use types (e.g., buildings, including apartments and commercial facilities, and other land uses, including factories, schools, and governmental facilities) based on the images for each observed year (Fig. 4). Unpaved roads were digitized for each year and main roads that were paved and had one or more lanes in 2000 were digitized separately using IKONOS imagery; both were in a polyline format. Although VHR satellite imagery represents our primary data source, we obtained supplementary GIS data from the international donor project implemented by the JICA entitled "The Study on City Master Plan and Urban Development Program of Ulaanbaatar City" (UBMPS). These data were obtained previously as part of the second Ulaanbaatar Services Improvement Project (USIP2). This was one of the primary donor projects in Ulaanbaatar, implemented by the World Bank in 2007 and subsequently utilized and modified by the JICA (JICA, 2009; The World Bank, 2012). We used this dataset to extract GIS data describing the locations of water kiosks. This is used as a social factor in our logistic regression model below. These datasets were also used to provide supplementary data for the construction of GIS datasets for buildings. Finally, ASTER imagery which is a DEM dataset in which cloudy pixels have been removed and residual anomalies corrected, is prepared (ASTER GDEM Validation Team, 2009).

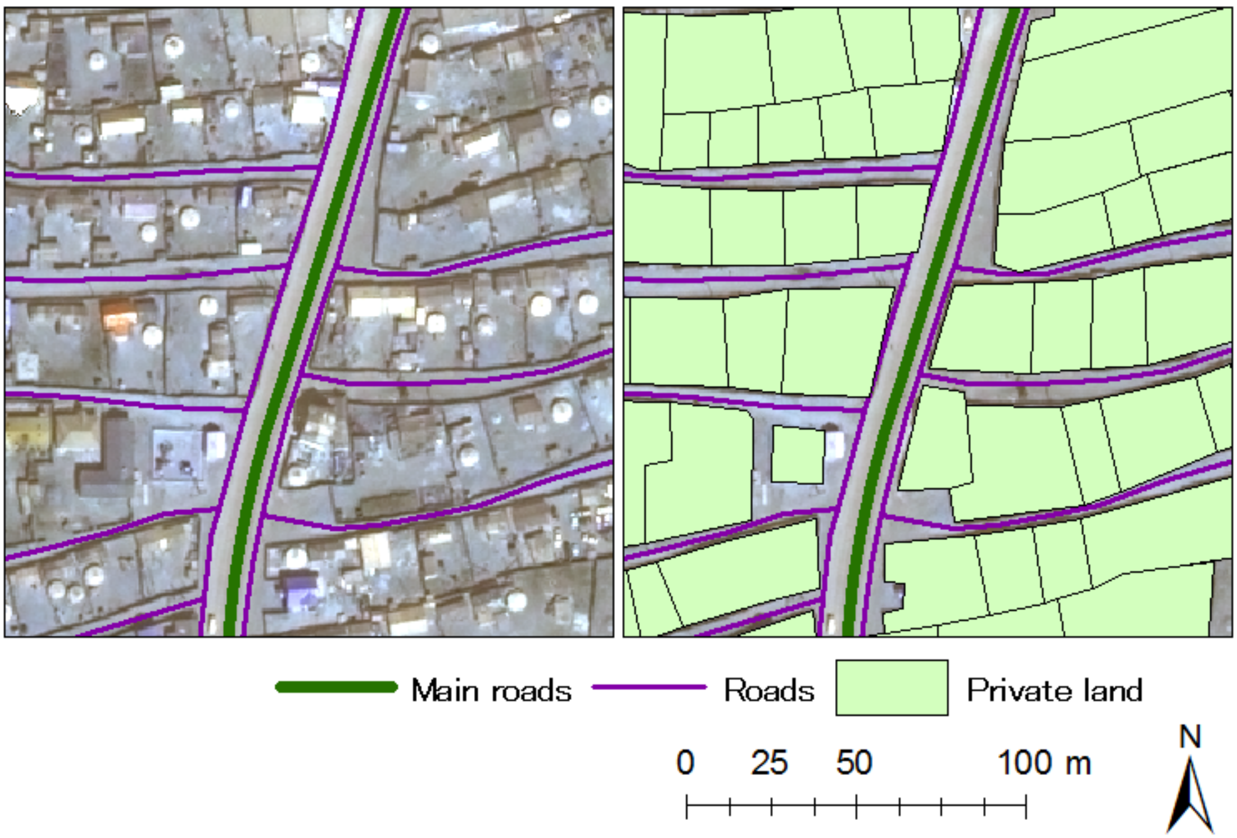

Fig. 4. Spatial layers digitized from high-resolution satellite imagery.
Left: A main road (green line) and other roads (purple lines)
Right: Private land (green polygons) enclosed by *khashaas*

To assess the accuracy of digitizing the feature-oriented GIS datasets using the traditional pixel-based confusion matrix, we randomly selected a total of 1,000 points in the study area. The land cover at each point was visually interpreted using the IKONOS and

QuickBird images. We distinguished four types of land cover—private lands, buildings, open lands, and others. Roads are classified as open lands because the GIS datasets for roads were built in the polyline format. Accuracy statistics including user's accuracy, producer's accuracy, and overall accuracy were calculated for each period (Chubey et al., 2006).

4.2 Logistic regression model

Logistic regression models are very useful in evaluating spatial characteristics relating to urban expansion (Cheng & Masser, 2003; Dubovyk et al., 2011; Fang et al., 2005; Hu & Lo, 2007; Huang et al., 2009; Pagnutti et al., 2003; Sudhira et al., 2004; Zeng et al., 2008). Logistic regression models have been shown to be particularly effective in the analysis of land use change owing to their explanatory power and spatial explicitness (Cheng & Masser, 2003; Dubovyk et al., 2011; Poelmans & Van Rompaey, 2010). A logistic regression model is expressed as follows:

$$ln\left(\frac{P(z)}{1-P(z)}\right) = a + b_1x_1 + b_2x_2 + \cdots b_mx_m + \varepsilon$$

where $P(z)$ is the probability of the dependent variable z; $x_1, x_2, \cdots x_m$ are independent variables; the parameter a is an intercept; $b_{1,} b_2, \dots, b_m$ are regression coefficients; and ε is a binomially distributed error. The variable z is binary (0 or 1) and represents the existence of a land use. $P(z)$ represents the probability of the occurrence of private land in this study and its value is between 0 and 1. Regression coefficients represent the contribution of each independent variable on $P(z)$. A positive regression coefficient indicates that the independent variable supports an increase in the probability of change, whereas a negative indicates the opposite effect (Cheng & Masser, 2003).

Although logistic regression models are known to be effective for the analysis of urban expansion, problems can arise if model residuals are spatially autocorrelated (Cheng & Masser, 2003; Dubovyk et al., 2011; Huang et al., 2009). To overcome this problem, we employed a random sampling scheme and reduced the number of samples until no spatial autocorrelation remained in the residuals. We chose a random sample of 500 points. Spatial dependency was tested by calculating Moran's I for residuals. The performance of our model was evaluated according to the area under the receiver operating characteristics (ROC) curve method, also known as the area under curve (AUC) method (Overmars et al., 2003).

As Li, Zhou and Ouyang (2013) mentioned, it is widely recognized that urban expansion is driven by physical, socioeconomic, neighborhood, and land use planning factors. Physical factors such as topography are regarded as the fundamental determinants of the extent and spread of urbanization. We focused on two physical features—elevation and slope—because migrants may prefer lower and flatter areas. Socioeconomic factors such as land prices and access to the city center are regarded as important factors affecting urban expansion. We considered the distances from roads, main roads, and water kiosks, because migrants may prefer areas that provide easy access to the city center and to tap water. Due to data constraints, we have not considered the attributes of land, such as land prices, in this study. Neighborhood factors relate to the similarity of land cover types. Here, we used the existence of private land as the neighborhood factor. Finally, land use planning factors usually include measures to regulate land use, such as zoning control and master plans. Such factors were irrelevant to our study because of the lack of regulation in Ulaanbaatar.

To implement the model, private land in 2000 and 2008 is rasterized as binary data. The distances from roads, main roads, and water kiosks were calculated from digitized data, and elevation and slope were calculated based on ASTER imagery. The variables of our logistic regression model are listed in Table 1. All independent variables were standardized according to the following formula: $(x - mean(x))/Std(x)$. This enabled comparison of the quantitative effects of regression coefficients between variables.

Table 1. Variables in logistic regression model.

Type of factor	Variable	Description	Nature of variable
Dependent	Private land in 2008	0: No private land 1: Existence of private land	Binary
Independent	Private land in 2000	0: No private land 1: Existence of private land	Binary
Independent	Distance from roads in 2000	Distance from roads in 2000 (m)	Continuous
Independent	Distance from roads in 2008	Distance from roads in 2008 (m)	Continuous
Independent	Distance from main roads	Distance from main roads (m)	Continuous
Independent	Elevation	Elevation (m)	Continuous
Independent	Slope	Slope (°)	Continuous
Independent	Distance from water kiosks	Distance from water kiosks (m)	Continuous

5. Results

5.1 Time-series changes in the spatial distribution of private land

The spatial distribution of private land in 2000, 2006, and 2008 is illustrated in Fig. 5. These time-series maps demonstrate that the area occupied by private land expanded significantly. The expansion of private land and roads was particularly prominent during the period 2000–2006. In 2000, private land was chiefly restricted to the flat terrain along main roads. By 2006-2008, it had spread across hillsides and into steep areas. With the spread of private land, roads began extending into hilly regions. Buildings were mainly concentrated in the southeastern portion of the study area, surrounded by major roads, while other land was concentrated in the southwestern portion, a pattern that did not change over the study period.

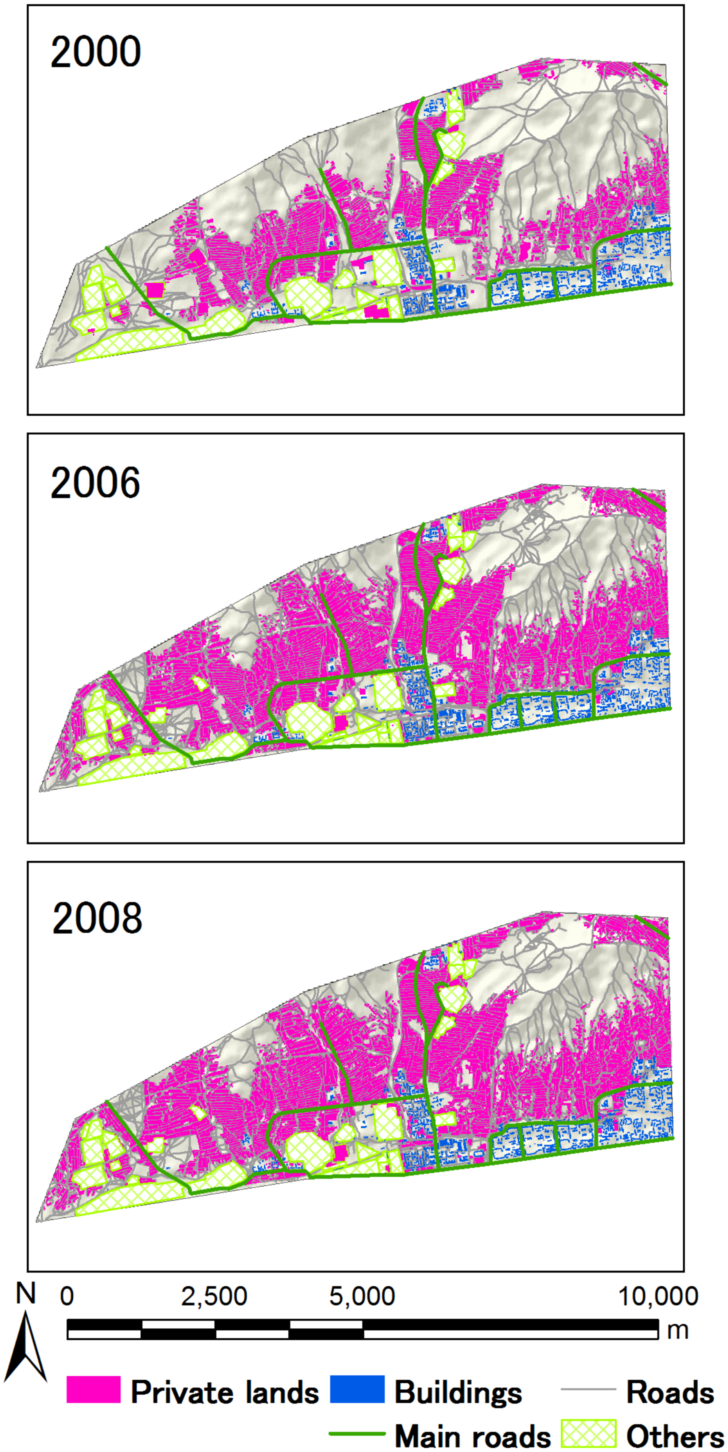

Fig. 5. Maps detailing private land, buildings, roads, main roads, and other features in 2000, 2006, and 2008.

Table 2 depicts trends in private land plots, buildings and other land. The most striking increase was in the number of private land plots, from 6,747 in 2000 to 12,656 in 2006 and 13,064 in 2008. The proportion of private land in the study area increased from 17.69% in 2000 to 30.58% in 2006 and 32.00% in 2008. Though these changes were drastic, the annual rate of change of the number of plots of private land was not constant. It decreased from 14.60% during the period 2000–2006 to 1.61% during 2006–2008. The number of buildings increased slightly from 856 in 2000 to 1,089 in 2006 and to 1,105 in 2008, while that of other land plots did not change. The proportions of buildings and open land are relatively low compared to that of private land. The proportion of buildings changed from 1.70% in 2000 to 1.84% in 2006 and 2008, while that of open land changed from 8.48% in 2000 to 8.86% in 2006 and 8.91% in 2008. The annual rates of change of these numbers and proportions were higher during the 2000–2006 period than in 2006–2008. The time series also shows the annual rate of road extension. The length of roads increased from 409.9 km in 2000 to 576.5 km in 2006 and 619.3 km in 2008. Thus, the annual rate of increase of road length was lower (higher) than that of private land during the period 2000–2006 (2006–2008).

Table 2. Changes in the number and the proportion of private land plots, buildings, and other land within the study area, and the total length of roads.

	2000	2006	2008	Change from 2000 to 2006	Change from 2006 to 2008
Number of private land plots	6,747	12,656	13,064	5,909	408
(Annual percent rate)	-	-	-	(14.60)	(1.61)
Proportion of private land plots within the study area (%)	17.69	30.58	32.00	12.89	1.42
(Annual percent rate)	-	-	-	(12.14)	(2.32)
Number of buildings	856	1,089	1,105	233	16
(Annual percent rate)	-	-	-	(4.54)	(0.73)
Proportion of buildings to the study area (%)	1.70	1.84	1.84	0.14	0.00

(Annual percent rate)	-	-	-	(1.37)	(0.00)
Number of other lands	24	27	28	3	1
(Annual percent rate)	-	-	-	(2.08)	(1.85)
Proportion of other land to the study area (%)	8.48	8.86	8.91	0.38	0.05
(Annual percent rate)	-	-	-	(0.75)	(0.28)
Total length of roads (km)	409.9	576.5	619.3	166.6	42.8
(Annual percent rate)	-	-	-	(6.77)	(3.71)

The results of the accuracy assessments are shown in Table 3. The overall accuracy of the 2000, 2006, and 2008 digitized datasets are 0.96, 0.94, and 0.95, respectively. The overall accuracy exceeded 0.9 in each period, indicating these digitized spatial data were highly accurate. User's accuracies were generally higher than producer's accuracies except for open land. Within our four categories of land use, user's accuracies ranged from 0.73 to 0.99, while producer's accuracies ranged from 0.52 to 0.99. In every year, buildings showed lower producer's/user's accuracies than the other land cover types. Private land plots showed the highest user's accuracies in all years, while open land had the highest producer's accuracies. In particular, the user's accuracy for the private land plots exceeded 0.98 in every year, indicating a very high level of accuracy.

Table 3. Evaluation of digitized spatial data for three periods.

Type	**2000**			**2006**			**2008**		
	Correct Number	PA	UA	Correct Number	PA	UA	Correct Number	PA	UA
Private lands	166	0.95	0.99	297	0.92	0.99	315	0.95	0.98
Buildings	13	0.52	0.76	19	0.76	0.73	20	0.77	0.77
Others	82	0.90	0.93	81	0.78	0.96	84	0.80	0.98
Open lands	702	0.99	0.96	545	0.99	0.92	535	0.99	0.94
OA	0.96			0.94			0.95		

PA= Producer's accuracy; UA= User's accuracy; OA= Overall accuracy

n=1,000

5.2 Statistical tests of geographical relationships

The results obtained using the logistic regression model are presented in Table 4. We found the distribution of private land in 2008 to exhibit a statistically significant positive relationship with the distribution of private land in 2000. Conversely, we found a statistically significant negative relationship between the distribution of private land in 2008 and distance from roads and water kiosks. No statistically significant relationships were found between the distribution of private land and distance from main roads, elevation, or slope. Comparing the absolute values of the regression coefficients, we find that private land plots in 2000 had the highest influence on private land in 2008, as indicated by a regression coefficient of 1.060. This was followed by the distance from water kiosks and that from roads in 2000, with regression coefficients of 0.781 and 0.551, respectively. This indicates that private land plots in 2008 tended to be built mostly near land occupied in 2000. To a somewhat lesser extent, they tended to be built near water kiosks and roads.

Table 4. Statistical results for logistic regression model.

		Coefficients
Dependent variable	Private land in 2008	
Independent variables	(Intercept)	-0.636 ***
	Private land in 2000	1.060 ***
	Distance from main roads	0.053
	Distance from roads in 2000	-0.551 *
	Elevation	0.090
	Slope	-0.164
	Distance from water kiosks	-0.781 ***
AUC value		0.838
Moran's I in residuals		0.025

*: Statistically significant at the 5% level (p-value $\leq$ 0.05)

***: Statistically significant at the 0.1% level (p-value $\leq$ 0.001)

Values of Moran's I for the residuals of the model were found to be 0.025 and statistical testing of autocorrelation in the residuals indicated no statistical significance. Consequently, the model is well developed in terms of spatial independence. The AUC value in the model was 0.838, indicating a prediction accuracy of 83.8%.

6. Discussion

Until recently, studies concerning the urban expansion have found it difficult to incorporate the effects of disaggregated human behaviors on urban surfaces. Land use changes in Ulaanbaatar have been analyzed at the metropolitan scale using MODIS, Landsat, and SPOT imagery in some previous studies (Amarsaikhan et al., 2009; Tsutsumida et al., 2013). However, residential-scale land use changes, which can depict urban expansion more precisely, have not been investigated in detail to date owing to the lack of time series of feature-oriented data reflecting urban components. Although it takes a lot of time and labor in our approach, the accuracy of such data is highly satisfactory. In this context, this study has achieved to explore urban expansion in detail. The results provide insight that could be essential to our understanding of the residential-scale formative processes of *ger* areas as a product of accumulated individual decisions.

It is important to understand the spatial dynamics and patterns of urban expansion when implementing sustainable development policies for a given region (Habibi & Asadi, 2011; Sudhira et al., 2004). The results obtained using our logistic regression model demonstrate the spatial characteristics of the distribution of private land. The development of private land has a positive feedback effect, fostering the development of further private land through the neighborhood effect. Consequently, our results confirm that the formation of *ger* areas is aggregated, rather than scattered. The distance from roads appears to be one of the primary forces governing the formation of *ger* areas. Most of the roads in *ger* areas began as informal tracks to private land in response to residents' demands for better access to social and public infrastructure. Subsequently, these tracks evolved in a haphazard manner to become earthen roads (Kamata et al., 2010). Based on these results, it is clear that road accessibility is important for migrants when selecting a location for their own plots of land. Water kiosks are also a key factor controlling the formation of *ger* areas. To be able to survive in *ger* areas, residents must purchase water at water kiosks, because no house or *ger* in any *ger* area has a private connection to a water distribution network (Kamata et al., 2010). In a blueprint for development strategy, water kiosks are located such that each serves approximately 900–1,200 people within 500 m (Kamata et al., 2010).

Although we found no significant relationship between distance from main roads and the distribution of private land, our model results indicate that land far from main roads has been developed most recently, likely because most of the land along or near main roads had already been occupied by private land, buildings, or other land cover types. Similarly, topographical indicators such as elevation and slope do not appear to have had a significant effect, although the newer developments appear to occur primarily at higher elevations and in areas with flatter slopes.

Potential "hot spots" for the future development of private land can be estimated spatially by comparing regression coefficients. These hot spots, which are typically closer to water kiosks and roads, exhibit a much greater probability of being developed. Accordingly, private land is likely to become concentrated around these hot spots, exhibiting spatial characteristics consistent with the aggregated formation of *ger* areas during the period 2000–2008. Fig. 6 illustrates the predicted probabilities for the future development of private land during 2008–2016, derived from the results of our logistic regression model. These results suggest that development is most likely to occur in unoccupied land adjacent to existing private land. Although we do not consider disaggregated human behaviors in making these predictions, our results may still provide valuable insight into the future development of *ger* areas and into their spatial relationships with geographical factors. In particular, our results demonstrate that social infrastructure influences the formation of *ger* areas much more strongly than natural geographical factors do.

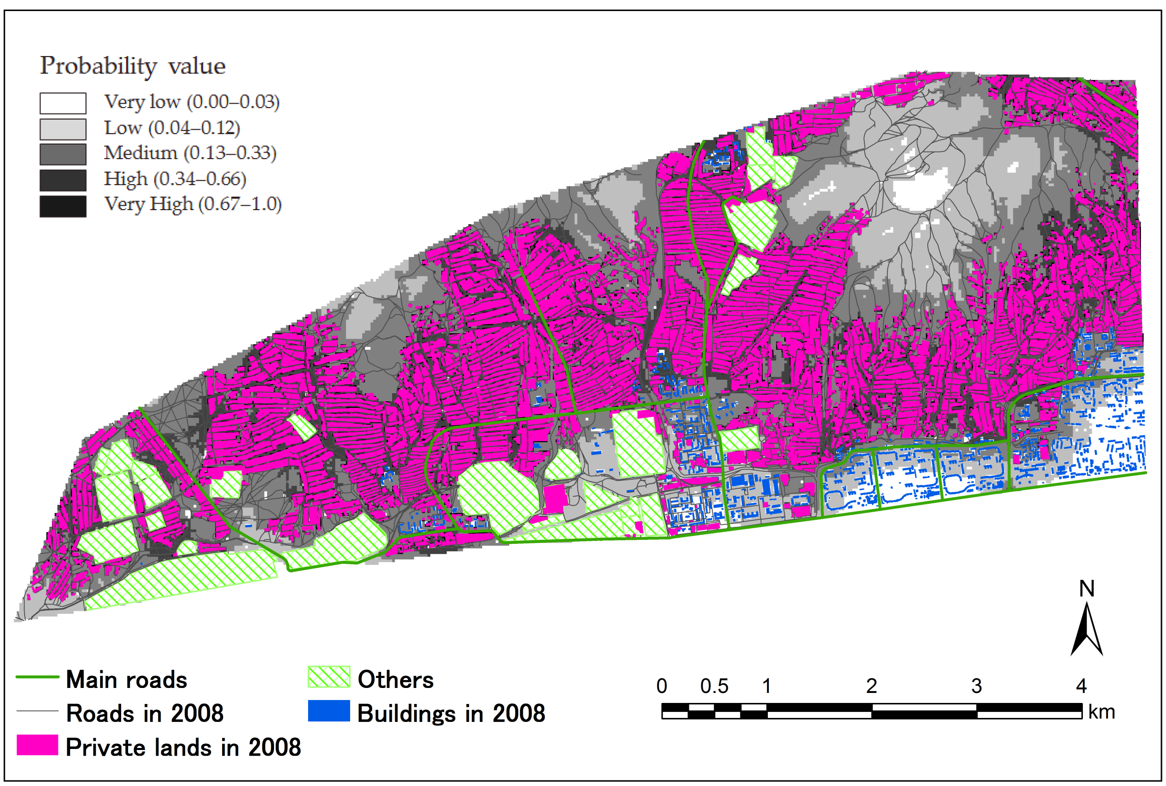

Fig. 6. Predicted probabilities of development of settlements based on the logistic regression model, 2008–2016.

7. Conclusions

We achieved to emphasize the time-series changes of the formation of private land in a fringe of Ulaanbaatar to create residential-scale GIS data. Furthermore, our logistic regression model produced some fruitful quantitative insights regarding the patterns and possible determinants of the expansion of private land. Consequently, we demonstrated that failures in land management resulted in the expansion of *ger* areas in the fringes of Ulaanbaatar. This expansion resulted in a deterioration in living standards and induced a disordered spatial pattern of urban fringes. The present urban plan seems ill equipped to stop this pattern.

Most demand for land is associated with residential use; accordingly, the associated concentration of (and increase in) population is likely to give rise to an unprecedented land use situation. Urgent action by urban planners and decision makers is necessary to mitigate the effects of urban expansion. In particular, encroachment around peripheral areas must be restricted through land use regulations, although it will be challenging to control this phenomenon without addressing political issues. Therefore, a comprehensive legal system encompassing both the new master plan and land laws is required.

To understand the ongoing urban expansion and evaluate the effects of the revised master plan, it will be essential to conduct further investigation and monitoring over a wide range covering the peripheral parts as well as the city center areas of Ulaanbaatar.

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