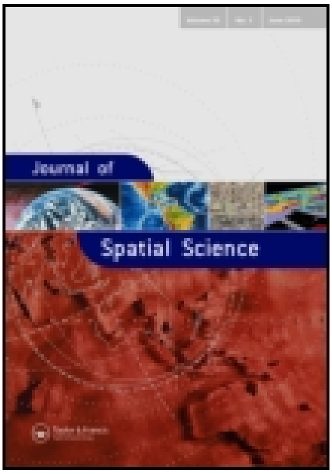

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A spatially explicit method to examine the impact of urbanisation on natural ecosystem service values

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A spatially explicit method to examine the impact of urbanisation on natural ecosystem service values

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We developed a spatially explicit method to examine the effects of urbanisation on ecosystem service values. Especially, a spatially explicit urban growth model was developed through incorporating a macro-scale model (system dynamics) and a micro-scale model (CLUE-S). In addition, spatially explicit ecosystem service values were simulated under three socio-economic scenarios: (1) current economic growth, (2) rapid economic growth, and (3) sustainable economic growth. Analysis of results suggests that the degradation of ecosystem functions is associated with the conversion from water body and farmland to built-up and barren lands. Moreover, obvious spatial variations were found associated with ecosystem service values.

Keywords: spatially explicit method; urban growth modeling; ecosystem service valuation

1. Introduction

Numerous urban growth models have been developed to predict the extent and locations of urban development (Jiang & Yao 2010). These models can be divided into two general groups: aspatial models and spatially explicit models. Aspatial models have been developed to predict the amount of urban developments in aggregated geographical areas (Seto & Kaufmann 2003; Irwin & Geoghegan 2001). One of the earliest aspatial models applies the bid-rent theory to explain new residential locations (Alonso 1960, 1964; Herbert & Stevens 1960). In the model, land use and land cover change (LUCC) is considered to be driven by accessibility to markets. Later, many sophisticated econometric models were developed and applied to examine the drivers of urbanisation in different cities (Chomitz & Gray 1996; Guldmann & Wang 1998; Huang *et al.* 2009; Landis & Zhang 1998). As an example, system dynamics (SD) models proposed by Forrester (1961, 1969) have been applied to examine causal factors of urbanisation, and simulate future urban growth in aggregated spatial units (Han *et al.* 2009; Leal Neto *et al.* 2006; Yu *et al.* 2011). Although aspatial models have been widely applied, critics of these models have emerged, and the specific locations of LUCCs have been predicted using spatially explicit models. These models include cellular automata (Clarke *et al.* 1997; Kamusoko *et al.* 2009; Li & Yeh 2002; Zhang *et al.* 2011), agent-based models (Evans & Kelley 2004; Mena *et al.* 2011; Parker *et al.* 2003), and the conversion of land use and its effects (CLUE) (Verburg *et al.* 2002, 2006).

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Parallel to the research of urban growth modelling, ecologists have attempted to identify the functions, including goods and services, provided by natural ecological systems and quantify the monetary value of these functions since the 1970s (Holdren & Ehrlich 1974; Odum 1977; Westman 1977). In particular, a pioneering study conducted by Costanza *et al.* (1997) divided the world's ecosystems into 16 biomes, each of which can provide 17 types of services (e.g. gas regulation, climate regulation, water supply, soil formation and retention). Further, Costanza *et al.* (1997) estimated the average world's ecosystem service value to be approximately US$33 trillion per year (based on 1994 US$) using a market valuation method. Since then, many scholars have applied the Costanza *et al.* (1997) valuation method to examine the value of ecosystem services for farmland, forest, grassland, and wetland ecosystems (Hu *et al.* 2008, Li *et al.* 2007, 2010; Tong *et al.* 2007; Zang *et al.* 2011; Zhao *et al.* 2004). However, according to the survey results from more than 200 Chinese ecologists, some ecosystem services have been found to be overestimated or underestimated when applied to Chinese cities (Xie *et al.* 2001). Xie *et al.* (2001, 2010) argued that, with Costanza *et al.* (1997)'s method, ecological services provided by farmland were insufficiently valued, while services provided by other biomes, such as wetlands and forest, were overvalued. In order to address this problem, Xie *et al.* (2001) proposed a "unit value"-based method to localise the parameters for ecosystem assessment in China, and it has been widely employed to examine the influences of urbanisation on the service value of surrounding ecosystems in China (Zhao *et al.* 2009).

Until now, most studies have emphasised examination of the impacts of urbanisation on ecosystem service values for an aggregated geographic area (e.g. a city or county), and ignored the spatial heterogeneity of ecosystem services (Zhang *et al.* 2010). Spatial heterogeneity, however, may be important as it may influence the process and pattern of an ecosystem significantly (Pickett *et al.* 1997). Therefore, examining the detailed spatial variations of ecosystem service values and their changes over time is essential. To address this problem, this study developed a spatially explicit method through integrating an urban growth model and an ecosystem valuation approach. With this approach, the spatial heterogeneity of the ecosystem value changes has been examined. The reminder of this paper is organised as follows. The next section introduces the study area and data. Section 3 reports the methodology employed in this study, including the spatially explicit urban growth model and ecosystem service valuation approach. The results of this research are reported in Section 4, and finally the paper concludes with Section 5.

2. Study area and data

Daqing City, Heilongjiang Province, China, has been selected as the study area. Daqing covers approximately 5144 square kilometers and lies between latitudes 45°46′ and 46°55′ north and longitudes 124°19′ and 125°12′ east (Figure 1). It is located in the continental monsoon climate region, and the annual temperature and precipitation are 5.6°C and 427.5 mm respectively. Daqing City consists of five districts: Saertu, Ranghulu, Longfeng, Datong, and Honggang. The population of Daqing was 1.25 million in 2005, which accounts for approximately 3.3% of the overall population in the Heilongjiang Province. The gross domestic product (GDP) was about US $17.7 billion in 2005, or 16% of the GDP of the Heilongjiang Province. Daqing has one of the largest oil production fields in the world, with an annual oil production over 1 billion tons. In particular, 60% of the GDP of Daqing can be attributed to the petroleum industry. The development of the petroleum industry has led to the rapid growth of GDP and population, and as a result an increasing area

Figure 1. Location of the Daqing City, Heilongjiang Province, P.R. China

of land has been converted from natural land to residential, industrial, and commercial land uses. Unlike natural lands, urban lands have profound and adverse effects on natural ecological systems, although they may also provide convenience and economic benefits to local residents. As an example, urbanisation leads to the urban heat island effect, reduced biodiversity, increased amounts of brownfields, as well as air and water pollution, all of which deteriorate the quality of life of local residents. Because of the lack of strategic planning, Daqing is facing many of the aforementioned challenging environmental problems, and it is essential to explore the effects of future urban development on the surrounding natural ecosystems.

For this study, we obtained Landsat thematic mapper (TM) imagery from 1990, 2000, and 2005 to derive historical land use maps of Daqing. These Landsat TM images, with six spectral bands (bands 1–5 and 7) and 30 m spatial resolution, were collected from the China Remote Sensing Satellite Ground Station and Heilongjiang Academy of Agricultural Science. In addition, digital elevation data were obtained from the global topography database with a spatial resolution of 3 arc-seconds (90 m). Soil maps were obtained from the Institute of Soil Science, Chinese Academy of Sciences. Transportation networks, including railways, provincial roads, and rural roads, were provided by the Surveying and Mapping Department, Heilongjiang Province. In order to validate all the collected data, including remote sensing imagery and GIS data, a topographic map with a scale of 1:5 was employed as the reference data. Finally, socio-economic data, including population information, GDP, etc., were obtained from the Daqing Statistics Yearbooks of 1991, 2001, and 2006.

With the Landsat TM imagery, land use maps of 1990, 2000, and 2005 were generated using a guided clustering method developed by Reese *et al.* (2002). This is a hybrid supervised/unsupervised classification technique which is proven to generate high-accuracy LUCC products. In this study, the adoption of this method is due to its convenience and high accuracy. Six land use types were identified: farmland, forest, grassland, water bodies (wetlands, lakes, rivers, reservoirs, ponds, etc.), built-up (residential, transportation, industrial including petroleum field), and barren land (alkaline and salinised land, sand, etc.). To ensure satisfactory classification accuracy, a post-classification review was conducted through manual interpretation and digitisation, with the topographic map and other historical maps as references. The overall classification accuracy was checked using 600 ground control points chosen with a stratified random sampling technique, and the accuracy for each land use map is higher than 85%.

3. Methodology

3.1 Spatially explicit urbanisation modelling

To simulate the urban growth of Daqing City under a number of socio-economic scenarios, we integrated the SD model and the CLUE-S model to develop future urban land use change scenarios. SD was initially developed by Forrester (1961, 1969), and subsequently applied in tourism management, watershed management, and land use change analysis (Georgantzas 2003; He *et al.* 2006; Leal Neto *et al.* 2006; Yu *et al.* 2010). SD is an effective means to examine the behaviours of a complex spatio-temporal system. It is effective in handling the feedback loops from both inside and outside the system and examining the impact of time lag on the behaviours of the system. The complex relationships among factors can be constructed as feedback loops, stocks, and flows. SD can reflect the structure, function and dynamic interactions among behaviours of a complex system. Therefore, it provides a useful tool for analysing the relationships between land use change and its driving forces. The driving forces of LUCC can be divided into three groups: natural factors, land use policy, and socio-economic factors (Nunes & Auge 1996; Turner *et al.* 1995; Vellinge 1998). As few variations are associated with natural factors (e.g. climate and topography) in Daqing, only land use policy and socio-economic factors have been considered in this study. Land use policies include zoning, the reclamation of barren land, and the returning of farmland to forest and grassland; and socio-economic factors include GDP, population, and technology (e.g. agricultural and forest production technology) progress at different levels. The SD model (see Figure 2) was constructed and calibrated using

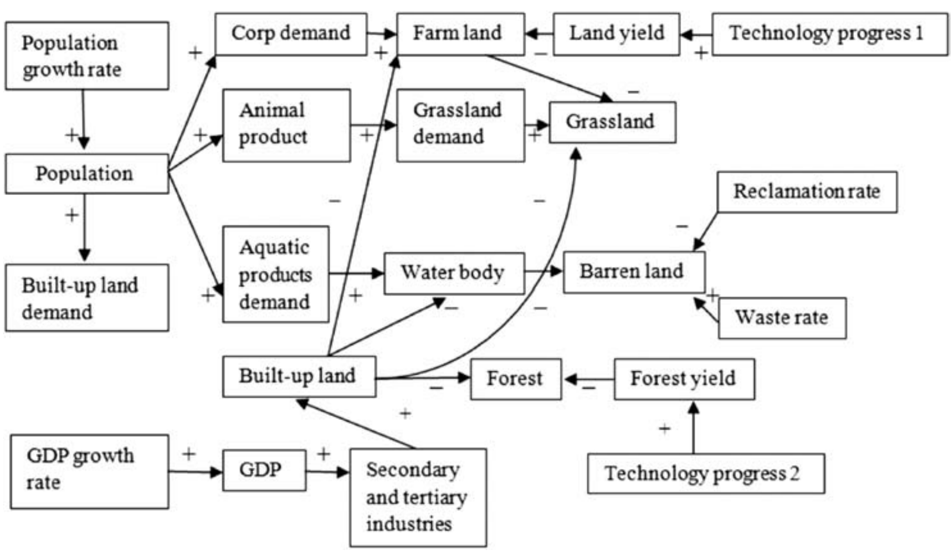

Figure 2. Framework of the System Dynamic Model (" + " represents positive feedback and " − " represents negative feedback)

the Vensim PLE 5.10, commercial software developed by Ventana Systems, Inc. (http://www.vensim.com/).

With the projected future urban growth demand at aggregated levels, the spatial module of the CLUE-S model developed by Verburg and his colleagues (Verburg *et al.* 2002; Verburg & Veldkamp 2004; Verburg & Overmars 2009) was applied to predict the urban development at specific locations. Especially, land use demands derived from the SD model have been translated into land use changes at different locations within the study area (Verburg *et al.* 2002). Nine variables, elevation, slope, soil type, distance to rivers and ponds, distance to railway, distance to provincial roads, distance to rural roads, distance to the nearest town, and distance to county boundary, were selected as driving factors to assess the likelihood of a cell being devoted to a particular land use category. In particular, the probability of a cell belonging to a particular land use type was calculated using a logistic regression model, detailed as follows.

$$\mathrm{Log}\left(\frac{P_i}{1-P_i}\right) = \beta_0 + \beta_1 X_{1,i} + \beta_2 X_{2,i} + \cdots + \beta_n X_{n,i} \qquad (1)$$

Where P_i represents the probability of a grid cell being assigned to a land use category i, $X_{j,i}$ represents the jth driving factors of land use category i, and n is the total number of driving factors. The relationship between land use probabilities and driving factors is shown in Table 1. The relative operating characteristic (ROC) value was utilised in this study to evaluate whether the model can explain all land use types with satisfactory accuracy (Pontius & Schneider 2001). ROC is a quantitative measure that examines the good-ness-of-fit between the simulated land use map and the reference map through calculating a statistical summary of a series of 2 by 2 contingency tables derived from a number of simulated results. The ROC values for these models were higher than 0.65, indicating the spatial distribution of all land use types can be well explained by the selected nine driving factors. Especially for forest, water body, and built-up land use categories, better ROC values (>0.8) were achieved.

After examining the driving factors using the logistic regression model, we also obtained the land use change elasticity (ELAS), which was calculated based on the conversion rates among land use types during the period 1990 to 2000 (see Table 2). The ELAS for each land use type ranges from 0 to 1, representing the difficulty of converting a land use type to other types. The higher the ELAS value, the more difficult is the conversion to other land use types. An ELAS value of 0.5 or under (e.g. farmland and water body) indicates that a land use type is more likely to be converted to other types (see Table 2). Otherwise, an ELAS value between 0.5 and 0.8 (e.g. grassland and barren land) indicates it is difficult to convert to other land use types. Furthermore, with a higher ELAS value (e.g. between 0.8 and 1 for forestland and urban land), a land use type is much more difficult to convert to other types (see Table 2). After estimating the logistic regression coefficients and the ELAS value for each land use type (Verburg *et al.* 2006), we applied the CLUE-S model to iteratively allocate the land use changes using probability maps and the ELAS values. The allocated area for each land use type was compared to the land use demand estimated by the SD model, and adjusted repeatedly until the allocated area was equal to the requirements for all land use types.

With the integrated SD and CLUE-S model, we simulated the urban growths of Daqing City under three socio-economic and land use scenarios: (1) current economic growth, (2) rapid economic growth, and (3) sustainable economic growth. With the current economic growth, the population growth rate was assumed to be approximately 0.9%, the GDP was set to grow about 7.2% annually, and

Table 1. Driving factors and their coefficients in the logistic regression model

Driver	Farmland	Forest	Grass land	Water body	Built-up	Barren land
Elevation (m)	0.09373	0.04119	− 0.12314	− 0.21594	0.10736	− 0.07571
Slope (degree)	0.41785	0.88919	− 0.58832	− 1.11537	0.23355	–
Soil						
Black soil	2.83867	–	1.41068	− 0.94117	–	–
Black & calcium soil	2.61342	1.96470	0.99938	− 1.20696	1.36258	0.65573
Sandy soil	2.29380	3.03149	–	− 0.61367	1.52491	–
Meadow soil	1.98455	1.13624	2.09927	− 0.96185	1.19111	1.21587
Swamp soil	–	3.42751	–	− 0.89905	–	1.89955
Saline-alkali soil	1.87478	–	2.65139	− 1.92370	–	2.04227
DRP (m)	0.00042	0.00016	0.00011	− 0.00276	–	− 0.00003
DR (m)	0.00001	–	0.00002	0.00001	− 0.00004	0.00001
DPR (m)	0.00004	− 0.00013	− 0.00004	− 0.00008	0.00004	− 0.00001
DRR (m)	0.00007	0.00029	− 0.00005	0.00007	− 0.00057	− 0.00014
DT (m)	− 0.00003	0.00015	0.00003	0.00004	− 0.00005	0.00001
DC (m)	0.00001	− 0.00009	− 0.00004	0.00004	− 0.00019	− 0.00002
Constant	− 16.21066	− 12.84005	12.89769	32.3295	− 17.86102	8.10157
ROC	0.769	0.838	0.740	0.940	0.861	0.692

− , not significant and not included in model at 0.05 significant level. DRP, distance to river and pond; DR, distance to railway; DPR, distance to provincial road; DRR, distance to rural road; DT, distance to town; DC, distance to country.

Table 2. Land use type conversion elasticity (ELAS) in Daqing, China

	Farmland	Forest	Grass land	Water body	Built-up	Barren land
ELAS	0.20	0.80	0.65	0.45	1.00	0.65

the technology progress was assumed to keep the present pace (1.2%). These numbers were utilised according to multiple reports from Chinese governments (State Council Information Office of China 2000; The Fifth Communist Party of China Central Committee 2002). With current population growth, GDP growth, and technology progress rates, their respective values under rapid and sustainable economic growth scenarios were determined according to relevant projected national and local socio-economic data from 2005 to 2015 (State Council Information Office of China 2000). In particular, under the rapid economic development scenario, population growth rate was set to be 1.1%, GDP growth rate was assigned to be 7.5% per year, and technology progress rate was set to be 1.5%. Under the sustainable economic growth scenario, population growth rate was set to be 0.7%, GDP growth rate was assumed to be 7%, and technology progress rate was set to a lower level (1%).

3.2 Spatially explicit ecosystem service valuation

In order to evaluate the impact of urbanisation on surrounding ecosystems in Daqing, China, we quantified the ecosystem service values for each biome using the valuation coefficients provided by Xie *et al.* (2008). In particular, the ecosystem service values were generated using the following steps. First, nine ecosystem service functions, food production, raw materials production, gas regulation, climate regulation, hydrological regulation, waste treatment, soil formation and conservation, biodiversity maintenance, and providing aesthetic values, were identified following Costanza's classification scheme. Second, as each biome provides 17 types of service, the ecosystem service value of food production, one of these services, is determined as approximately 1/17 of the total values. Therefore, the unit service value for food production of farmland was assigned to be 1/17 of the agricultural production market price. In this research, the per hectare farmland service value was set to be US$131, which was calculated using the price data for major crops in 2005. Further, the ratios between the service values of other ecosystem functions and the food production service value of per unit farmland were estimated through a questionnaire survey approach (see Table 3). In this study, due to the difficulty of having a perfect match, the river/lake and wetland were grouped into one class (water body), and desert was considered to be equivalent to barren land. With the food production service value of per unit farmland and the corresponding ratios, the service values of other ecosystem functions were derived (see Table 4). Consequently, the ecosystem service per unit value for each land use category was generated as the summation of each ecosystem service function value (see Table 4). Finally, the overall value of ecosystem services in Daqing was estimated using the following equation.

$$\mathrm{ESV} = \sum_{k=1}^{n} (A_k \times \mathrm{VC}_k) \qquad (2)$$

Where ESV is the estimated ecosystem service value, A_k is the area (ha) for land use category k, VC_k is the value coefficient (US$/ha/year) for land use category k and n is the overall number of land use categories.

Table 3. Ratio between ecosystem service value and food production service value provided by farmland (revised from Xie *et al.* 2008)

Service types	Farmland	Forest	Grassland	Wetlands and water	Urban	Barren land
Food production	1.00	0.33	0.43	0.45	0	0.02
Raw material production	0.39	2.98	0.36	0.30	0	0.04
Gas regulation	0.72	4.32	1.50	1.46	0	0.06
Climate regulation	0.97	4.07	1.56	7.81	0	0.13
Hydrological regulation	0.77	4.09	1.52	16.11	0	0.07
Waste treatment	1.39	1.72	1.32	14.63	0	0.26
Soil formation and conservation	1.47	4.02	2.24	1.20	0	0.17
Biodiversity maintenance	1.02	4.51	1.87	3.60	0	0.40
Providing aesthetic values	0.17	2.08	0.87	4.57	0	0.24
Total	7.9	28.12	11.67	50.13	0	1.39

In order to better examine the estimated error of VC values, a sensitivity analysis was applied to examine the dependence of ecosystem service values on the employed valuation coefficients. The coefficient of sensitivity (CS) was applied to evaluate the elasticity of ESV, and can be calculated as follows (Kreuter *et al.* 2001; Wang *et al.* 2006).

$$CS_k = \frac{(ESV_j - ESV_i)/ESV_i}{(VC_{jk} - VC_{ik})/(VC_{ik})} \tag{3}$$

Where CS_k is the coefficient of sensitivity for a land use type k, ESV is the ecosystem service value, VC is the value coefficient, 'i' represents the initial stage, and 'j' represents the adjusted stage. The coefficient of sensitivity indicates the sensitivity of the total ESV to the change of the ecological system valuation coefficient for a specific land use category. The greater the coefficient of sensitivity, the more critical is an accurate ecosystem VC for a specific land use type.

4. Results

4.1 Urban growth modelling

The SD model was constructed using the 1990–2000 land use data, and validated with the 2001–2005 data. Validation results (see Table 5) indicate that the SD model performed reasonably well, as the relative error of the simulated land use demand is less than 10% when compared to the reference land use area for the same year (2005). Therefore, the

Table 4. Ecosystem service value coefficients for each land use category (\$ $ha^{-1}year^{-1}$ revised from Xie *et al.* 2008)

Service types	Farmland	Forest	Grassland	Wetlands and water	Urban	Barren land
Food production	131	43	56	59	0	3
Raw material production	51	390	47	39	0	5
Gas regulation	94	566	197	191	0	8
Climate regulation	127	533	204	1023	0	17
Hydrological regulation	101	536	199	2110	0	9
Waste treatment	182	225	173	1917	0	34
Soil formation and conservation	193	527	293	157	0	22
Biodiversity maintenance	134	591	245	472	0	52
Providing aesthetic values	22	272	114	599	0	31
Total	1035	3683	1528	6567	0	181

Table 5. Prediction accuracy of the SD model (assessed using 2005 data)

	Year	Farmland	Forest	Grass land	Water body	Built-up	Barren land
Start	2000	332,596	3,048	18,820	69,132	28,156	62,700
Reference data	2005	326,948	3,616	19,892	55,628	32,380	75,988
Simulation results	2005	329,354	3,726	19,597	59,043	31,939	70,793
Relative error (%)		0.74	3.03	− 1.48	6.14	− 1.36	− 6.83

developed SD model has adequate accuracy, and can be employed to simulate future land use demands.

After calibration and validation, the developed SD model was applied to simulate land use demands for the next 10-year period (2006–2015). The simulated scenarios of land use demands for 2015 and associated changes are shown in Table 6. Results indicate, from 2005 to 2015, human-dominated land uses such as built-up land and barren land have increased rapidly together with the significant decrease of water body and farmland. Moreover, land use changes vary significantly under different socio-economic and land use scenarios. For example, built-up land is projected to increase from 32,380 ha in 2005 to 44,707.6 ha in 2015 under the current economic growth, to 47,070 ha under rapid economic growth or to 43,040 ha under sustainable economic growth, with an overall increment of 38.07%, 45.37%, or 32.92% respectively. With the incoming depletion of oil resources, Daqing is facing the challenge of transforming from an oil-resource-based city to a city with a diversified economy. Associated with high demand for built-up land for economic development, a high speed of urban expansion will occur in the following years. Meanwhile, as high-speed economic development is at the cost of land resources and natural environments, barren land is projected to increase 15,979 ha with the current economic growth, 31,959 ha with rapid economic development growth or 12,453 ha with sustainable economic growth, an increment of 21.03%, 42.06%, or 16.39% respectively. In addition, the water body will decrease significantly from 2005 to 2015. During this period, its area decreases from 55,628 ha to 29,446 ha under current economic growth, to 19,309 ha under rapid economic growth, or to 38,504 ha under sustainable economic development, with a total decrement of 47.07% (4.71% annually), 65.29% (6.53% annually), or 30.78% (3.08% annually) respectively due to a great amount of water consumption. The decrease of the water body will be mainly due to the large amount of water

Table 6. Land use change from 2005 to 2015 under different socio-economic scenarios

		Farmland	Forest	Grassland	Water body	Built-up	Barren land
2005 (ha)		326,948	3,616	19,892	55,628	32,380	75,988
2015 (ha)	Current	321,442	5,630	21,261	29,446	44,706	91,967
	Rapid economic	318,124	4,502	17,500	19,309	47,070	107,947
	Sustainable	312,831	6,308	25,328	38,504	43,040	88,441
Change (ha)	Current	− 5,506	2,014	1,369	− 26,182	12,326	15,979
	Rapid economic	− 8,824	886	− 2,392	− 36,319	14,690	31,959
	Sustainable	− 14,117	2,692	5,436	− 17,124	10,660	12,453
	Current	− 1.68	55.71	6.88	− 47.07	38.07	21.03
% change	Rapid economic	− 2.69	24.50	− 12.02	− 65.29	45.37	42.06
	Sustainable	− 4.31	74.45	27.33	− 30.78	32.92	16.39
	Current	− 0.17	5.57	0.69	− 4.71	3.81	2.10
% per year	Rapid economic	− 0.27	2.45	− 1.20	− 6.53	4.54	4.21
	Sustainable	− 0.43	7.45	2.73	− 3.08	3.29	1.64

consumption during the process of oil extraction and production, in addition to residential, commercial, and other industrial usages. Due to the policy of returning farmland to forest and grassland, forest and grassland will increase noticeably, and the total increment of forest will be 55.71% with the current economic growth, 24.50% with rapid economic growth, or 74.45% with sustainable growth. In summary, as a result of economic development, human-dominated land will increase noticeably at the cost of water body.

With the knowledge of aggregated LUCC in Daqing, it is necessary to examine the specific locations of the changes. Through applying the land use data from 1990 to 2000, the CLUE-S model was developed to distribute the aggregated land use demands predicted by the SD model to specific spatial locations. The Kappa value was employed to assess the modeling accuracy (Cohen 1960). It is an important index that measures the association between the simulated and the reference images. Kappa ranges from −1 to 1, and a value of 1 indicates a perfect agreement. In this study, the Kappa value is 0.82, indicating that the CLUE-S model has generated satisfactory results for simulating the spatial distribution of future land use demands. Then, this CLUE-S model was applied to simulate the LUCC for the period from 2006 to 2015. Several conclusions can be obtained through visualising the spatial changes of land use types from 2005 to 2015 (see Figure 3). First, it is projected that significant land use changes will take place during these 10 years, and due to rapid urbanisation many hectares of farmland will be

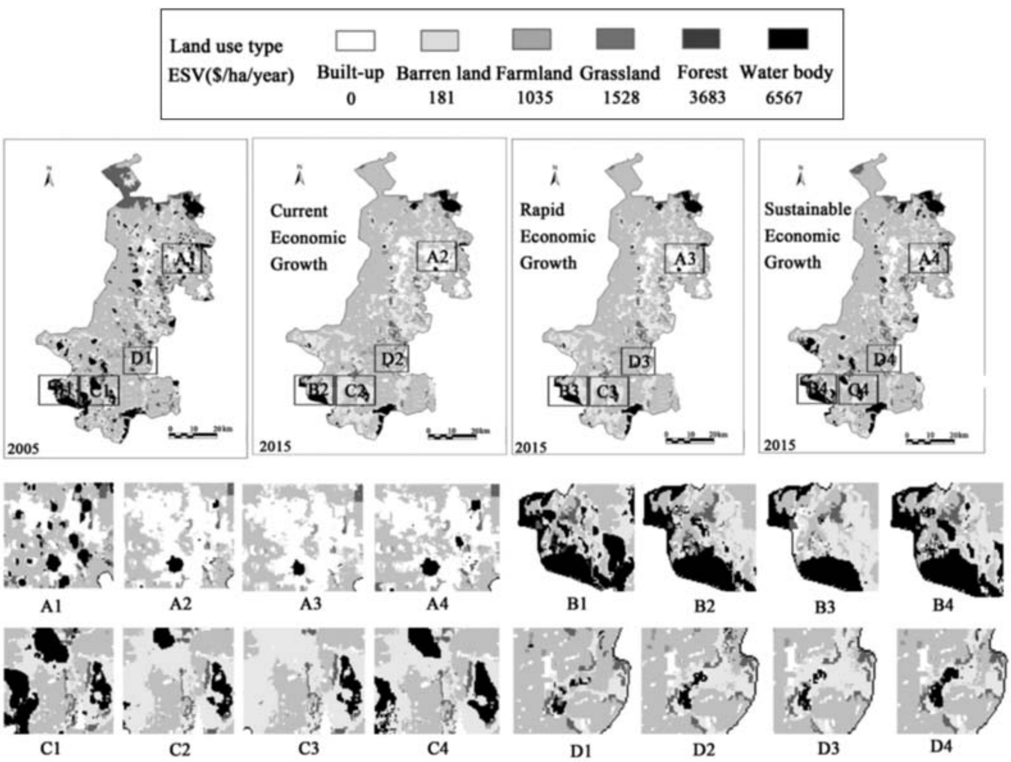

Figure 3. Land use and ecosystem service value change in Daqing, China from 2005 to 2015 under three socio-economic and land use policies

converted to built-up lands, in particular in the northeastern part of Daqing (from A1 to A2, A3, or A4). Further, due to the increasing demand for food, some forest will be converted to farmland, and some forest and grassland will be transformed to barren land because of environment degradation. An example of this trend can be clearly identified in the southwest of Daqing (from B1 to B2, B3, or B4). Associated with these patterns, the shrinking of water bodies (from C1 to C2, C3, or C4) and farmland (from D1 to D2, D3, or D4), and the expansions of barren lands are clearly shown in the southern part of Daqing.

4.2 Ecosystem service value change analysis

With the results of land use changes, the ecosystem service valuation method developed by Xie *et al.* (2008) was applied to examine the impact of land use change on surrounding natural ecosystems in Daqing during the period 2005 to 2015 (Table 7). As can be discerned from Table 7, the total ecosystem service value in Daqing was about \$761.16 million in 2005, and this value is projected to decrease to \$595.94 million under current economic growth, \$518.92 million under rapid economic growth, or \$654.58 million under sustainable economic growth in 2015, with a total reduction of 21.71%, 31.83%, or 14% (2.17%, 3.18%, and 1.40% annually). This is mainly due to the significant decrease of water body, as the total ecosystem service value of water body will decrease from \$365.31 million to \$193.37 million (under current economic growth), \$126.80 million (under rapid economic growth), or \$252.86 million (under sustainable economic growth), or 47.07%, 65.29%, or 30.78% (4.71%, 6.53%, or 3.08% annually) respectively. In addition, the ecosystem service value of farm land will decrease slightly from 2005 to 2015 (see Table 7). Conversely, the ecosystem service values provided by forest and grassland are projected to increase from 2005 to 2015. In particular, the ecosystem service values provided by forest will increase 55.71% (5.57% annually) under current economic growth, 24.47% (2.45% annually) under rapid economic growth, or 74.40% (7.44% annually) under sustainable economic growth respectively. And the ecosystem service values provided by barren land will increase 21.09% (2.11% annually) under current economic growth, 42.11% (4.21% annually) under rapid economic growth, or 16.44% (1.64% annually) under sustainable economic growth respectively. Similarly, the ecological service value provided by grassland will also increase

Table 7. Ecosystem service value change from 2005 to 2015 under different scenarios

		Farmland	forest	Grass land	water body	Built-up	barren land	total
ESV 2005 (10^6\$)		338.39	13.32	30.39	365.31	0	13.75	761.16
ESV 2015 (10^6\$)	Current	332.69	20.74	32.49	193.37	0	16.65	595.94
	Rapid economic	329.26	16.58	26.74	126.80	0	19.54	518.92
	Sustainable	323.78	23.23	38.70	252.86	0	16.01	654.58
Change (10^6\$)	Current	−5.7	7.42	2.1	−171.94	0	2.9	−165.22
	Rapid economic	−9.13	3.26	−3.65	−238.51	0	5.79	−242.24
	Sustainable	−14.61	9.91	8.31	−112.45	0	2.26	−106.58
% change	Current	−1.68	55.71	6.91	−47.07	0	21.09	−21.71
	Rapid economic	−2.70	24.47	−12.01	−65.29	0	42.11	−31.83
	Sustainable	−4.32	74.40	27.34	−30.78	0	16.44	−14.00
% per year	Current	−0.17	5.57	0.69	−4.71	0	2.11	−2.17
	Rapid economic	−0.27	2.45	−1.20	−6.53	0	4.21	−3.18
	Sustainable	−0.43	7.44	2.73	−3.08	0	1.64	−1.40

slightly. These increments, however, cannot offset the loss of ecological service values due to the diminishment of water body.

With the knowledge of overall ecosystem service value change in Daqing, we further examined the specific locations with noticeable changes. Through applying the ecosystem service value coefficients to the land use change map generated from the integrated SD and CLUE-S model, we derived the ESV maps of 2005 and 2015, and illustrated the spatial and temporal dynamic changes of ESV (see Figure 3). Several impressions can be obtained from Figure 3. First, around the original city boundary, ESV is projected to decrease significantly due to rapid urbanisation. In these areas, a large number of natural lands, particularly water body, will be transformed into built-up land, and the ESV will decrease sharply, as can be seen from the district A (A1 to A2, A3, or A4) in Figure 3. Second, in the northwestern part of Daqing City, the ESV decreases slightly due to the conversion from forest and grassland to farmland and barren lands (see district B). This can be explained by the increasing need for farmland for food production. Finally, in the southern part of Daqing, there is an apparent and significant decrement of ESV due to the shrinking of water body and expansion of barren lands (see districts C and D).

5. Discussion and conclusions

In this study, we developed a spatially explicit method to examine the effects of urbanisation on ecosystem service values by integrating urban growth modelling and ecosystem service valuation methods, and developed future LUCCs under different socio-economic and land use scenarios. In particular, future urban growth was simulated through integrating an aspatial (the SD model) and a spatially explicit (the CLUE-S model) urban growth model. Ecosystem service values for different scenarios were quantified using Xie *et al.*'s ecosystem service valuation method. Further, future land use and ecosystem service value changes were simulated under three socio-economic scenarios: (1) current economic growth, (2) rapid economic growth, and (3) sustainable economic growth. Analysis of results suggests several conclusions.

First, from the analysis of land use change from 2005 to 2015, it can be concluded that the human-dominated lands, such as built-up land and barren land, have increased rapidly, together with a significant decrease of water body and farmland. The area of built-up land will increase 38.07% under current economic growth, 45.37% under rapid economic growth, or 32.92% under sustainable economic growth. During the same period, water body is projected to decrease 47.07%, 65.29%, or 30.78% under these three different socio-economic and land use scenarios. In addition, the area of farmland will decrease slightly, and forest and grassland will increase as the result of the policy of returning farmland to forest and grassland.

Second, future ecosystem service values will vary significantly under different development scenarios. Under the condition of current economic growth, the total ecosystem service value will decrease about \$165.22 million from 2005 to 2015, a total decrease of 21.71% (2.17% annually). With rapid economic growth, due to the rapid expansion of built-up land and decline of natural lands (e.g. water body), the ecosystem service value will decrease significantly (approximately \$242.24 million, or 31.83%). This scenario involves rapid economic development accompanied by high risks for natural ecosystems. Finally, under the condition of sustainable economic growth, with a relatively low economic growth rate, low population growth rate, and more means of environmental protection, the ecosystem service value will decrease slightly (approximately \$106.58 million, or 14%). When compared to the scenarios with current and rapid economic growth, the decreasing rate of ecosystem service value has been controlled, mainly because the land use transformation from natural lands, particularly water body and forests, to human-dominated lands (e.g. built-up and barren lands) has been slowed down. In addition, as the result of the policy of returning farmland to forest and grassland, the ESV of forest and grassland will increase about 74.40% and 27.34% respectively.

Finally, through exploring the spatial pattern change of ecosystem service values in Daqing, China, we found apparent spatial variations of ESV changes, mainly due to (1) conversion from water body and farmland to built-up lands around the city boundary (as shown in the district A, Figure 3, northeast part of Daqing City), (2) transformation of forest and grassland to farmland (as illustrated in district B, Figure 3, northwest and southwest of Daqing), (3) the change of natural lands, in particular water body, to barren lands (shown in the district C of Figure 3), and (4) the increment of forest and grassland and slight decrease of farmland as a result of the policy of returning farmland to forest and grassland (e.g. district D in Figure 3, southeast part of Daqing).

In summary, the combined SD-CLUES model provides a new means to examine the spatial change of ecosystem service values under different development scenarios, which can offer valuable references to local governments and urban planners. The current research can be improved in the following two directions. First, in this study, a combined impact of urbanisation and petroleum industry development on ecosystem service values was examined through the integration of spatially explicit urban growth modelling and ecosystem service valuation. Their respective contributions, however, cannot be examined with the current modelling approach. For the purpose of planning in a resource based city like Daqing, the identification of respective impacts of natural urbanisation and petroleum industry development may provide meaningful references as Daqing is facing the challenges of urban economic transformation. Second, it is highly necessary to incorporate city planning maps into land use scenario simulation and ESV change analysis. Because of data limitations, we did not incorporate Daqing city urban planning maps. Urban planning maps, however, may provide much more detailed information about the city development trends and facilitate more realistic land use simulations and ESV change analyses.

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