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Combining system dynamic model and CLUE-S model to improve land use scenario analyses at regional scale: A case study of Sangong watershed in Xinjiang, China

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ABSTRACT

Uses of models of land use change are primary tools for analyzing the causes and consequences of land use changes, assessing the impacts of land use change on ecosystems and supporting land use planning and policy. However, no single model is able to capture all of key processes essential to explore land use change at different scales and make a full assessment of driving factors and impacts. Based on the multi-scale characteristics of land use change, combination and integration of currently existed models of land use change could be a feasible solution. Taken Sangong watershed as a case study, this paper describes an integrated methodology in which the conversion of land use and its effect model (CLUE), a spatially explicit land use change model, has been combined with a system dynamic model (SD) to analyze land use dynamics at different scales. A SD model is used to calculate area changes in demand for land types as a whole while a CLUE model is used to transfer these demands to land use patterns. Without the spatial consideration, the SD model ensures an appropriate treatment of macro-economic, demographic and technology developments, and changes in economic policies influencing the demand and supply for land use in a specific region. With CLUE model the land use change has been simulated at a high spatial resolution with the spatial consideration of land use suitability, spatial policies and restrictions to satisfy the balance between land use demand and supply. The application of the combination of SD and CLUE model in Sangong watershed suggests that this methodology have the ability to reflect the complex behaviors of land use system at different scales to some extent and be a useful tool for analysis of complex land use driving factors such as land use policies and assessment of its impacts on land use change. The established SD model was fitted or calibrated with the 1987–1998 data and validated with the 1998–2004 data; combining SD model with CLUE-S model, future land use scenarios were analyzed during 2004–2030. This work could be used for better understanding of the possible impacts of land use change on terrestrial ecosystem and provide scientific support for land use planning and managements of the watershed.

1. Introduction

Increased efforts have been made to understand the processes, trends and driving forces of land use change and its ecological consequences (Verburg et al., 1999; Geist and Lambin, 2002; Irwin and Geoghegan, 2001; Lambin, 2002; Ojima et al., 2002; Parker et al., 2003; Gutman et al., 2004; Turner et al., 2007). Identifying the primary causes and estimating the processes and trends of land use change are crucial for land use planning, utilization of regional resources, and management of the environment (Ojima et al., 2002; Turner, 2002). Land use change is determined by the spatial–temporal interactions between biophysical and human factors at different scales (Turner et al., 1995; Veldkamp et al., 2001; Verburg et al., 2004).

Models of land use changes are useful tools for analyzing driving forces and processes of land use changes, assessing the ecological impacts of land use change and decision-making for land use planning. In the past 10 years, scientists have developed different models of land use/cover change (LUCC) depending on their objectives and background (Verburg et al., 2004). But no

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single model is capable of seizing all crucial processes of land use change at the different scales (Verburg et al., 2008). Each LUCC model has its own potentials and constraints. Some current land use models are either only valid for one of the processes to represent land use change or lack ability to reflect the spatial dimensions of land use change (Hubacek and Sun, 2001; Lambin et al., 2000). In order to couple more important aspects to land use modeling it is necessary to develop an integrated approach which better addresses the multi-scale characteristics of the land use system, explicitly deals with temporal and spatial dynamics, and achieves a higher level of integration between disciplinary approaches (Verburg et al., 2004). Combination and integration of current land use models could be a feasible and potential solution.

The conversion of land use and its effects (CLUE) model is a model with multi-scale characteristics, which can better understand the processes that determine changes in the spatial pattern of land use and explore possible future changes in land use at the different spatial scales (Verburg et al., 2008). It also can specify the scenario conditions for future land use in detail (Verburg et al., 2002; Verburg and Veldkamp, 2004). However, its ability to reflect the macro-demand for land use based on the given socio-economic scenario is still limited. In the some study cases, the objectives of the authorities are used as the input data of the land demands. In the other researches, some related models were introduced to calculate the land demands, e.g. a model named GTAP (Global Trade Analysis Project), which was proved to a feasible solution for the limitation of CLUE model (Verburg et al., 2006).

System dynamics (SD) is a methodology for understanding certain kinds of complex problems. It was originally proposed by Jay W. Forrester in the 1950s (Forrester, 1968), which focuses on how the thing being studied interacts with the other components of the system. System dynamics was proposed to achieve systems thinking with computer models in solving complicated management problems. Since environmental management involves complicated interactions, some system dynamics models have been developed for environmental management and ecosystem assessment (Saysel and Barlas, 2001; Leal Neto et al., 2006; Sufian and Bala, 2007). Moreover, it is often used to predict the demand for land use based on the micro-social-economic conditions or scenarios for land use planning and management (Saysel et al., 2002; Yu et al., 2003). It is important and useful to develop a system dynamics model for land use management. However, SD model's ability to represent the spatial process is weak because it cannot deal with a mass of spatial data well and cannot describe and model the distribution and situation of those spatial factors in the system (Zhang, 1997).

Based on the discussion above, we would like to make our efforts to develop an approach by the combination of SD model and CLUE model to deal with some shortcomings of the existing land use model and to properly address the processes at different scales that give rise to the land use dynamics. The approach presented in this study will be helpful to understand the complexity of land use change and provide scientific support for land use planning and managements. The objectives of the study are (1) to develop a SD model to calculate and predict demands for different land use types at the macro-scale as a whole, (2) to improve the characterization and presentation of the land use change processes by developing a CLUE model that will transfer and allocate land demands from SD model to spatially explicit land use patterns at a finer spatial scales (e.g., at 50 m resolution in our study), and (3) to discuss the advantages and disadvantages of combining and integrating the current land use change models to improve land use change modeling and projection.

2. Data and methods

2.1. The study area

The Sangong River drains Tianshan Mountains and flows northward into the southern Junggar Basin in Xinjiang, with a total drainage area of 1670 km^2 (Fig. 1). The drainage basin consists of three physiographical units, Tianshan Mountains to the south, oasis in the middle, and, to the north, the southern flank of the Gurbantonggut Desert. Oases, more productive than the surrounding deserts, are the primary sites for human settlement because of the availability of fertile soil, fresh groundwater, and surface runoff from the nearby mountains (Jia, 1996). The oasis in the Sangong River drainage covers the piedmont of Tianshan and the margin of the Junggar Basin with a size of about 942 km^2, sloping to the north with an elevation ranging from 700 to 465 m above sea level. Alluvial fans often containing a narrow, distal phreatic zone dominate the southern part of the oasis and, in the north, a flat, low-gradient alluvial plain occurs.

Over the past 50 years, the local vegetation and soil have been changed or modified by large-scale land reclamation, irrigation and cultivation, as well as the application of fertilizers across the Sangong watershed (Luo et al., 2003). There are two typical land use patterns in the Sangong watershed, Farm-based Land Use (FLU) with large-scale intensified agricultural activities and Household Responsibility-based Land Use (HRLU) with small-scale family farming which are prevailing in the arid region of Xinjiang. In the Sangong River drainage, the HRLU region, which is mainly managed by local government, is situated on the alluvial–diluvial fan, including Chengguan Rural Area, Jiuyunjie Rural Area and Fukang City, while the FLU region, which is mainly managed by Xinjiang Production and Construction Corps (XPCC), is sited in the alluvial plain, including Fubei Farm and Liuyunhu Farm. Although there are no evidence indicating climate differences between in the HRLU region and in the FLU region there are obvious differences in soil and soil water conditions (Wang and Zhao, 2001). In this study, the Fubei Farm in FLU area was chosen as a study area (Fig. 1).

2.2. Data

Remotely sensed data used to characterize land use change in the study area includes 65 black and white aerial photographs at 1:35,000 scale taken in August 1978, 26 color-infrared aerial photographs at 1:70,000 scale taken in July 1987, a Landsat TM image taken in August 1998, and a SPOT image taken in July 2004. Geo-rectification and mosaic of these images were conducted using ERDAS image processing software and 1:50,000 scale topographic maps. The TM image has a resolution of 30 m, satisfying the precision required for mapping at a scale of 1:100,000. For this reason, all the images were converted to plane coordinates at 1:100,000 scale.

The land was categorized into various units or types prior to land use change analysis. As a general practice in China, this study follows the system of current land use surveys (State Bureau of Land Administration, 1997). Six land use types were identified, including farmland, woodland, grassland, residential and industrial lands, waters, and unused lands. Some linear surface features, such as roads, irrigation canals and shelter-forest belts, could not be individually categorized due to the resolution limitation of the images. Subsequently, they are included into the above six land types. A GIS database of land use types was developed at 1:100,000 scale and the topographic relationships were generated. Attributes related to land use changes were derived from the images. Visual interpretation of the images was assisted in classifying the land use types. Field visits to the study area were repeatedly conducted to check and validate the accuracy of the interpreted images. Based

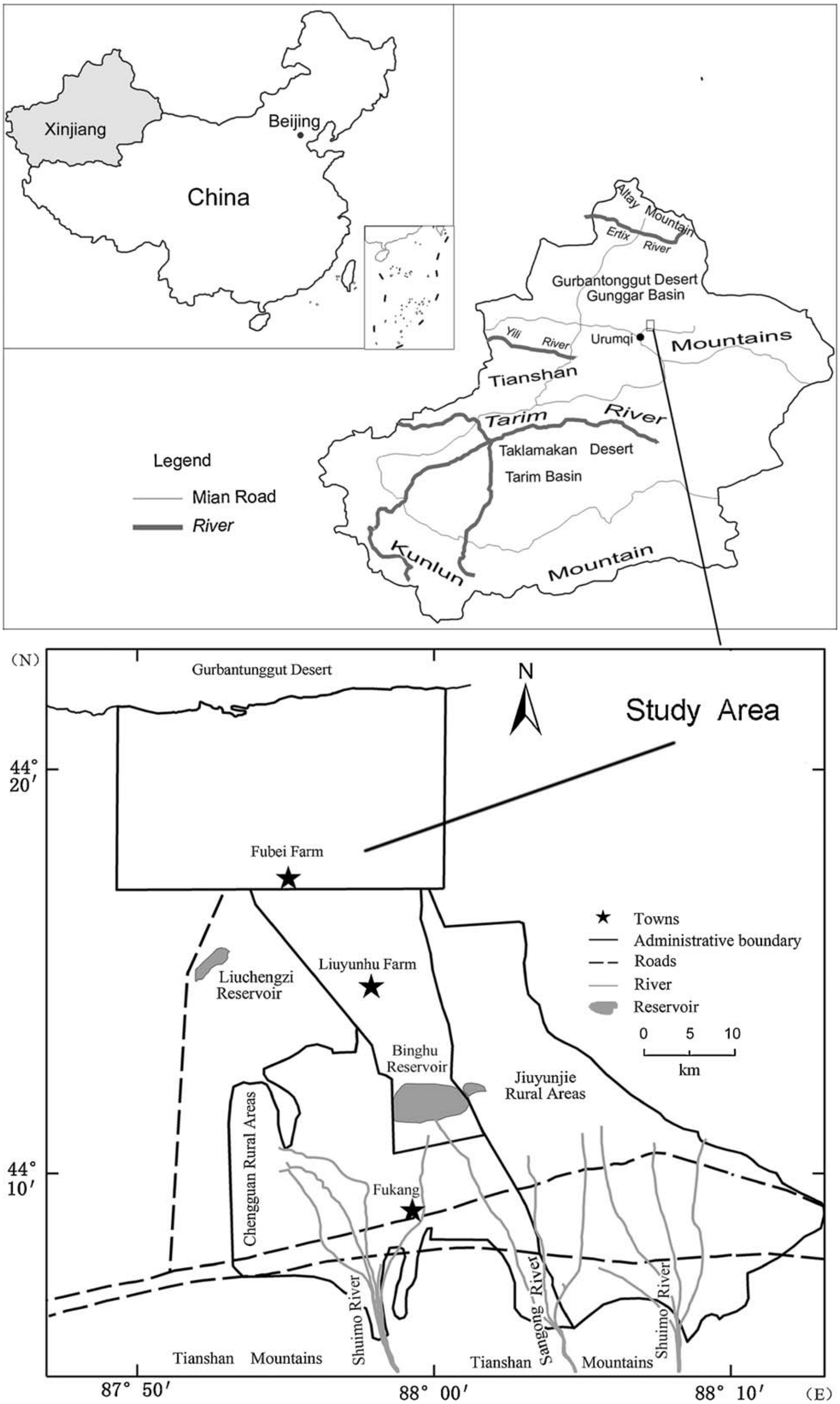

Fig. 1. Location of the study area. The oasis of the Sangong River is outlined. DFP: demand for farming product; DGL: demand for grassland; DIL: demand for industrial land; DL: demand for livestock; DURL: demand for urban residential land; DRRL: demand for rurul residential land; DSDFL: difference of supply and demand of farmland; DSDGL: difference of supply and demand of grassland; DTL: demand for transportation land; GDP: gross demestic product; Rural P: rural population; T land: transportation land; Urban P: urban population.

on the on-site visits and the information provided by the local residents, the classification accuracy of the land types for 1978, 1987, 1998 and 2004 were estimated to be 93%, 96%, 94% and 95%, respectively.

Besides remotely sensed data, the other biophysical data collected for this study included 1:50,000 scale topographic maps, monthly groundwater table and quality data from 16 wells during 1976–2005, distribution maps of soil type, soil organic matter and nutrients data derived from 236 soil samples in 1981, 1992 and 2002, respectively. 1:50,000 scale topographic maps were used to establish the digital elevation model using triangulated irregular network and accordingly created the maps of altitude and slope using the 3D Analyst module of ARCGIS. Spatial distributions of soil organic matter and nutrients, groundwater table and quality were created by spatial interpolation using the method of inverse distance weighted, and its accuracy met the need for model analyses.

Socio-economic data were originated from population and agricultural censuses during 1975–2005, including population census data, population density, livestock density, water consumption by unit area, crop production by unit area. They were presented at the level of village administrative units, and can be represented by a polygon. Census data in the vector format could be used for direct analysis, and also be transformed to a grid format with a 50 m resolution for raster-based modeling. The spatial accessibility to the main water resources, roads, and residential and industrial area was calculated by shortest distance. Finally, the spatial grid maps including four-periods of land use and each impact factor with resolution of 50 m were prepared for model data input.

Finally, an integrated GIS database was constructed by merging the satellite- and biophysical- and census-based data in the vector or raster format.

2.3. Model description

This study is built on an integrated CLUE model with SD model to account for the structure of land use change processes in Sangong watershed. The proposed model mainly unfolds at two scales, local and regional. But we need to assess the influence of driving forces such as provincial or national policies at the higher level on land use. At the regional scale or higher level, SD model is used to simulate the demand for land use types as a whole without spatial consideration with social-economic development, including parameters such as population density, population growth rate, economic factors, marketing condition as well as technology advances and macro-policy constraints. In arid land, water resource is the most important determinant natural factor for the social-economic development, the restriction of water resources on social-economic factors at the regional scale is also considered during the establishment of a SD model. A CLUE model is used to simulate spatial dynamics and makes top-down implementation for the spatial allocation of land use types.

2.3.1. SD model

Land use demand is closely related with the regional socio-economic development which is mainly driven by human factors, including population, GDP, market and technology progress, policies at different levels and so on. The SD model has been proved to be a useful tool for analyzing the complex connection between land use and socio-economic development (Saysel et al., 2002; Yu et al., 2003). Furthermore, it is easier and more flexible to use a SD model to design plausible land use scenarios based on the different socio-economic developments which are presented by the different combinations of human factors.

In the study, the SD model was divided into driving force and land use parts. The driving force part dealt with the impact of non-spatial human factors on land use change, mainly including human living demand, economy development, technology progress and market adjustment, while the land use part focused on the interaction and conversions between land use types driven by non-spatial human factors and natural factor such as water and land resources. On the base of analyses on driving forces of land use change in the study area (Tang et al., 2007), the structure of SD model on land use is drawn with the causality functions and feedback loop structure between a large numbers of socio-economic and policy variables (Fig. 2). For example, Population$^{+} \rightarrow$ Demand for farm product, residence and transprotation$^{+} \rightarrow$ Demand for different land use type$^{+} \rightarrow$ Demand for land$^{+} \rightarrow$ Defference between supply and demand of farmland, and residential and industrial land$^{+} \rightarrow$ Population^{-}.

The Ventana Vensim PLE v5.4d software (http://www.vensim.com) was used to design the stock and flow diagram according to the causal loop diagram of SD model and automatically generate the corresponding equations based on the designed stock and flow diagram. The stock and flow diagram includes 10 state variables, 14 rates, over 100 auxiliaries and arrows as well as over 100 equations. The SD model simulations begin with 1978. The model was calibrated with the 1987–1998 land use data and validated with the 2004 data in the FLU. Table 1 shows that the SD model is reliable with <5% relative errors of simulation results compared with reference data and can be used to simulate the future demand for land use types.

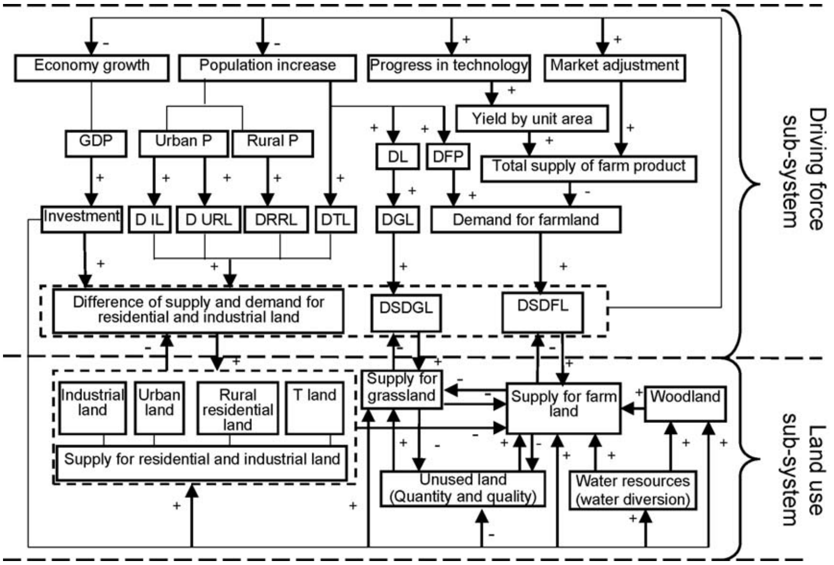

Fig. 2. The causality functions and feedback loop structure of SD model on the land use change in the Sangonghe oasis.

Table 1
The SD model simulation precision and its validation results in the FLU.

		Farmland	Woodland	Grassland	Residential and industrial land	Unused land
Reference data	1987	6006	1790	4048	452	402
	1998	6001	1860	3980	536	321
	2004	7611	1083	2873	541	590
Simulation results	1987	5945	1799	4107	453	394
	1998	5847	1875	4116	527	333
	2004	7557	1030	2961	562	588
Relative error (%)	1987	−1.02	0.48	1.48	0.14	−2.05
	1998	−2.58	0.80	3.42	−1.62	3.67
	2004	−0.72	−4.91	3.05	3.93	−0.32

Table 2
Scenarios design of the population increase, economic growth, technology development and marketing during 2004–2030.

	2000–2004	Scenario 1	Scenario 2	Scenario 3
Increase rate of population	9.1%	High (P1) 11.0%	Medium (P2) 9.0%	Low (P3) 7%
Growth rate of GDP	8.2%	High (G1) 9.2% (2005–2015) 7.2% (2016–2030)	Medium (G2) 8.2% (2005–2015) 6.5% (2016–2030)	Low (G3) 7.2% (2005–2015) 5.7% (2016–2030)
Marketing adjustment: ratio of grain self-support	97%	High (M1) 115%	Medium (M2) 100%	Low (M3) 85%
Technology progress: increase rate of grain productivity	1.1%	High (T1) 1.5% (2005–2015) 1.1% (2016–2030)	Medium (T2) 1.1% (2005–2015) 1.1% (2016–2030)	Low (T3) 1.1% (2005–2015) 0.9% (2016–2030)

2.3.2. *Scenarios of SD model*

Based on the local statistical social-economic information from 1975 to 2004, related macro-economic planning and policies at the provincial and national level, three variable settings of the population increase, economic growth, technology development and marketing have been designed in the next 26 years from the year of 2004 (see Table 2). Then according to the combination of these settings, three future socio-economic scenarios have been defined and their demand for land use can be predicted during 2004–2030 using the SD model. The first scenario is the reference one (P2, G2, M2 and T2) which almost keeps the present pace with social and economic development. The second scenario is the economic one (P1, G1, M1 and T2) which may speed up socio-economic development. The third scenario is the ecological one (P3, G3, T3 and T1) which is favorable to ecological improvement.

2.3.3. *CLUE-S model*

The conversion of land use and its effects (CLUE) methodology (Verburg et al., 2002; Verburg and Overmars, 2009) was developed at Wageningen University, the Netherlands, to project and visualize the spatial patterns of changes in land use as they are expected to develop under a set of conditions that are specified in scenarios. In the study, because of its ability to represent multi-scale land change, the CLUE-S version of the CLUE model, has been applied, based on high-resolution data in which each pixel only contains one land use type. This version has mainly been used in case studies with a local to regional extent and a resolution ranging from 20 to 1000 m (Verburg et al., 2002; Verburg and Veldkamp, 2004; Overmars et al., 2007).

The CLUE-S model is based on the dynamic simulation of competition between land uses while the spatial allocation rules can be specified based on an empirical analysis, user-specified decision rules, neighborhood characteristics or a combination of these methods. Verburg et al. (2006) showed its basic structure. The actual allocation is based on the constraints and preferences defined by the user based on the characteristics of the land use type or the assumed processes and constraints relevant to the scenario. Overview of the CLUE-S modeling procedure was shown in Fig. 3 (Verburg and Overmars, 2007).

According to Fig. 3, the CLUE-S model needs to consider the following four parts, land use requirements, location characteristics and suitability, spatial policies and restrictions, and land use type specific conversion settings. We used the SD model to deal with the land use requirements (demand).

(1) Land use requirements (demand): the land requirements (demand) for the different land use types are calculated with the SD model described above (Fig. 2).
(2) Location characteristics and suitability: the demand for land by the different land use types determines the overall competitive capacity of the different land use types, but the location suitability is a major determinant of the competitive capacity of the different land use types at a specific location. The location suitability is a weighted average of the suitability based on empirical analysis capturing the historic and current location preferences in response to location characteristics, and suitability based on scenario specific decision rules (Verburg et al., 2008). The location characteristics in this study include groundwater table and quality, soil type, soil organic matter and nutrients, altitude and slope, population density and livestock density, and accessibility to water sources, roads and the built-up areas, which are regarded as the potential factors of land use suitability. The empirical analysis was conducted to estimate the contribution of different location characteristics (potential factors) to the suitability of a location for a specific land use type based on a logistic regression relating land use patterns to a wide range of potential factors (Verburg et al., 2004). In this study logistic regression was used to indicate the probability of a certain grid cell to be devoted to a land use type given a set of potential driving factors following:

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

where P_i is the probability of a grid cell for the occurrence of the considered land use type i and the X are the driving factors. The value of Relative Operating Characteristics (ROC) put forward by Pontius and Schneider (2001) is used to indicate the validation of the model.

Based on this GIS dataset logistic regression models were constructed to determine the relations between land use and a set of a set of potential driving factors. For each of the land use types, a logistic regression was run in 1978, 1987 and 1998, respectively (Table 3). Seven driving factors, including population density, soil organic matter, groundwater table, elevation, gradient, livestock density, groundwater quality, were selected to evaluate the suitability of a certain grid cell to be devoted to a land use type. From the table it can be seen that not all driving factors were actually included in the regression models. The spatial distribution of all land use types could well be explained by the selected driving variables as indicated by the high ROC test statistics (>0.7).

(3) Spatial policies and restrictions: in addition to the land requirements and location suitability, the model accounts for the spatial policies and restrictions for the specific land use type that influence the conversion and cause differences in spatio-temporal behavior. Changes in farmland area are usually restricted, particularly the protection areas of basic farmlands within which special protection is carried out for the cultivated lands according to Agriculture Law of the People's Republic of China. Due to its agglomeration effects, built-up area extension may be allowed to properly take up the neighborhood farmland only after neighborhood other land use types are preferentially converted into built-up. Shelter forests among woodland are usually not allowed to be converted to other land use types in the study area.

(4) Land use type specific conversion setting: for each of the scenarios, land use type specific conversion settings were defined and implemented by the relative elasticity for change (ELAS) for the land use type into any other land use type in the model (Verburg et al., 2002). The relative elasticity ranges between 0 and 1. The higher the defined elasticity, the more difficult it gets to convert this land use type. In the study areas, the change in land use showed frequent conversion between land use types during 1978–1998 (Luo et al., 2008). Based on the reference data during 1987–2004, the values of conversion elasticity for different land use types were tuned so that they are suitable for the calibration of the model. According to the defined scenarios (see Section 2.3.2), specific conversion elasticity values of land use types were defined and implemented in the model during 2004–2030 (Table 4).

3. Results

3.1. Simulation of demand for the land use types

The SD model was used to project the demand for the land use types during 2004–2030. The timeframe for the SD model simulations is from 2004 to 2030 with yearly time steps in the FLU. According to the three different modes defined above (see Section 2.3.2), the demand for areas of different land use types in 2010, 2020 and 2030 were projected. The projection results are presented in Table 5.

3.2. Simulation of land use during 2004–2030

The data of 1987 and 1998 were used to calibrate the model to specify the model parameters and variable settings. The data of 2004 was used to validate the model to evaluate its ability of

Table 3
Beta values[a] for regression results of the spatial distribution of land use on the in the FLU area during 1978–1998.

Drivers		Population density		Soil organic matter		Groundwater table		Elevation		Gradient		Livestock density		Groundwater quality		Constant	ROC value
		Beta	$\text{Exp}(B)-1$	Beta	$\text{Exp}(B)-1$	Beta	$\text{Exp}(B)-1$	Beta	$\text{Exp}(B)-1$	Beta	$\text{Exp}(B)-1$	Beta	$\text{Exp}(B)-1$	Beta	$\text{Exp}(B)-1$		
Farmland	1978	0.007	0.007	1.214	2.367	1.072	1.921	−0.083	−0.080			0.332	0.394			35.295	0.754
	1987	0.256	0.292	1.220	2.387	0.650	0.916	−0.048	−0.047	0.104	0.110	0.587	0.799			20.930	0.766
	1998	0.346	0.413	1.272	2.568	0.598	0.818	−0.087	−0.083	0.155	0.168	0.574	0.775			38.570	0.763
Woodland	1978	0.135	0.145	−0.399	−0.329	−0.120	−0.113	0.072	0.075	0.480	0.616					−36.893	0.757
	1987	0.126	0.134	−0.866	−0.579	−0.118	−0.111	0.069	0.071	0.009	0.009					−33.758	0.750
	1998	0.047	0.048	−1.542	−0.786	−0.080	−0.077	0.105	0.111	0.281	0.324			−0.001		−49.101	0.750
Grassland	1978	0.230	0.259	−0.831	−0.564	−1.483	−0.773	0.025	0.025			−0.692	−0.499			−8.940	0.790
	1987	0.746	1.109	−0.748	−0.527	−0.163	−0.150	−0.025	−0.025			−1.855	−0.844			12.250	0.790
	1998	0.420	0.522	−0.964	−0.619	0.099	0.104	0.028	0.028	−0.830	−0.564	−1.251	−0.714			−11.377	0.746
Built-up	1978	0.673	0.960	0.705	1.024			−0.019	−0.019	−9.264	−1.000	0.188	0.207			8.033	0.978
	1987			−0.655	−0.481			0.061	0.063	−8.209	−1.000					−22.722	0.965
	1998	0.408	0.504	−1.617	−0.802			0.070	0.073	−4.230	−0.985	0.159	0.172			−25.390	0.956
Unused land	1978	−10.049	−1.000			−0.723	−0.515	0.244	0.276	−6.081	−0.998	0.454	0.575			−16.974	0.838
	1987	−3.327	−0.964	−0.328	−0.280	0.043	0.044	0.184	0.202	−1.817	−0.837	0.260	0.297			−9.458	0.838
	1998	−10.753	−1.000	−1.444	−0.764	−0.331	−0.282	0.304	0.355	−1.590	−0.796	0.201	0.223			−40.698	0.900

Exp(B) values indicate the change in odds upon one unit change in the independent variable. When $\text{Exp}(B)-1>0$ the probability increases upon an increase in the value of the independent variable, when $\text{Exp}(B)-1<0$ the probability decreases. The driving factors that have no significant contribution to the explanation of the land use distribution are excluded from the final regression equation.

[a] All variable (driving forces) significant at $p<0.01$.

Table 4
Values of land type conversion elasticity (ELAS) in FLU area.

	Scenario	Farmland	Woodland	Grassland	Built-up	Unused land
1978–2004		0.7	0.6	0.4	0.9	0.6
2004–2030	Reference scenario	0.7	0.6	0.4	0.9	0.6
	Economic scenario	0.7	0.5	0.6	0.9	0.7
	Ecological scenario	0.6	0.7	0.3	0.9	0.7

Table 5
The land use demand in the FLU area during 2004–2030 (units: ha).

	Mode	Farmland	Woodland	Grassland	Residential and industrial land	Unused land
2004		7611	1083	2873	541	590
2010	Reference scenario	7412	1145	2931	559	651
	Economic scenario	7577	1072	2852	579	618
	Ecological scenario	7102	1250	3090	556	700
2020	Reference scenario	7217	1217	2999	608	657
	Economic scenario	7677	1025	2764	684	548
	Ecological scenario	6439	1573	3350	594	742
2030	Reference scenario	7265	1304	2926	692	511
	Economic scenario	8131	978	2436	881	272
	Ecological scenario	5947	2040	3469	652	590

projection. Fig. 4 shows the actual land use distribution and simulated land use in 1987, 1998 and 2004, respectively. The Kappa statistic was employed to evaluate the accuracy of the model. The values of the kappa statistic are 0.83, 0.84 and 0.81 in 1987, 1998 and 1994, respectively, which indicates the model was reliable and could be used to project the land use in the future based on the given scenarios. Fig. 5 shows the simulated future land use pattern for each mode in 2010, 2020 and 2030 according to three scenarios. For different land use types, the relative differences of the actual allocation areas from CLUE model and the demand areas derived from the SD model is 0.35–3%.

4. Discussion

It is important to acknowledge that no single model is able to capture all of key processes to explore land use change at the different spatial and temporal scales relevant to make a full assessment of driving factors and impacts (Verburg et al., 2008).

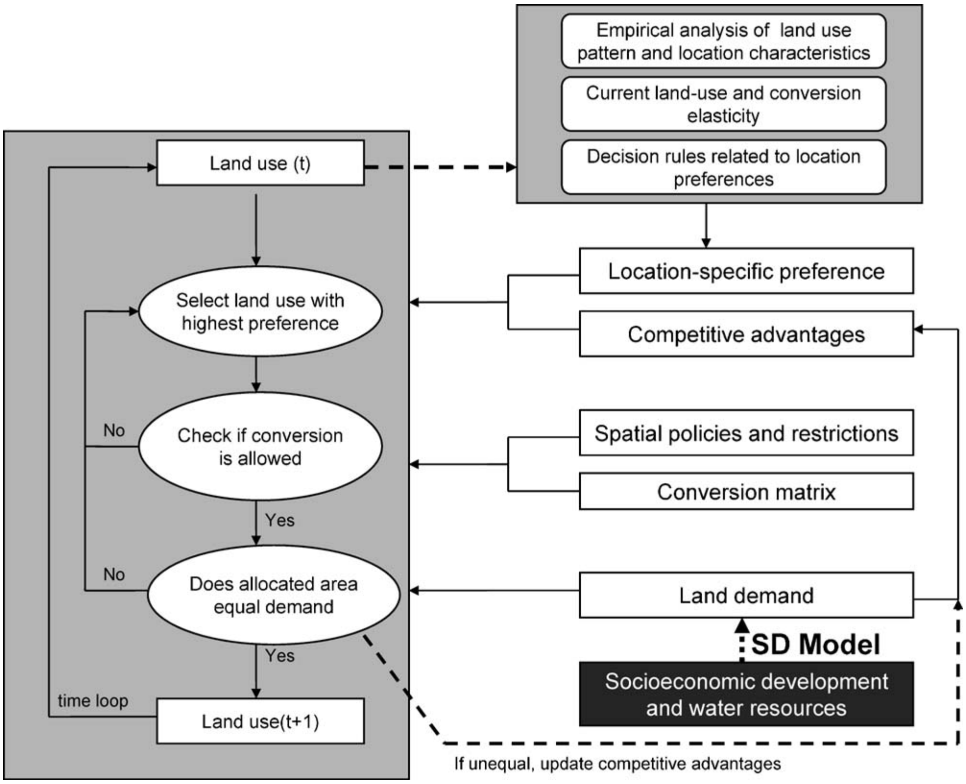

Fig. 3. Overview of the CLUE-S modelling procedure modified from Verburg and Overmars (2007).

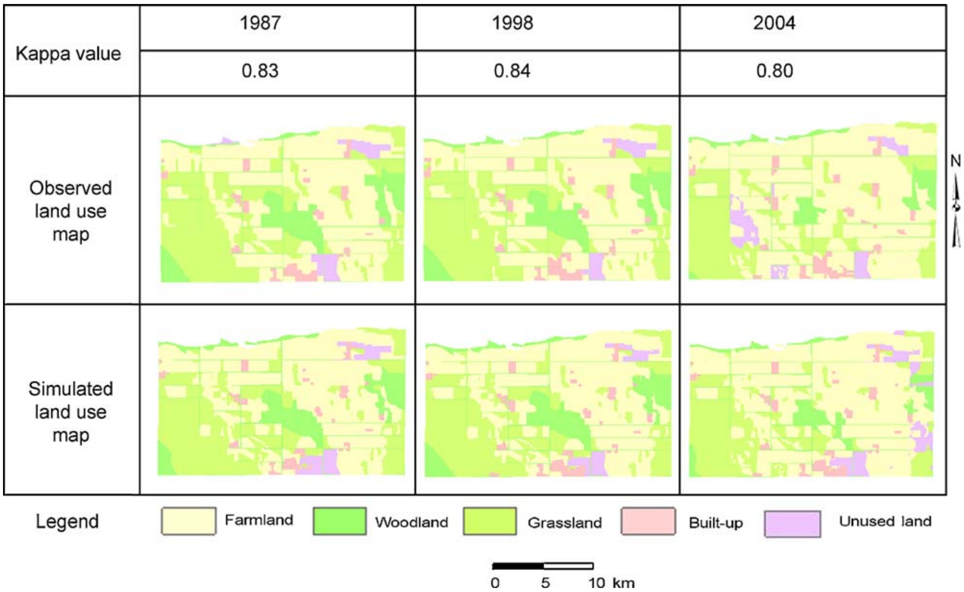

Fig. 4. Observed land use in the FLU area of the Sangong watershed in 1987, 1998 and 2004 and simulated land use for the corresponding period.

Fig. 5. Simulated land use in the FLU area of the Sangong watershed for 2010, 2020 and 2030 corresponding the reference, economic and ecological scenario.

Each LUCC model has its own potential and constraints. This paper accounted for such a perspective that the combination or integration of existing land use models based on the multi-scale characteristics of land use change could improve land use change and land use scenario analyses.

In this study, we have successfully integrated the SD model and CLUE-S model to characterize the land change processes at different scales and improve the simulation ability of current land use change model to reflect the complexity of the land use system. The SD model can project the demand for land use types as a whole with the consideration of biophysical and social-economic factors but spatial consideration. This could be regarded as a ‘‘top-down’’ implementation process at the high level of land user making decision. The SD methodology can account for the effect of the social-economic factors on land use demand at the macro-level such as country, province, and local. It is also able to take into account of the resource limit of biophysical factors on land use demand at local or regional scale. The CLUE methodology does not explicitly determine the resource limits of both biophysical and socio-economic factors on the projections of future land use (Verburg et al., 2002), but it can allocate the land use demand determined by the SD model at the local or regional scale with the spatial consideration of land use suitability, spatial policies and restrictions and neighborhood effect to satisfy the balance between land use demand and supply. The application of the combination of SD and CLUE model in Sangong watershed suggests that the methodology have the ability to reflect the complex behaviors of land use system at different scales to some extent and be a useful tool for analysis of complex land use driving factors such as land use policies and assessment of its impacts on land use change. The methodology adopted in the study could also indicate possible patterns of land use change under the different social-economic and environmental "what-if" scenarios. The possible land use changes and the 'hot spots' could be foreseen. Therefore, it could be used as a tool for understanding the possible impacts of land use change on terrestrial ecosystem and providing scientific support for land use planning and managements.

Due to the complexity of land use system, it is necessary to think and combine different land use processes within a single modeling framework to assess land use dynamics. Usually, there is an obvious difference in land use between urban and rural area. In this study, we could not allow for this situation. In fact, urban expansion is derived from more complicated driving forces (e.g., decision-maker' behavior), which is difficult for the SD and CLUE model to account for. In this case, an agent-based model could be selected to analyze urban land use dynamic, which can explicitly address the decision-making process about urban expansion. If the combination or integration of these three models within one modeling framework is successfully applied to assess land use dynamics, a good balance between maneuverability of the integrated model and representation of the complexity of the land use change may be achieved. We should make our efforts to facilitate such attempt to develop integrated approaches with different expertise and complementary knowledge on the land use system, which is helpful to explicitly address uncertainty land use modeling.

The definition of conversion elasticity in the CLUE model is based on the user's knowledge of the situation, and the setting of for the conversion elasticity has an important influence on the resulting land use patterns as they are directly related to the trajectories of change and land use histories (Verburg et al., 2002). This probably results in some uncertainty for simulation of land use change. It is therefore necessary to put forward a new solution to better define it quantificationally by using available historical data for land use, and improve settings of model parameters during the calibration of the CLUE model.

5. Conclusion

This paper improves the characterization and presentation of the land use change processes by combining a CLUE model with a SD model, which gives insight into better understanding of the possible impacts of land use change on terrestrial ecosystem and provides scientific support for land use planning and managements. The SD model presented is used to calculate area changes in demand for land types as a whole without the spatial consideration while the CLUE model is used to transfer these demands to spatially explicit land use patterns at a finer scales with the spatial consideration of land use suitability, spatial policies and restrictions to satisfy the balance between land use demand and supply. The successful application of the methodology in Sangong watershed has proved that the integration of currently existed models based on the multi-scale characteristics of land use change within a single modeling framework could be a feasible solution, because it is able to reflect the complexity of the land use system and capture key processes of land use change at the different scales. The integration of existing land use models within a single modeling framework should be encouraged and enhanced in the future research on land use dynamics due to the complexity of land use systems.

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References

Forrester, J.W., 1968. Principles of Systems. Wright-Allen Press, MIT, MA.

Geist, H.J., Lambin, E.F., 2002. Proximate causes and underlying driving forces of tropical deforestation. BioScience 52, 143–150.

Gutman, G., Janetos, A.C., Justice, C.O., Moran, E.F., Mustard, J.F., Rindfuss, R.R., Skole, D., Turner II, B.L., Cochrane, M.A., 2004. Land Change Science: Observing, Monitoring and Understanding Trajectories of Change on the Earth's Surface. Kluwer Academic Publishers, Dordrecht.

Hubacek, K., Sun, L.A., 2001. Scenario analysis of China's land use and land cover change: incorporating biophysical information into input–output modeling. Structural Change and Economic Dynamics 12, 367–397.

Irwin, E.G., Geoghegan, J., 2001. Theory, data, methods: developing spatially-explicit economic models of land use change. Agriculture, Ecosystems and Environment 85, 7–24.

Jia, B., 1996. Discussion on some theoretical problems of oasis landscapes. Arid Land Geography 19 (3), 58–65 (in Chinese with English abstract).

Lambin, E.F., Rounsevell, M.D.A., Geist, H.J., 2000. Are agricultural land-use models able to predict changes in land-use intensity? Agriculture, Ecosystems and Environment 82, 321–331.

Lambin, E.F., 2002. Linking causes, drivers and pathways with rates and patterns of land change. LUCC Newsletter No. 8, 16.

Leal Neto, A., Legey, L., González-Araya, M., Jablonski, S., 2006. A system dynamics model for the environmental management of the Sepetiba Bay watershed, Brazil. Environmental Management 38, 879–888.

Luo, G.P., Chen, X., Zhou, K.f., Ye, M.Q., 2003. Temporal and spatial variation and stability of the oasis in the Sangong River Watershed. Science in China, Series D 46 (1), 62–73.

Luo, G.P., Zhou, C.H., Chen, X., Li, Y., 2008. A methodology for characterizing the status and trend of land change in oases: a case study of the Sangong River watershed, Xinjiang, China. Journal of Environmental Management 88, 775–783.

Ojima, D., Lavorel, S., Graumlich, L., Moran, E., 2002. Terrestrial human-environment systems: the future of land research in IGBP II. IGBP Global Change Newsletter No. 50, pp. 31–34.

Overmars, K.P., Verburg, P.H., Veldkamp, A., 2007. Comparison of a deductive and an inductive approach to specify land suitability in a spatially explicit land use model. Land Use Policy 24, 584–599.

Parker, D.C., Manson, S.M., Janssen, M., Hoffmann, M.J., Deadman, P.J., 2003. Multi-agent systems for the simulation of land use and land cover change: a review. Annals of the Association of American Geographers 93, 316–340.

Pontius, R.G., Schneider, L.C., 2001. Land-cover change model validation by an ROC method for the Ipswich watershed, Massachusetts, USA. Agriculture, Ecosystems and Environment 85, 239–248.

Saysel, A.K., Barlas, Y., 2001. A dynamic model of salinization on irrigated lands. Ecological Modeling 139, 177–199.

Saysel, A.K., Barlas, Y., Yenigun, O., 2002. Environmental sustainability in an agricultural development project: a system dynamics approach. Journal of Environmental Management 64, 247–260.

State Bureau of Land Administration, 1997. Working rules of the overall planning of land at county-level (Trial implementation) (in Chinese).

Sufian, M.A., Bala, B.K., 2007. Modeling of urban solid waste management system: the case of Dhaka city. Waste Management 27, 858–868.

Tang, F., Chen, X., Luo, G., Lin, Q., Liu, H., 2007. A contrast of two typical LUCC processes and their driving forces in oases of arid areas: a case study of Sangong River Watershed at the northern foot of Tianshan Mountains. Science in China, Series D 50, 65–75.

Turner II, B.L., 2002. Toward integrated land-change science: advances in 1.5 decades of sustained international research on land-use and land-cover change. In: Steffen, W., Jäger, J., Carson, D.J., Bradshaw, C. (Eds.), Challenges of a Changing Earth. Proceedings of the Global Change Open Science Conference, Amsterdam, the Netherlands, 10–13 July 2001. Springer, Berlin, pp. 21–26.

Turner II, B.L., Lambin, E., Reenberg, A., 2007. The emergence of land change science for global environmental change and sustainability. PNAS 104, 20666–20671.

Turner II, B.L., Skole, D., Sanderson, S., et al., 1995. Cover Change Science/Research Plan, IGBP Report No. 35, HDP Report 7. IGBP of the ICSU and HDP of the ISSC, Stockholm and Geneva.

Veldkamp, A., Kok, K., de Koning, G.H.J., Verburg, P.H., Priess, J., Bergsma, A.R., 2001. The need for multi-scale approaches in spatial specific land use change modelling. Environmental Modeling and Assessment 6, 111–121.

Verburg, H.P., Veldkamp, A., Bouma, J., 1999. Land-use change under conditions of high population pressure: the case of Java. Global Environmental Change 9, 303–312.

Verburg, P.H., Eickhout, B., van Meijl, H., 2008. A multi-scale, multi-model approach for analyzing the future dynamics of European land use. The Annals of Regional Science 42, 57–77.

Verburg, P.H., Overmars, K.P., 2007. Dynamic simulation of land use change trajectories with the CLUE model. In: Koomen, E., et al. (Eds.), Modelling Land-Use Change. Springer, pp. 321–335.

Verburg, P.H., Overmars, K.P., 2009. Combining top-down and bottom-up dynamics in land use modeling: exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model. Landscape Ecology 24, 1167–1181.

Verburg, P.H., Schot, P., Dijst, M., Veldkamp, A., 2004. Land use change modelling: current practice and research priorities. GeoJournal 61, 309–324.

Verburg, P.H., Schulp, C.J.E., Witte, Veldkamp, N.A., 2006. Downscaling of land use change scenarios to assess the dynamics of European landscapes. Agriculture, Ecosystems and Environment 114, 39–56.

Verburg, P.H., Soepboer, W., Limpiada, R., Espaldon, M.V.O., Sharifa, M., Veldkamp, A., 2002. Land use change modelling at the regional scale: the CLUE-S model. Environmental Management 30, 391–405.

Verburg, P.H., Veldkamp, A., 2004. Projecting land use transitions at forest fringes in the Philippines at two spatial scales. Landscape Ecology 19, 77–98.

Wang, Y.C., Zhao, C.Y., 2001. Formation of landscape pattern of Sangong River Basin and its environmental heterogeneous characters. Journal of Soil and Water Conservation 15 (3), 98–101 (in Chinese with English abstract).

Yu, C.H., Chen, C.H., Lin, C.F., Liaw, S.L., 2003. Development of a system dynamics model for sustainable land use management. Journal of the Chinese Institute of Engineer 26 (5), 607–618 (in Chinese with English abstract).

Zhang, H., 1997. A simulation of the dynamics of soil erosion in the loess hills of Shanxi and Shaanxi provinces. Chinese Science Bulletin 42 (7), 743–746 (in Chinese).