APPLYING SLEUTH FOR SIMULATING AND ASSESSING URBAN GROWTH SCENARIO BASED ON TIME SERIES TM IMAGES: REFERENCING TO A CASE STUDY OF CHONGQING, CHINA

Jingnan Huang[a *], Jinting Zhang[b], X.X. Lu[c]

[a]School of Urban Design, Wuhan University, Wuhan, Hubei Province, 430072, PR China, - Huangjn73@hotmail.com
[b]School of Resource and Environmental Science, Wuhan University, Wuhan, Hubei Province, 430072, PR China, - whzjtwh@163.com
[c]Department of Geography, National University of Singapore, 117570, Singapore, - geoluxx@nus.edu.sg

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ABSTRACT:

This research simulates the urban growth and therefore the landscape change of a mountain city of Chongqing, China through a Cellular Automata (CA) based model of SLEUTH. The fundamental data were four Landsat TM images of 1978, 1988, 1993, and 2001 which were utilized for generating maps of land use, road networks, and urbanized area. Three alternative development scenarios, including business as usual, compact city and decentralized concentration, were interpreted into the model to reveal urban development mechanism in a mountain environment and to decide on the optimal planning scenario. Business as usual assumes historical development would continue. Compact city aims to achieve a compact and continuous urban form. Decentralized concentration promotes polycentric urban structure. Consequence, especially ecological consequence, was assessed by a proposed selection of landscape metrics. The result exhibits several interesting findings which provide planners with significant implications in physical planning. First, it was noted that predominant urbanization modes in mountain regions were “spread”, indicating that new developments usually occurred at the edge of existing urban areas. Second, “breed” indicating that emerging small and sporadic urban patches easily become new growing poles and induce new developments was another major growth mode. Moreover, setting limitation to development on steep slopes has largely restricted urban expansion and effectively protected forests. However, it was also suggested that there exists no optimal scenario as urban development and nature conservation are conflicting goals in terms of the selected landscape metrics.

1. INTRODUCTION

Accelerating land use/cover changes have become a global concern (Turner and Meyer, 1994; Lambin et al., 2001), as they are believed to be responsible not only for the increasing natural disasters and extreme weather, but also for the ecological degradation such as habitat impairment and biodiversity decline. However, the more devastating yet indiscernible consequence might be the undermining of ecosystems’ function in providing ecological services and goods such as regulating temperature, controlling soil erosion, storing nutrients, preventing flooding, and ensuring safety water, etc. (de Groot et al., 2002; The World Conservation Union, 2005). To sustain these important ecological functions for the total ecosystem (including humans), ecological principles must be taken account into planning (Szaro et al., 1998; Ahern, 2002). However, traditional or “orthodox ” planners know little about how to link spatial planning with ecological science (Hersperger, 1994; McHarg and Steiner, 1998; O' Neill, 2001).

Both local and global landscape changes are largely the result of broadening extent of human development activities such as agriculture, infrastructure construction and settlement development(Bockstael, 1996; Wiens, 1999). With the increasing world city population particularly in developing countries and enhanced demand on land resource, urban development, the most intensive and dynamic human development activity, has become the leading forces behind these changes (Swenson and Franklin, 2000; Randolph, 2004). Humans, however, cannot afford the failure of risky development policymaking because damages to environment and ecosystem are often irreversible, especially in the fragile bio-geographical environment such as mountains (Harrison and Price, 1997; Jansky, 2000).

Planning has been increasingly recognized as a dynamic and adaptive “process” rather than a “blueprint” (Cheng, 2003). This requires planners to timely adjust inappropriate development courses. Pre-testing alternative development scenarios and taking proactive measures thus become crucial. This must be grounded on an in-depth understanding of past development processes and an accurate estimation of the future landscape pattern. This task, however, is not easy as both cities and urban growth are complex systems (Cheng, 2003). Modeling, particularly the new generation models based on complexities science, is now considered the only feasible way as laboratory platform to investigate these complex systems (Wu, 2002a). Modeling has been regarded as one essential part in planning process (Harms et al., 1993). Present researches, however, have paid most interests in modeling itself. How to assess consequences, especially ecological consequences through modeling has yet not been fully investigated (Gustafson, 1998; Leitao and Ahern, 2002).

This research aims to estimate the consequence, in particular ecological effect, of alternative development scenarios through urban growth modeling. It, however, does not focus on modeling details, but on utilizing existing models to reveal urban development mechanism and therefore to decide on an optimal planning scenario in a mountain environment.

2. LANDSCAPE METRICS AND PHYSICAL PLANNING

The ecological value of natural landscape in urban areas has long been acknowledged in planning profession. This was evidenced by the earliest modern landscape design works of “central park” in New York City, the later greenway movement and the present “green infrastructure” practices. However, the planners knew little on how to scientifically integrate ecological principles into planning, especially into physical planning which seeks the optimization of land resources distribution within a limited space (van Lier, 1998). One major reason is that there is lack of spatially explicit ecological rules and thresholds that can be understood by traditional planners (Opdam et al., 2002). Landscape metrics, a series of indices which quantify categorical, patch-represented landscape, now seem promising to fill this void (Leitao and Ahern, 2002). Landscape metrics, developed with information theory and fractal geometry since 1980s, take multiple dimensions to represent land mosaic. In terms of the landscape hierarchy, landscape metrics were classified into three levels. Patch-level indices describe the fundamental and geometrical characteristics of individual patch, including size, perimeter and shape. Class-level indices measure the amount and composition of one specific patch type. Landscape-level metrics represent the characteristics of the entire land mosaic (McGarigal and Marks, 1995). In terms of pattern types, landscape metrics have two categories. Composition indices quantify the landscape features without referencing to spatial attributes while configuration indices quantify the layout of landscape with spatial information (McGarigal and Marks, 1995; Gustafson, 1998). Therefore, landscape metrics provide both non-spatial explicit indices (composition) and spatial explicit indices (configuration) for the representation of landscape pattern.

Although landscape metrics bear great potential in physical planning, the application was largely limited to academic suggestions. Leitao and Ahern (2002) attributed this to the ambiguity of landscape metrics. Specifically, interpretation of landscape metrics often do not make sense because ecosystem is scale-dependent and different species may perceive their living environment distinctly (Weber, 2003). For instance, one piece of land might be large enough for a specific animal, but may also be insufficient to another species. In the same vein, a corridor might be a conduit for some animals, and also a barrier for others. As a consequence, the ecological implication of landscape metrics across scales in physical planning has always been unclear. Another factor for the limited applications is that landscape metrics are often highly correlated (Riitters et al., 1995; Mcgarigal and Mccomb, 1995; Hargis et al., 1998). Deciding appropriate landscape metrics among similar ones has always been a problem. To address this issue, various methods have been conducted, including principal component analysis (Mcgarigal and Mccomb, 1995; Tinker et al., 1998) and factor analysis (Riitters et al., 1995). However, most of these methods were based on mathematical analyses, and metrics selection was rarely considered for the planning purpose (Leitao and Ahern, 2002).

Landscape metrics are particularly useful in modeling alternative scenarios (Gustafson, 1998; Leitao and Ahern, 2002). This is founded on the nature of landscape ecology which explicates the reciprocal relation between spatial structure (or pattern) and ecological function (or process). Ecological consequence can thus be estimated, and desirable landscape be anticipated in advance (Turner, 1989; Wu and Hobbs, 2002). One major advantages of such modeling is that hypothesized disturbances did not alter actual landscape which may lead to disastrous consequences (Turner, 1989). Alternative scenarios, based on the same landscape, generate comparable landscape, which essentially make sense of the comparison of landscape metrics.

3. CA-BASED MODELING AND THE URBAN GROWTH MODEL OF SLEUTH

Urban modeling has revived since the 1980s, largely due to the following reasons. Firstly, the popularity of Geographical Information System (GIS), as a new powerful tool, enables the storage and manipulation of the large amount of geospatial data. Secondly, new geospatial data acquirement methods such as remote sensing and Global Positioning System (GPS) provide recurrent and up-to-date information of ground features. Thirdly, advancement in system science and relevant theories, such as catastrophe theory, chaos theory, dissipative structure theory, fractals and so on, inspired new modeling manners. Lastly but the most importantly, sustainable development, the emerging concept responding to the global environmental crisis, gave the new impetus for a deeper understanding of the complex urban system (Lee, 1994). Many new urban growth models have been raised and put into practice , such as California Urban Futures (CUF) Model, Growth Simulation Model (GSM), LUCAS, SLEUTH, UrbanSim, What if?, etc. These new models are distinct from traditional models that assume all urban behaviors operate in centralized, aggregate, static and top down ways (Torrens and O'Sullivan, 2001). New generation models, based on complexity science, has shifted modeling methods from macro to micro, aggregate to disaggregate, static to dynamic, linear to non-linear, top-down to bottom-up, structure to process, and space to space-time (Cheng, 2003).

Among them, Cellular Automata (CA) model has drawn the most research attentions as they match our intuitive sense that human’s spatial activities are not centrally organized, but stochastic (Hallsmith, 2004). Because of its affinity with complex urban system, CA-based models have been widely used in exploring various urban phenomena, such as urbanization (Clarke et al., 1997; Wu and Webster, 1998; Wu and Martin, 2002), urban form change (Wu, 1998a; Wu, 1998b; Li and Yeh, 2000), urban growth effect (Wu, 2002b; Loibl and Toetzer, 2003; Syphard et al., 2005a; Syphard et al., 2005b), etc. Furthermore, CA models are powerful planning tools as they are robust in simulating the result of stochastic decisions of various actors involved in urban development such as residents, developer and government departments (White and Engelen, 1997). However, present research about CA modeling is not without problem. First, most researches focused on construction details while CA’s ability to investigate urban theory and urban dynamics has not been fully realized (White and Engelen, 1997; Batty et al., 1998; Li and Yeh, 2001). They often “explain how to build urban CA without really exploring why” (Torrens and O'Sullivan, 2001). The ultimate objective of modeling, providing planners with knowledge and information for policymaking, has thus been greatly dwarfed. Second, current CA studies are normally limited to either repeating past change trajectory or projecting future patterns based on historical data. Planning factors such as development policies and scenario hypothesis were rarely integrated into modeling. This may be caused by the inherent weakness of CA models, that is, difficulty in interpreting planning ideas into simple transition rules (Torrens and O'Sullivan, 2001). Third, assessment of modeling result focuses on spatial effects. In other words, current researches have paid most interests in estimating future urban expansion and the consequent land use change such as the loss of farmlands and forests. However, few of them take into account ecological consequence caused by new development. This may be connected with the understanding of the concept of landscape. The predominant land use/cover change assessment essentially still takes landscape as a geographical unit, i.e. “a piece of land” or “a mosaic of land cover” (Cosgrove, 2002). However, the discipline of landscape ecology has articulated the ecological implication of landscape as “a group of ecosystems” (Naveh and Lieberman, 1984; Forman, 1995). In this regard, ignorance of ecological effect in modeling assessment may only suggest the incomplete understanding of the modern landscape concept.

This research employed a CA-based model of SLEUTH as a laboratory platform to reveal urban growth mechanism and verify alternative planning scenarios in a mountain environment. The SLEUTH names after the six input layers, including Slope, Land cover, Exclusion, Urbanization, Transportation, and Hillshade (Clarke et al., 1997). As a well designed sophisticated model, SLEUTH has been successfully applied to many international urban regions (Clarke et al., 1997; Silva and Clarke, 2002). SLEUTH carries out two phases of simulation: “calibration” derives growth parameters based on historical data, and “predict” projects urban growth based on the calibration. SLEUTH is robust in simulating urban growth as it includes various types of urbanization, including spontaneous growth (random urbanization), new spreading center growth (growth around new development), edge growth (development at the edge of existing urban area), and road-influenced growth. To capture these four growth modes, SLEUTH calculates five coefficients in the calibration phrase, including Slope (terrain resistance to urbanization), Dispersion (random urbanization), Breed (new spreading center growth), Spread (edge growth), and Road gravity (road-influenced growth). Choosing SLEUTH in this research was guided by several considerations. First, in contrast to conventional urban growth models which are grounded on land economics, social segregation and transportation theory, SLEUTH focuses on exploring urban expansion process itself. This particularly fits the research as relevant social, economic and demographic data are limited or unavailable. Second, SLEUTH pays special interest in terrain resistance which is essential to understand urban development in a mountain environment. Third, SLEUTH not only simulates urban growth, but also incorporates a land use change model, which makes possible the estimating impact of urban development on surrounding landscape. Other than these, SLEUTH provides various ways to interpret transformation rules such as adjusting growth coefficients, setting up roads and changing its gravity, and defining exclusion layer, all of which make it an ideal tool to compare alternative planning scenarios.

4. METHODOLOGY AND DATA PROCESSING

Interpretation of planning scenarios in SLEUTH: The easiest way to interpret planning hypothesis in SLEUTH is to define the “exclusion layer” which represents the impossibility degree of development. In this research, three alternative scenarios were designed. “Business As Usual” (BAU), based on historical data, assumes that historical urbanization mode would persist on (Figure 1a). Therefore, there is no limitation to new development except the non-developable areas of the Yangzte and Jialing Rivers. The second scenario is “Compact City” (CC). The compact city policy has been highly applauded particularly in Europe. Planners hope that the measures such as limited urban size, compact design, mixed land uses and so on, can curb inefficient land development modes (e.g. urban sprawl) and preserve precious nature resources such as forest, farmland and open space. However, its effectiveness has not been fully proved (Ewing, 1997). In this research, a compact city scenario is defined as follows to promote compact urban form: First, the vacant interstices within the city and the buffer zone within 1 km distant from the existing urban area are fully developable. Second, areas between 1km and 2 km from the existing urban area have the 50% possibility of being developed. Third, areas beyond 2km from existing urban area would not be considered for development (Figure 1b). To depress sprawled development especially the frog-leap, tiny and isolated patches were not allowed for further expansion, and only the large urban patches (e.g.10 ha in this research, which is roughly the acreage of the smallest community unit of quarters (Xiaoqu) in China’s residential planning system and also the minimum size of real estate projects in China) are considered as new growing poles. The third scenario was “Decentralized Concentration” (DC) which refers to a regional urban structure consisting of a group of urban clusters connected by road networks. Decentralized Concentration promotes a polycentric urban form. Decentralized indicates that in large regional scales, urban development should be relatively dispersed in order to avoid adverse effects such as congestion and pollution. Concentration suggests that in a relatively small scale, settlements should agglomerate for a less land occupation and a vibrant living community. This research argues that DC is an applicable development strategy in mountain regions because urban growth in this environment is greatly restricted by natural boundaries of rivers and mountain ranges, which often result in natural polycentric urban structure. Moreover, recent researches have suggested that natural units, such as watersheds, are more effective in managing nature resources than political ones (US EPA, 1993; Randolph, 2004). Mountain ridgelines, which are de facto watershed boundaries, were thus delineated as urban growth boundaries. Non-developable lands in DC include the higher mountains above 500 meters in altitude which in fact have no access to existing water supply systems and areas below 200 meters which are the traditional floodplain. This scenario also set slope limitation to test the terrain resistance to development. A common agreement is that above 25% no development should occur. However, in the study area, buildings and constructions beyond this threshold were common due to the limited developable land. Developments in slopes exceeding 25% were thus partially allowed (20%). However, steeper slopes beyond 40% were completely prohibited (Figure 1c). In the similar vein, to control inefficient urban development, small urban patches would stop growing in simulation.

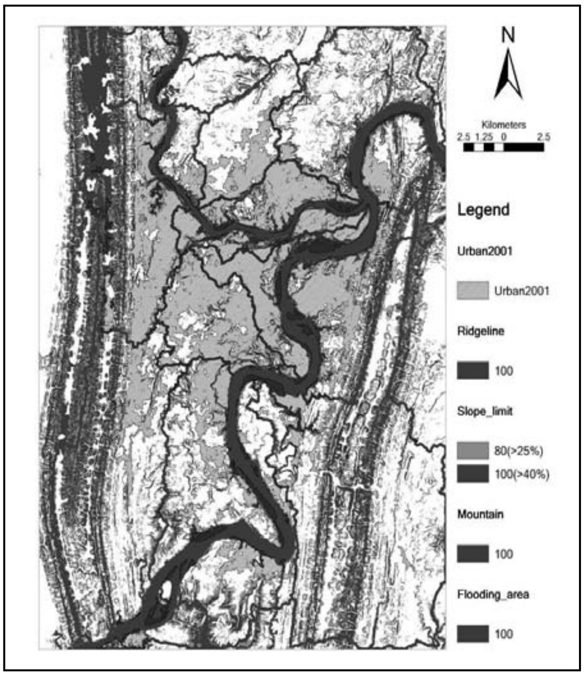

Figure 1 a

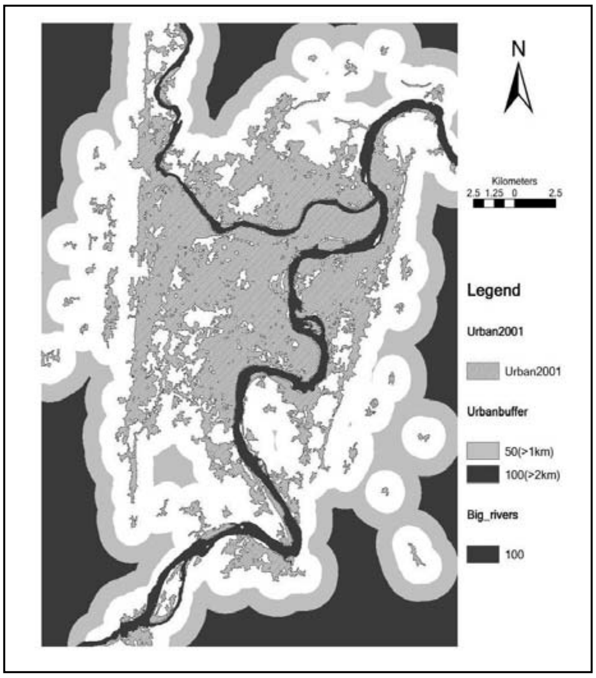

Figure 1 b

Figure 1a. Chongqing's urban and forest in 2001. As can be seen, forests mainly left on the tops of the two mountain ranges. "Business As Usual", taking this map as starting point, assumes that historical development trend would go on.

Figure 1b. Definition of exclusion layer in Compact City scenario. Gray areas indicating 50% possibility to be developed are buffer zones between 1 km and 2 km from existing urban areas. Dark areas are non-developable land, including the Yangtze River, the Jialing River and the areas beyond 2 km from the existing urban areas. White areas are developable lands, including vacant areas and buffer zones within 1 km from the existing urban areas.

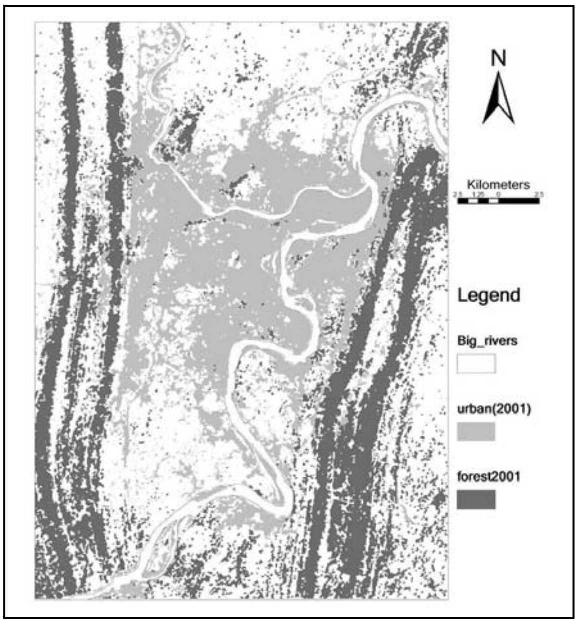

Figure 1c

Figure 1c. Definition of exclusion layer in Decentralized Concentration scenario. To prevent too large aggregation, ridgelines were delineated as the growth boundaries. Non-developable lands include the higher mountains, floodplains and steep slopes beyond 40%. Slopes between 25% and 40% have the 20 % possibility to be developed.

Landscape metrics selection: This research proposes a set of landscape metrics representing seven dimensions of landscape patterns, including area, size, shape, diversity, fragmentation, connectivity and core area, for ecological effect assessment (Table 1). Such selection was decided by the following factors. First, these metrics are commonly used but of great ecological significance. Second, they are understandable, especially by traditional planners. Third, they can be easily calculated by existing landscape analysis software package. Other than these, correlations among landscape metrics were also taken into account. Basically, area, size, shape, diversity and core area are composition indices while fragmentation and connectivity represent configuration indices.

Area. Habitat area is the most important factor in ecological integrity. Researches have proved that a larger share of habitat areas corresponds to more, and therefore higher diversity, of species (Forman and Godron, 1986).

Size. Habitat size exerts great influences to ecological functions as well. Large vegetated patches could protect aquifers (Dramstad et al., 1996). Moreover, most species have a minimum size requirement for their habitats. Although small patches may also be ecologically valuable, either as stepping stones or ecological networks (Jongman et al., 2004; Opdam et al., 2006), by and large, larger patches are more conducive to all species, especially interior species.

Shape. Patches shape also affects habitat quality. Jagged and convoluted patches promote interactions between living organisms and their surroundings due to the higher interior-to-edge ratio. This is particularly important for edge species. In contrast, regular and circular patches suggest fewer disturbances from exteriors, which lend themselves to sheltering interior species.

Diversity. Biodiversity normally shows positive relation to habitat diversity which is generally a function of local geomorphologic, geological, hydrological and climatic factors. However, variation in patch size could also influence habitats diversity. A higher variation value of habitat size often suggests more habitats options for local species.

Core area. Core areas are zones that have no or few disturbances from exteriors. Core areas are extremely significant as they provide a safe living environment for all species, especially interior species

Compared to the characteristics of individual patches, configuration of land mosaic nowadays receives more attentions (Forman, 1995; Ahern, 2002). This is because landscape is not simply a group of isolated patches, but a hierarchical and interacting ecosystem (Naveh and Lieberman, 1984; Forman, 1995).

Fragmentation. Habitat fragmentation is the process that large habitats disintegrate into small and disjunct parts. Habitat fragmentation is the leading factor of biodiversity decline (Wilcox and Murphy, 1985; Fahrig, 1997). Three types of fragmentation are habitat loss, shrinkage and isolation (Andren, 1994). Fragmentation makes the greatest impact on animals with large ranges such as birds and large mammals (Beier, 1993). Recent researches have suggested that in a fragmented landscape, some animals such as reptiles and small mammals may survive its viable population (metapopulation) in the form of ecological network (Soule, 1991; Opdam et al., 2006).

Connectivity. Measure to prevent fragmentation is to increase the connectivity or cohesion (e.g. corresponding to ecological networks) of landscape elements. Connectivity enhances the movement of species and therefore the higher viability of metapopulation (Bennett, 1998; Jongman et al., 2004). Research indicates that connectivity benefit not only the persistence potential of animals, but also the reproduction of plants (Van Dorp et al., 1997). The common way to increase connectives is to build continuous corridors such as forested streams and mountain ridgelines which link scattered patches (Dunning and Smith, 1986).

Data processing: The fundamental data in this research are four Landsat TM images in 1978, 1988, 1993, and 2001. To fulfill the input requirement of the SLEUTH model, supervised image classification were carried out to generate land use maps, road networks and urban extent (Table 2). One topographic map was employed to establish a Digital Elevation Model (DEM) for generating slope map, hillshade background and watershed boundaries. Road networks were delineated from the satellite images through referencing to two city road maps of 1996 and 2002. Growth coefficients derived from calibration phases were introduced into SLEUTH for simulation. Projection periods ranged from 2001 to 2020. Finally, landscape metrics were calculated by a public domain ArcVIEW extension, Patch Analyst (Rempel, 2004).

Metrics	Abbr.	Dimension	Description	Ecological implications
Class Area	CA	Area	Sum of all patches areas of a specific class (e.g. forest).	A higher CA value represents more habitats, and therefore higher species diversity.
Mean Patch Size	MPS	Size	Average patch size	Large patch shelter more species, especially the interiors species.
Area Weighted Mean Shape Index	AWMSI	Shape	Sum of patches perimeter divided by the square root of patch area,	AWMSI measures the irregularity of patch shape. A higher AWMSI value has a lower interior-to-edge ratio which is especially helpful for edge species.
Patch Size Standard Deviation	PSSD	Diversity	Standard Deviation of patch areas	A higher PSSD suggests a wider variation of patches size, and thus higher habitat diversity.
Number of Patches	NUMP	Fragmentation	Total number of patches	Although a higher NUMP may benefit some animals preferring small patches, it generally indicates a more fragmented landscape, which is harmful to most species.
Mean Nearest Neighbour	MNN	Connectivity	Average distance of all patches (edge to edge).	A higher MNN indicates a higher connectivity, which is beneficial to most species.
Mean Proximity Index	MPI	Connectivity	A measure of isolation degree in terms of a given distance threshold	The higher the MPI value, the less fragmented the landscape.
Total Core Area	TCA	Core Area	Sum of all core habitat area	A higher TCA value suggests more core habitats for interior species.
Total Core Area Index	TCAI	Core Area	Proportion of core area in the entire landscape	A higher TCAI value suggests more opportunities for interior species.

Table 1. Selected landscape metrics and the dimensions represented, descriptions and ecological implications (McGarigal and Marks, 1995

Input layers	Data requirement	Extraction
Slope	One slope map	Generated from DEM
Land use	At least two land use maps were required. In this research four land use maps were employed to increase the calibration accuracy	Supervised image classification from Landsat TM images of 1978, 1988, 1993, and 2001
Exclusion	One map represented the area that cannot be developed	Definition based on interpretation of planning scenarios
Urbanization	At least four periods of urban extent for calibration	Extracted from TM images through image classification
Transportation	At least two road networks. This research employed four roads networks maps	Delineated from images with assistance of two city road maps of 1996 and 2002
Hillshade	Background for display purpose	Derived from DEM

Table 2. Data requirement and generation methods

5. RESULT

Change of urban area and forest: Simulation displays the distinct result of three alternative scenarios, especially between "businesses as usual" and two planning scenarios. It can be seen that if historical trend goes on, urban area would ascend to 327.7 km^2 by 2020, namely an additional increase of 48% compared with 2001 (Table 3). It was noted that most of the new developments occurred contiguous with the existing urban areas, particularly in the urban fringe of the north Yubei district and south Jiulongpo and Dadukou districts (Figure 2a). This is consistent with the calibration result of SLEUTH which suggests that dominant growth mode in the study area was "spread" (the coefficient value of 96)*. Moreover, large shares of new developments were circled around small and sporadic urban patches, especially along the left side of Zhongliang Mountain (Figure 2a). This lends testimony to the great influence of another major growth mode of "breed" (the coefficient value of 68). In contrast, spontaneous urbanization ("dispersion") was rarely observed (the coefficient value of 1). However, if business goes on as usual, forest areas would decline dramatically by a proportion of 78%. Moreover, large forest patches would disintegrate into tiny parts, leading to a much more fragmented forest (Figure 2a).

Scenarios	Urban			Forest		
	Area (km2)	Change (km2)	Change (%)	Area (km2)	Change (km2)	Change (%)
BAU	+327.70	+106.20	+47.95	+46.41	-164.62	-78.01
CC	+262.83	+41.34	+18.66	+150.40	-60.62	-28.73
DC	+249.56	+28.07	+12.67	+185.60	-25.43	-12.05

Table 3. Projected urban area and forests of the three scenarios by 2020 compared with those in 2001. (Note: BAU= Business as Usual; CC= Compact City. DC= Decentralized Concentration. "+" indicates the increase in value while "-" indicates decrease).

Overall, both the two planning scenarios have greatly restricted urban expansion. For CC, urban area increased by 41.34 km^2, or 18.66% compared with that of 2001. Most of the new developments were proximate to existing urban areas in north Yubei district and south Jiulongpo and Dadulou districts. In particular, developments in the south have filled many vacant interstices, resulting in an increasingly compact urban landscape (Figure 2b). However, there were almost no developments observed on the left side of Zhongling Mountain. In contrast, most forests were remained (i.e. 28% loss) in CC, especially those in the two mountain ranges. The DC depressed urban growth even more than CC did. In this scenario, urban areas only increased by 28.07 km^2, or 12.67%. Similar to CC, new developments mainly took place at the edge of existing urban areas in the north Yubei district and the south Jiulongpo and Dadulou districts. However, large amounts of vacant areas in the southern parts were not filled by new developments. In addition, most forests kept intact especially in the two mountain ranges and only a small fraction of 12% was lost (Figure 2c).

Comparison of landscape metrics: Landscape metrics analysis suggests profound ecological changes for the forest landscape.

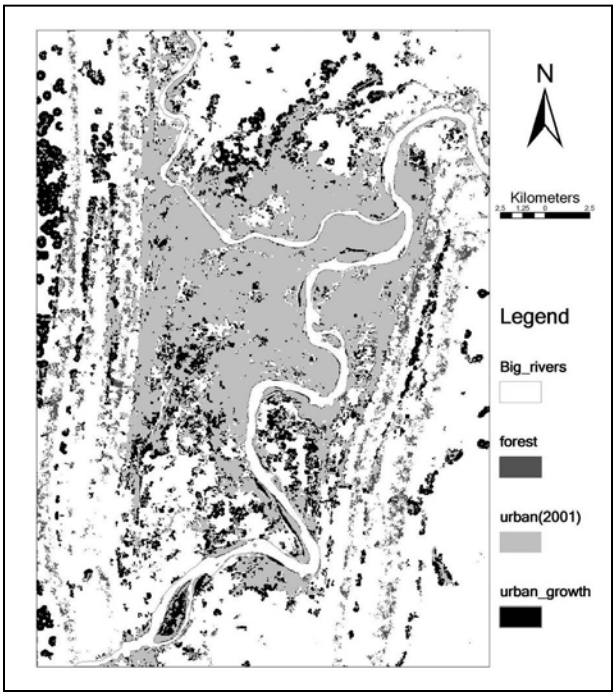

Figure 2a

* Coefficient value ranging from 0 to 100 represents the strength of growth. The higher the value, the most influential the growth type.

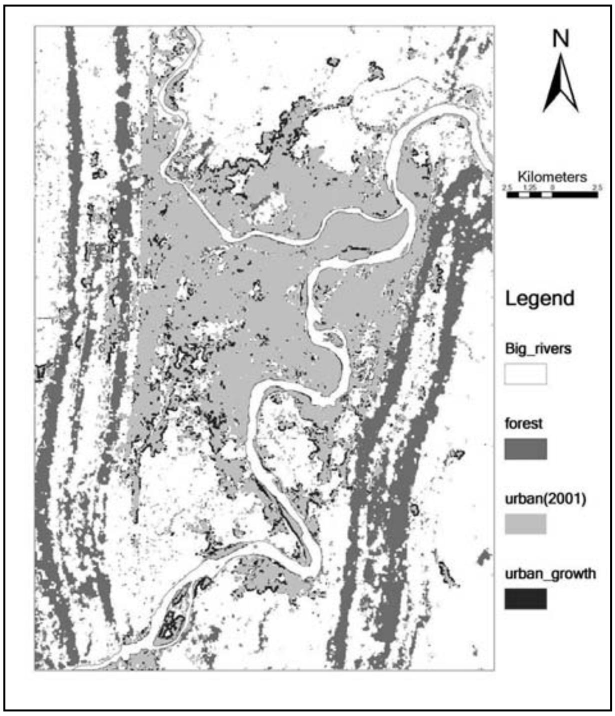

Figure 2b

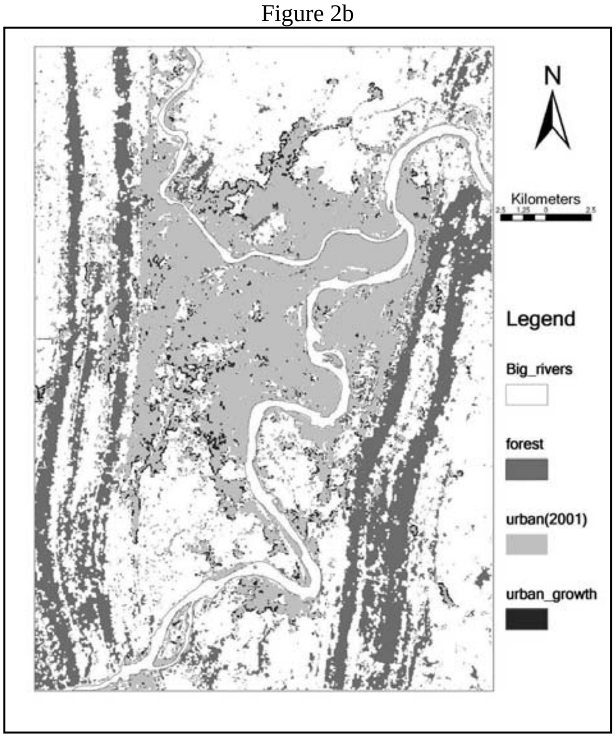

Figure 2c

Figure 2a. Simulation of "Business As Usual" by the year of 2020. The result shows that urban area has experienced a substantive expansion, while most forests were lost or became fragmentized.

Figure 2b. Simulation of "Compact City" by 2020. It was noted that urban areas experienced moderate growth, most of which were contiguous with or within existing urban areas while forests were largely preserved.

Figure 2c. Simulation of "Decentralized Concentration" by 2020. It can be seen that urban areas only showed minimal growth at the edge of the existing areas, and most of the forests was remained.

Overall, BAU performed worst in forest protection among the three scenarios. First, the lowest CA indicates that most of the habitats have been lost. The lowest MPS value suggests big habitats have been broken into numerous small patches. Meanwhile, forests became more fragmented in terms of the increased NUMP. BAU also resulted in a limited habitat diversity as indicated by the lowest PSSD (Table 3). Other than these, most of the core areas would not exist (Figure 3). Therefore, if historical development goes on, forest would either disappear or shrink, leading to a declined ecological integrity.

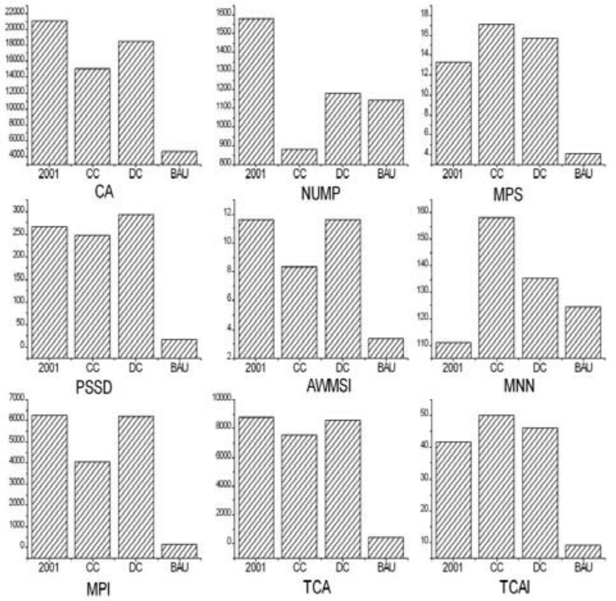

Figure 3. Comparison of landscape metrics among three scenarios and that in 2001. Overall, decentralized concentration performed best in habitat protection while business as usual performed worst.

CC generated not only a compact urban form, but also a compact forest landscape. The lowest NUMP indicates that forest in this scenario was the least fragmented. The highest MNN and relatively higher MPI suggest the overall highest connectivity (Figure 3). Compared with BAU, habitats were largely preserved in terms of the higher value of CA and MPS. However, habitats shape has become more irregular as evidenced by AWMSI. The higher PSSD indicates that there are more choices to realize species' requirement for various habitat (Figure 3).

DC has the highest habitat quality. First, most habitats were preserved in terms of the largest CA and MPS. Moreover, PSSD suggested the highest habitat diversity . Compared with the other two scenarios, core areas were largely protected. The highest value of AWMSI, however, also suggests that habitats shape have become more irregular, which is unfavorable to interior species (Figure 3).

6. DISCUSSION AND CONCLUSION

This research employed SLEUTH model to investigate urban growth mechanism in a mountain environment and evaluate three alternative scenarios. The result revealed some interesting findings.

First, calibration of the model shows that the major growth modes in the study area were "spread" and "breed". In other words, new developments tended to occur either at the edge of existing urban areas or circled around newly developed areas. In contrast, random urbanization was unnoticeable. This may be explained by the features of urban development in a mountain environment. On one hand, factors in mountain regions such as slope, relief, river separation and so on, are natural constraints to infrastructure construction as well as settlements development (Dorward, 1990). Under the condition of limited financial and technical capacity, urban infrastructures, including road networks and crossing-river bridges, were often in short supplies, leading to isolated self-contained settlement clusters. This can be seen from Chongqing's dispersed urban form and incomplete road systems in 1978 and 1983 images. Therefore, settlements were often originally developed either in terrace and valley bottom with tender slope or in river confluent areas with convenient external communication. This may explain why there was almost no random development observed in the study area. On the other hand, scales effect (or aggregation effect), which is inherent property of urban growth, suggests that subsequent settlements tend to agglomerate around existing area for better production organization and service delivery (Krugman, 1991). New developments thus usually took place contiguous with existing area (spread), and newly urbanized patches easily became the growing poles inducing further development (breed). This also explains why specification of setting growth limitation to small patches has largely depressed urban development in the two planning scenarios.

Second, calibration shows that road attraction in the study area is not a strong factor (with a coefficient value of 15), which is inconsistent with other researches on settlement development in mountain regions. For instance, Sharma's (1998) study on India's Himalayas cities showed that market towns which are significant to local economy were normally connected by mountain roads. Vias and Carruthers's (2005) study on land use change in the Rocky Mountain West indicated that although new settlements were foot-loose, most of them have close connection with the metropolitan areas. The inconsistency may be caused by the property of SLEUTH. Specifically, although SLEUTH examines the effect of road attraction, it did not consider the change of road gravity. Previous research (Huang et al., 2007) on the study area has suggested that in the past two decades development axes in the study area have shifted from rivers to roads. However, this cumulative effect of the increased road attraction was ignored in the SLEUTH model. Sparse road networks in1978 and 1983 may account largely for the insensibility of roads induced development.

Three scenarios performed distinctly with respect to urban growth and forest protection. If historical mode continues, there would be substantive new development, but most of the forests would be lost. In contrast, two planning scenarios seem effective in limiting urban expansion and preserving forest. A comparison among the three scenarios also suggests that urban development and forest protection are opposing goals as the area of new development show a positive relation with the lost forest (Table 2). Specially, BAU generated not only the largest new urban area, but also the most forests loss. DC showed the least urban growth as well as the least forest loss. CC exhibited both moderate urban growth and moderate forest loss. This may indicate that urban development was the major dynamics of forest landscape change in the study area.

It was also noted that slope did not appear a strong resistance to urban development in the study area in terms of the derived slope coefficient (with a coefficient value of 3). This is consistent with the conclusions of previous research (Huang et al., 2007) that suggest that the percentage of development in different slope categories has remained unchanged in the past two decades. In fact, contiguous development and infill development were common in the study area, also indicating the ignorance of terrain constraint. However, setting slope threshold to development in Decentralized Concentration scenario actually made a huge difference to forest preservation even compared with another planning scenario of compact city. This essentially reaffirms the conclusion of the same previous study which exhibited that most forests were remained basically on the steep slopes. Therefore, setting limitation to development activities, such as slope grading, cut and fills, and flattening small protruded hills, on steep areas may reduce the possibility of deforestation.

Above findings are of significant implication for urban planning in a mountain environment. First, as tiny and isolated urban patches could easily induce new development, freezing growth around these patches could prevent the inefficient sprawled urban growth. Second, to protect forests which are precious habitats of wild species and of important recreational value to humans, setting limitations to urban development on steep slopes might be an applicable measure.

A selection of landscape metrics representing multiple aspects of landscape patterns were employed to evaluate the ecological consequences of three development scenarios. Business As Usual led to a remarkable decline in habitat quality as the remained forest ranked last in the indicators of area, size, variability, connectivity and core areas. Compact City resulted in not only a compact urban form, but also a compact forest landscape in terms of the smallest fragmentation index (NUMP) and the largest connectivity indices (MNN and MPI). Overall, Decentralized Concentration generated the highest ecological integrity as most of the forests and core habitats were remained.

Result, however, also suggests that there is no optimal solution as urban development and nature conservation are conflicting goals. If priority is given to development, Business As Usual is preferable as it produced the largest new development. However, if the priority is nature conservation, the other two scenarios are considerable as forests were largely protected. Even only in terms of habitat quality, there is no optimal scenario inasmuch as ecological integrity is multifold. Although most forest was lost in "Business As Usual", the shape of resulting patches is the most regular, which is beneficial to interior species. Compact City scenario produced the least fragmented forest landscape in terms of the lowest NUMP and the overall highest connectivity, which is particularly favorable for interior species. Although decentralized concentration preserved the most forest in terms of CA and MPS, it also generated the most irregular patch shape (AWMSI) and the most fragmented landscape (NumP), which is detrimental to interior species. Therefore, the selection of planning scenarios should depend on the protection purpose.
As thus, this research shows that landscape metrics can be the measurable indicators in planning scenarios comparison although it did not give an unambiguous answer. The interpretation of landscape metrics presents planners with important information in the balance between urban development and natural conservation, especially in mountain regions with limited developable land and fragile environment.

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