Sustainability in African cities: Land Use/Cover Changes and Modelling Urban Growth in Nairobi City

Charles N. Mundia, Yuji MURAYAMA

Abstract: Urban population is increasing in Africa's major cities at a much faster rate than in the rest of the world, leading to dramatic sprawl with associated undesirable environmental and social consequences. Using Nairobi as an example of a major African city, we studied the dynamics of land use and land cover changes using satellite data and post classification analysis with GIS and addressed the need for urban management tools that can provide perspective scenarios. Urban growth simulation for Nairobi city using Cellular Automata (CA) that integrates biophysical factors with dynamic spatial modelling is described. The model was calibrated and tested using time series of urbanized areas derived from remote sensing imageries, and future growth projected out to 2030. The results showed that continued lack of a comprehensive regional plan for Nairobi is leading to an "unorganised" urban system following road network, with forecast highlighting an unsustainable sprawled urban growth. The results show the capability of urban growth modelling in addressing regional planning issues.

Keywords: urban growth, dynamic spatial model, cellular automata, Nairobi city, urban simulation

Introduction

Suitable urban planning is a top priority for future development but unfortunately, sound planning has not taken place in many African cities as heavy rural-urban migration continues to cause cities to expand at uncontrollable rates (Rakodi, 2004; Oucho, 1996; Chaudhuri, 2000). Despite the lack of basic amenities and infrastructure in such cities, human agglomerations still attract population from the surrounding regions. As a consequence, the urban population in Africa is increasing at a much faster rate than in the rest of the world, contributing to the augmentation of the existing problems (Ngigi, 2007; Lavalle *et al*., 2001; Obudho, 1997; Njeru, 2006). The concentration of population in cities comprises as much as 60% of the total population in most countries. In these immense urban agglomerations the environmental and social consequences are disastrous (Baredo, & Demicheli, 2003).

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Cities in Africa such as Nairobi are witnessing the establishment of slums spreading out from the fringes of the city or from localities that otherwise would not have been settled due to undesirability or legal restrictions (Mundia & Aniya, 2005; Brockerhoff & Brennam, 1998). The main consequences in these cities can be summarised as unsuitable land-use, inadequate transportation systems, pollution, depletion of natural resources, urban sprawl, collapse of public services, proliferation of epidemics, and other negative environmental and social effects. The transforming of surrounding land due to urban expansion and urban dwellers ever-increasing demand for energy, food, goods and other resources is behind the degradation of local and regional environment which is threatening the basic ecosystem services and biodiversity. Problems linked to sustainable urban development in African cities are many and complicated and requires an integrated approach (Abiodun, 1997; Berstein 1995). Such an integrated urban planning approach needs to recognise and anticipate urban dynamics and their consequences (Baredo & Demicheli, 2003).

Cellular Automata (CA) are gaining attention for their utility in predicting spatial patterns of urban development and can be used to investigate planning regimes and land use patterns (Silva & Clarke, 2002; Clarke & Gaydos, 1998). As a planning tool, CA urban modelling which is interactive can be visualized and quantified and can play an important role in investigating the consequences of the African urban agglomerations to avoid environmental and social consequences as a result of the rapid spatial expansion.

The aim of this paper is to produce an urban growth model for the city of Nairobi using CA dynamic spatial model. The model for Nairobi city was calibrated using multistage Monte Carlo method and a 30 year prediction simulation was run until 2030. The aim of the model is to predict future land use development under existing policies in order to assess the effect on future land use development.

Methodology

The Clarke Cellular Automaton Urban Growth Model (UGM) was modified and calibrated for this research.

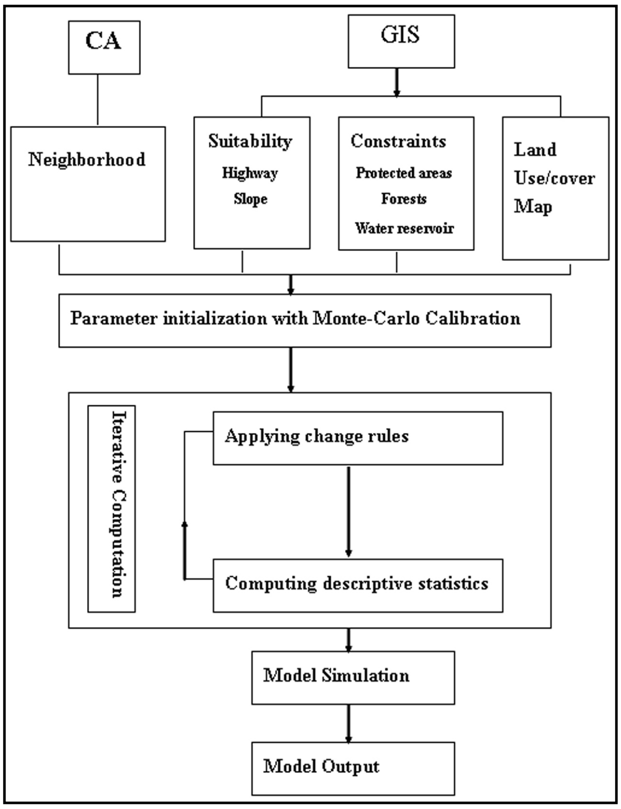

Figure 1: Framework of the urban expansion model

Figure 1 shows the framework adopted for the urban expansion modelling. UGM used CA, terrain mapping and land use/cover modelling to address urban growth.

Modelling of Nairobi city utilized a number of input data layers: “slope”, “land use/cover”, “areas excluded from development”, “urban areas”, “road network” and “hillshade”. Various types of urban land use change were simulated. These included: spontaneous growth, new spreading centres growth, edge growth, and road-influenced growth. These growth types were applied sequentially during each growth year and were controlled through the interactions of five growth parameters which describe an individual growth characteristic and when combined with other characteristics describe several different growth processes.

Input data and dataset preparations

Multi-temporal Landsat images for 1976, 1988, and 2000 were used in a post classification analysis with GIS to map land use/cover changes for Nairobi city (Figure 2). The urban extents for the various years were extracted from the land use/cover maps.

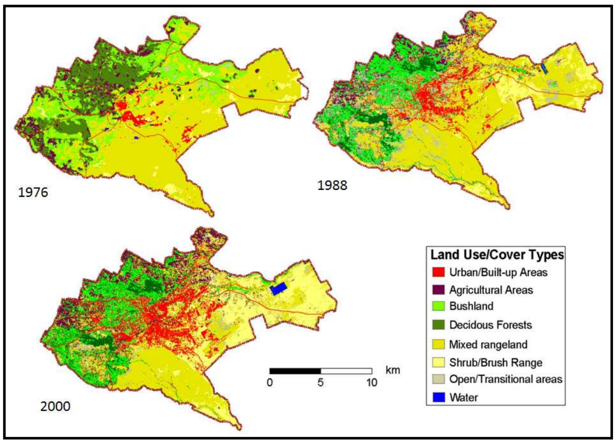

Figure 2: Land use/cover for Nairobi

Two time periods for transportation were prepared for 1976 and 1988 from topographical maps. Slope layer and the layer of all “areas excluded from development” were generated from topographical maps. Additional data set preparations such as geo-registration, data type standardization and resolution check were necessary to ensure that all data sets had the same extent in terms of longitude and latitude, the same data standards and the same number of rows and columns. Using these data, calibration was done to derive parameters for forecasting urban growth.

Model Calibration

Model calibration was achieved through a brute force Monte Carlo calibration method. This method determines, given a starting image of urban extent, a set of initial control parameters that lead to a model run that best fits the observed known data. The method steps through the coefficient space in a complete, regular and irreducible manner.

By running the model, a set of control parameters were refined in the sequential calibration phases (coarse, fine, and final calibrations). Between calibration phases, attempts were made to extract the value that best matched the five coefficient factors that controlled the behaviour of Nairobi city: diffusion (overall scatter of growth), breed (likelihood of new settlements being generated), spread (growth outward and inward from existing spreading centres), slope resistance (flat more preferred), and road gravity (attraction of urbanization to roads and diffusion of urbanization along roads).

Coefficients combinations resulted in 13 metric measures. These metric measures were coefficients of determination of fit between actual and predicted values either for the pattern (such as number of pixels, number of edges, number of clusters), for spatial metrics such as shape measures, or for specific targets, such as the correspondence of land use and closeness to the final urban pixel count. The calibration using Monte Carlo simulations computed the averages across multiple runs to ensure robustness of the solutions. This made it possible to adapt the model to existing different and unique characteristics for Nairobi city throughout the various stages of calibration by using different spatial resolutions and the sequential multistage optimization of the coefficient that controlled the system. To examine the role of spatial resolution on model calibration and outputs, calibrations were performed at different fixed resolutions. The quarter calibration was performed using only the quarter resolution data (216 x 186). The other two calibrations were the half (432 x 372) and the full (864 x 743) calibrations. By narrowing both the spatial scale and the range of parameters in the three calibration sequences, it was possible to close in on the parameter set that best simulates the urban growth for Nairobi city. These parameters were then used to determine the coefficient values that best allow the model to predict the future urban growth of Nairobi city.

Results

Calibration results

Results from the three phases of calibration (Coarse, Fine, and Final calibrations) are presented in Table 1.

Growth Parameter	Dispersion	Breed	Spread	Slope	R/ Gravity
Coarse Calibration					
Range	1-100	1-100	1-100	1-100	1-100
Monte Carlo Iterations	4				
Total number of iterations	3125				
Compare statistic	0.78				
LeeSalee	0.27				
Population statistic	0.95				
Input data resolution	1/4(216x186)				
Medium Calibration					
Range	1-100	1-100	1-100	1-100	1-100
Monte Carlo Iterations	8				
Total number of iterations	4502				
Compare statistic	0.57				
LeeSalee	0.19				
Population statistic	0.96				
Input data resolution	1/2(432x372)				
Final Calibration					
Range	1-100	1-100	1-100	1-100	1-100
Monte Carlo Iterations	10				
Total number of iterations	6752				
Compare statistic	0.11				
LeeSalee	0.09				
Population statistic	0.97				
Input data resolution	Full (864x743)				

Table 1: Calibration results

The calibration results show successive improvement in the parameters that control the behaviour of the urban expansion.

After the coarse calibration, the resulting values narrowed and became more sensitive to the local conditions within the city. The comparison of the modelled final "population" (number of urban pixels) and the urbanization of the control years give a high summary correlation of 0.95 and a compare statistic of 0.78 making it reasonable to say that the prediction of the model based on the initial seed year of the present urban pattern is quite accurate. The shape and form of urbanization seems also to confirm that calibration adjusts the values to reflect the actual characteristics of Nairobi city. The final calibration correlation were 0.99 in case of the score r^2_edges (modelled urban edges against the urban edges of the control year), and 0.95 in the case of the cluster_r^2

score (modelled urban clustering against known urban clustering). Figure 3 summarizes the resulting final calibration coefficients obtained for Nairobi city.

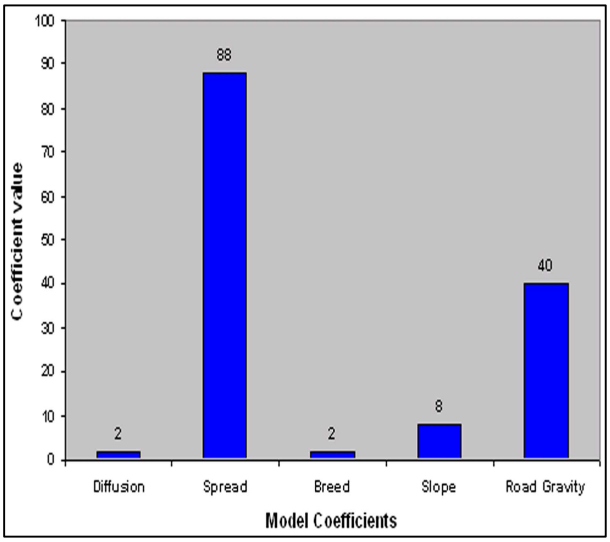

Figure 3: Final calibration coefficients

The spread coefficient was the highest followed by the road gravity coefficient. The slope coefficient was ranked third suggesting that slope is also a factor in the urbanization process of Nairobi city. The resulting coefficients suggest that the urbanization of Nairobi city has tended to occur from the main nucleus (spread coefficient at 88) and along the main roads network (road gravity coefficient at 40) with some influence from the local terrain (slope coefficient at 8).

From the overall analysis of the results, it was noted that model performance improved with increased spatial and parameter resolution. From an initial coefficient of coarse calibration, it was possible to narrow down to a road gravity coefficient of 40 in the final calibration phase. An erratic behaviour was noted between the coarse and final calibration as the model adjusted to the characteristics of the city. The LeeSallee score, which measures the degree of shape match between the modelled growth and the known urban extents for the control years, varied from the course through to the final calibration phase suggesting that the model grew in different ways with different intensities and directions over the study period.

Trends in Urban development

Analysis of the trend in urban expansion until the year 2000 showed that growth was highest between 1988 and 2000. Urban growth evolution indicated that expansion until 1985 was mainly radial, around the established city.

This radial growth was mainly infill and edge development. However, this changed after 1988 to assume the characteristic star-shaped urban development as growth evolved along the main transport routes.

Figure 4 and Table 2 summarises the spatial accuracy assessment for 1988, 1995 and 2000. The overall spatial accuracy was high at 80% for 1995 and 86% for 2000. The overall κ statistics for the two years were 0.21 and 0.30 respectively. Errors of omission (producer's accuracy) and commission (user's accuracy) for the urban class for both years suggest that the prediction of the location of urbanized pixels was reasonably accurate.

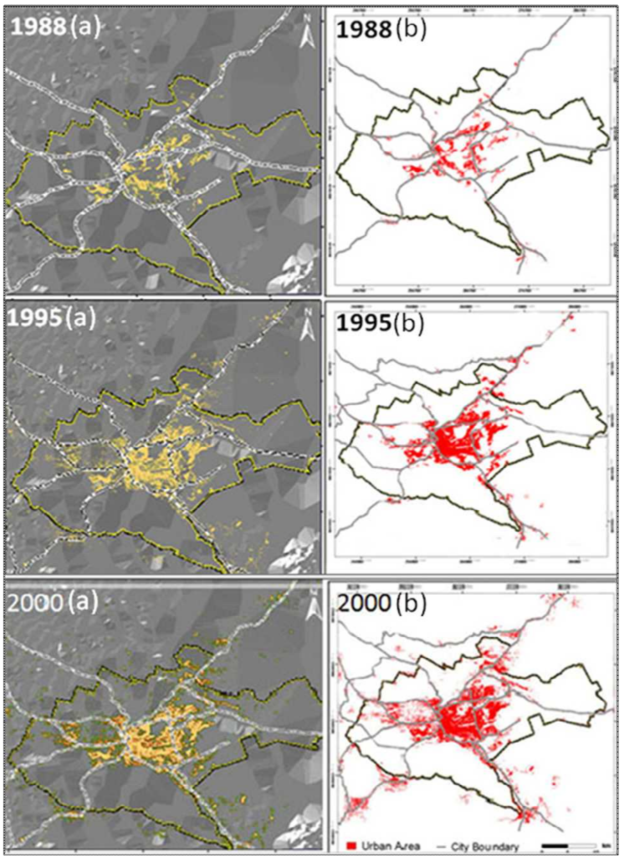

Figure 4: Spatial accuracy assessment (a) simulated results, and (b) result from satellite data.

Table 2: Model Accuracy assessment result

Year 1995		
Class Name	Producers Accuracy	Users Accuracy
Urban	47.2%	69.6%
Non-Urban	95.45	79.9%
Overall Accuracy	80.0%	
Year 2000		
Class Name	Producers Accuracy	Users Accuracy
Urban	45.2%	67.6%
Non-Urban	97.4%	80.9%
Overall Accuracy	86.2%	

Prediction

Figure 5 show projected growth pattern of Nairobi city up to 2030. The model prediction output indicates a significant amount of growth from 2000 to 2030 including the occupation of large tracts of non urbanized land. The downtown Nairobi is predicted to urbanize substantially by 2030. The predicted results show dramatic growth, with urban land occupying most of the total land. Such a massive growth of urban land will cause substantial change to the landscape and loss of resource lands. From a visual point of view the simulated map maintains a similar shape to the current city.

The results indicate that the city will continue expanding mainly to the northeast, southeast and northwest, following the major transportation network. The built up areas have grown, in most cases, continuously from the initial city core.

The suitability factors such as terrain and slope are not important factors for urban development due mainly to the plain topography of the city and surrounding areas. The simulations, unconstrained by suitability factors, have produced an extensive development style and consequently an evident sprawl process.

In addition to the aforementioned, an interesting option for planners would be to produce simulations following different trend scenarios. By applying certain development mechanism, it would be possible to obtain different scenarios of future land-use based on a variety of assumptions.

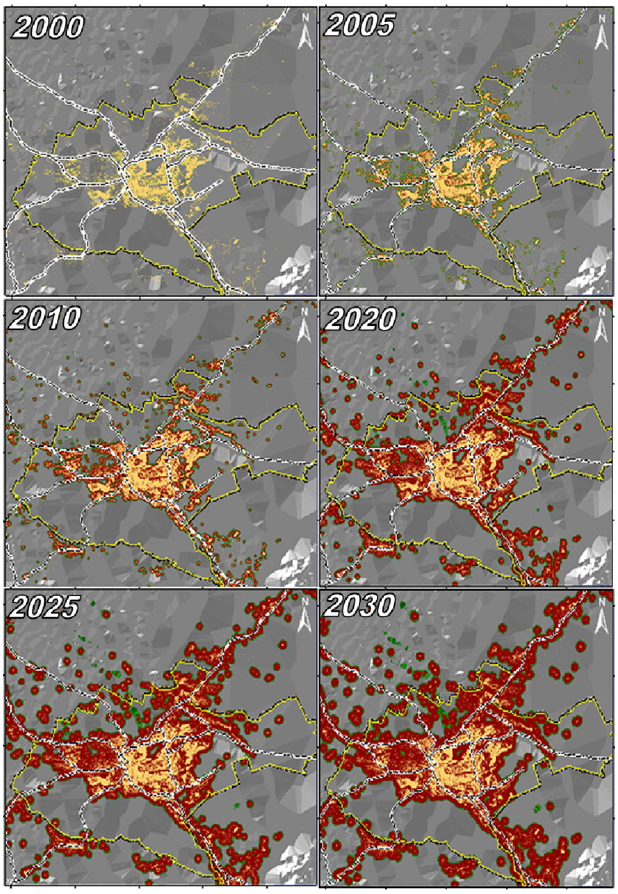

Figure 5: Simulated urbanised areas from 2005 - 2030

Conclusion

The spatial results obtained in the simulation for 2030 raises some pertinent questions and indicate that Nairobi city is moving into the future without any strategic planning and with no shared vision of how the city should look like in the next 30-50 years. There is a very urgent need to take urban development and planning measures to manage a city with the characteristics of Nairobi by 2030 taking into consideration the existing demographics, economic and social constraints. Because of the ability to simulate complex behaviour of urban systems, CA represents a viable approach for regional modelling. This research has explored the suitability of utilizing CA for regional planning applications and the model was found to be useful for demands for regional modelling and an effective tool to foresee the spatial consequences of poor planning policies in the context of many African cities. Alternative scenario development and the ability to visualize and analyze the model outcome spatially can be very useful for planning purposes and especially in coming up with different planning strategies.

Some assumptions about growth processes prevented the model from being able to capture a wider range of growth patterns and processes for Nairobi city. Despite these considerations, the model was found to be a useful tool for assessing the impact of urban development. The capacity of the model to reproduce the actual urban shape through a bottom-up approach is remarkable and will provide planners with more powerful tools for urban and regional scenarios generation.

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