Simulating Land Use and Land Cover Dynamics in the Ecuadorian Amazon through Cellular Automata Approaches and an Integrated GIS

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These materials are written in support of the presentation of the same title given at the “2001 Open Meeting of the Human Dimensions of Global Environmental Change Research Community in Rio de Janeiro, Brazil, October 6-8, 2001.”

Abstract

This research uses unique multi-thematic and spatially-explicit data combined with expert knowledge, a set of analytic results, and dynamic modeling approaches to describe, explain, and explore the consequences of land use and cover change (LUCC) in the Ecuadorian Amazon. First, two cellular automaton (CA) models representing LUCC are developed, calibrated, and validated using a time series of remotely sensed images from the region in Northeastern Ecuador linked to spatially referenced biophysical and socioeconomic coverages as input data combined with “rules” derived from empirical analyses of those data. Second, the models are used in dynamic simulations to explore LUCC as both cause and consequence of: a) patterns of village settlement in a frontier environment; b) road development; c) agricultural extensification and intensification; and d) exogenous factors, e.g. the direct and indirect impacts of Plan Colombia (the US based program to eradicate drug production in bordering Columbia). Finally, Complexity Theory is discussed within the spatial and temporal dynamics associated with population/environment interactions. In this paper the theoretical justification for the modeling scheme, a brief overview of one of the models, and two sample scenarios are presented.

Introduction and Significance

It is now well-recognized that, at local, regional, and global scales, land use changes are significantly altering land cover, perhaps at an accelerating pace (e.g. Turner et al., 1994; Houghton 1994). This transformation of the Earth’s surface, particularly through deforestation, is, in turn, linked to a variety of scientific and policy issues affecting the Earth system, such as a) climate change, b) carbon cycling, and c) land degradation, sustainability, and resilience (e.g. Intergovernmental Panel on Climate Change, 1996; Liverman et al 1998). Further, the world’s scientific community is increasingly recognizing what, in retrospect, should have been obvious: that human behavior and agency is a critical driver of LUCC. This is cogently argued in the chapter contributed by the National Academy of Sciences (NAS) Committee on the Human Dimensions of Global Change, Global Environmental Change: Research Pathways for the Next Decade (1999). It is again stated forcefully in the recently issued document identifying the "Grand Challenges in Environmental Sciences" (see challenge #7, NAS Committee on Grand Challenges in Environmental Sciences 2000). As a result, various branches of science are now requesting realistic models of LUCC at multiple and interacting spatial and temporal scales.

The development of predictive scenarios of LUCC requires a basic understanding of human behavior and decision-making in conjunction with a wide variety of biophysical processes. Further,
we would argue that this human decision-making is taking place on variety of spatial (e.g., global, national, provincial or state, district or county, town or village, household, and individual) and temporal scales (e.g., intra-annual, inter-annual, decadal, and beyond), and that models are needed that integrate human dimensions at these space-time scales together with the scales at which biophysical processes are operating. In the research presented here, human and biophysical processes are integrated at a variety of space-time scales with substantial time depth in each thematic domain to develop spatially explicit predictive scenarios of LUCC.

Consider first, human dimensions in land use. At the most micro scale, it is self-evident that individuals and households make decisions that affect and are affected by land use, and hence land cover. While a global accounting is not available, nevertheless it seems reasonable to assert that a substantial proportion of the globe’s land is owned or controlled by individuals or households (as opposed to governments, corporations, or other large organized social entities). Individuals and households make decisions on the use of millions of parcels of land based on their own interpretation of what might be best for them within the context of legal, economic, technological, biophysical, and other constraints. At the other extreme, increasingly there is a global market for agricultural and manufactured products, and this market can and does affect local land use decisions. For example, in the portion of Ecuador where we have intensively studied, farmers make decisions on planting coffee primarily based on the demand (perceived or actual) for coffee in Europe and on import substitution policies established by the Ecuadorian government. Between households and global markets, there are decisions at the local, provincial, and national levels on such issues as the placement of roads, bridge locations, and truck taxes, all of which can affect LUCC. Models yielding LUCC scenarios need to allow for the integration of a diversity of levels at which human behavior could affect land use. One very significant aspect of the proposed research is that the data span the spectrum, from individuals and households to exogenous drivers to resource endowments.

However, it is also important to recognize that biophysical processes are a vital component to LUCC. Important factors include soil type and fertility, slope and elevation, landforms, climate, and flow of water. The interrelationships among these factors have received more attention from the ecological sciences and other modeling communities than have the human dimensions. In this research, theoretical and practical extensions are built upon what is known from existing work in modeling biophysical processes as they affect LUCC. In addition, human dimensions at a variety of space-time scales are incorporated. As part of a previous NASA funded project, two comprehensive social surveys exist that encompass the study region. The surveys collected in 1990 and 1999 span the period of greatest change with the Ecuadorian Amazon. With these data and combined with the satellite image data, it is possible to look at initial conditions, short- and long-term time lags, and spatial dependencies.

In the context of northeastern Ecuador, it is readily apparent that individual, social, and structural processes occur at different scales and do so through feedbacks and thresholds within and across various domains. Individuals can choose incorrectly, they may make decisions based upon the decisions of their neighbors or other units of social organization, or decide to satisfy perceived needs of a society far removed from their own (Sioli 1985). There are in fact many possible routes that an individual might take in making land use decisions (Boserup 1965).

The changing temporal and spatial signature of development provides insight into the activities that currently encourage land clearing (Allen and Barnes 1985). In this way, spatial patterns point to a set of factors that can explain recent changes in regional rates of LUCC and provide focused spatial constructions suitable for modeling. The recent NAS report on the "Grand
Challenges in Environmental Science" mentions explicitly the need to develop innovative applications of dynamic spatial simulation techniques as one component of challenge #7, “to develop a systematic understanding of changes in land uses and land covers critical to ecosystem functioning and human welfare.” This specific goal is addressed by using CA models built to explicitly allow for nonlinearities and feedbacks. As such, complexity theory is incorporated by having a set of ongoing processes and relationships that are non-linear and which embody hierarchical linkages operating with time lags and scale dependencies (Messina 2001).

The goal of the science of complexity is to understand how simple, fundamental processes can combine to produce complex holistic systems (Gell-Mann 1994). Complex systems are systems that are more than the sum of the parts. Non-equilibrium systems with feedbacks can lead to non-linearity and may evolve into systems that exhibit criticality (Bak 1998). This approach is based on the contention that some systems become complex, and hence for which computer simulation modeling is appropriate to capture the dynamics that reductionist-based, process-driven science cannot appropriately explain. Some systems contain multiple variables with apparent complexity. But a system based on multiple variables does not in itself guarantee complexity. Complex systems generally exhibit processes and relationships that are non-linear as well as embody hierarchal lineages that operate at different spatial and temporal levels. According to Clarke et al. (1997) and Cilliers (1998), complex systems consist of (a) elements not effectively described by conventional means, (b) elements that may interact dynamically, (c) interaction that may be non-linear and operate through feedback mechanisms, (d) adjacent elements that are specified through neighborhood functions, (e) dis-equilibrium and open systems that characterize its scope, and (f) past conditions that imprint the present as well as the future.

CA models were originally conceived by Ulam and Von Neumann in the 1940s to provide a formal framework for investigating the behavior of complex, extended systems (Von Neumann 1966). Cellular automata are dynamic, discrete space and time systems. A cellular automaton system consists of a regular grid of cells, each of which can be in one of a finite number of k possible states, updated synchronously in discrete time steps according to a local, identical interaction rule. The state of a cell is determined by the previous states of a surrounding neighborhood of cells (Wolfram 1984). However, it is important to remember that the early work on CA systems was fundamental theoretical work. Using it with powerful computing technology (both hardware and software) and appropriate data did not start until relatively recently.

The difficulty in modeling population-environment interactions has historically been the need to have a dual simulation mode of model construction. Human systems are necessarily stochastic, while many natural systems are adequately modeled deterministically. Combining stochastic and deterministic processes in a single model is a critical challenge, and based on ongoing research (e.g. Messina and Walsh 2001) the approach here is to use empirical analyses to establish the manner in which human behavior is associated with LUCC, and then use CA (and the associated complexity theory) to spatially and temporally model the process. Various scenarios are examined based on empirical relationships, ranging from the history of village settlement, to accessibility, to demographic and land use allocation resulting from exogenous policy decisions (e.g. Plan Colombia). Results of the scenario simulations will, in the future, be used to examine the spatial distribution as well as the composition of LUCC, LUCC trajectories at the pixel and other levels, and temporal and spatial scale dependencies. It should be noted that this coupling of the simulation power of CA modeling (with its ability to allow for non-linearities and feedbacks) with a rich set of empirical relationships is a major advantage of this research. To date, the overwhelming majority of
relationships built into various CA models have been based on assumptions about relationships between variables rather than empirical evidence of those relationships.

**Specific Hypotheses**

A. Land Use and Land Cover Change Dynamics are the result of the decisions of the individual farmer, transportation and accessibility, exogenous forces (e.g. Plan Colombia), and biophysical conditions

B. Satellite imagery can be used to identify ground level conditions produce accurate maps of land use and land cover

C. Complexity theory can be used to integrate multiple data sources (e.g. GPS and satellite imagery) and types (e.g. household surveys and biophysical conditions) across multiple physical, geographical, and social domains and across multiple temporal and spatial scales

D. Dynamic Spatial Simulation Models and specifically cellular automaton models can be used to extend complex systems theory into LUCC prediction.

**Ecuadorian Study Site**

The study site in the Northern Oriente region of the northeastern Ecuadorian Amazon is significant from a social, biophysical, and geographical basis. Settlers in the Napo and Sucumbios provinces are generally poor, small scale farmers, who originally settled on 50 hectare plots called *fincas*, clearing primary forest to grow subsistence crops (e.g., yucca), as well as commercial crops (e.g., coffee), and to create small pastures for cattle. Particularly high fertility and mortality rates characterize this rural population of in-migrant settlers. The "natural" process of frontier settlement in Ecuador's Amazon is not confounded by chronic conflict and land disputes (as in much of Brazil) or by illegal coca growing (as in Peru) (Blaikie and Brookfield, 1987). Furthermore, rapid urbanization, large-scale logging and large ranches are not found in Ecuador as in other Amazonian countries. As a consequence, the opportunity exists to evaluate the combination of agricultural intensification on a declining resource base with patterns of regional frontier settlement to achieve a clearer understanding of LUCC.

The focus on the Ecuadorian Amazon is also significant for environmental and socio-economic reasons. Oil exploration, road construction, and in-migration threaten major conservation areas contiguous to colonization zones. An examination of LUCC across areas differing by degree of human intervention is possible by comparing official settlement zones, both colonists and indigenous sites (*comunas*), with the remaining protected forests of the Cuyabeno Faunal Reserve and Yasuni National Park. Also, land conversion or development intensities vary across the landscape relative to time since colonization, access to communities and markets, road connectivity, and natural resource endowments.

**Data**

Because of funding received for earlier research, a variety of data sets were acquired or created including: two panels of individual, household, and village-level data (1990, 1999); a time-series of remotely sensed data that includes aerial photography (1990) and Landsat (1973 - 1999), and IKONOS very high spatial resolution satellite data (1999); a digitized base-map and a collection of derived GIS thematic coverages; verification data from multiple field visits; and sketch maps of past and current land use for every farm visited (approximately 500). Land use maps for targeted
study areas were also created (Messina and Walsh 2001). This is the most complete database covering the social, biophysical, and spatial domains of the Ecuadorian Amazon and one of the most complete in the entire Amazon basin. Much of the development of these data sets and the household survey collection methodology can be found in Bilsborrow and Walsh (1999), Messina (2001), and Walsh et al. (2001).

Methodology

**General Modeling Approach: Cellular Automata.**

A cellular automaton (CA) system consists of a regular grid of cells, each of which can be in one of a finite number of possible states, updated synchronously in discrete time steps according to a local interaction rule. Expanding upon the urban systems modeled by Clarke et al. (1996, 1997), the modeling scheme implemented in this research attempts to follow, and then go beyond, biological patterns and ecological system behavior (Messina 1999, Messina et al. 1999, Messina and Walsh 2000, Messina and Walsh 2001). Transition probabilities for the typical CA model depend on the state of a cell, the state of its surrounding cells, the physical characteristics of the cell (e.g., terrain, soil quality, vegetation, hydrology, and demographic characteristics), and the weights associated with the neighborhood context of the cell (e.g., proximity to other villages and the time since settlement). These weights and neighborhood conditions are determined from empirical analyses of LUCC based on social survey data, the GIS database that represents resource endowments of a site, and the spatial linkages between villages, land parcels, and other critical landscape features.

It is important to emphasize that the temporal depth, areal extent, and grain size of the social surveys and the remote sensing and GIS data afford a unique capability to examine complex systems operating within a complexity theory context. Using logic and multi-level models, equations and relationships can be developed that contain key variables and their appropriate weightings for spatially-explicit modeling using CA approaches. Uncertainties associated with “selecting” variables and “assigning” weights for simulating land cover patterns are substantially reduced because of the statistical power and flexibility of the combined existing and proposed data sets with their large sample size and the spatial reference of the data elements.

Methodologically, there are three different ways that the satellite time-series are used in the development of the CA models. First, a subset of the satellite images was used to build the baseline model within the CA context. A second distinct subset of the satellite images was used in this calibration process. A third set was used for validation and finally, the CA models were further tested by back-simulating the LUCC models of current conditions to periods within the assembled satellite time-series that were not used for the actual model development or calibration. This verification/calibration design can only be accommodated through a rich and highly populated remotely sensed time-series and a longitudinal social survey. The assembled satellite and aerial photography time-series affords the capability to recreate initial conditions in advance of real historical events that are hypothesized to have affected the pattern of LUCC. These mapped, modeled, and hypothesized events further serve to contextualize the population / environment matrix.

**Complexity-Based Simulations of LUCC Dynamics**

Focusing on the spatial and temporal dynamics of deforestation, agricultural extensification, and plant succession, a cell-based morphogenetic model of LUCC was developed as the foundation for a predictive model of regional LUCC dynamics and landscape diversity. LUCC simulations,
achieved through CA methodologies, are run on an annual basis to the year 2020 using either 1973 (a Landsat MSS image) or 1986 (Landsat Thematic Mapper image) as the initial conditions. The choice of moving forward 20 years, while somewhat arbitrary, reflects the current judgment as to how far into the future CA models can be pushed and still obtain credible results. While 20 years seems reasonable, if the results suggest it is worthwhile to go out further, it is easy to do so. Starting with the 1973 image has the advantage that nearly unbroken forest existed with only a few oil roads to influence development. Starting with the 1986 TM image has the advantage of higher spatial resolution and is consistent with the majority of the time series of imagery. The satellite and air photo image time-series serve as the "check points" in the simulations for model calibration as well as verification. Proof of concept models have been developed using the Imagine Spatial Modeler of the ERDAS image processing software, and enhanced using the Spatial Modeler Language (SML) (Messina and Walsh 2001). A second generation model introduced here was created in pseudo-code and built using IDL software, with the preliminary model on already coded software directly translated into the new and more powerful programming environment.

The CA model, in general, works by (a) simulating the present by extrapolating from the past using the image time-series, (b) validating the simulations via the remotely sensed time-series of past conditions and through the available collection of field observations, (c) allowing the model to iterate to the year 2020 (or any other selected date), and (d) comparing model outputs to an autoregressive time-series approach for annual conditions that are compared via paired t-tests or other similar tests of pattern metrics run at the landscape-level to define compositional and structural differences.

Within the hierarchy of mathematical - computer - simulation, models are used as heuristic aids in problem solving, where specifiable relationships are assumed. Using the metaphor of software accretion, the model presented here was developed in modules with core elements developed first with enhancements added later. As a subset of the broader category of ecosystem models, dynamic spatial simulation models predict the spatial and temporal patterns, here of LULCC. As an abstraction, the models reflect the process of occupation and agent interaction with the landscape. As a cellular automata theory-based simulation, model building focuses on small localities surrounding the surveyed locations where high quality data are available for model development and validation (Messina et al., 1999). It is expected, via a priori assumptions, that there are both nonlinear and hierarchical relationships among the physical, spatial, and socio-economic factors that govern LULCC.

**Morphological and Cellular Processing**

Morphological and cellular processing refer to a class of spatial filtering operations used throughout this research to change the shape of the binary "ON" region of a class within a larger class-map. The method of assigning membership to the active community of cells is very specifically cellular processing, which uses arithmetic evaluations of pixel values over a specified neighborhood and a comparison of results to an assigned threshold:

\[ \Theta(i, j, \eta) = \sum_{(n, m) = \eta} I(n, m) \]

Equation 1. Cellular Processing

where \( I = \) the image; and \( \eta \) describes the neighborhood pixels around the center pixel. The second component calculates the number of connected groups of pixels in the neighborhood \( x(i, j, \eta) \).
results are compared with user-set thresholds $T_0$ and $T_x$ discussed in the next paragraph. The center pixel is then essentially turned ON or OFF (Seul et al., 2000).

**General Growth Rules**

Growth rules might more accurately be described as change rules. The process of change and its defining characteristics are the subject of this section. To simplify the continuity of the presented models with existing models, a common vocabulary is used. There are essentially three types of growth or change that occur with both the older model (Messina and Walsh 2001) and the presented model. The first is "organic growth" which spreads outward from existing urban centers, representing the tendency of cities to expand. Dispersive growth promotes the random dispersed development of urban centers regardless of proximity functions (Clarke et al., 1996). Spontaneous growth occurs when a randomly chosen cell falls near an already urbanized cell, simulating the influence that urban areas have on their surroundings (Clarke et al., 1997). This particular change implementation is really more of an extension of the organic growth model to incorporate random number fields. This particular component is built into both of the developed models, but spontaneous growth is embedded within the organic implementations. Road influenced growth, possibly the most important driver of landscape alteration in the Oriente, encourages “anthropomorphized” cells to develop along the transportation network, replicating the effects of increased accessibility. The likelihood of settlement and consequent deforestation along a road is high yet variable depending upon access to markets and road surface type. Road-influenced growth encourages urbanized cells to develop along the road network; the accessibility of these locations attracts development. This component is the most important driver of new development in terms of non-adjacent change. Organic growth is the dominant driver of LULCC, but accessibility is the single most important directional forcing of change. The river systems provide a regular transportation infrastructure, but are less important overall to the road network. As with any system, certain components may be defined as exclusionary or limiters to change. Within the physical world, soils, slope, water availability, any number of conditions may be viewed as restrictions to growth. Within the Northern Oriente, the same conditions occur and are accounted for within the models. Exclusion elements specifically included are slope, urban areas (when evaluated within the context of change in agriculture and secondary forest), rivers, and the borders. (Author’s note: these rules are more definitively characterized in Messina and Walsh 2001)

**IDL Based CA Modeling**

IDL is designed to facilitate the complex manipulation of multi-dimensional arrays. Within IDL, the Visual IDL Programming environment (VIP) was used to facilitate the assembly and testing of individual model components. The visual nodes are tools used to place graphics representing input data, functions, criteria, and output data on a page to create a graphical model in the form of a flow chart. Figure 1 illustrates the model logic and all basic elements used for each model run. You will notice that the annual output feeds back into the spatial partitioning component. This loop runs on a preset cycle representing the number of years specified in the model parameterization. In the paper presented here, the specific processes of parameterization and model development are not reported as they have been reported elsewhere (e.g. Messina and Walsh 2001) and are under-development or in review for future journal publication.
One of the primary purposes of dynamic spatial simulations is to run "what if" scenarios. This section focuses on two scenarios considered relevant to current conditions within the Oriente. The first scenario is based upon Plan Columbia, the United States' plan to combat drug production in Ecuador. The second scenario is an agricultural example where coffee production is ended and cattle production increased as a result of market demand in Europe after the culling of their herds due to livestock diseases.

Plan Colombia was created during the Clinton administration to reduce the impact of drugs in the United States. The specific goals of the plan are as follows: "one is a push into Southern Colombia; second is support for narcotics interdiction efforts; third is support for the Colombian National Police; fourth is support for developmental and particularly alternative development programs and approaches; fifth is support for justice and other social sector reform. A sixth element,
which does not directly affect Colombia itself, is (the U.S.A) support for issues outside of Colombia, forward-operating locations, as well as several other countries that are affected by what happens in Colombia (source: U.S. DEPARTMENT OF STATE, Office of the Spokesman, March 12, 2001)."

As an example of the currency of this situation, excerpted below is a wire report from Reuters (6 September 2001):

QUITO, Ecuador (Reuters) - Colombia's defense minister traveled to Ecuador on Thursday to talk with President Gustavo Noboa about boosting border security as fears grow of a regional spillover from Colombia's war on rebels and drug traffickers. This year, brief clashes on the border between Ecuadorian security forces and Colombian Marxist rebels raised worries Colombia's intensifying battles with guerrillas, paramilitaries and drug dealers will spill into neighbors like Ecuador. A U.S. backed anti-drug offensive in Colombia, the world's biggest source of cocaine, has been criticized for adding tension along the borders, with reports of rebels and refugees crossing into Ecuador for safety.

Plan Colombia has influenced the northern portions of the study site to the point where it is no longer safe to work in these areas. From personal experience, large groups of farmers have been displaced, crops have been damaged and access to markets severely limited. These effects will be visible via the proposed satellite data acquisitions and force the modeling environment to address shocks to the system and the effects of other less dramatic exogenous variables.

The sample Plan Columbia scenario was run in comparison with a control image, specifically, the final image from the calibrated time-series of LULC maps. The basic assumptions as placed within the model include: 1) typical or expected parameter settings through 1998 (Messina 2001), 2) starting in 1999, increased urbanization due to more remote farmers being forced off their land due to threats by drug lords and based upon the current process of demographics in Latin America where urbanization occurs along with population growth and expansion of the settlement front, 3) an increase in the effect of transportation on urban processes due to a greater constraint upon agricultural production and increased smuggling activities, 4) an even split in agriculture and secondary forest in the flux class due to less controls in either functional direction, and 5) a reduction in relief influence as drug production is likely to occur in any acceptable available area. By referring to Figure 1, the locations for the respective parameter adjustments may be identified.

The results of the model (Figure 2) run show dramatic increases in the amount of urban and a significant decrease in the amount of dense forest. One of the interesting simulation results centers on the increase in urban in the lower right portion of the image associated with the enhanced transportation effect. The change in transition probabilities had little affect on the total amount of land in agriculture or secondary forest as compared to the reference image. With the 50/50 split though, patchiness should increase. Given these results, it is reasonable to summarize the impacts of Plan Columbia on the region as causing significant urban expansion and reducing the amount of land in dense forest. The first outcome was expected, but the second was not.
The second or "Mad Cow" scenario is another practical scenario resulting from changes in market conditions. Recently, Europe has experienced great agricultural problems due first to mad cow disease and then more recently, hoof and mouth disease. The demise of a large percentage of the European livestock population impacted international beef prices. In Ecuador, the local farmers are often able to react quickly to changing market conditions given the diffusion of information and the continuous growing cycle of the region. The beef scenario was run in comparison with a reference image, specifically, the final image from the time-series maps and calibration phase. The basic assumptions as placed within the model include: 1) the urbanization constraints are held constant, 2) the relief constraint is reduced in order to open up more lands for pasturage, 3) all new agricultural lands are pasture, and 4) the new parameters begin in 2001.

The results from the scenario (Figure 3) show that agricultural production in the form of pasture accounts for significantly more of the new land conversions than in the control. This output is expected given condition 3. However, the spatial location of the new lands is an unknown. Under this scenario, new agricultural lands appear in patches along existing forests and where the best
access and relief conditions can be found. One of the benefits of cellular modeling is that it provides an alternative to cartographic modeling for environmental conditions. This particular scenario is another very real possibility. The ramifications of dramatically increased pasturage in the agricultural flux cycles include changes in the small climatological cycle and remnant forest isolation leading to larger ecological problems.

Figure 3. The beef scenario (L) output compared to a simulated control (R) image. (Class 1 is Dense Forest – dark green, Class 2 is Secondary Forest – light green, Class 3 is Agriculture - yellow, Class 4 is Urban – cyan).

**Concluding Comments**

The true measure of spatial complexity as applied in a CA context is one not yet fully realized in the literature. The tools exist to build complex (in the complicated not complexity sense)
models to predict LULCC in a variety of environments and time periods. By integrating new computational methods, data sources and theory, the underpinnings of LULCC may be explored and future scenarios predicted. However, without further development of the theoretical foundations of complexity theory and spatial pattern, addressing for example, "what is a good fit," the models run the very real risk of over-specification and unverifiable results. While some landscape level characteristics can be predicted that meet traditional tests of significance, the spatial pattern of a place remains unknown. The geographic perspective as tied to LULC promotes the idea of change as opposed to simple cell switching as in binary on/off or Markovian transitions. Further, the geographic perspective introduces an element of order, scale, and hierarchy, beyond simple emergence and correspondingly, using CA as a spatial surrogate to statistical tests allows the assignment of class to place.

This research attempts to integrate the social and physical, public policy and technology, and computer simulations with theory. Given the currency of policy, place and science, and the expected and demonstrated impact of exogenous conditions, the potential of this research for policy analysis and spatial prediction is exciting and certainly warrants further research.

References


NSB 00-22 National Science Foundation. 2000. “Gaps and potential sources of future funding - programmatic gaps or areas needing enhancement in the current NSF environment portfolio identified by the board programmatic area description.” Environmental Science and Engineering for the 21st Century; The Role of the National Science Foundation.


Walsh, S.J. et al., 2001. Landscape Dynamics in the Ecuadorian Amazon: Characterizing Patterns & Processes of Deforestation and Agricultural Extensification through Space & Time Dependent Models of Change, Open Meeting of Ecology LBA. NASA, Atlanta, GA.