Simulating Land Use Dynamics in Southeast Asia: A Cellular Automaton Approach

2001-2004: NASA Land Cover/Land Use Change Program

Abstract

This project, using recently developed cellular automaton modeling procedures and a temporally, substantively rich case study, develops spatially-explicit model-based simulations of future LCLUC scenarios for Nang Rong, Thailand and the broader Southeast Asian region, including Vietnam, Cambodia, and China. The research draws heavily on recent work in remote sensing, demography, sociology, complexity theory, and related social and biophysical disciplines. The scenarios are based on empirically observed relationships in the following areas: a) history and spatial pattern of village settlement; b) road development, expansion of available vehicles, and changing geographic accessibility; c) migration and household formation; d) land titling and linkages to investment in various land uses; e) climate and monsoon history; f) global economic factors, including world cassava prices and the 1997 economic crisis; and g) electrification, and the accompanying rise in TV viewership and consumerism. Results of the simulations will be used to examine the spatial distribution and composition of LCLUC.

The project exploits a rich collection of interlinked data sets for Nang Rong, some of which were developed under previous NASA funding. There is a collection of previously analyzed Landsat images (TM and MSS) dating back to 1973. Other remotely sensed data available includes AVHRR, SPOT, and SAR, as well as aerial photos dating back to the1950s. Community and household level surveys are available for 1984, 1994, and 2000. Out-migrants have been followed, and in-migrants added to the data set. Digital coverages showing roads, rivers, elevation, soil types and other spatial-thematic data are available within our GIS. Daily precipitation and temperature data are available since 1965. Human dimensions and Landsat derived land use data can be linked at the village level for 1984, 1994, and 2000, and at the household level for approximately 10,000 households in 2000.

After developing, calibrating, and validating the cellular automaton modeling scenarios for Nang Rong through the use of a deep satellite time series, spatially explicit LCLUC patterns will be derived for the period 1950- 2020. We will increase the extent of our geographic reach into the surrounding region, including Cambodia, China, and Vietnam, by relating LCLUC patterns in these countries and their drivers to our scenarios for Nang Rong. These are countries with significant extant forest coverage, some of which has likely been preserved due to their difficult political and social histories in the past 50 years. While prediction is difficult, it seems that at least a sub-set of these countries is poised for substantial social and economic change, with resulting implications for LCLUC and the carbon cycle.

Objectives

The proposed 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 cover and land use change (LCLUC) in Southeast Asia. **First**, a cellular automaton (CA) model representing LCLUC will be developed and validated using a time series of remotely sensed satellite and aircraft images from Northeast Thailand linked to spatially referenced biophysical and socioeconomic coverages as input data combined with “rules” derived from empirical analyses of those data. **Second**, the CA model will be used in dynamic simulations to explore LCLUC as both cause and consequence of: a) patterns of village settlement in a frontier environment; b) road development and increases in vehicular traffic; c) migration and household formation; d) land tenure; e) monsoonal variability; f) major shifts in world markets; and g) electrification, rise in television ownership, and the spread of consumerism. **Third**, the spatial extent of the CA modeling and scenario evaluation will be expanded regionally by comparing Northeast Thailand to other sites in Northeast Cambodia, Southern China (Yunnan Province), and Northern Vietnam. Using relationships, rules, and weights from these test sites, relative to our Nang Rong scenarios, we simulate LCLUC dynamics by perturbing our CA-based Nang Rong simulations for conditions that represent alternate development processes that have occurred elsewhere within our Southeast Asia region.

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 LCLUC. 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). It is also recognized in the organization of new cross-cutting themes by a set of international research programs and organizations (International Geosphere-Biosphere Programme, International Human Dimensions Programme, and World Climate Research Programme) (See the October 2000 *LUCC Newsletter*). Indeed, the upcoming Global Change Open Science Conference starts from the understanding that the Earth’s habitability is affected as never before by human activities (www.sciconf.igbp.kva.se). As a result, various branches of science are now requesting realistic models of LCLUC at multiple and interacting spatial and temporal scales.

The development of predictive scenarios of LCLUC 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 proposed here, we integrate human and biophysical processes at a variety of space-time scales with substantial time depth in each thematic domain to develop spatially-explicit predictive scenarios of LCLUC.

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 yet 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 entity). 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 Thailand that we have intensively studied, farmers make decisions on planting cassava primarily based on the demand for cassava in Europe where it is used as a high calorie feed for cattle. Between households and global markets, there are decisions at the local, provincial, and national levels on such issues as the placement of roads, extension of the electric grid, and truck taxes, all of which can affect LCLUC. Models yielding LCLUC 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 our proposed research is that our data span the spectrum, from individuals and households to world cassava prices to resource endowments – something that is remarkably unusual in the land use arena.

However, it is also important to recognize that biophysical processes are a vital component to LCLUC. Important factors include soil type, slope and elevation, landforms, climate, flow of water, and soil fertility. The interrelationships among these and related factors have received more attention from the ecological sciences and other modeling communities (e.g., Lambin 1996; Martens and Lambin 2000) than have the human dimensions. In the proposed research, we build upon what is known from existing work in modeling biophysical processes as they affect LCLUC. However, we do not stop there. Instead we bring in human dimensions at a variety of space-time scales. We have 50 years of data and hence can look at initial conditions, short- and long-term time lags, and spatial dependencies.

Environmental modeling often takes the approach that events are static in time and space. The more complex models, attempting to define processes over time (e.g. Gap and GCM), rarely, if ever, include human activity as an integrated process. These human effects are difficult to model and do not follow the mechanistic forms favored by ecological modelers. The process of land change and degradation, while in many cases visible to the eye, has not been modeled to any significant degree (Blaikie and

Brookfield, 1987). Redclift (1994) cites three primary flaws in the current paradigm used for the evaluation of LCLUC processes: a) biological determinism, b) avoidance of time and space in the modeling process and c) regionalization (fitting society into tight discrete social units for measurement). This last flaw requires a bit more explanation. One problem in incorporating human activity into biophysically-driven CA models is making the human actions and agency spatially explicit. In the proposed work we are able to do this because we have spatially explicit data on population processes. The second problem is going beyond simply modeling the fact that humans live in a given area. If we are to make progress incorporating human activity in CA or other simulation models, we need to be more explicit about what humans are doing and why, and at specific locations and for specific time periods. The richness of our social data allows us to move beyond just incorporating the fact that people live in a given area, but how they live, what are their connections to other locations, and what are the feedbacks between human behavior and landscape patterns.

In the context of northeast Thailand, 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). Also, time-lags in land use patterns associated with agricultural commodity prices or climatic trends (Walsh et al. forthcoming) and relationships to local and regional infrastructure (Crews-Meyer, 1999) affect LCLUC decisions.

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 LCLUC and provide focused spatial constructions suitable for modeling. The "discretization" of landscape phenomena in a dynamic simulation defines morphogenesis, and for our proposed analyses, the changing spatial conditions of the Nang Rong landscape are characterized using cellular automata (CA). 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.” We do so using CA models that will be built to explicitly allow for nonlinearities and feedbacks. As such, we incorporate complexity theory by having a set of on-going processes and relationships that are non-linear and which embody hierarchical linkages operating with time lags and scale dependencies (Walsh et al. 1999). The goal of the science of complexity is to understand how simple, fundamental processes can combine to produce complex holistic systems (Gell-Mann 1994). 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, for which computer simulation modeling is appropriate and may capture some of the dynamics, and for which reductionist-based process-driven science cannot appropriately explain.

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 our ongoing research (Walsh et al forthcoming) our proposed approach is to use empirical analyses to establish the manner in which human behavior is associated with LCLUC, and then use CA (and the associated complexity theory) to model the process.

Our overall approach is to start from strength, using the wide array of data that we have been collecting or assembling for Nang Rong district, northeast Thailand, as well as some established relationships from earlier analyses (Rindfuss et al. 1996, Entwisle et al. 1999, Walsh et al. 1999), supported by our current NASA grant (NAG5-6002). We will examine scenarios based on empirical relationships in seven areas, ranging from the history of village settlement, to monsoon history, to construction of the electric grid. Results of the scenario simulations will be used to examine the spatial distribution as well as the composition of LCLUC, LCLUC trajectories at the pixel and other levels, and temporal and spatial scale dependencies.

After the cellular automaton (CA) is built and validated for Nang Rong, we will use it to examine other areas within Southeast Asia. This is a region of the world that still has significant forest reserves. About one-third of tropical Asia is in forest cover, and approximately two-thirds of Cambodia, but it is a region poised for rapid transformation of land use (Ruangpanit 1995). A number of countries (Cambodia, Laos, Vietnam and Burma) in the region have had very difficult histories in the second half of the Twentieth Century, which may have served to limit cutting of the forest cover and to keep them from growing crops for the world market. Now, Cambodia and Vietnam, in particular, seem poised to rapidly change. Cambodia is currently struggling with land tenure issues and Vietnam has begun rivaling Thailand to supply cassava to Europe. Both are taking steps towards market economies. With appropriate help from experts on the region, we will expand the extent of our geographic reach of the cellular automaton model, asking a series of “what if” questions for other areas in Southeast Asia. By applying and then perturbing our base-line model of LCLUC dynamics in Nang Rong and referencing our scenarios to regional conditions in other neighboring countries, we will extend our geographic research from the local to the regional. In that way, we will explore actual, hypothetical, and modeled characteristics of drivers of LCLUC dynamics that have shaped the landscape of Nang Rong as well as those that might have developed under a different sets of circumstances.