# Simulating Complexity in a Dynamic Landscape

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## 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 (LUCC) in Southeast Asia. **First**, a cellular automaton (CA) model representing LUCC will be developed, calibrated, 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 LUCC 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) agricultural intensification; g) cooperative use of the hydrological layer; h) major shifts in world markets; and i) electrification, rise in television ownership, and the spread of consumerism. **Third**, the simulations will be packaged into a multimedia GIS database together with other materials explaining the site and situation, adapted to and tested for use at the secondary and college levels in the United States and in Thailand, and then made publicly available on the internet.

## 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 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 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 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 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 our proposed research is that our data span the spectrum, from individuals and households to world cassava prices 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 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 LUCC. 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. For these 50 years, we will be able to look at spatial-temporal dependencies integrated within empirical models, and visualized through simulations derived through cellular automata (CA) approaches.

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 LUCC 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, and consider how they live, their connections to other locations, and 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 LUCC 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 LUCC 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). Luhman (1985) argues that "complex systems" are systems that contain more future possibilities than could ever be actualized.

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, and hence for which computer simulation modeling is appropriate to capture the dynamics and 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 linages that operate at different spatial and temporal levels.

The ability of a system to grow and then alter its rate of growth and possibly reverse or "die" is a fundamental goal in biological or human system CA modeling. Ermentrout and Edelstein-Keshet (1993) performed CA applications in biological modeling. The systems modeled by Clarke et al. (1996, 1997) attempted to follow biological patterns of development. Research framed within complexity theory might address the rates and patterns of LUCC dynamics and the possible non-linear feedbacks between the process of change and the existing patterns of LUCC. Land use changes may depend partly on the existing patterns of land-use, which may involve critical points where a small amount of land use change significantly alters the feedback processes and leads to a new pattern or equilibrium. Balanced positive feedbacks produce critical points, where slight changes in landscape composition and pattern can alter system behavior, leading to possible system phase changes.

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 LUCC, 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). 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 LUCC, LUCC trajectories at the pixel and other levels, and temporal and spatial scale dependencies. We should note 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 the proposed 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.

## Nang Rong Study Site

Our primary study site is Nang Rong district, in Northeast Thailand. Northeast Thailand (or Isan) contains about one-third of the country's area, has about a quarter of the country's population, and generates about one-fifth of the GNP. The dominant occupation in the region is farming and the majority of farm households own an average of three hectares of land (Ghassemi et al., 1995). Per capita income is the lowest in the country, largely because of low and unstable agricultural production resulting from erratic rainfall and generally poor soils (Arbhabhirama et al., 1989; Parnwell, 1992). The Southeast Asian monsoon climate prevails in the Northeast, with over 80 percent of the average annual precipitation occurring as unevenly distributed torrential rains during April - November (Kaida and Surarerks, 1984; Rigg, 1991).

Nang Rong is our laboratory for the study of LUCC, particularly human dimensions aspects (Entwisle et al. 1996). Deforestation associated with agricultural expansion has been underway for a century or more (Feeny, 1988). Prior to World War II, this was associated with increased production of paddy rice, largely for subsistence. More recently, there has also been extensive deforestation in the upland areas associated with the cultivation of cash crops such as cassava, in response to a shifting world demand. Migration flowed initially into Nang Rong until the 1970s, after which flows reversed. Roads were developed and extended, beginning in the 1960s. Electrification occurred in the 1970s and 1980s, followed by a rapid increase in the ownership of televisions and other consumer durables. People live in nucleated villages.