International Congress on Environmental Modelling and Software

2nd International Congress on Environmental Modelling and Software - Osnabrück, Germany - June 2004

Jul 1st, 12:00 AM

Coupled Human and Natural Systems: A Multi-Agent Based Approach

M. G. Monticino

M. F. Acevedo

B. Callicott

T. Cogdil

M. Ji

See next page for additional authors

Monticino, M. G.; Acevedo, M. F.; Callicott, B.; Cogdil, T.; Ji, M.; and Lindquist, C., "Coupled Human and Natural Systems: A Multi-Agent Based Approach" (2004). *International Congress on Environmental Modelling and Software*. 53.
https://scholarsarchive.byu.edu/iemssconference/2004/all/53

Presenter/Author Information
M. G. Monticino, M. F. Acevedo, B. Callicott, T. Cogdil, M. Ji, and C. Lindquist

Coupled Human and Natural Systems: A Multi-Agent Based Approach

Monticino, M[a], Acevedo M., Callicott B., Cogdill, T, Ji M., and Lindquist, C.

University of North Texas, Denton, Texas, U.S.A. ([a]monticno@unt.edu)

Abstract. A major force affecting many forest ecosystems is the encroachment of residential, commercial and industrial development. Analysis of the complex interactions between development decisions and ecosystems, and how the environmental consequences of these decisions influence human values and subsequent decisions will lead to a better understanding of the environmental consequences of private choices and public policies. Determining conditions on the interactions between human decisions and natural systems that lead to long-term sustainability of forest ecosystems is one goal of this work. Interactions between human stakeholders are represented using multi-agent models that act on forest landscape models in the form of land-use change. Feedback on the effects of these actions is received through ecological habitat metrics and hydrological responses. Results are presented based on a study of a riparian area of the Dallas-Fort Worth (Texas, U.S.A.) region facing intense residential development.

***Keywords**:* Biocomplexity; Multi-agent models; Land-use change dynamics; Decision models.

1. INTRODUCTION

Few ecosystems are free of extensive human influence. A major force affecting many forest ecosystems is the encroachment of residential, commercial and industrial development. The complex interactions between development decisions and ecosystems, and how the consequences of these decisions may then influence human values and subsequent decisions is an important area of study. Analysis of these interactions will lead to a better understanding of the environmental consequences of private choices and public policies. This paper presents a coupled natural-human system model and analyzes the dynamics of land-use change under various scenarios for a rapidly urbanizing region of north Texas. The main focus here is on the human component, which uses multi-agent models to capture essential features of the decision processes and stakeholder values that lead to land-use changes. This work is part of an interdisciplinary Biocomplexity in the Environment project supported by the National Science Foundation with study sites in north and southeast Texas, and two study sites in Venezuela. Results from one of the Venezuela study sites are reported in another paper in these proceedings (Barros, et al [2004]).

The agents represent a variety of interacting human stakeholders, including municipal governments, land developers, landowners of large tracts of undeveloped land, and homeowners. For example, homeowner agents may decide to "protest" a proposed commercial development, thereby affecting the government agent's decision of whether to approve the development. A government agent's approval of a protested development may then lead to homeowner agents voting a new government agent into office. The decision models used by the stakeholder agents are based on decision-analysis utility functions derived from quantitative and qualitative surveys. As noted in Hoffmann, et al. [2001], the multi-agent approach accounts for the complex interactions between stakeholders that are an essential part of land-use change dynamics. The decision analysis framework provides a flexible structure for investigating likely outcomes of growth management strategies and the sensitivity of these outcomes to variations in stakeholder values. Barros, et al [2004] use a logic-based approach to model agent behavior as their work places less emphasis on encoding stakeholder values. The two approaches supplement each other and allow for future comparisons of coupled system dynamics

The natural systems portion of the coupled model includes a land-cover transition model, a hydrological model and a wildlife habitat model. The structure of each of these components is generic enough to accommodate the various study sites in the overall project, and yet allow the level of detail necessary to accurately represent specific systems. Thirteen land cover types, based on remote sensing studies (Newell, et al. [1997], CWRAM [2002]) are used for the north Texas study site. The types can be broadly categorized as vegetated-natural, vegetated-managed, and developed. Dynamics within the vegetated-natural category are dominated by succession from oldfield to wetland, upland or bottomland forest depending on topography. Succession is modeled with MOSAIC using parameters estimated from detailed gap-model simulations (see Acevedo, et al. [2001], and Monticino, et al. [2002]). Vegetated-managed dynamics and transitions to developed types are controlled by the human system model. All the natural systems models provide feedback to the human system. The land-cover transition model provides land-cover maps; the hydrological model outputs metrics derived from rainfall runoff, sediment yield, and nutrient concentration; and the wildlife habitat model gives metrics related to habitat quality.

2. DECISION FLOW

2.1 Study Area and Agent Classes

The study area represented by the model is a region of north central Texas (Denton County), U.S.A., experiencing rapid residential and commercial growth. Denton County grew from a population of 273,575 to 504,750 from 1990 to 2003. From 1995 to 2000, the percent of developed land doubled from 13% to 26.8%; and, in just the two-year period from 2000 to 2002, the number of housing units increased by over 10% (NCTCOG [2003]).

While this paper focuses on modeling the essential features of the decision processes that lead to land-use changes in this study area, an equally important objective of the work is developing a model framework flexible enough to be adapted to regions with other land-use dynamics and stakeholder interactions. In particular, the model was designed so that it would be straightforward to include other decision attributes, value systems and available actions.

A representation of the process of land-use change was developed for the study area based on formal focus group sessions and quantitative surveys of area residents, local developers, real estate agents, large landowners, and municipal government officials. Four main classes of stakeholders are defined. Landowner agents represent owners of large (undeveloped) parcels of land suitable for residential, commercial or industrial development. Developer agents model residential, commercial or industrial land developers. Homeowner agents represent collections of municipal residents within a particular tract of land. (Homeowner agents are assigned a weight representing the number of residents in the tract and their influence on land-use decisions – e.g., homeowner agents representing a large number of high-income residents are assigned a higher weight than agents representing sparsely populated low-income tracts.) Government agents characterize municipal governments that can approve, modify or reject a development proposal. Several types of agents are defined within each agent class. As discussed in section 3, agent types are characterized by value structures that influence the actions selected by the agent.

2.2 Agent Interactions and Decision Flow

The model is initialized by setting values for two sets of parameters. The natural system model uses the first parameter set. These parameters characterize the current land-use and cover type of each parcel of land in the study area. A parcel's description also includes physical metrics such as its percent of impervious surface and/or soil type, its slope and elevation. The natural system uses land-use information both to model the succession dynamics of undeveloped land and to provide feedback to the human system. For example, peak water flows from rainfall runoff at various points in the study area are passed to the human system to provide information to the stakeholder agents on how land-use changes have affected flooding patterns in the region. The second set of initialization parameters is used by the human system. These parameters involve ownership assignments to undeveloped parcels of land, assigning agent types to residential and undeveloped land parcels, and assigning the initial type of government agent. Once initialized, the decision/information flow between stakeholder agents and between the natural and human systems proceeds as follows. (A model schematic is available at www.geog.unt.edu/biocomplexity.)

- At the beginning of a time step (typically a one year increment), landowner agents decide whether to hold or to sell their land. If the decision is to sell, then the land becomes available to developer agents. Landowner agents that decide to sell their land become inactive in the model.

- Once land is made available for development, then a development category – residential, commercial or industrial – is selected probabilistically based on a development-potential map for the region. This map gives the likelihood of a development category based on factors such as proximity to roads, proximity to other developments, and inclusion in municipal jurisdictions.
- After the development category is chosen, a developer type is selected. Developer types are characterized by the development proposals they will make. The developer type is selected probabilistically as a function of the current type of government agent.
- The developer type selected submits a development proposal to the government agent. Homeowner agents affected by the proposal are also notified of the proposal.
- The homeowner agents then decide whether to protest the proposed development or not. The protest decision is based on the homeowner agent type, the development proposal, and the type of residential development in which the homeowner agent resides.
- The government agent decides whether to approve, approve with modifications, or reject the development proposal. The decision is based on the government agent type, proposal type, weights of the homeowner agents protesting the proposal, and environmental information provided by the natural systems model.
- Once government agent decisions are made for all pending proposals, any changes in land-use are passed to the natural system model. Any parcel that has become a residential development is assigned a homeowner agent. The agent type and weight is a function of the type of proposal approved.
- Before the next time increment, the human system model receives input (e.g., rainfall-runoff and landscape fragmentation information) from the natural systems model on the effects of the approved land-use changes. Based on this information and the government agent's decisions, homeowner agents may modify their values – i.e., change type.
- Homeowner agents then vote on the government agent type that will be in power for the next time iteration. Different homeowner agent types vote for the various government agent types with different probabilities. Election results are determined by the weights of the homeowner agents casting ballots. The new government agent is in place at the start of the next time increment.
- The next iteration begins again with the current set of landowner agents deciding whether to hold or sell their land.

3. AGENT DECISION MODELS

3.1 Decision Analysis Overview

Agents select their actions from a specified set of available actions. Intuitively, agents select the action that best conforms to their values. These values are quantified within a statistical decision analysis framework (see, for instance, Keeney and Raiffa [1993]). The decision analysis (DA) framework encodes the value tradeoffs and uncertainties inherent in stakeholder decisions. Mathematically, agents evaluate the worth of each available action according to a multi-attribute utility function and then select that action with the highest expected utility. Utility functions were developed from focus group sessions for the landowner, developer and government agent classes and from a formal conjoint analysis survey for the homeowner agents. The DA framework provides a consistent structure for adapting the model to other study areas where stakeholders may have different available actions and value structures. It is not uncommon to observe that elicited value models and the resulting decisions prescribed by a DA model may differ from the decisions actually observed – people are not always rational decision makers. However, the DA models used here provide important benchmarks for investigating the effect of growth management strategies on land-use dynamics, and for evaluating the sensitivity of these dynamics to variations and temporal changes in the elicited value structures.

3.2 Multi-attribute Utility Functions

Faced with making a decision, agents first define the set of possible consequences, $\{c_1(A), c_2(A), \ldots c_m(A)\}$, and their respective probabilities, $\{p_1(A), p_2(A), \ldots p_m(A)\}$, for each available action A. The value of consequence $c_i(A)$ is evaluated with respect to an additive multi-attribute function of the general form

$$U(c_i(A)) = k_1 U_1(c_i(A)) + \ldots + k_n U_n(c_i(A)).$$

The functions U_j represent the partial utilities of value attributes associated with the decision. The constants $k_1, k_2 \ldots k_n \geq 0$ indicate the relative value that the agent places on the respective attributes. Following standard practice, the partial utilities functions take values between 0 and 1, and $k_1 + k_2 + \ldots + k_n = 1$. The expected utility of action A is $E[U, A] = \sum_{i=1}^{m} p_i U(c_i(A))$. Agents select the action with the maximum utility.

3.3 Landowner Agents

Each privately owned undeveloped parcel of land is assigned a landowner agent. Landowner agents (LAs) are assigned an initial wealth and a number of years that they have owned their parcel at initialization time. For many regions, the time that a landowner has owned a parcel is available from government records. If not, landowner agents are randomly assigned an ownership time. An agent's initial wealth is based on the assessed value of the land (from government records) and the current land-use. A landowner's value for wealth is assumed to follow a classic decreasing marginal utility model given by $U_W(m) = 1 - e^{-Rm}$. The value of the constant R characterizes the rate at which additional wealth is discounted (R can also be viewed as a measure of risk aversion). Each LA is assigned a value for R at initialization. Using a decreasing marginal utility model and assigning an initial wealth to each LA allows the model to represent landowners with different sensitivities to farming/ranching income and to changes in land prices.

Two actions are available to LAs – hold their land and maintain its current use, or sell it. Expected utility calculations are based on the possible consequences of each action with respect to three value attributes – wealth, tradition value and neighboring land-use. Wealth is the monetary return from an action – farming or ranching income if the land is held, or profits received from selling the land. Agents assess monetary return based on an economic trend model that provides nominal, high and low values (along with respective probabilities) for land prices and the present value over given time horizon for farm/ranch income. Land prices are also affected by government agent actions that tend to increase the cost of development. The partial utility for wealth is U_W. Tradition value represents the intrinsic worth of the land to the landowner. A farm that has been in a family for several generations may have a higher tradition value than a recently purchased "hobby" ranch. Accordingly, the partial utility for tradition, U_{Tr}, is a non-decreasing function of the time that the parcel has been owned by the LA. Neighboring land-use indicates the type of land-use surrounding the landowner's parcel. This attribute provides a way to measure the desirability of maintaining rural land-use when surrounded by residential or commercial development. The partial utility for neighboring land-use, U_{NL}, is a decreasing function of the percentage of developed land bordering the landowner. LAs project historical development trends to evaluate the potential value of U_{NL} for their current land and for a new location if they were to sell. The utility function for LAs is given by $U = k_W U_W + k_{Tr} U_{Tr} + k_{NL} U_{NL}$. The attribute weights, k_W, k_{Tr} and k_{NL}, indicate the relative value that a landowner places on wealth, tradition and neighboring land-use. Each LA agent is assigned a set of attribute weights. LA types are defined by their attribute weights along with their initial wealth and wealth discount rate. For example, taking $k_W = .6$, $k_{Tr} = .1$, and $k_{NL} = .3$ represents landowners primarily interested in wealth maximization, while taking $k_W = .3$, $k_{Tr} = .4$, and $k_{NL} = .3$ models landowners placing a higher value on the intrinsic worth of their land.

3.4 Developer Agents

There are three types of developer agents for each development category, labeled environmentally-sensitive, environmentally-moderate, and environmentally-insensitive. Developer agent types are characterized by the type of development that they are most likely to propose. For example, environmentally-sensitive residential developer agents are most likely to propose developments that preserve a high percentage of existing tree cover and leave more open space. Three development types are classified within each development category – environmentally-sensitive, environmentally-moderate, and environmentally-insensitive. Metrics defining the classification includes housing density, percent impervious surface, percent tree cover, and pollution emission. The likelihood of selecting a given developer agent type is a function of the government agent type and the development category. For example, if a progressive government agent is currently in office, then an environmentally-insensitive commercial developer is less likely to obtain a parcel than if an economic-growth government agent was in office. The likelihood of a developer agent type proposing a given development type is a function of the developer type and the government agent type.

3.5 Homeowner Agents

Two actions are available to homeowner agents (HAs) when faced with a neighboring development proposal – to protest the development, or not. An HA's utility function involves four attributes – economic property value, residential setting, neighboring land-use, and community effort – giving the utility function $U = k_{EPV}U_{EPV} + k_{RS}U_{RS} + k_{NL}U_{NL} + k_{CE}U_{CE}$. The partial utility for economic property value evaluates the consequence of a proposed development on the agent's home value. Residential setting represents the compatibility of residential development within the HAs immediate locality. Neighboring land-use corresponds to the suitability and perceived environmental effect of commercial and industrial land-use in a wider neighborhood around the agent. Community effort measures the perceived effort in taking a particular action. Four types of agents are defined – apathetic, property-value, neighborhood, and environmentalist. HA types are characterized by the form of the partial utility functions and the attribute weights. For example, an apathetic HA has a large value for k_{CE} and a partial utility U_{CE} that decreases rapidly as a function of perceived effort, making it unlikely that an apathetic HA will protest a development proposal. On the other hand, environmentalist HAs have high values for k_{RS} and k_{NL} , and are likely to protest most commercial and industrial development proposals. Property value HAs have a high k_{PV} value and the partial utility function U_{PV} is sensitive to decreases in property value. Neighborhood HAs place a high weight on residential setting.

The expected utility of an action is calculated by specifying the possible consequences of a development proposal with respect to each attribute and the respective probabilities of these consequences. Consequence probabilities are a function of the action, development proposal, HA type, and current type of government agent.

The probability of an HA changing to another type is a function of the development decisions made, the natural system feedback, and the current HA type. For example, if a property-value HA protested a commercial development eventually approved by the government agent and localized flooding increased because of parking lot runoff, then the agent is likely to change to an environmentalist agent. After possibly changing types, HAs vote for the type of government agent. The probability of voting for a particular government agent type depends on the HA type. Environmentalist HAs will vote for a progressive government agent with a high probability, while property-value HAs are more likely to vote for an economic-growth government.

3.6 Government Agents

Given a pending development proposal, the government agent (GA) selects one of three actions – approve, conditionally approve at a higher environmental sensitivity level, or reject. GAs select their action based on four attributes – business relations, citizen relations, environmental consequences, and tax base effect. Their utility function is $U = k_{BR}U_{BR} + k_{CR}U_{CR} + k_{EC}U_{EC} + k_{TB}U_{TB}$. GA types are defined by the form of the partial utility functions and the attribute weights. Economic-growth GAs have attribute weights $k_{BR} = .4, k_{CR} = .1, k_{EC} = .1$ and $k_{TB} = .4$. Moderate and progressive GAs place more weight on community relations and environmental consequences.

The consequences of each action and their respective probabilities are evaluated with respect to the partial utility functions. For instance, the community-relations partial utility of approving an industrial development in spite of protesting HAs will be small; whereas, the business-relations partial utility approval will be high. Perceived environmental consequences of a potential action are a function of the GA type and feedback received from natural system model on environmental consequences of previous land-use decisions. As with the other agent classes, the GA evaluates the expected utility of each action and selects that action with the highest value.

4. SIMULATION RESULTS

Land-use change dynamics were simulated for several scenarios, varying by the initial distribution of landowner, homeowner and government types, and economic model assumptions. The model produced land-use change dynamics qualitatively similar to those observed in the study area. For instance, starting with an economic-growth GA, increasing land prices and stagnant farm/ranch income (as seen in the north Texas study site), LAs steadily sold their land for development. The first to sell were those with low to moderate personal wealth and who placed a high value on wealth. As more land was developed, LAs placing weight on neighboring land-use and tradition begin to sell. Eventually, only LAs placing a very high value on tradition and who were initially next to existing development were left. When government decisions on development proposals had only a moderate effect on land price trends, changes in land-use occurred fairly rapidly, before changes in homeowner and government types had an effect on land-use dynamics. On the other hand, when government development decisions had a more substantial effect on land prices, an interesting oscillatory effect was noticed. As initial landowners sold and development occurred, more homeowners began to protest and the government did not approve as many developments. This dampened the increase in land prices and slowed the rate that landowners sold and so slowed development. Homeowners and government then became less active, land prices started climbing again and another burst of development occurred with the subsequent increase in homeowner and government activism. Comparing these development cycles to empirical data is part of current model validation work. Simulations also investigated effectiveness of variations of proactive growth management strategies. One strategy that has been suggested is purchasing landowners' development rights in order to create open-space preserves. Landowners retain all land-use rights except development. Simulations were conducted to examine effective ways to selectively purchase development rights – in particular, investigating ways of purchasing rights so as to leverage the neighboring land-use values of other landowners to effectively take more land out of development. Two simple scenarios were compared. First a corridor of undeveloped land was set aside, and second the same amount of land was set aside but scattered across the study area. Both strategies generally resulted in land other than that set aside not being developed (in the absence of open-space preserves this land was developed). The scattered open-space scenario consistently resulted in a higher proportion of undeveloped land over a 25-year time horizon. Thus, neglecting any ecological disadvantages, scattering open-space preserves appears to offer a higher likelihood of limiting development.

5. CONCLUSIONS

The goal of this work was to develop both a specific model for the study area and a general framework that captures essential features of land-use change dynamics. Simulations produced qualitative patterns of land-use change similar to those observed in the north Texas study area. This helps validate the overall modeling approach as other sites are studied and more quantitative results are derived from the model. The simulations also illustrated key sensitivities of land-use dynamics to model assumptions. Principal drivers of land-use change are the land-price model and the sensitivity of the landowner agents' decision about whether to sell to changes in land prices. Accordingly, an important component of future research will be eliciting landowner values through quantitative surveys and developing a more comprehensive economic model. The model also indicates that decisions by resident agents to protest developments and subsequent government agent decisions to limit development may have effects in controlling land-use change over and above the specific properties targeted. Moreover, development management strategies may be augmented by geographically dispersing, when possible, open space preserves.

6. ACKNOWLEDGEMENTS

This work was supported by an NSF Biocomplexity in the Environment grant CNH BCS-0216722. We wish to thank the other grant participants for their valuable contributions.

7. REFERENCES

Acevedo M.F., S. Pamarti, M. Ablan, D.L. Urban and A. Mikler, Modeling forest landscapes: parameter estimation from gap models over heterogeneous terrain. *Simulation* 77, 53-68, 2001.

Barros, R., Davila, J., Moreno, N., Quintero, R., Ablan, M., Modeling of the biocomplexity at Caparo Forest Reserve, submitted to the Proceedings of the Second IEMSS Conference, Osnabruck Germany, 2004.

CWRAM, Watershed atlas for Ray Roberts, Lewisville, and Grapevine (Center for Watershed and Reservoir Assessment and Management), UNT, 2002.

Hoffman, M., Kelly, H., and Evans, T., Simulating land-cover change in Indiana: An agent-based model of de/reforestation, in *Complexity and Ecosystem Management: The Theory and Practice of Multi-agent Systems*, ed. M. A. Janssen, Northampton, Mass., Edward Elgar Publ., 218-247, 2002.

Keeney, R.L., Raiffa, H., *Decisions with Multiple Objectives*, Cambridge University Press, 569 pp., Cambridge, 1993.

Monticino M.G., Cogdill T. and M.F. Acevedo, Cell Interaction in Semi-Markov Forest Landscape Models. pp 227-232. In: Rizzoli A.E. and A.J. Jakeman (Eds.). *Integrated Assessment and Decision Support,* Proceedings of the First Biennial Meeting of the IEMSS. Lugano Switzerland, 2002.

Newell J., K.L. Dickson, J.W. Fitzgerald, S.F. Atkinson and M.F. Acevedo, A landscape ecological characterization of the Ray Roberts Lake study area, north-central Texas: temporal variations in landscape pattern 1987-1992, *Romanian Journal of Optoelectronics*, 5, 95-110, 1997.

NCTCOG, North Central Texas Council of Governments Demographic Estimates, www.dfwinfo.com, 2003.