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Coupled human and natural systems: A multi-agent-based approach

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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 of 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 on the dynamics of land-use change under different growth management strategies based on an 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 are 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 (Pahl-Wostl, 2004). This paper presents a coupled natural–human system model and analyzes the dynamics of land-use change under various scenarios based on a rapidly urbanizing region of north Texas. For example, different open-space preserve strategies are examined to understand how stakeholder values may be capitalized upon to most effectively manage development. Results indicate that integrating ecological and human value considerations when targeting land to be set aside as open-space may lead to more effective growth management strategies.

The main focus here is on the human system component of the coupled model. The human system uses a multi-agent model to capture essential features of the decision processes and stakeholder values that lead to land-use changes. This work is part of a larger interdisciplinary Biocomplexity in the Environment Project supported by the U.S. 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 Barros et al. (2004). Related spatial agent-based studies include Brown et al. (2004) where the effectiveness of greenbelts in delaying development is examined, and Loibl and Toetzer (2003) who consider landscape changes in suburban areas.

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 development proposed by a developer agent, thereby affecting the government agent's decision of whether to approve the

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development. A government agent's approval of a protested development may then lead to homeowner agents voting a new government agent into office. The actions of the new government would then affect the rate and type of future development. The decision models used by the stakeholder agents are based on decision analysis utility functions derived from quantitative and qualitative surveys. As noted in Hoffman et al. (2002), the multi-agent approach accounts for the complex stakeholder-to-stakeholder and stakeholder-to-environment interactions that are an essential part of land-use change dynamics. Moreover, agent models themselves can provide important feedback to the actual stakeholders represented by the agents, helping guide a more integrated approach to solving environmental challenges (Pahl-Wostl, 2005). 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.

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; Monticino et al., 2002). Vegetated-managed dynamics and transitions to developed types are controlled by the human system model. All the natural system 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 percentage of developed land doubled from 13% to 26.8%; and, in just a 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. Land-use 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 percentage 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. Fig. 1 illustrates this flow and the interactions between agents.

- 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

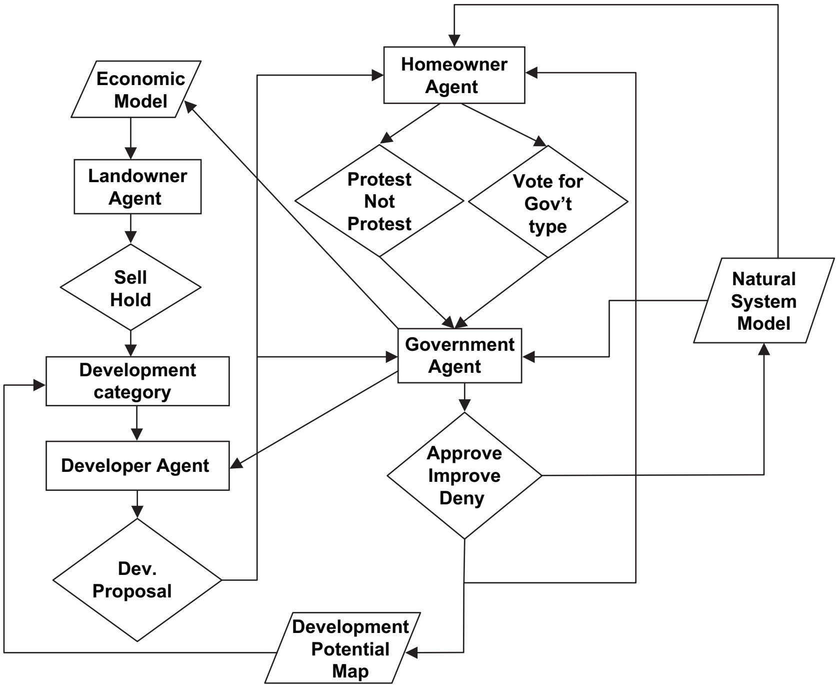

Fig. 1. Human systems model decision and information flow.

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 system 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 system 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 e.g., 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 conjoint survey was a full profile survey in which respondents were presented a set of scenarios and asked to rank them from best to worst case. Scenarios differed by the type and location of development represented, projections of property values, and estimates in the amount of community involvement necessary to achieve various land-use settings. Assuming a standard additive orthogonal model, utility functions were developed for homeowners that represented attribute values and tradeoffs between attributes. Cluster analysis was then performed to identify classes of homeowners with similar values. These classes defined the homeowner agent types discussed below. Similar, but less formal, methods were used during the focus group sessions to derive types for the landowner, developer and government agents. For example, sessions with municipal government planning staff identified four broad factors considered by municipalities when considering development proposals. Based on the expressed relative importance of these factors for different municipalities, the three representative government agents described below were developed.

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 made – 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, $\{c_1(A), c_2(A), \dots, c_m(A)\}$, and their respective probabilities, $\{p_1(A), p_2(A), \dots, p_m(A)\}$, 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 $U(c_i(A)) = k_1 U_1(c_i(A)) + \cdots + k_n U_n(c_i(A))$. The function U_j represents the partial utilities of value attributes associated with the decision. The constants $k_1, k_2, \dots, k_n \geq 0$ indicate the relative value that the agent places on the respective attributes. Following standard practice, the partial utility functions take values between 0 and 1, and $k_1 + k_2 + \cdots + k_n = 1$. 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.

As described in more detail below, agent classes are characterized by the set of available actions and the attributes accounted for in the utility function. In short, classes are defined by what the agents can do and what factors they consider when deciding what to do. All agent types within a class have the same available actions, same perceived consequences, and consider the same attributes when selecting an action. Types differ from one another in the form of the partial utility functions, which determine the values they assign to consequences, and the relative value they place upon the various attributes. This framework makes it relatively straightforward to introduce other stakeholders – agent classes – and to explore the effect of changing stakeholder values – varying agent types.

3.3. Agent interactions

Interactions between stakeholders are reflected among the agents in several ways. First, actions by agents can affect the subsequent actions of other agents. This can occur between agents within a class and between agents across classes.

- Decisions by landowner agents to sell or keep their property can make it more or less likely that neighboring landowners will sell during the next time period.
- Homeowner agents protesting a development proposal can make it less likely that government agents will approve the development.
- Decisions by government agents to reject a development can decrease the land price being offered to landowners (through the economic model), thus decreasing the likelihood that landowners will decide to sell.

Second, actions by agents, along with feedback from the natural system model, can cause agents to change their values, that is, to change type.

- Government agent decisions to approve developments may result in homeowner agents changing type.
- Voting actions by homeowner agents can lead to a new government agent type.

And, the agent types and their actions affect the initial type of other agents.

- The current government agent type affects the type of developer agent that will buy from a landowner.
- The type of residential development approved by government agents affects the initial type of homeowner agent associated with the approved residential development.

These interactions are discussed in more detail below.

3.4. 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 a 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. For the simulations described in Section 4, U_{Tr} was taken to be a simple step function with steps at 20-year increments. This increment approximates a generation of land ownership. 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} if they were to continue ownership. To evaluate U_{NL} for selling, LAs look back to a benchmark state of neighboring land-use – in the simulations given here, the benchmark used was midway between the initial state and the current state of neighboring land-use. That is, LAs compare what their neighborhood was to what it is becoming when deciding whether to sell or not. The neighboring land-use attribute governs the interactions between landowner agents. If neighbors of a given LA sell, then that LA is more likely to sell during the next simulation iteration. How strongly an LA is affected by its neighbors' decisions is determined by the relative value that the LA places upon the neighboring land-use attribute.

The utility function for LAs is given by $U = k_{\mathrm{W}}U_{\mathrm{W}} + k_{\mathrm{Tr}}U_{\mathrm{Tr}} + k_{\mathrm{NL}}U_{\mathrm{NL}}$. 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 $k_{\mathrm{W}} = 0.6$, $k_{\mathrm{Tr}} = 0.1$, and $k_{\mathrm{NL}} = 0.3$ represents landowners primarily interested in wealth maximization, while taking $k_{\mathrm{W}} = 0.3$, $k_{\mathrm{Tr}} = 0.4$, and $k_{\mathrm{NL}} = 0.3$ models landowners placing a higher value on the intrinsic worth of their land.

3.5. Developer agents

As described in Section 2, if a landowner agent decides to sell, then the land is made available for development and a development category (residential, commercial or industrial) is selected based on the development-potential map. Given the development category, a developer agent type is selected. 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 include housing density, percentage impervious surface, percentage tree cover, and pollution emission. The likelihood of selecting a given developer agent type is a function of the current 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.

3.6. 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. The utility function for HAs is given by $U = k_{\mathrm{EPV}}U_{\mathrm{EPV}} + k_{\mathrm{RS}}U_{\mathrm{RS}} + k_{\mathrm{NL}}U_{\mathrm{NL}} + k_{\mathrm{CE}}U_{\mathrm{CE}}$. 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 forms 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 the partial utility functions U_{RS} and U_{NL} give low values to environmentally moderate and environmentally insensitive development proposals (very low values for these types of commercial and industrial proposals). Thus, environmentalist HAs are likely to protest most 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, the HA type, and the current type of government agent. In particular, consequence probabilities include a locus of control parameter for each HA type. This represents an agents' perception about how effective their protest of a development proposal would be in improving or stopping the proposal. This is based on the HA type and the type of development in which they reside. For example, an apathetic HA living in an environmentally insensitive development would attach a low probability to stopping any type of development. While a property-value HA living in an environmentally sensitive development would suppose a high probability of stopping an environmentally insensitive commercial development. It is possible to have an agent's perception of control change in response to whether past protest actions were successful or not.

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.

3.7. 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 $k_{BR} = 0.4$, $k_{CR} = 0.1$, $k_{EC} = 0.1$ and $k_{TB} = 0.4$. 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, GAs evaluate the expected utility of each action and select the 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 the 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.

The effectiveness of proactive growth management strategies was also investigated. One policy 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 study various ways to selectively purchase development rights. In particular, simulations studied strategies for purchasing rights so as to leverage the land-use values of neighboring landowners to effectively take more land out of development. Strategies were compared for hypothetical distributions of landowner types under various economic scenarios. Two main LA types were assumed – LAs oriented towards acquiring wealth ($k_W = 0.8$, $k_{Tr} = 0.1$, $k_{NL} = 0.1$) and LAs also concerned on neighboring land-use ($k_W = 0.5$, $k_{Tr} = 0.1$, $k_{NL} = 0.4$). LAs were split evenly between the two types (50% wealth-oriented and 50% neighboring land-use (NL) oriented). For each type, spreads of initial wealth, marginal utility for wealth, and initial time of ownership were used. The rate of price increases for land was varied from low to high. Simulations started with an economic-growth GA. Approximately 5% of undeveloped land was targeted for open-space and purchased at the start of the simulation. Strategies included:

- Purchasing a corridor of undeveloped land. This models an existing riparian corridor of parkland in the north Texas study area.
- Scattering land purchases across the region. The motivation for this strategy is to provide dispersed development buffers to landowners likely to sell if surrounded by development.
- Wealth-oriented targeting. This plan targeted purchases towards those landowners with wealth-oriented values ($k_W = 0.8$) with the highest numbers of neighboring land-use oriented neighbors. The motivation was to remove those landowners influenced by rising land prices and to provide development buffers to landowners influenced by neighboring development.
- NL-oriented targeting. Targets purchase towards those landowners with neighboring land-use oriented values ($k_{NL} = 0.4$) with the highest numbers of neighboring land-use oriented neighbors. Again, the intention was to provide development buffers to NL-oriented landowners, but this plan also purchased land from those concerned with neighboring development.
- NL-oriented size-adjusted targeting. All parcels are scored by the number of NL-oriented neighbors divided by parcel size. The highest scoring parcels owned by NL-oriented landowners are purchased. The strategy was created in response to results from the other targeted plans. The size-adjusted strategy tends to buy many small parcels, while the other targeted plans buy larger but fewer parcels.

All the strategies resulted in land other than that purchased not being developed (in the absence of open-space preserves this land was developed). Fig. 2 shows the percentage of land left undeveloped for each strategy (besides that purchased for open-space) after 25 years for low, moderate and high rates of land price increases. Strategies that purchased parcels from NL-oriented landowners were more effective in slowing development than those that purchased from wealth-oriented LAs. This appeared to be because the NL-oriented LAs were more sensitive to changes in neighborhood development (i.e., more likely to sell) than wealth-oriented LAs were to changes in land prices. Interestingly, the NL-oriented targeted strategy performs best for slower increases in land price, while NL-oriented size-adjusted targeting performs best for faster increases. This seems to be the result of interactions between protesting HAs, the GA type and the economic model. When land is purchased for open-space, fewer parcels of land are sold early in the simulation. This results in fewer protests by homeowners and thus the initial GA remains economic-growth type longer. So land prices are allowed to rise longer, and ultimately this leads to increased development. The effect is most pronounced for an assumed low rate of land price increases. Therefore, since the NL-oriented targeted strategy buys fewer parcels it performs better with slower land price increases. On the other hand, when land prices are increasing fast enough to spur LAs to sell from the start, the NL-oriented size-adjusted targeting strategy buys many parcels and thus provides development buffers to more LAs than the other strategies, and hence more effectively limits development.

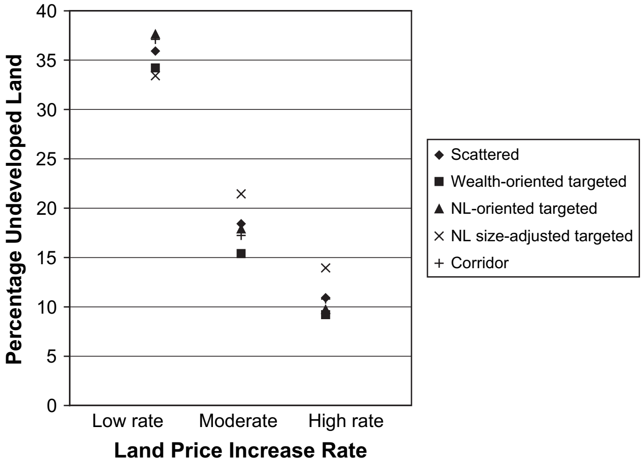

Fig. 2. Percentage of land left undeveloped (besides that purchased for open-space) for each strategy after 25 years for low, moderate and high rates of land price increases. Values shown are average percentages of undeveloped land over 100 repetitions of simulation. Individual simulations differed in random assignment of landowner types to parcels.

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 in response to changes in land prices and neighboring development. 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 growth management strategies involving open-space purchases may have effects in controlling land-use change over and above the specific properties targeted. Moreover, the model implies that considering landowner values when implementing these strategies may lead to more successful outcomes. However, not unexpectedly, the interplay between strategies and stakeholder interactions is complex — indicating the merit of models like the one discussed here for exploring the consequences of public policies on land-use change dynamics.

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