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THE STUDY OF POPULATION-ENVIRONMENT INTERACTIONS

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Models of natural and human dynamics in forest landscapes: Cross-site and cross-cultural synthesis

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Abstract

We synthesize the study of coupled natural and human systems across sites and cultures through a process of simplification and abstraction based on multiple dimensions of human-nature connectedness: satisfaction of basic needs, psycho-cultural connectedness and regulation of use of natural resources. We thus provide both a place-based and general understanding of value-driven anthropogenic environmental change and response. Two questions guide this research: what are the crucial stakeholder values that drive land use decisions and thus land cover change? And how can knowledge of these values be used to make decisions and policies that sustain both the human and natural systems in a place? To explore these questions we build simulation models of four study sites, two in the State of Texas, United States, and two in Venezuela. All include protected areas, though they differ in the specifics of vegetation and land use. In the Texas sites, relatively affluent individuals are legally converting forests to residential, commercial, and industrial uses, while in Venezuela landless settlers are extra-legally converting forests for purposes of subsistence agriculture. Contemporary modeling techniques now facilitate simulations of stakeholder and ecosystem dynamics revealing emergent patterns. Such coupled human and natural systems are currently recognized as a form of biocomplexity. Our modeling framework is flexible enough to allow adaptation to each of the study sites, capturing the essential features of the respective natural and anthropogenic land use changes and stakeholder reactions. The interactions between human stakeholders are simulated using multi-agent models that act on forest landscape models, and receive feedback of the effects of these actions on ecological habitats and hydrological response. The multi-agent models employ a formal logic-based method for the Venezuelan sites and a decision analysis approach using multi-attribute utility functions for the Texas sites, differing more in style and emphasis than in substance. Our natural-systems models are generic and can be tailored according to site-specific conditions. Similar models of tree growth and patch transitions are used for all the study sites and the differing responses to environmental variables are specified for each local species and terrain conditions.

Keywords: Biocomplexity; Texas; Venezuela; Land use; Land cover; Change; Coupled natural–human systems; Forest; Landscapes; Agents

1. Introduction

The age-old human activity of clearing forested land to grow crops or to build roads and houses became global in scope during the last century; its continued and rapid

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increase has led to the recognition that land use/land-cover (LU/LC) change represents a major global environmental challenge for the 21st Century (Houghton, 1994; Lambin et al., 2001; Lepers et al., 2005; Moran and Ostrom, 2005; Ojima et al., 1994; Walker, 2004; Watson et al., 2000). The social sciences examine patterns of human ''development'', while the natural sciences study ecosystem succession and biogeochemical processes. However, recently social scientists have recognized the impact of ecology on human behavior (Evans and Moran, 2002; Kellert, 1997) and ecologists have recognized the importance of LU history as a fundamental part of ecological understanding (e.g., Foster et al., 1998; Harding et al., 1998). The interactions between natural and human systems produce complex emergent LU/LC change dynamics that can be best analyzed through coupled natural–human (CNH) systems models. These models need to account for interactions between human stakeholders and the natural landscape, interactions among the human stakeholders, and reactions of stakeholders to perceived changes in the natural environments resulting from their actions.

The study of CNH systems resonates with geography along several axes. It helps address the calls by Openshaw (1994, 1995) to develop methodologies within human geography that seek computational solutions to problems involving both numeric and symbolic data (Parker et al., 2003). It also serves as a prospectus for bridging the divide between human and physical geography (Fig. 1). Furthermore, human environmental attitudes and values are intimately linked with the concept of place in geography and philosophy (Buttimer and Seamon, 1980; Callicott et al., 2006). The distinction made by many geographers between place and space and its hierarchical nesting has an analog in the way spatial scale is treated in spatial models (Sheppard and McMaster, 2004; Tuan, 1977). Recent discussions of the history of these concepts illustrate their relationship to human environmental values and how much human-nature connectedness and interaction can be embedded in the concept of place (Agnew and Smith, 2002; Casey, 1993, 1997; Entrikin, 1991; Malpas, 1999, 2001; Schein, 1997; Snyder, 1995; Smith, 2001; Tuan, 1973). Place is considered to be more than simply a locality within a region by including a dynamic web of linkages and social interaction between individuals and interdependences with other places (Massey, 1999; Oakes, 1997). While this notion focuses on the social aspects, place is treated as a geographical expression of intersecting actions, human and nonhuman (Oakes, 1997). At the same time, the stretching of those interactions across space connects places and the peoples who live in them with other places and peoples.

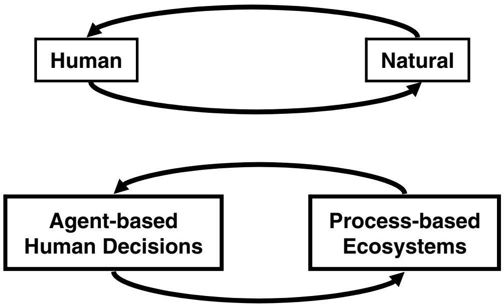

Fig. 1. Coupled natural–human systems (top) mutual feedback (bottom) modeling approach.

The mutual interactions of humans with their natural environments particularly under long-term historical and pre-historical perspectives have been the subject of systematic study by geographers and others for many years (e.g., Gomez-Pompa and Kaus, 1990, 1992; Gragson, 1998; Kasperson et al., 1995; Redman, 1992, 1999; Sauer, 1927; Turner, 1976; Turner et al., 1990a; Vidal de la Blache, 1926). While studying the mutual interactions of humans with their natural environments is not a new idea, recently developed mathematical and computational techniques have increased our capacity to understand such mutual interactions.

Contemporary multi-agent modeling techniques now facilitate simulations that represent the behavior of human systems. These models capture essential features of the decision processes and stakeholder values that lead to LU changes – and the effects of these changes on environing natural systems, as simulated by process-based models (see bottom diagram of Fig. 1). Moreover, computational capabilities allow increasingly sophisticated analysis of the emergent patterns of CNH systems, currently recognized as a form of ''biocomplexity''. Several unique aspects characterize the study of biocomplexity: multiple temporal and spatial scales, multiple levels of biological organization, interacting feedbacks and nonlinear behavior (Anderson, 2003; Cottingham, 2002; Covich, 2000; Dybas, 2001; Michener et al., 2001; Pickett et al., 2005).

Multi-agent models are proving to be an effective tool for the study of CNH systems and integrated environmental and ecosystem policy analysis (Bousquet and Le Page, 2004; Hare and Deadman, 2004; Parker and Meretsky, 2004). Applications of agent-based models for simulating human decisions and subsequent LC change have been expanding rapidly (Deadman et al., 2004; Evans et al., 2001; Hoffman et al., 2002; Ligtenberg et al., 2001; Parker et al., 2003; Schneider and Pontius, 2001). Agent models have been applied to analyze the effectiveness of Greenbelts in delaying development (Brown et al., 2004), to landscape changes in suburban areas (Loibl and Toetzer, 2003), and to tropical deforestation (Huigen, 2002; Lim et al., 2002; Manson, 2002). Such studies are particularly useful where increased demand for use of natural resources is accelerating changes in LU. Characteristics of these models include: the fruitful linking of models among themselves and with geospatial technologies (Arima et al., 2005; Bhaduri et al., 2000; Mas et al., 2004); the importance of socio-economic and demographic factors (Walker et al., 2002; Walker, 2003); the explicit consideration of human-induced drivers (Aspinall, 2004); the ability to separately model LU change as a result of these drivers that in turn affects LC change (Brown et al., 2000); the links to stakeholders and potential management applications (Pahl-Wostl, 2004, 2005); and the integration of multiple spatial scales (Evans and Kelley, 2004).

Landscape ecology also recognizes the importance of spatial patterns in ecological processes and in the dynamics of LC change, where humans are considered agents or entities that participate actively in the landscape (e.g., Brandt et al., 2002; Lundberg, 2002; Zube, 1987). This is particularly useful when considering fragmentation and biodiversity conservation (Metzger, 2000). Identifying the importance of agents in landscape ecology, Haber (2004) states that research must include the role that humans play mentally, not just materially, in the "people–landscape interaction" through loops of actions and reactions.

Values drive the decisions of the human stakeholders in a geographical place (Lambin et al., 2001). For purposes of modeling, these values should be expressed quantitatively in a functional form that represents competing factors that influence stakeholders' actions. The conventional way of doing this is by means of a monetary metric. This approach has been criticized for reducing the complex and multifaceted suite of human values to a single type, economic value (Hargrove, 2000; Norton, 1991; Rolston, 1985). Economists protest that money is only a metric for expressing otherwise incommensurable values (Freeman, 1993). However, when people are asked what they would be willing to pay for things that they regard as "priceless" – cultural icons, natural beauty, and dependable ecosystem services among them – they often feel uncomfortable and sometimes enter "protest bids" (Sagoff, 1988). Finding alternative ways of quantifying values in multi-agent models of CNH systems has been a motivation for our research. We will describe our approach more fully below.

The overarching question that gives geographical meaning to the research presented in this paper is whether LU and consequently LC can be made sustainable over the long term. More specifically we address two questions: what are the crucial stakeholder values that drive LU decisions and thus LC change within the different formal (legal) and informal (cultural) governance structures in a place? And how can knowledge of these values be used to guide decisions and policies that sustain both the human and natural systems in a place?

The purpose of this paper is twofold. First, we present a conceptual synthesis of CNH systems that could potentially shed light on the geographical questions posed above. To this end we look at four study sites, two in the United States and two in Venezuela (Fig. 2), where there exists a tension between exploiting natural resources for economic gain and preserving the natural character of the landscape. Second, we describe models designed to explore these questions at two of these study sites, one in Texas and one in Venezuela. We use a general modeling framework that is flexible enough to allow application to many different sites, but that also captures the essential features of the respective natural and anthropogenic LU/LC changes and stakeholder reactions in these places. Such a framework permits a consistent analysis of how differences in environmental values drive patterns of site-specific LU change while providing the opportunity for generalizations. The interactions between human stakeholders are simulated using multi-agent models that act on forest landscape models in the form of LC change; the multi-agent models then receive feedback about the effects of these actions through ecological habitat metrics and hydrological responses provided by the forest landscape models. Stakeholders and policymakers can then see the potential effects of their current LU

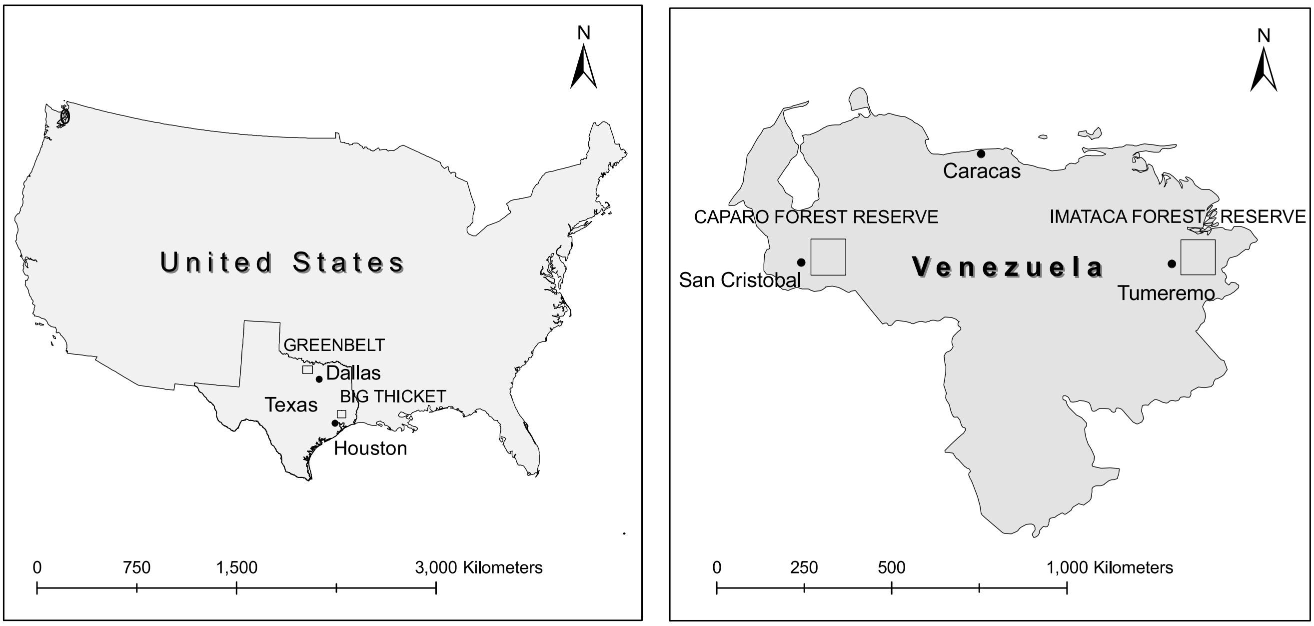

Fig. 2. Study sites in North and South America; two sites in Texas, USA and two in Venezuela.

decisions on the place they inhabit and reconsider those decisions to better satisfy their value priorities.

Our CNH models were designed to capture essential features of the decision processes and stakeholder values that lead to LU changes in our study areas. The goal of the models is to address the questions stated above by revealing LC trends and, more importantly for policy makers, sensitivities of LU change to stakeholder actions, including the spatial distribution of stakeholders with differing values. Of particular interest to the field of human geography are our methods of quantifying values. In our Texas sites model, stakeholder values are represented explicitly within a statistical decision analysis framework using multi-attribute utility functions (see, for instance, Keeney and Raiffa, 1993). The utility functions encode value tradeoffs and uncertainties inherent in stakeholder decisions as agents respond to economic opportunities within local governance and cultural contexts. For example, when landowners consider whether to sell or hold onto their land, they weigh the additional wealth they will obtain from selling against the bio-cultural integrity of the place that they inhabit. Agents within our model evaluate the worth of each action available to them according to a multi-attribute utility function and then select that action with the highest expected utility. Compared to a purely economic metric, we consider this to be a far more realistic way of capturing the values that drive LU decisions that people actually make.

Our models are dynamic, not only with respect to LU/LC change, but also in regard to the stakeholder values that drive such changes. Agents may alter their character in response to the decisions of other agents, to local changes in the formal and informal governance structures of their localities and to the LU/LC changes they "perceive", reflecting the evolving values of real stakeholders. For example, in response to LU change that results in increased local flooding due to loss of permeable surface area to development, homeowner agents in our Texas models may adjust their value structure so as to place a higher weight on the perceived environmental effects of a development rather than focusing primarily on a development's effect on home values. Homeowner agents may also affect change in the government agents by voting in a government that places higher weight on environmental consequences of development policy than on business relations and maximizing the tax base. The models do not explicitly model larger cultural shifts in values. However, the models are sufficiently flexible that scenarios of such "value dynamics" could be incorporated into the framework. For now, we have preferred to take the epistemologically more conservative approach and concentrate on value changes that are responsive to local conditions, temporally as well as spatially, because assumptions about future large-scale social shifts in values are speculative and the belief that they will occur is often influenced by wishful or apocalyptic thinking.

In the following pages we provide a brief description of the study sites, and then discuss a conceptual synthesis based on several dimensions of CNH systems connectedness. We then give a description of the model methodology, sample results of simulation runs, and comment on the patterns that emerge. Models are then compared to contribute to the conceptual synthesis process. We indicate how our approach to studying biocomplexity in the form of CNH systems can be synthesized across sites and cultures through a process of simplification and abstraction to achieve a general method applicable to many forested landscapes subject to anthropogenic disturbance. This synthesis helps explore relations among people, place, and environment by merging modeling efforts with place-based understanding of environmental attitudes and values of diverse human stakeholders. It is also intended to be useful for stakeholders and policymakers in taking prudent decisions. Each one of our sites is a place not only by virtue of its scale in relationship to the space in which it is located, but also because of the way its natural and human systems intertwine to form its character.

2. Study areas

2.1. Overview of general characteristics

Our study sites (Figs. 3 and 4) are: (1) The Greenbelt Corridor in North Texas (Monticino et al., 2004, 2005); (2) the Big Thicket in southeast Texas (Callicott et al., 2006); (3) the Caparo Forest Reserve in western Venezuela (Ablan et al., 2003; Quintero et al., 2004; Terán et al., 2005); and (4) the Upper Botanamo watershed, most of which is part of the Imataca Forest Reserve in eastern Venezuela (Delgado et al., 2005). All the sites include protected areas: a narrow riparian gallery forest in North Texas; the Big Thicket National Preserve, in southeast Texas; and the Caparo and Imataca reserves in Venezuela which are regulated by law for forest management.

Analyzing across sites allows us to generalize and understand the fundamental principles of LU/LC change, as we will discuss later in the synthesis section. We take advantage of the commonalities as well as the uniqueness of the study sites. Although the two Texas sites are both temperate, they differ in dominant vegetation; likewise in the two sites in Venezuela, the vegetation also differs, but both consist of tropical species. In the Texas sites, relatively affluent individuals are legally converting forests to residential, commercial, and industrial uses, while in Venezuela, landless and impecunious people are extra-legally converting forests for the purposes of subsistence agriculture.

The study sites also share many similarities. For example, they have relatively flat relief and a similar precipitation range (approximately 1100–1600 mm annually). Ecological processes and services are common across sites: biodiversity, water (quantity and quality), and habitat fragmentation. Threats to the natural systems are also common, LU change, resulting in deforestation. Seasonality is present in all sites, although those in Texas are temperate

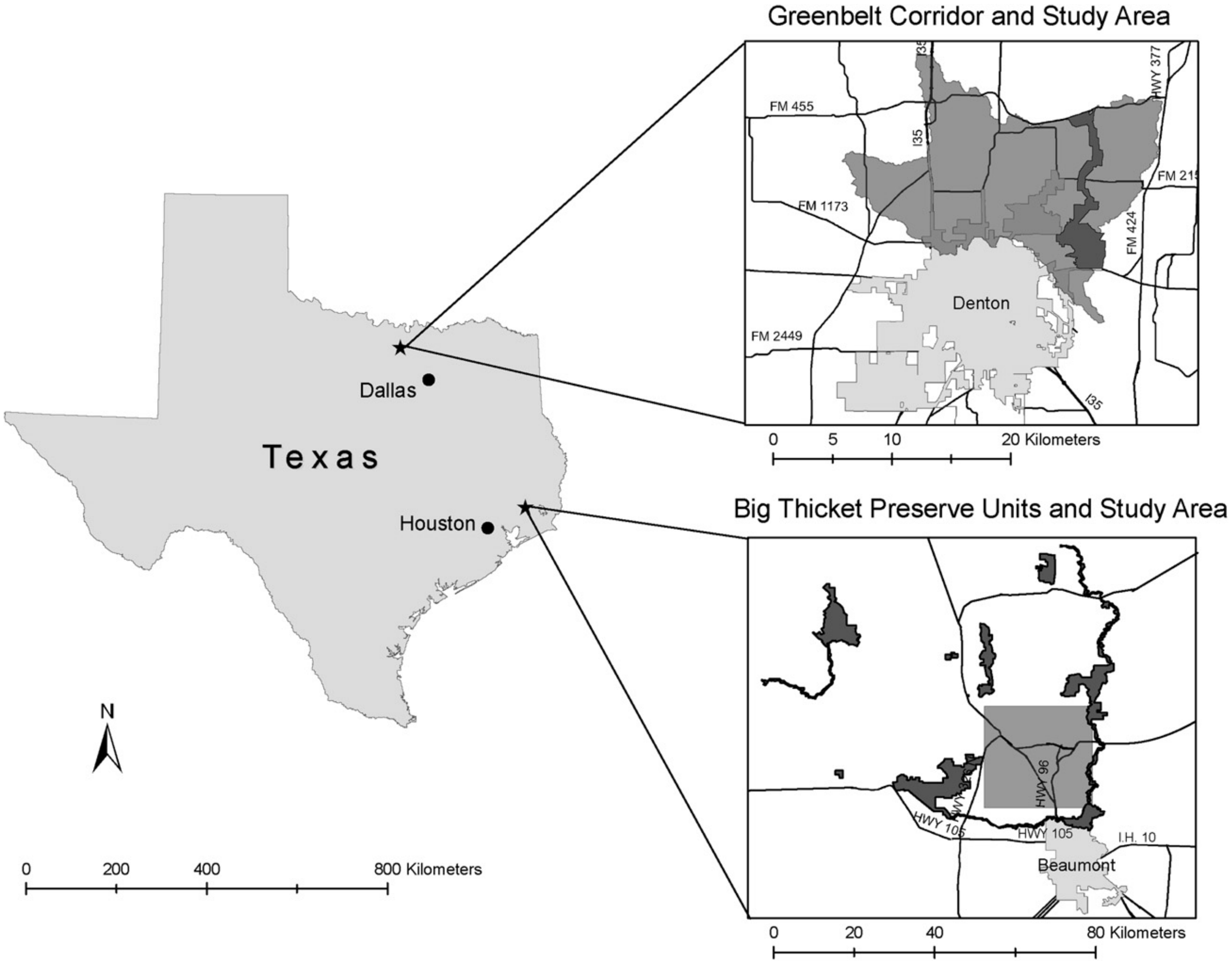

Fig. 3. Study sites in USA: the Greenbelt Corridor (GBC) of the Trinity River in North Central Texas and the Big Thicket (BT) in Southeast Texas.

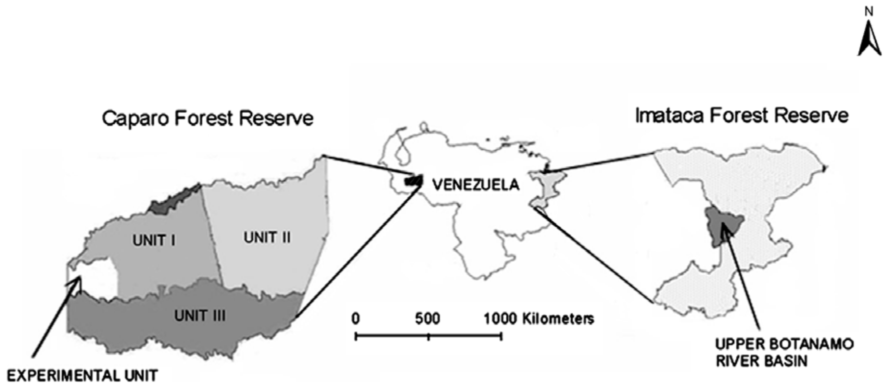

Fig. 4. Study sites in Venezuela: the Caparo Forest Reserve (CFR) in the western plains and the Upper Botanamo Watershed (UBW), which covers part of the Imataca Forest Reserve, in eastern Venezuela.

(four seasons – spring, summer, fall, winter) and those in Venezuela are tropical (two seasons – wet and dry).

2.2. Texas sites: Big Thicket and Greenbelt Corridor

Near the Gulf of Mexico, the Big Thicket is one of the most biologically diverse regions in North America (Gunter, 1993). Its legally preserved areas, administered by the US National Park Service, are small and tenuously connected by riparian corridors (Cozine, 2004). They are located in a matrix that is lumbered, farmed, mined (oil/gas extraction), and residentially developed. The climate is humid subtropical with rainfall evenly distributed throughout the year. The region was so unsuited to agriculture and so difficult to traverse that it was not permanently inhabited by any group of American Indians, who occasionally ventured there only to hunt, or by French and Spanish colonials (Callicott et al., 2006). During the mid-19th Century, as Texas separated from Mexico and joined the United States it was sparsely settled by Americans but remained in a virtual wilderness condition until the turn of the century, when timber harvesting and oil drilling began in earnest. Because it was so wild and unsettled the Big Thicket was a haven first for runaway slaves, then draft dodgers and conscientious objectors during the Civil War, and, in the 20th Century, for outlaws and fugitives from justice—despite the inroads of the timber and oil industries (Cozine, 2004).

The Greenbelt Corridor study site is a region of north central Texas located in a suburban and agricultural matrix near the City of Denton in the floodplain of the Elm Fork of the Trinity River between two reservoirs. Its protected part covers $\sim 20\ \text{km}^2$ of the Cross Timbers and Prairies biogeographic province of Texas and is administered by Texas Parks and Wildlife. Historically covered by bottomland hardwoods and oak-savanna uplands, the Greenbelt Corridor is now patchy, ranging from open grassy areas to stands of tall late-succession forest. The human history of the area is no less romantic than that of the Big Thicket, but its traces have been largely obliterated by far more intense settlement than in the Big Thicket, first by farmers and ranchers, then by suburbanites and exurbanites (Bates, 1976). The historic American Indian inhabitants followed the mounted plains tradition and the county and its capital city were named for an "Indian fighter" in service of American settlement (Allen, 1905). The area is presently experiencing very rapid residential and commercial growth, lying, as it does, at the apex of the Dallas-Fort Worth "Metroplex" triangle. Denton County grew from a population of 273,575 to 531,450 from 1990 to 2004. From 1995 to 2000, the percent of developed land doubled from 13% to 26.8%; and in the 5-year period from 2000 to 2005, the number of housing units increased by over 26% (NTCOG, 2005). Lessons learned from this study site are providing guidance to the model currently being developed for the Big Thicket site in southeast Texas.

2.3. Venezuela sites: Caparo forest reserve and Imataca Forest Reserve

The Caparo Forest Reserve covers $\sim 1800\ \text{km}^2$ of the Venezuelan western alluvial plains formed from sedimentary materials from the Andes. Its forests are in the transition between dry tropical forest and humid tropical forest. Caparo was created in 1961 to support the development of a logging industry, while preserving one of the more productive forests of Venezuela. It is divided into three management units (Fig. 4). Our study focuses on Unit I ($\sim 530\ \text{km}^2$), which includes an experimental unit, used for research and educational activities. Currently, only $70\ \text{km}^2$ of forest remain in the reserve, all located in the experimental unit. Inappropriate forest management practices; contradictions between different governmental entities and policies; poverty; demand for arable land; and politics have all contributed to deforestation in Caparo (Ablan et al., 2003).

The Caparo area has experienced the typical agrarian settlement process of forest reserves in the Venezuelan western plains described by Rojas (1993). During the "First stage" or "Primary cycle" a settler takes possession of a parcel of land in the reserve and practices subsistence swidden (i.e., slash and burn) agriculture. Settlement may occur on uncultivated land (previously deforested and unoccupied) or on forested land, which is then cleared by the settler. Typically, within 5 years the soils are exhausted, and the harvests are no longer sufficient to sustain the settler and his family. Some settlers try to expand their farms by clearing and cultivating adjacent parcels. However, 5 years later, they will end up facing the same situation.

The "Second Stage" or "Land Market Cycle" consists of seeding pasture grasses to prevent soil erosion, and then selling these newly created grasslands to larger landowners for use as cattle pasture. After selling these grass-covered lands, settlers may buy land from other more recent settlers and try to switch from farming to ranching themselves, or they may initiate a new primary cycle of invasions, or they may work as ranch hands for the landowner that bought pasture from them. This second stage involves two notable positive feedback processes: (1) ownership of the cleared parcels is granted to the settlers, under the Agrarian Reform legislation, and then transferred, at very low prices, to politicians, military officers, and cattle ranchers, (2) who then use their political influence to support the primary settlement-cycle (Centeno, 1997). The upshot is that small-scale cattle ranching begins to replace swidden agriculture as the dominant LU in the second stage.

The third stage, "Cattle Ranch Consolidation", leads to large-scale cattle ranching as the main LU in previously forested land. Large-scale ranchers buy deforested land rights from the settlers and small-scale ranchers and consolidate pasture LC for cattle grazing, typically under the auspices of a holding corporation. This process, characterized by the concentration of land ownership, leads to more landless people, who then initiate the primary settlement-cycle or turn to wage-earning work on the big ranches (Sánchez, 1989).

The Imataca study focuses on an area of $\sim 2500\ \text{km}^2$ in the upper basin of the Botanamo River of the Guiana Shield mostly within the federally protected Imataca Reserve (Fig. 4). In this large reserve, associated with a spatial precipitation gradient, there are, respectively from high to low, evergreen forests, semi-deciduous forests (i.e., a mix of evergreen and deciduous species), and scattered savannahs within the forested areas (CVG TECMIN, 1987). The canopy height of the evergreen forests typically exceeds 25 m. Imataca is considered to be one of the most valuable forest reserves in Venezuela and South America, characterized not only by the abundance of commercially valuable timber species and genetic wealth, but also by overall species richness and a variety of fragile ecosystems (Miranda et al., 1998; UCV-MARNR, 2002).

Imataca is home to five indigenous ethnic groups, whose livelihoods and cultures depend on their natural surroundings: the Warao, Arawako, Kariña, Akawaio and Pemón Indians (Mansutti et al., 2000). The forests of the western sector have been fragmented by agricultural and grazing activities near the town of Tumeremo, located on the edge of the reserve. Until the mid-17th Century, the region was populated only by the Kamaracoto indigenous groups, who practiced swidden agriculture, as the indigenous peoples still do in the continuous forests of the Imataca; in the late 18th Century, the Spanish founded a mission at Tumeremo, a site selected because of favorable conditions for cattle ranching, thus initiating the process of forest fragmentation. By the 19th Century, cattle ranching encircled public lands around Tumeremo in a five km radius; latex began to be extracted and gold mined in the first half of the 20th Century and the first timber concessions were granted in the area in the second half of the 20th Century (Callicott et al., in press).

Currently, 83% of the Botanamo study area is covered by forests, of which 56% is designated for forestry use in the Imataca reserve. About 12% of the area is in savanna and cattle pasture. The remaining 5% is in subsistence agriculture, houses, and urban areas. Immigration is accelerating forest conversion. Timber extraction, mining, and cattle ranching are the most profitable LUs; agriculture remains a small-scale subsistence activity, which – because practiced largely by the indigenous peoples on tribal lands– has not resulted yet in the three-stage process characterizing Caparo. Timber extraction and expanded mining for gold, diamonds and other minerals represent the greatest threat to the area.

3. Conceptual synthesis of coupled natural–human systems

In order to understand and provide guidance to achieve balance between LU/LC change and preserving the natural character of landscapes, a general analysis of the dimensions in which human systems and natural systems interface is necessary. We postulate that an important characteristic of CNH systems is the "connectedness" of the natural systems with associated human systems. We identify three dimensions of connectedness: satisfaction of basic human material needs, psycho-cultural relationships, and regulation of the human use of natural resources. This last form of connectedness can be further divided into two modalities: formal and informal. We express these concepts graphically by means of the diagrams in Figs. 5 and 6.

The horizontal axis in Fig. 5 represents a gradient of satisfaction of basic human material needs—to what degree local natural systems supply stakeholders with food, clothing, shelter, medicines, and so on. The vertical axis in Fig. 5 is psychological and cultural connectedness—to what degree are stakeholders invested in local natural systems for such things as personal and cultural identity, for

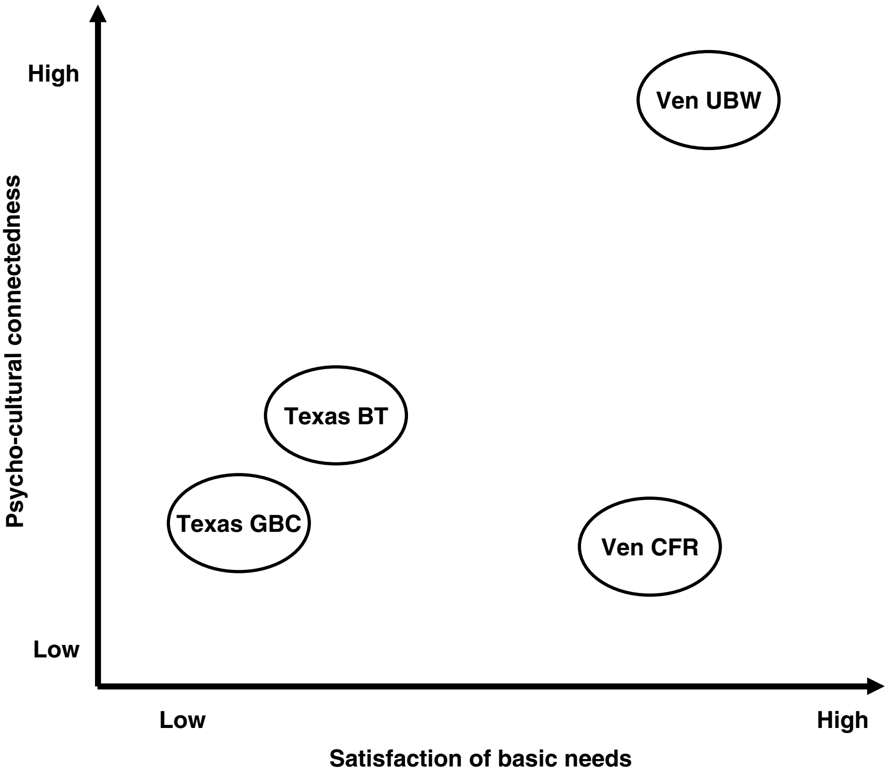

Fig. 5. Location of the study sites in a two-dimensional cross-section of the multi-dimensional space of CNH connectedness.

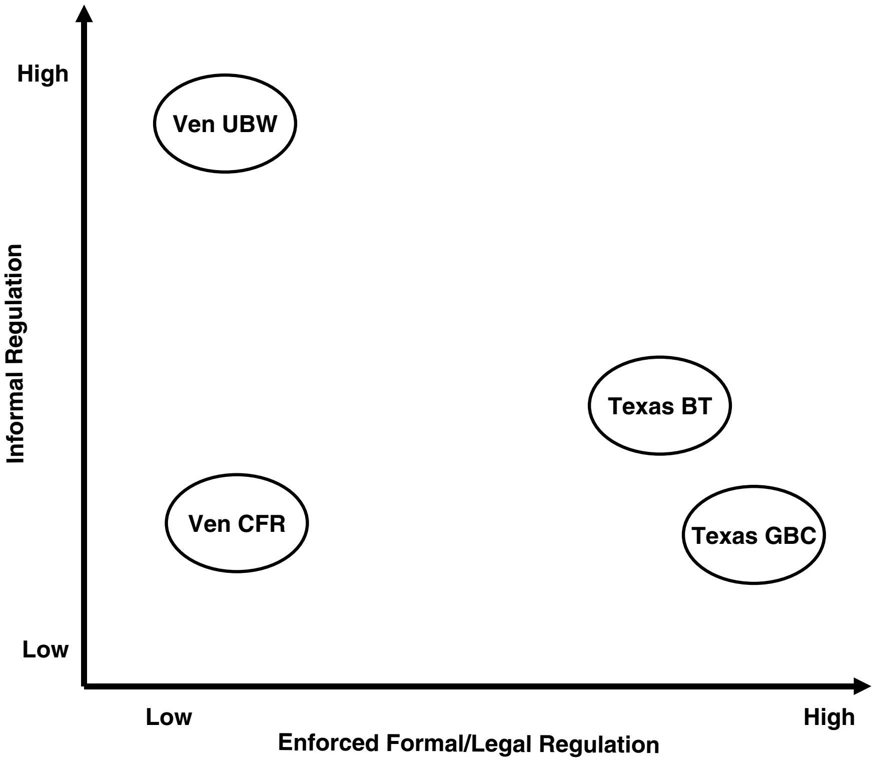

Fig. 6. Location of the study sites in another two-dimensional cross-section section of the multi-dimensional space of CNH connectedness. This cross-section represents regulation of use of natural resource.

symbolic meaning, for religious practice, and such. The two regulatory modalities are an enforced formal (legal) governance regime (horizontal axis in Fig. 6) and an informal governance regime of social (cultural) traditions, mores, and expectations (vertical axis in Fig. 6). We have approximately located each of the four study sites in these graphs. Future research will be necessary to express these relationships more precisely.

In the two sites in Venezuela, stakeholders derive more of their basic human material needs directly from local natural systems than do the stakeholders in the Texas sites. In the Caparo, however, the settlers can supplement their subsistence livelihoods with purchased goods produced and sold in the national and international marketplace. By contrast, the indigenous stakeholders in the Imataca derive more of their livelihoods from local natural systems. Nor are the stakeholders in the two Texas sites equally connected in this dimension. The Big Thicket is more rural and economically disadvantaged than the Greenbelt Corridor and many stakeholders in the former farm, ranch, hunt, fish, pump drinking water, and harvest timber. Many stakeholders in the Greenbelt Corridor live in subdivisions or on small "hobby" farms and ranches, meeting almost all of their basic material needs through the international marketplace, although some grow gardens and keep livestock to produce "organic" vegetables and meat. Thus, connectedness of stakeholders in the Greenbelt Corridor is less than that of those in the Big Thicket on this gradient (Fig. 5).

Across all four sites, the indigenous stakeholders of the Imataca site have the greatest psycho-cultural connectedness, while stakeholders in Caparo have the least psycho-cultural connectedness among all four sites. In Caparo, landless settlers, cattle ranchers, and timber concessionaries move in from elsewhere and are little invested in the local landscape for personal or cultural identity or for spiritual sustenance. In Texas generally, both personal and cultural identity are strongly invested in the landscape. Indeed, one of the values that may incline agents in the Texas human systems models – which we describe in detail below – to hold on to their land and not sell it is "tradition value". But, we propose that psycho-cultural connectedness is greater in the Big Thicket than in Greenbelt Corridor – in part because the Big Thicket has a long history of inhabitants seeking refuge in nature (Callicott et al., 2006). As the Big Thicket develops and more "settlers" (homeowners) move in from larger metropolitan areas in the region, stakeholders in the Big Thicket may, on average, become less connected to the landscape than those in the Greenbelt Corridor on this gradient (Fig. 5).

In the Texas sites, laws that are enforced and generally obeyed govern most uses of natural systems. Most fundamentally, many LUs are legally constrained by land ownership; residential, commercial, and industrial developers first secure title to the lands they transform. Municipalities legally regulate LU through zoning and other restrictions, such as building codes and water and sewage services. Law on private as well as public property regulates sport and subsistence hunting and fishing. The two Texas sites lie very close to the same point on the enforced formal (legal) regulation gradient, although in the Big Thicket – again because of its ''outlaw'' heritage – LU may be a bit more extra-legal than in the Greenbelt Corridor. LU in the Venezuela sites is also governed by formal laws but they are not strictly enforced and obeyed (Fig. 6).

Supplementing enforced formal (legal) restrictions on LU, social traditions, mores, and expectations constrain, to various degrees, stakeholder LU in our study sites. In a famous paper, Garret Hardin (1968) argued that in the absence of formal legal regulation (''mutual coercion mutually agreed upon''), resource exploitation of commonly held or publicly owned natural systems inevitably leads to ''tragedy''. Subsequent research indicates that indigenous peoples have developed informal systems of regulating LU (Ostrom, 1990). Such systems are well developed among the indigenous stakeholders in the Imataca, so that site is located on the high end of this gradient. Such systems are poorly developed in the other three sites: in Caparo, indigenous social constraints on LU are not robust, and in both Texas sites most stakeholders rely on formal legal regulations to govern LU. In Texas there prevails a cultural mystique about the sanctity of private property. Formal (legal) regulation of LU is accepted as consistent with a climate of legal regulation of all sorts of actions, but Texans commonly believe that each property owner should be free to use his/her land any way he or she sees fit to do so. Thus in the Greenbelt Corridor, one property owner allowed a radio broadcasting tower to be erected in the face of opposition from neighboring property owners; another set up a small cement plant in the floodplain on property adjacent to the protected riparian gallery forest. Generally speaking, Texas stakeholders do not expect to conform to regional LU traditions nor to the wishes of neighboring property owners; instead they expect formal (legal) regulation from governmental stakeholders to constrain LU (Fig. 6).

The illustrations in Figs. 5 and 6 only aim to create a conceptual basis for synthesis and generation of hypotheses that could later be tested with the simulation models. We are in the process of using one such hypothesis to compare simulations results using a sustainability metric for comparison. For example, what happens if the government vigorously regulates resource exploitation and promotes environmental protection to curb urban sprawl in Texas? And compare that with what happens when the government of Venezuela legislates environmental protection, but its regulations are not enforced? The analysis would also allow for an explanation of the interplay of the multiple dimensions. For example, is the absence of legal regulation in the Imataca compensated by high human-nature connectivity, both psycho-cultural and in terms of satisfaction of basic human needs, and a high degree of informal regulation? At the moment, we are in the process of completing the Big Thicket and Imataca models so that we can execute this analysis. In addition, sites not included in this study could be located in these diagrams of multidimensional space for generalized understanding of CNH systems.

Even though these diagrams are only conceptual, they could be used to develop a biocomplexity index of CNH systems. Other research has been able to express forms of biocomplexity in more quantitative terms. Anderson (2003), for example, provides a three-dimensional model of the biocomplexity of protistan communities (protists include many microbes, including slime molds, protozoa and algae). The three indices are biotic dimensions: species richness, spatial diversity, and patchiness of the distribution. The index of biocomplexity is identified by the position of the point and its geometric distance from the origin.

4. Modeling methodology

Our modeling framework is based on the essential features of the respective natural and anthropogenic LU/LC changes and stakeholder reactions (Fig. 7). The left hand side depicts the human-system models based on agents that interact under several social and economic scenarios and receive feedback from the natural-system models, which are depicted by the right hand side. In this block, landscape and hydrological models are affected by agents' actions, and produce changes in habitat and water quality under climatic and natural disturbance scenarios. These changes are fed back to the human-system model. We have implemented models for the Greenbelt Corridor site in Texas and the Caparo Forest Reserve in Venezuela. We describe these in the following two sub-sections. Table 1 summarizes the techniques used in the models to describe agents (human decision-makers). Further discussion of the scope, strengths and weaknesses of each method is provided in a section on the similarities and differences of human-system models.

4.1. Texas: Greenbelt Corridor site

Each agent in the Texas human-system models has an assigned value system, set of available actions and a decision framework. Agents respond to and interact with other agents in the model, as well as to feedback from the natural-system model. The value systems of agents may change in response to actions taken by other agents and to feedback from the natural system (Monticino et al., 2005).

4.1.1. Agents

Four main classes of agents representing stakeholders are defined: (1) landowner agents represent owners of large parcels of land suitable for residential, commercial, or industrial development; (2) developer agents represent residential, commercial, or industrial land developers; (3) homeowner agents represent collections of residents within the study area; and (4) government agents represent municipal governments that can approve, modify, or reject development proposals. For the Big Thicket model (in pro-

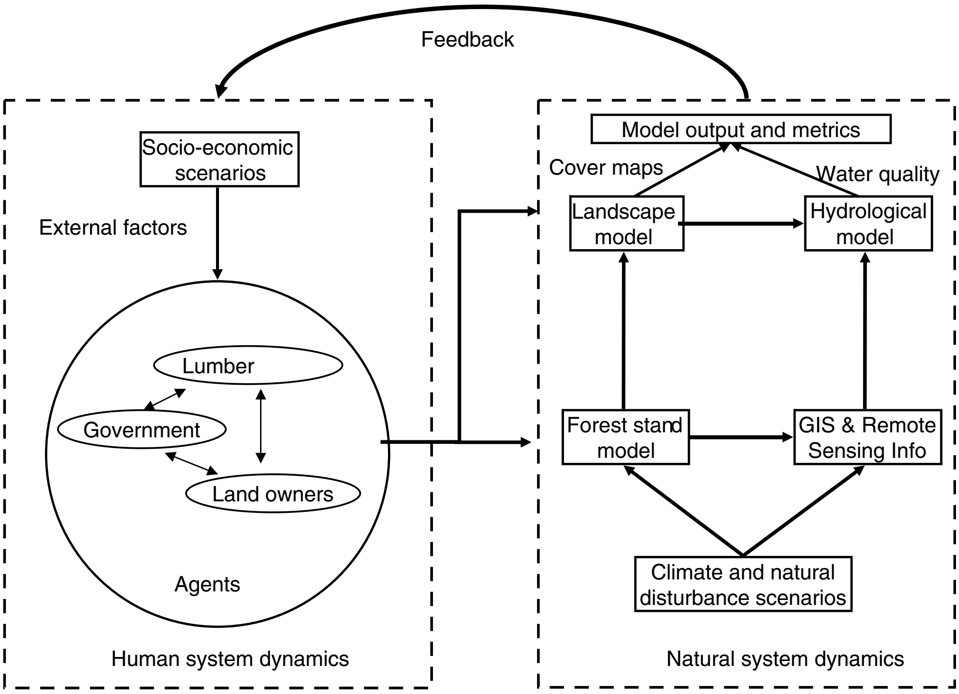

Fig. 7. Modeling framework illustrating major CNH components and their interaction.

gress), timber companies and NGOs are also included as agents.

4.1.2. Agent behavior: encoding values and directing decisions

Several types of agents are defined within each agent class and are characterized by value structures that determine the actions selected by the agent. A set of available actions is specified for each agent. Agents select the action that best conforms to their values. These values are quantified within a statistical decision analysis framework (e.g., Keeney and Raiffa, 1993). 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. The utility functions encode the essential value attributes and tradeoffs in stakeholder decisions. For the Greenbelt corridor, 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. Cluster analysis was performed to identify groups of homeowners with similar values. A typical value structure was identified for each cluster and then was used to define a homeowner type. This set of homeowner types is used to populate the model. Similar, but less formal, methods were used with the focus group data to derive landowner, developer and government agent types.

Faced with making a decision, an agent defines a set of possible consequences, $\{c_1(A), c_2(A), \ldots, c_m(A)\}$, and respective probabilities, $\{p_1(A), p_2(A), \ldots, p_m(A)\}$, for each available action A. The worth of consequence $c_i(A)$ is evaluated with a multi-attribute utility 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 functions U_i represent the partial utilities of value attributes associated with the decision. The constants k_1, $k_2, \ldots, k_n \geqslant 0$ indicate the relative value that an agent places on the respective attributes. In particular, the relative magnitudes of the k_i's and the form of the U_i's characterize the value structure of each agent. 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 expected utility.

Each privately owned undeveloped parcel of land is assigned a landowner agent. Two actions are available to landowner agents – hold their land and maintain its current use, or sell it. Landowners select an action based on the possible consequences with respect to three value attributes – wealth, tradition value, and neighboring LU. 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 for land prices and the present value over a given time horizon for farm/ranch income. Each agent is assigned an initial wealth and a partial utility for wealth, U_{W}, based on a decreasing marginal utility model, allowing representation of landowners with different sensitivities to farming/ranching income and changes in land prices. 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. The partial utility for tradition, U_{Tr}, is a non-decreasing function of the time that the parcel has been owned by the agent. The neighboring LU attribute indicates the positive externality effect of maintaining rural LU when bordered by development. The partial utility for

Table 1
Agent representation

Models	Inputs-observations	Agent roles	Decision rules	Preferences	Learning	Outputs-actions
Texas: Greenbelt Corridor	List all observations types		Bounded rationality via Decision Analysis Model Select actions that maximizes expected utility	Weights on attributes, e.g. A landowner that has a higher weight on *economic value* than on *tradition*, will be more likely to sell	Agents may adjust their preferences and, therefore, adapt their actions	List all actions types
Venezuela: Caparo	LU/LC	Settler Concessionary Landowner Government	A set of rules to define a role. Many roles per agent. For instance, a Settler agent would have the set of high level goals and these could change as the simulation advances	Preferences are wired-into the rules, by means of special conditions. This solution, however, does not exclude the use of a decision-theoretic mechanism. We have used the former, because it is better suited than the later for modeling systems where data gathering is difficult	It is not implemented at the moment. We will develop a type of learning beyond weight adjustment to obtain new rules of behavior (Dávila and Uzcátegui, 2005)	Settle Plant Cut Move Sell Buy land Bargain Police
Venezuela: Imataca-Botanamo	Ownership of land	Indigenous Concessionary Farmer Government Miner	A set of rules to define a role. Many roles per agent	Weights on attributes (*economic*, *cultural* and *ecological* ones), e.g. A Landowner that has a higher weight on *economic value* than on *cultural value*, will be more likely to sell		

neighboring LU, U_{NL}, is a decreasing function of the percentage of developed land bordering the landowner. To evaluate the neighboring LU partial utility for selling or continuing ownership, landowners project development trends and look back to the state of neighboring LU at the start of the simulation to evaluate whether development trends have generated positive or negative externalities. The neighboring LU attribute influences the interactions among landowner agents. If neighbors sell, then a landowner is more likely to sell during the next simulation iteration. How strongly a landowner is affected by his neighbors' decisions is determined by the relative value that the landowner places upon the neighboring LU attribute. The overall utility function for a landowner is given by $U = k_{\mathrm{W}}\mathrm{U}_{\mathrm{W}} + k_{\mathrm{Tr}}\mathrm{U}_{\mathrm{Tr}} + k_{\mathrm{NL}}\mathrm{U}_{\mathrm{NL}}$. Attribute weights k_{W}, k_{Tr} and k_{NL} indicate the relative value a landowner places on wealth, tradition and neighboring LU. Landowner types are defined by their attribute weights, initial wealth and wealth discount rate. For example, taking $k_{\mathrm{W}} = 0.8$, $k_{\mathrm{Tr}} = 0.1$, and $k_{\mathrm{NL}} = 0.1$ represents landowners primarily interested in wealth maximization, while taking $k_{\mathrm{W}} = 0.5$, $k_{\mathrm{Tr}} = 0.1$, and $k_{\mathrm{NL}} = 0.4$ models landowners placing a relatively higher value on their surroundings.

If landowner agents decide to sell, their parcels are made available to developer agents. A development potential model is used to select a development category (residential, commercial, or industrial) for each parcel. The development potential model scores the suitability or potential for development of a parcel, deriving development category probabilities that are then used to select the development category. Factors used to estimate the development potential of a parcel include distance to the nearest major road, distance to the nearest road (major or minor), population density within a specified radius around the parcel, density of each development category within a specified radius around the parcel, and the existence of natural impediments within or surrounding the parcel – e.g., a flood plain. Three types of developer agents are defined for each development category – environmentally -sensitive, -moderate, and -insensitive. Developer agent types are characterized by the type of development they are 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. Metrics defining the kinds of development proposals include 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 current government agent type and the development category. For instance, if a progressive government agent is 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.

As mentioned, 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 LU decisions. For example, agents representing a large number of high-income residents are assigned a higher weight than agents representing sparsely populated low-income tracts. Homeowner agents have two actions available to them when faced with a development proposal in their neighborhood – to protest the development, or not. A homeowner agent's utility function has four attributes – economic property-value, residential setting, neighboring LU, and community effort. The partial utility for economic property-value evaluates the consequence of a proposed development on the value of the agent's home. Residential setting represents the compatibility of residential development within the agent's immediate locality. Neighboring LU corresponds to the suitability and perceived environmental externality effect of development 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. An apathetic homeowner has a partial utility for community effort that decreases rapidly as a function of perceived effort, making it unlikely an apathetic homeowner will protest a development proposal. Environmentalist homeowners place high value on residential setting and neighboring LU and have associated partial utility functions that give low evaluations to environmentally insensitive development proposals. Thus, environmentalist homeowners are likely to protest most development proposals. Property-value homeowners place high value on their property values and are sensitive to decreases in property value, while neighborhood homeowner agents place a high value on residential setting. Homeowner agents may change type in response to development decisions made by the government and to feedback from the natural system feedback. For example, if a homeowner agent with a property-value orientation protested a commercial development that was 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 homeowner. Homeowner agents may also change type by "backsliding" to less engaged homeowners. Thus, we allow homeowner agents value systems to change over time.

Presented a development proposal from a developer agent, the government agent selects one of three actions – approve, conditionally approve at a higher environmental sensitivity level, or reject. Government agents select their actions based on four attributes – business relations, citizen relations, environmental consequences, and tax-base effect. Three government agent types are defined – economic growth, moderate, and progressive. Economic growth agents place relatively high weight on business relations and tax-base effect, while moderate and progressive government agents place more weight on community relations and environmental consequences. A government agent's type influences their perception of the consequences of actions. For instance, an economic growth government agent will perceive environmental consequences of a potential action as less serious than may a progressive agent.

4.1.3. Simulation algorithm

Once initialized, the decision/information flow between stakeholder agents and between the natural and human systems proceeds according to the following algorithm.

- At the beginning of a time step (typically a 1 year increment), landowner agents decide whether to sell their land. If the decision is to sell, the development potential model is used to select a development category.
- A developer type is selected as a function of the current government agent type. Developers submit proposals to the government agent, and homeowner agents affected by the proposals are notified.
- Homeowner agents decide whether to protest proposed developments. Decisions are based on homeowner agent type, the development proposal, and the type of residential development in which the homeowner agent resides.
- Government agents decide whether to approve, approve with modifications, or reject development proposals. Decisions are based on the government agent type, development proposal, weights of the homeowner agents protesting, and feedback from the natural-system model.
- Any changes in LU are passed to the natural-system model, which informs the human-system model on the LC and hydrological effects of the approved LU changes. Homeowner agents may then modify their values – i.e., change type. Parcels that have become residential developments are assigned a homeowner agent. Homeowner agent type and weight is a function of the proposal type approved.
- Homeowner agents 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.

4.1.4. Simulation scenarios and results

Land use change dynamics have been simulated for a variety of scenarios, varying by the initial distribution of landowner, homeowner and government types, and economic assumptions. A common trend observed among scenarios was a cascade of relatively rapid development with a subsequent leveling off at some percentage of developed land. Such synchronicity is similar to the Kuznets city building economic growth cycles (Berry, 1991) with development overshoot being followed by collapse. In the model simulations rapid development is followed by negative homeowner response that results in the election of growth management oriented local governments, thus slowing (at least temporarily) further development. Similar resident responses to rapid development have been documented (e.g., Austin, TX; Eugene, OR; Loudoun County, VA) throughout the United States (Duerksen and Snyder, 2005). The magnitude of the ''stable'' percentage of developed land appears to be a function of the time at which the cascade occurred and the geographic distribution of the landowner types. In fact, it appears that a considerable portion of the observed variation in the stable portion of developed land depends directly upon the spatial interactions of the landowner types. Proactive growth management strategies that account for values of landowners have also been investigated. One management policy employed by governments and NGOs for maintaining undeveloped land is to create open space preserves. Typically, land or development rights are purchased based on ecological concerns or when land fortuitously becomes available. Our simulations have examined the impact of targeting land based on landowner values with the goal of leveraging LU values of neighboring landowners to effectively protect more land from development. Results indicate that open space preserve strategies result in land other than that purchased not being developed, while in the absence of open space preserves such land was developed. The preserves provide ''development buffers'' to landowners sensitive to neighboring LU. In particular, open space strategies that purchased parcels near landowners who place high value on the neighboring LU attribute were generally more effective in slowing development than purchasing near wealth-oriented landowners. Fig. 8 shows development results for three simulations differing only in the initial locations of landowner types under an open space preserve strategy of purchasing near neighboring LU oriented landowners. The figure illustrates the variation in dynamics attributable to spatial distribution of landowner values. The proportion of landowner types was the same in each case.

4.2. Venezuela: Caparo forest reserve site

Our model captures only the ''First Stage'' of the agrarian settlement process of forest reserves in the Venezuelan western plains, where Caparo is located. That is, a settler occupies a parcel of land in the reserve and practices subsistence agriculture that typically exhausts the soil within 5 years. Some settlers then expand their farms, resulting in new deforestation, or move on to a second stage (not modeled yet) that involves selling their occupation rights to cattle ranchers.

4.2.1. Agents

Settlers, concessionaries, and the government officials constitute the model agents. Settlers are people of limited economic resources that practice swidden agriculture. They arrive in the area aiming to improve their economic status and to obtain title to the land that they have illegally occupied. Concessionaries are timber companies that have been granted rights to extract timber under government-supervised management plans. The governmental agent is charged with stewardship of the reserves by overseeing timber extraction. Because settler's activities are illegal and accessing the site is difficult, direct surveys of the settlers' values are impractical. Accordingly, the settler agents are modeled using information from previous research (CESIMO, 1998; Rojas, 1993; Sánchez, 1989). Because the current version of the model emphasizes the first stage, it includes 100 settler agents, but only one concessionary agent and one governmental agent.

4.2.2. Agent behavior: encoding values and directing decisions

Three different actions were coded for the government agent, based on the policies they implemented, and simulation scenarios were run using each: hands-off, pro-forestry and agro-forestry policies. These three actions represent possible future roles of the government at Caparo, all of which have in fact been implemented during the past. Their specification is as follows. First, the ''hands-off'' policy is to neither interact nor interfere with the actions of the other agents. Nor does the hands-off government agent have a monitoring function. Second, the ''pro-forestry'' policy is to keep settlers out of protected forest areas. This agent has a monitoring function, and any settler found in Caparo is evicted. Furthermore, if the concessionaire agent, in its extraction process, finds a settler in the zone, the government agent receives that information from the concessionaire and the indicated settler agents will be removed from Caparo in the government's next monitoring and action cycle. Third, an ''agro-forestry'' government agent also monitors the forest area and acts to protect it; but when it finds a settler agent, the settler agent is relocated to a special area for agricultural activities. As in the case of the pro-forestry government agent, the agro-forestry government agent receives information about settlement from the concessionaire agent and the indicated settler agents are relocated. Under both pro-forestry and agro-forestry policies the government agent monitors the concessionaire's harvest and plantation quotas. The concessionaire permit is revoked for 3 years if it does not comply with its assigned quotas. Monitoring is based on a function that identifies the places that are more attractive for settlement (buffers around rivers, borders, and roads).

The settler-agent behavior starts with a settlement function that considers those sites that are most attractive to the settler agent: sites where LU is not monitored, such as tree plantations, secondary shrubs, and fallow. At the same time, this function models the movement of the settlers, using vectors weighted by distance from rivers, borders, and roads—because they are the entry points to the reserve. The 100 settler agents were placed in different initial locations. During the simulation they differ in extent and duration of occupation as well as in their effects on the forest environment. The logic implemented for a settler agent's expanding its territory is the following. If an area is

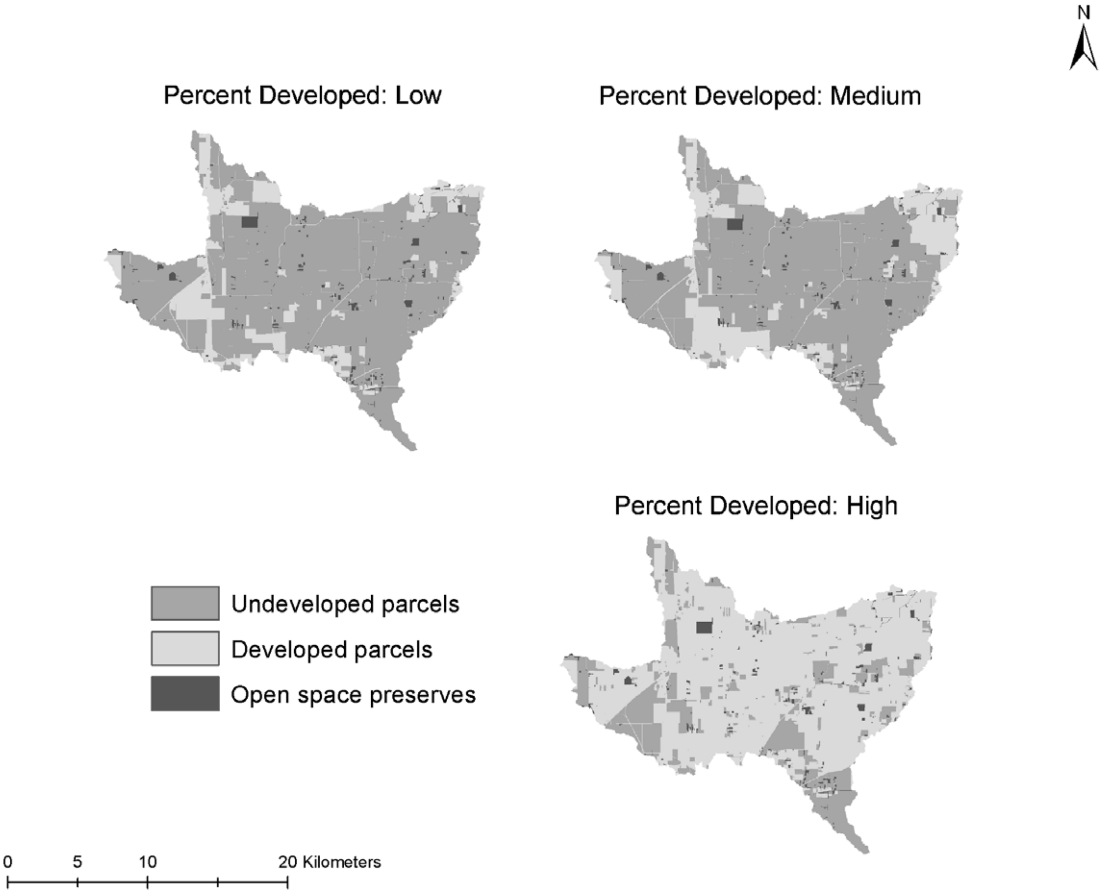

Fig. 8. Simulation results of the Greenbelt Corridor illustrating the variation in the percentage of developed land over 25 years attributable to the spatial distribution of landowner values, under an open space preserve strategy of purchasing from neighboring LU oriented landowners. Simulations initially differed only in the initial locations of landowner agent types (the proportion of landowner types was the same in each case) (from Monticino et al., 2005).

"perceived" as (a) not occupied, (b) not under surveillance, (c) not previously occupied, and (d) its current LU falls into one of the following categories: primary or secondary forest; primary or secondary shrubs; fallow; plantation; or logged forest, then the agent is allowed to settle or expand (provided that it does not go above a certain maximum limit for expansion).

The concessionaire agent extracts commercially valuable tree species and creates and monitors forest plantations (Ablan et al., 2003). When the concessionaire agent finds a settler agent on its concession, it continues to work at another site that is not occupied by settlers. There are two actions available to the concessionaire agent, depending on the government agent's policy. If the government agent follows a hands-off policy, it ignores the settler agent. If the government agent follows the pro-forestry and agroforestry policies, it removes the settler agent from the concession. The concessionaire agent operates under a 30-year logging cycle and it is allowed to harvest 1200 ha annually from a set of "compartments" that rotate sequentially on an annual basis. After the concessionaire agent harvests timber on a site, the LU is changed to "logged forest". Once the 30-year cycle is over, the concessionaire agent can harvest the first compartment again.

Formally, each agent "reasons" forward to conditional goals; and then backwards from the chosen goals to the corresponding actions as means to achieve them. Whenever the agent "observes" the achievement of one such goal in its neighborhood, it will pursue the same goal. Changes in the system state (global and local) are thus driven by rules that encode agents' preferences for actions. Those sets of rules provide a clear, humanly understandable, account of the agents' intentions, particularly suitable for verbal discussion and qualitative validation. One way of validating models is to see if they can simulate certain patterns of behavior observed in the real world. If well built, one may expect a certain level of correspondence between the simulated and the real worlds. Qualitative validations, however, are still essential because a model can produce many different system states and the same states could arise from different modeling assumptions. Mathematical analysis of emergent patterns in multi-agent models helps to validate modeling assumptions, but qualitative validation based on the clarity and intelligibility of assumptions and their correspondence to empirical information about actual human values and behaviors is an important test of a model's capacity to reliably identify trends and sensitivities and thus inform individual choice and public policy.

4.2.3. Simulation algorithm

The Caparo multi-agent model is spatially explicit (i.e., agents respond to other agents depending in part on their mutual spatial locations) and is linked to a model of secondary forest succession, which is implemented in a cellular automata format (Hogeweg, 1988). Cell transition rules are defined using LU/LC state and time spent in this state, occupation by a settler or by a concessionary agent, and the compartment's sequence that will be followed by the concessionary agent as prescribed in the management plan. A cell remains in the same state until the required transition time is achieved. In absence of agents' actions, the system path will be that indicated by natural succession. The combined multi-agent cellular automata model proceeds as follows:

- A settler agent can occupy an unoccupied forest cell changing its LU/LC to agriculture.
- The government agent can evict a settler from the occupied area, with LU/LC changing back to unoccupied forest.
- A settler agent can expand its occupation to neighboring unoccupied cells.
- After 5 years, the soils are exhausted and then the settler agent moves to another cell, changing the previously occupied cell to fallow LU/LC.
- When a concessionary agent extracts timber, an unoccupied forest cell changes to logged forest.
- To reforest, the concessionary agent acts on unoccupied cells with fallow or secondary shrubs LU/LC. Then, the LU/LC is changed to plantation.

4.2.4. Simulation scenarios and results

The model was run to simulate 65 years, with a 6-month time step, from an initial state given by 1987 LU/LC (Pozzobón, 1996) under three policy scenarios: pro-forestry, agro-forestry, and hands-off. The simulation time was chosen because this is the estimated time for succession from logged forest to mature forest. Fig. 9 shows the resulting maps at the end of the simulation for each one of the policy scenarios. The spatial pattern is more homogeneous and less fragmented in the pro-forestry scenario, and more heterogeneous and fragmented in the hands-off and agro-forestry scenarios, particularly along the areas near the perimeter. In these areas, pastureland patches fragment a

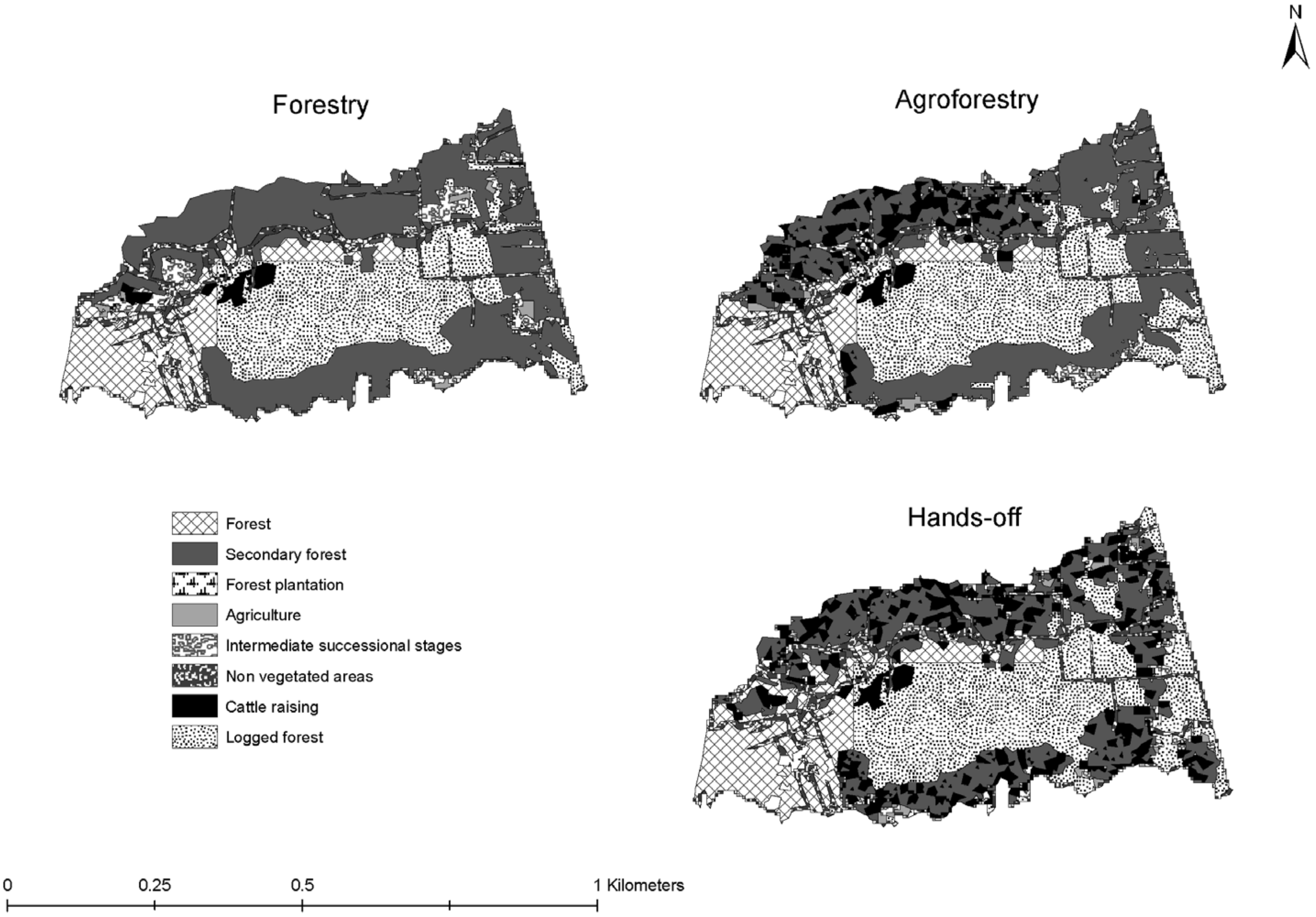

Fig. 9. Simulation results of the Caparo area at the end of the 65 years run for each type of government policy. The initial condition is the same in all cases. Higher fragmentation of forest cover occurs under the agro-forestry and hands-off scenarios. From Quintero et al. (2004).

secondary forest matrix (Fig. 9). In all the scenarios, the original mature forest is replaced by logged and secondary forest, but each scenario differs in the rate at which this transformation occurs and in the relative influence of the concessionary and the settler agents in the LU/LC change.

At the end of the simulation, for all scenarios the percentage of the total area in mature forest decreases to about 15%, while agricultural LU is less than 2%. This illustrates that the simulated primary cycle leads to an eventual decline in agriculture followed by an increase of cattle pasture, reaching 6% for the agro-forestry scenario and almost 15% for the hands-off scenario. The average time that a cell remains in agricultural use varies by scenario from 2 to 3 years, and settlers repeats settlement of a given cell at most once for all scenarios.

As the Big Thicket model is more complex than the Greenbelt Corridor model, so the Imataca model is more complex than the Caparo. And as the Big Thicket model is still a work in progress, so is the one for Imataca. The agents identified for the Imataca model include forest concessionaries, cattle ranchers, mining concessionaries, small miners, farmers, urban and ex-urban people, indigenous people, and government operatives. Analysis of the social system indicates that the forces driving LU/LC change are the stakeholders' economic conditions and distribution patterns, the dynamics of migration and land tenure, and health problems. So far, we have concentrated the study on collecting field data to demonstrate the relation of forest fragmentation to biodiversity and water quality. Both terrestrial and aquatic ecosystems were studied and compared for contrasting forest LC (continuous vs. fragmented). The variables analyzed include species richness, abundance of trees and birds, and water quality. All these variables responded to fragmentation. Water quality analysis indicate that sewage in the populated areas and washing of organic wastes from indigenous villages close to the rivers increases conductivity and pH as well as phosphate concentration and coliform bacteria.

In the Imataca model we are including variables that describe how the terrestrial and aquatic systems influence stakeholders' perception of the land, as determined according to their basic material needs, cultural values, and beliefs. These are the basic drivers of changes in the social-state variables—that is, in the spatial distribution, migration, and mortality of the stakeholders. These variables, in turn, influence the rates of LU/LC change through decision rules and utility functions.

5. Modeling framework for synthesis

5.1. Models' uniqueness and commonalities

Our natural-systems models are generic and similar for all sites, but parameterized to each site to account for differing species composition, hydrological response to deforestation, and ecosystem processes and functions. Thus, changes in humanly perceived and valued ecosystem services and amenities, such as water quantity and quality and biodiversity, are similar across sites. We attempt to use common elements (e.g., trees and water) to determine the model structure so that the effects of LU/LC change are integrated via the natural-system models. For this reason, across sites we use models that are similar in structure, e.g., patch transitions or forest succession models (Acevedo et al., 2001). Dynamics within the vegetated-natural category are dominated by succession, modeled using transition parameters estimated from detailed gap-model simulations (Acevedo et al., 2001; Monticino et al., 2002). The models use LC types based on remote sensing studies (e.g., CWRAM, 2002; Newell et al., 1997; Pozzobón, 1996). For some sites we are also using hydrological models and wildlife habitat models. The structure of each of the natural-system models is generic enough to accommodate all the various study sites in the project, and yet allow the level of detail necessary to accurately represent specific systems.

The human systems models use similar approaches but are expressed in different forms. Table 1 summarizes the techniques used to describe agents (simulated human decision-makers). For the Venezuelan sites the models employ a formal logic-based method, specifying a set of rules that define the actions to be taken by an agent, whereas the models for the Texas sites emphasize stakeholder value sets, following a decision analysis method based on utility functions. These methods differ more in style and emphasis than in substance. While the logic-based approach explicitly defines decision rules, it also implicitly defines a value set and utility function for the associated agent. Similarly, the decision analysis approach explicitly indicates a value set, but it implicitly defines a set of decision rules.

These methods have been applied according to the needs and circumstances of each study site. The data for Caparo are based on existing literature and expert opinion (indirect or secondary source) and thus rule-based models were deemed more practical and appropriate to this case. In the Greenbelt Corridor study there is sufficient empirical primary data (from survey and focus groups) to support a decision analysis based approach. In the Imataca site, for additional methodological synthesis, we are in the process of following a combination of the Caparo rule-based method and the Greenbelt-Corridor decision analysis method based on field surveys.

In all models, agents represent stakeholders – individuals, collections of individuals, private organizations and government institutions – who take actions that affect LU/LC change, directly or indirectly. In the Greenbelt-Corridor model, only developer agents directly change LU, whereas in the Caparo and Imataca models, most agents directly affect LU. Interactions between model agents can be characterized in terms of broadly overlapping categories. All the models contain interactions in each category; the difference between the models with respect to agent interaction is mainly how explicit these categories of interactions are. In the Greenbelt-Corridor model, spatial interaction among landowner agents and decision history is less explicit; each agent does not directly react to the action of neighboring agents, but to the current system state, which contains the history of past decisions. For example, a landowner's decision to sell land is influenced by neighboring development resulting from a neighbor selling land (and not directly to the neighbor's action of selling). On the other hand, homeowner and government agents explicitly interact. Government agents rule on development proposals based on homeowner protests, and homeowner agents respond to the government agent decisions. The Caparo model includes explicit spatial interactions and decision history; agents react directly to others and to previous actions. This makes the model more expressive (i.e., the agents use this additional information for decision making) but heavier for computation.

The two decision methods we have employed can be mutually converted for further synthesis. For example, decision rules can be formulated using utility functions with binary values (0 or 1) assigned to agents that reflect the type of agent and the agent's beliefs and preferences. Attributes, the associated partial utility functions, and attribute weights can be specified to encode decision rules. Likewise, decision analysis expressions can be converted into logic, because each agent has an associated set of observations, actions, outcomes, probability, and utility of the outcomes. Using this set, selection rules can be formulated that are combined with an instruction for the agent to select the action with the greatest priority, and eventually extended to include future-oriented processes, such as planning. Decision analysis presents a connection between decisions and patterns of LU change by providing a framework for changing values (e.g., by changing attribute weights) and investigating resulting changes in LU.

5.2. Functional commonalities

While actual human beings arrive at a LU decision on the basis of a multitude of values and preferences, the agents in our models characterize only the essential value structures of the LU/LC decision processes; and the actions available to them represent only broad categories of LU/LC change. Thus, while a settler's decision either to plant maize or some other crop may be of great importance to him, our models characterize only the essential decision to clear forested land and convert it to agricultural use rather than preserve it. Similarly, while home and lot size may make a crucial economic difference to a residential developer, our models characterize only LU/LC changes following a landowner's decision to sell forested land for conversion to single-family residential development. More generally still, whether poor settlers are clearing forests for subsistence agriculture or wealthy developers are clearing forests to build up-scale homes, the effects on the natural systems and ecological services are comparable.

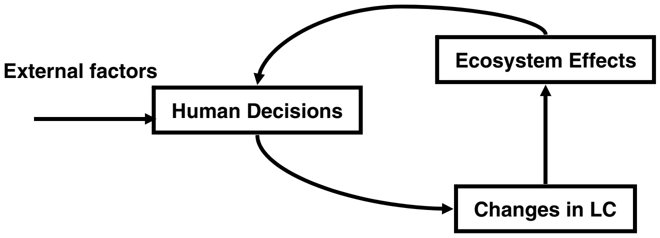

Fig. 10. Conceptualizing LC change and ecosystem effects. Common approach to CNH interactions.

Consequently, across sites, agents in the human systems models exhibit functional similarities in their LU activities and in their effects on LC change. Thus, we can pair them in order to conduct cross-cultural and cross-site synthesis. However, they operate under different legal and regulatory conditions. In the Texas models, we consider the legal and regulatory process of LU change in the US, including interactions between economic conditions and government agents, which in turn affect subsequent actions of landowners. The Caparo model includes the Venezuelan legal framework for LU and its enforcement or lack thereof. Further, this imposes an important difference in ownership or tenure. While the Venezuelan settlers and Texas developers may have similar functions, the developers own the land that they impact; the settlers do not. Similarly in the case of the timber concessionaries in Venezuela and the lumber companies in Texas; the latter can own land but the former cannot. The Caparo site is completely within forest-reserve land that remains public property unless it is removed from legal reserve status. The Texas sites include land that can be publicly owned by the government or privately owned by homeowners, NGOS, lumber companies, or development companies.

All of the LU/LC classifications used by the models can also be grouped. While there are many types used in the model, they can be classified into four broad categories: (1) developed land, (2) agricultural/ranching land, (3) mature forest, and (4) forest in succession. The diagram in the bottom of Fig. 10 illustrates the process at work in all sites in which human decisions and natural systems affect one another. The external factors are used to describe factors that affect human decisions and that are out of the agents' control, including the current economic environment (stable, strong, declining, etc), current events such as natural disasters, and federal policy.

6. Conclusions

Several different approaches have been reported in the literature to model LU/LC change. Some models are empirical, based on extrapolations of the patterns of change observed over the past, with a limited representation of the driving forces of this change. The combined multi-agent and patch transition model (including cellular automata rules) allows representation of the human decisions that drive the LU/LC change with the advantage of a spatial representation that is able to capture the location and magnitude of the change. Simulations produced qualitative patterns of LU/LC change similar to those observed in Greenbelt Corridor and Caparo. This helps validate the overall modeling approach as other sites are studied and more quantitative results are derived from the model.

Simulation results of the Greenbelt-Corridor model indicated that considering agent values when formulating growth management strategies might lead to more successful outcomes. Agent interactions produced complex dynamics, and the simulations revealed key sensitivities of these dynamics. In particular, the principal drivers of LU change were the land-price assumptions, sensitivities of landowner agents' decisions to changes in land prices and neighboring development, and the spatial interactions between landowners. While sensitivity to economic values comes as no surprise, the simulations revealed another sensitivity that could be of importance to governmental interest in controlling sprawl, managing development, and sustaining natural systems and their ecosystem services. Landowner agents that were assigned a relatively high value for neighboring LU and/or tradition were more likely to hold on to their properties if neighboring properties remained undeveloped. Therefore if governments purchased properties or development rights for "strategic open spaces" from landowners who sold at lower price-increase thresholds, those neighboring landowners sensitive to neighboring LU would resist the temptation to sell at modest increases in land prices. Thus dollars for publicly owned open spaces that might otherwise be spent on large tracts, could be more efficiently spent on scattered, smaller parcels as these would have a contagious effect on neighboring private properties—and in effect multiply open space per dollar spent.

At the same time, local governments would need to be aware of the potential downside effects of such a strategy. Lower density development generally results in higher costs for local service provision, increased air and light pollution and may result in leap-frogging development that would exacerbate these problems. However, by directing development toward landowner agents whose values are more profit oriented the strategy would both concentrate development into smaller areas and stretch public dollars spent purchasing development rights or land parcels by leveraging landowners whose values are oriented toward neighboring LU and/or tradition. Such a strategy would reduce the number of places characterized by cascading development and ultimately help achieve the goal of mutually sustaining human and natural systems. Accordingly, an important component of the current work in the Big Thicket study area is a comprehensive LU value survey of individual landowners in that region in order to analyze LU change dynamics with specific placement of landowner types (while respecting the confidentiality of survey participants).

The Caparo model was evaluated by qualitative comparison of the results to the known history of LU change in the area. Simulation results agree qualitatively with what is known about LU change, tropical forest succession, and forest management in the area. And again important sensitivities were revealed. In Caparo, the models reveal that vigorous enforcement of laws and regulations governing all LU activities is the key to achieving a mutually sustaining relationship between the human and natural systems of the region. In Imataca, we hypothesize that ensuring the rights of the indigenous inhabitants of the region will be the most effective policy for achieving a mutually sustaining relationship between the human and natural systems in that region (Callicott et al., in press). Indigenous patterns of subsistence have coexisted with the forested character of Imataca from time immemorial. But as the Caparo experience suggests, subsistence swidden agriculture is compatible with sustaining forest LC only if population densities remain low. Hence, also controlling immigration will likely prove to be a key policy for maintaining mutually sustaining natural and human systems in the Imataca region. Once all the cycles of the conceptual model of colonization are implemented, more quantitative validation will be undertaken in Caparo, using landscape indices (e.g., Turner et al., 1990b) to compare simulated results with actual LU maps. Nevertheless, as stated by many authors, such as Parker et al. (2003) and Bousquet and Le Page (2004), the validation of agent based models poses important challenges that are subject to further discussion and research.

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References

Ablan, M., Dávila, J., Moreno, N., Quintero, R., Uzcátegui, M., 2003. Agent modelling of the Caparo Forest Reserve. In: Di Marino, B., Yang, L.T., Bobeanu, C. (Eds.), The 2003 European Simulation and Modelling Conference, Section: Simulation and Biology, Subsection: Simulation of Ecosystems. EUROSIS-ETI, Ghent, Belgium, pp. 367–372.

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

Agnew, J., Smith, J., 2002. American Space/American Place: Geographies of the Contemporary United States. Routledge, London.

Allen, W., 1905. Captain John B. Denton, Preacher, Lawyer, and Soldier: His Life and Times in Tennessee, Arkansaw, and Texas. R.R. Donnelle, Chicago.

Anderson, O.R., 2003. A model of biocomplexity and its application to the analysis of some terrestrial and marsh eukaryotic microbial communities with an emphasis on amoeboid protists. The Journal of Eukaryotic Microbiology 50 (2), 86–91.

Arima, E.Y., Walker, R.T., Perz, S.G., Caldas, M., 2005. Loggers and forest fragmentation: behavioral models of road building in the Amazon Basin. Annals of the Association of American Geographers 95 (3), 525–541.

Aspinall, R., 2004. Modelling land use change with generalized linear models—a multi-model analysis of change between 1860 and 2000 in Gallatin Valley Montana. Journal of Environmental Management 72 (1–2), 94–103.

Bates, E.F., 1976. History and Reminiscences of Denton County. T. Wheeler Printing, Denton, TX.

Berry, B.J.L., 1991. Long-Wave Rhythms in Economic Development and Political Behavior. Johns Hopkins University Press, Baltimore.

Bhaduri, B., Harbor, J., Engel, B., Grove, M., 2000. Assessing watershed-scale, long-term hydrologic impacts of land-use change using a GIS-NPS model. Environmental Management 26 (6), 643–658.

Bousquet, F., Le Page, C., 2004. Multi-agent simulations and ecosystem management: a review. Ecological Modelling 176, 313–332.

Brandt, J.J.E., Bunce, R.G.H., Howard, D.C., Petit, S., 2002. General principles of monitoring land cover change based on two case studies in Britain and Denmark. Landscape and Urban Planning 62 (1), 37–51.

Brown, D.G., Pijanowski, B.C., Duh, J.D., 2000. Modelling relationships between land use and land cover on private lands in the Upper Midwest, USA. Journal of Environmental Management 59 (4), 247–263.

Brown, D.G., Page, S.E., Riolo, R., Rand, W., 2004. Agent-based and analytical modelling to evaluate the effectiveness of Greenbelts. Environmental Modelling & Software 19 (12), 1097–1109.

Buttimer, A., Seamon, D., 1980. The Human Experience of Place and Space. Croom Helm, London.

Callicott, J.B., Acevedo, M.F., Gunter, P., Harcombe, P., Lindquist, C., Monticino, M., 2006. Biocomplexity in the Big Thicket. Ethics, Place and Environment 9, 21–45.

Callicott, J.B., Rozzi, R. Delgado, L., Monticino, M., Acevedo, M., Harcombe, P., in press. Biocomplexity and conservation of biodiversity hotspots: three case studies from the Americas. Philosophical Transactions of the Royal Society B.

Casey, E.S., 1993. Getting Back into Place: Toward a Renewed Understanding of the Place-World. Indiana University Press, Bloomington.

Casey, E.S., 1997. The Fate of Place: A Philosophical History. University of California Press, Berkeley.

Centeno, J.C., 1997. Deforestaciones fuera de control en Venezuela. Universidad de los Andes, Mérida, Venezuela.

CESIMO, 1998. Gaia. Caso Venezuela: deforestación y políticas de la propiedad de la tierra en la Reserva Forestal de Caparo. Centro de Simulación y Modelos de la Universidad de los Andes, Mérida, Venezuela. http://cesimo.ing.ula.ve/GAIA/CASES/VEN/INGLES/firstp.html.

Cottingham, K.L., 2002. Tackling biocomplexity: the role of people, tools, and scale. BioScience 52 (9), 793–799.

Covich, A., 2000. Biocomplexity and the future: the need to unite disciplines. BioScience 51, 908–914.

Cozine, J.J., 2004. Saving the Big Thicket: From Exploration to Preservation, 1685–2003. University of North Texas Press, Denton, TX.

CVG TECMIN, 1987. Informe de avance de Clima, Geología Geomorfología Suelos y Vegetación. Hoja NB-20-4. Ciudad Bolívar, Venezuela: CVG Técnica Minera C. A. Proyecto Inventario de los Recursos Naturales.

CWRAM, 2002. Watershed Atlas for Ray Roberts, Lewisville, and Grapevine. Center for Watershed and Reservoir Assessment and Management at the University of North Texas, Denton.

Dávila, J., Uzcátegui, M., 2005. Agents that learn to behave in multi-agent simulations. In: Tonella, G. (Ed.), Proceedings of the Fifth International Conference on Modelling, Simulation, and Optimization (MSO 2005), The International Association of Science and Technology for Development (IASTED). Acta Press, Anaheim, pp. 51–55.

Deadman, P.J., Robinson, D.T., Moran, E., Brondizio, E., 2004. Effects of colonist household structure on land use change in the Amazon Rainforest: a stakeholder based simulation approach. Environment and Planning B: Planning and Design 31, 693–709.

Delgado, L., Rosales, J., Blanca, R., Castellanos, H., Figueroa, J., Leal, S., Mansutti, A., Rodríguez, A., Sanchez, B., Valeri, C., 2005. A conceptual model of biocomplexity in the upper Botanamo river basin. In: Tonella, G. (Ed.), Proceedings of the Fifth International Conference on Modelling, Simulation, and Optimization (MSO 2005), The International Association of Science and Technology for Development (IASTED). Acta Press, Anaheim, pp. 297–302.

Duerksen, C., Snyder, C., 2005. Nature Friendly Communities: Habitat Protection and Land Use. Island Press, Washington, DC.

Dybas, C.L., 2001. From biodiversity to biocomplexity: a multidisciplinary step toward understanding our environment. BioScience 51 (6), 426–430.

Entrikin, N., 1991. The Betweeness of Place: Towards a Geography of Modernity. Johns Hopkins University Press, Baltimore.

Evans, T.P., Kelley, H., 2004. Multi-scale analysis of a household level agent-based model of land-cover change. Journal of Environmental Management 72, 57–72.

Evans, T.P., Moran, E.F., 2002. Spatial integration of social and biophysical factors related to land cover change. Population and Development Review 28, 165–186.

Evans, T.P., Manire, A., de Castro, A., Brondizio, E., McCracken, S., 2001. A dynamic model of household decision making and parcel level land-cover change in the eastern Amazon. Ecological Modelling 143, 95–113.

Foster, D.R., Motzkin, G., Slater, B., 1998. Land-use history as long-term broad-scale disturbance: regional forest dynamics in central New England. Ecosystems 1, 96–119.

Freeman III, A.M., 1993. The Measurement of Environmental and Resource Values: Theory and Methods. Resources for the Future, Washington.

Gomez-Pompa, Kaus, A., 1990. Traditional management of tropical forests in Mexico. In: Anderson, A.B. (Ed.), Alternatives to Deforestation: Steps Toward Sustainable Use of the Amazon Rainforest. Columbia University Press, New York, pp. 45–64.

Gomez-Pompa, A., Kaus, A., 1992. Taming the wilderness myth. BioScience 42, 271–279.

Gragson, T.L., 1998. Potential vs. actual vegetation: human behavior in a landscape medium. In: Baleé, W., (Ed.), Advances in Historical Ecology, pp: 213–231.

Gunter, P.A.Y., 1993. The Big Thicket: An Ecological Evaluation. University of North Texas Press, Denton, TX.

Haber, W., 2004. Landscape ecology as a bridge from ecosystems to human ecology. Ecological Research 19, 99–106.

Hardin, G., 1968. Tragedy of the commons. Science 162, 1243–1248.

Harding, J.S., Benfield, E.F., Bolstad, P.V., Helfman, G.S., Jones III, E.B.D., 1998. Stream biodiversity: the ghost of land use past. Ecology 95, 14843–14847.

Hare, M., Deadman, P., 2004. Further towards a taxonomy of agent-based simulation models in environmental management. Mathematics and Computers in Simulation 64, 25–40.

Hargrove, E.C., 2000. Toward teaching environmental ethics: exploring problems in the language of evolving social values. Canadian Journal of Environmental Education 5, 1–20.

Hogeweg, P., 1988. Cellular automata as a paradigm for ecological modelling. Applied Math and Computation 27, 81–100.

Hoffman, M., Kelly, H., Evans, T., 2002. Simulating land-cover change in Indiana: an agent-based model of de/reforestation. In: Janssen, M.A. (Ed.), Complexity and Ecosystem Management: The Theory and Practice of Multi-agent Systems. Edward Elgar Publisher, Northampton, pp. 218–247.

Houghton, R.A., 1994. The worldwide extent of land-use change. Bioscience 44, 305–313.

Huigen, M.G.A., 2002. Spatially explicit Modelling of land-use change in the Sierra Madre, Philippines, The MameLuke Project. In: Parker, D.C., Berger, T., Manson, S.M. (Eds.), Agent-based Models of Land-use and Land-cover Change, Report and Review of an International Workshop Irvine, California October 4–7, 2001. LUCC International Project Office, Bloomington, Indiana.

Kasperson, J.X., Kasperson, R.E., Turner, B.L., IIII (Eds.), 1995. Regions at Risk: Comparisons of Threatened Environments. United Nations University, Tokyo.

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

Kellert, S.R., 1997. Kinship to Mastery: Biophilia in Human Evolution and Development. Island Press, Washington, DC.

Lambin, E.F., Turner, B.L., Geist, H.J., Agbola, S.B., Angelsen, A., Bruce, J.W., Coomes, O.T., Dirzo, R., Fischer, G., Folke, C., George, P.S., Homewood, K., Imbernon, J., Leemans, R., Li, X., Moran, E.F., Mortimore, M., Ramakrishnan, P.S., Richards, J.F., Skanes, H., Steffen, W., Stone, G.D., Svedin, U., Veldkamp, T.A., Vogel, C., Xu, J., 2001. The causes of land-use and land-cover change: moving beyond the myths. Global Environmental Change 11, 261–269.

Lepers, E., Lambin, E.F., Janetos, A.C., DeFries, R., Achard, F., Ramankutty, N., Scholes, R.J., 2005. A synthesis of information on rapid land-cover change for the period 1981–2000. Bioscience 55, 115–124.

Ligtenberg, A., Bregt, A.K., Lammeren, R.V., 2001. Multi-actor-based land use modelling: spatial planning using agents. Landscape and Urban Planning 56, 21–33.

Lim, K., Deadman, P., Moran, E., Brondizio, E., McCracken, S., 2002. Agent based simulations of household decision making and land use change near Altamira, Brazil. In: Gimblett, H.R. (Ed.), Integrating Geographic Information Systems and Agent-based Modelling Techniques for Simulating Social and Ecological Processes. Oxford University Press, Oxford, pp. 277–309.

Loibl, W., Toetzer, T., 2003. Modelling growth and densification processes in suburban regions – simulation of landscape transition with spatial agents. Environmental Modelling and Software 18, 553–563.

Lundberg, A., 2002. The interpretation of culture in nature: landscape transformation and vegetation change during two centuries at Hystad, SW Norway. Norwegian Journal of Geography 56, 246–256.

Malpas, J.E., 1999. Place and Experience: A Philosophical Topography. Cambridge University Press, Cambridge.

Malpas, J.E., 2001. Comparing topographies: across paths/around place: a reply to Casey. Philosophy and Geography 4, 231–238.

Manson, S.M., 2002. Integrated assessment and projection of land-use/land-cover change in the southern Yucatán peninsular region of Mexico. In: Parker, D.C., Berger, T., Manson, S.M. (Eds.), Agent-based Models of Land-use and Land-cover Change, Report and Review of an International Workshop Irvine, California October 4–7, 2001. LUCC International Project Office, Bloomington, Indiana, pp. 56–59.

Mansutti, A., Flores, A.L., Perozo, A., Rigores, A., Figueroa, I., Sevilla, V., Navarro, A., Hernández, L., Castellanos, H., De Martino, A., 2000. Diagnóstico de los conflictos socio-ambientales en Imataca: Líneas estratégicas para el resguardo y la consolidación de los asentamientos humanos ubicados en la Reserva Forestal Imataca. UNEG/Banco Mundial/MARN, Ciudad Bolívar.

Mas, J.F., Puig, H., Palacio, J.L., Sosa-Lopez, A., 2004. Modelling deforestation using GIS and artificial neural networks. Environmental Modelling and Software 19, 461–471.

Massey, D., 1999. Space-time, 'science' and the relationship between physical geography and human geography. Transactions of the Institute of British Geographers, New Series 24 (3), 261–276.

Metzger, J., 2000. Tree functional group richness and landscape structure in a Brazilian tropical fragmented landscape. Ecological Applications 10, 1147–1161.

Michener, W.K., Baerwald, T.J., Firth, P., Palmer, M.A., Rosenberger, J.L., Sandlin, E.A., Zimmerman, H., 2001. Defining and Unraveling Biocomplexity. Bioscience 51, 1018–1023.

Miranda, M., Hernández, L., Ochoa, J., Yerena, E., Blanco-Uribe, A., 1998. All That Glitters is Not Gold: Balancing Conservation and Development in Venezuela's Frontier Forests. World Resource Institute, Washington.

Monticino, M.G., Cogdill, T., Acevedo, M.F., 2002. Cell interaction in semi-Markov forest landscape models. In: Rizzoli, A.E., Jakeman, A.J. (Eds.), Integrated Assessment and Decision Support: Proceedings of the 1st Biennial Meeting of the IEMSS. IEMSS, Lugano, Switzerland, pp. 227–232.

Monticino, M.G., Acevedo, M., Callicott, B., Cogdill, T., Ji, M., Lindquist, C., 2004. Coupled human and natural systems: a multi-agent based approach. In: Pahl-Wostl, C., Schmidt, S., Rizzoli, A.E., Jakeman, A.J. (Eds.), Complexity and Integrated Resources Management: Transactions of the 2nd Biennial Meeting of the International Environmental Modelling and Software Society (IEMSS), vol. 1. IEMSS, Manno, Switzerland, pp. 196–202.

Monticino, M.G., Acevedo, M., Callicott, B., Cogdill, T., 2005. Multi-agent model of human values and land-use change. In: Tonella, G. (Ed.), Proceedings of the 5th International Conference on Modelling, Simulation and Optimization (MSO2005) of the International Association of Science and Technology for Development (IASTED). Acta Press, Anaheim, pp. 279–284.

Moran, E.F., Ostrom, E. (Eds.), 2005. Seeing the Forest and the Trees: Interactions in forest ecosystems. MIT Press, Cambridge, MA.

Newell, J., Dickson, K.L., Fitzgerald, J.W., Atkinson, S.F., Acevedo, M.F., 1997. 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.

Norton, B.G., 1991. Thoreau's insect analogies: or why environmentalists hate mainstream economists. Environmental Ethics 13, 235–251.

NTCOG, 2005. North Central Texas Council of Governments. Demographic Estimates. Retrieved 10.12.2005. <http://www.nctcog.org/>.

Oakes, T., 1997. Place and the paradox of modernity. Annals of the Association of American Geographers 87, 509–531.

Ojima, D.S., Galvin, K.A., Turner II, B.L., 1994. The global impact of land-use change. Bioscience 44, 300–304.

Openshaw, S., 1994. A geographical study of scale and aggregation problems in region building, partitioning, and spatial modeling. Transactions of the Institute of British Geographers. New Series 2, 499–508.

Openshaw, S., 1995. Human systems modeling as a new grand challenge area in science: what has happened to the science in social science? Environment and Planning A 26, 499–508.

Ostrom, E., 1990. Governing the commons: the evolution of institutions of collective action. Cambridge University Press, Cambridge, England.

Pahl-Wostl, C., 2004. The implication of complexity of integrated resources management. In: Pahl-Wostl, C., Schmidt, S., Rizzoli, A.E., Jakeman, A.J. (Eds.), Complexity and Integrated Resources Management: Transactions of the 2nd Biennial Meeting of the International Environmental Modelling and Software Society (IEMSS), vol. 1. IEMSS, Manno, Switzerland, pp. 25–33.

Pahl-Wostl, C., 2005. Information, public empowerment, and the management of urban watersheds. Environmental Modelling and Software 20, 457–467.

Parker, D.C., Manson, S.M., Janssen, M.A., Hoffman, M.J., Deadman, P., 2003. Multi-agent systems for the simulation of land-use and land-cover change: a review. Annals of the Association of American Geographers 93, 313–337.

Parker, D.C., Meretsky, V., 2004. Measuring pattern outcomes in an agent-based model of edge-effect externalities using spatial metrics. Agriculture, Ecosystems, and Environment 101, 233–250.

Pickett, S.T.A., Cadenasso, M.L., Grove, J.M., 2005. Biocomplexity in coupled natural–human systems: a multidimensional framework. Ecosystems 8, 225–232.

Pozzobón, E., 1996. Estudio de la dinámica de las deforestaciones en la Reserva Forestal de Caparo mediante imágenes HRV SPOT. Universidad de Los Andes. Facultad de Ciencias Forestales. Escuela de Ingeniería Forestal. Departamento de Ingeniería. Mérida-Venezuela.

Quintero, R., Barros, R., Dávila, J., Moreno, N., Tonella, G., Ablan, M., 2004. A Model of the biocomplexity of deforestation in tropical forest: Caparo case study. In: Pahl-Wostl, C., Schmidt, S., Rizzoli, A.E., Jakeman, A.J. (Eds.), Complexity and Integrated Resources Management: Transactions of the 2nd Biennial Meeting of the International Environmental Modelling and Software Society (IEMSS), vol. 2. IEMSS, Manno, Switzerland, pp. 840–845.

Redman, C.L., 1992. The impact of food production: short-term strategies and long-term consequences. In: Jacobsen, J.E., Firor, J. (Eds.), Human impact on the environment: ancient roots, current challenges. Westview Press, Boulder, CO, USA, pp. 35–49.

Redman, C.L., 1999. Human Impact on Ancient Environments. University of Arizona Press, Tucson, Arizona, USA.

Rojas, J., 1993. La colonización agraria de las Reservas Forestales: ?un proceso sin solución? Universidad de los Andes, Instituto de Geografía, Mérida, Venezuela, Cuaderno Geográficos 10, pp. 110.

Rolston III, H., 1985. Valuing wildlands. Environmental Ethics 7, 113–128.

Sagoff, M., 1988. The Economy of the Earth. Cambridge University Press, Cambridge.

Sánchez, M., 1989. Situación actual del proceso de ocupación de la Reserva Forestal en Caparo. Universidad de los Andes, Instituto de Geografía y Conservación de Recursos Naturales, Mérida, Venezuela.

Sauer, C.O., 1927. Recent developments in cultural geography. In: Hayes, E.C. (Ed.), Recent Developments in the Social Sciences. J.B. Lippincott, Philadelphia.

Schneider, L.C., Pontius, R.G., 2001. Modelling land-use change in the Ipswich watershed, Massachusetts, USA. Agriculture, Ecosystems and Environment 85, 85–94.

Schein, R.H., 1997. The place of landscape: a conceptual framework for interpreting an American scene. Annals of the Association of American Geographers 87, 660–680.

Sheppard, E., McMaster, R.B., 2004. Scale and Geographic Inquiry: Nature, society and method. Blackwell, Malden, MA.

Snyder, G., 1995. A Place in Space: Ethics, Aesthetics and Watersheds. Counterpoint, Washington, DC.

Smith, M., 2001. An Ethics of Place: Radical Ecology, Postmodernity, and Social Theory. State University of New York Press, Albany.

Terán, O., Alvarez, J., Jaimes, M., Ablan, M., 2005. Land occupation and land use change in a forest reserve: A MABS Approach. CABM-HRMA-SMGET Joint International Conference on Multi-Agent Modelling for Environmental Management, Saint Maurice – Les Arcs, France, 21–25 March, 2005.

Tuan, Y.F., 1973. Ambiguity in attitudes toward environment. Annals of the Association of American Geographers 63, 411–423.

Tuan, Y.F., 1977. Place and Space: The Perspective of Experience. The University of Missouri Press, Minneapolis.

Turner, B.L., 1976. Population density in the classic Maya lowlands: new evidence for old approaches. Geographical Review 66, 73–82.

Turner, B.L., IIII, Clark, W.C., Kates, R.W., Richards, J.F., Mathews, J.T., Meyer, W.B. (Eds.), 1990a. The Earth as Transformed by Human Action: Global and Regional Changes in the Biosphere over the Past 300 Years. Cambridge University Press, Cambridge.

Turner, S.J., O'Neill, R.V., Conley, W., Conley, M.R., Humphries, H.C., 1990b. Pattern and scale: statistics for landscape ecology. In: Turner, M.G., Gardner (Eds.), Quantitative Methods in Landscape Ecology. Springer, USA, pp. 17–49.

UCV-MARNR., 2002. Ordenamiento territorial de la Reserva Forestal Imataca y sus áreas adyacentes. II Etapa. Bases del Plan de Ordenamiento. II Informe Técnico. Caracas, Venezuela: MARN.

Vidal de la Blache, P., 1926. Principles of human geography. In: Emmanuel de Martonne (Ed.). Bingham, Holt and Company, New York (translated from the French by Millicent Todd).

Walker, R., 2003. Mapping process to pattern in the landscape change of the Amazonian frontier. Annals of the Association of American Geographers 93 (2), 376–398.

Walker, R., 2004. Theorizing land-cover and land-use change: the case of tropical deforestation. International Regional Science Review 27, 247–270.

Walker, R., Perz, S., Caldas, M., Silva, L.G.T., 2002. Land use and land cover change in forest frontiers: the role of household life cycles. International Regional Science Review 25, 169–199.

Watson, R.T., Noble, I.R., Bolin, B., Ravindranath, N.H., Verardo, D.J. (Eds.), 2000. Land use, Land-use Change, and Forestry: A Special Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Zube, E., 1987. Perceived land use patterns and landscape values. Landscape Ecology 1, 37–4.