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A dynamic graph automata approach to modeling landscape change in the Andes and the Amazon

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Abstract. A generalization of cellular automata was developed that allows flexible, dynamic updating of variable neighborhood relationships, which in turn allows the integration of interactions at widely disparate spatial and temporal scales. Cells in the landscapes were modeled as vertices of dynamic graph automata that allow temporally variable causal connectivity between spatially nonadjacent cells. A trial was carried out to represent changes in an Amazonian and a tropical Andean landscape modeled as dynamic graph automata with input from a Landsat TM-derived Level 1 classification with the following classes: for the Amazon—forest, nonforest vegetation, water, and urban or bare (soil); for the Andes—forest, scrub (shrub or grassland), agriculture, and bare or exposed ground. Explicit automata transition rules were used to simulate temporal land-cover change. These rules were derived independently from fieldwork in each area, including vegetation plots or transects and informal interviews. Such a generalization of cellular automata was useful for modeling land-use – land-cover change (LULCC), although it potentially increases the computational complexity of an already data intensive process (involving 5 – 8 million cells, in 1000 stochastic simulations, with each simulation encompassing 15 annual time steps). The interannual predicted LULCC, while more nuanced in the Andean site, poses a serious threat to compositional and configurational stability in both the Andes and the Amazon, with implications for landscape heterogeneity and habitat fragmentation.

Introduction

In principle, automata-based models can be used to examine hypotheses about spatial organization, landscape-change dynamics, and their predicted social and environmental consequences in any landscape at any spatial scale. Here we develop the framework of dynamic graph automata, which are a generalization of traditional cellular automata. This framework is used to simulate land-use – land-cover change (LULCC) in two sections of a study area extending from the high mountains of the central Andes down into the Amazon lowlands of eastern Peru. We have so far modeled an Amazonian landscape and a tropical Andean landscape, using as input Landsat Thematic Mapper (TM) data, to study the outcomes of different rules and conditions for LULCC. The generality of the framework allows a variety of LULCC rules to be modeled in tandem, thus demonstrating the potential for its use for realistic modeling of LULCC.

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Data from TM images were integrated into models in which ecological units are represented as vertices (nodes) of dynamic graph automata (see, for example, Milgram, 1975; Rosenfeld, 1975), releasing the model from the cell-similarity and symmetric-geometry restrictions of tessellated traditional cellular-automata models (Gutowitz, 1991). By also modeling simultaneously natural and human systems as agents of LULCC, the behavioral feedbacks between the two types of system can be comparatively ascertained for explanatory power in such models. By working in an area spanning the Andes to the Amazon (Crews-Meyer, 2006; Kintz et al, 2006), we tested the strength of this approach across a variety of human and natural systems. Critical as a 'hotspot' of both deforestation (Achard et al, 2002; also Santos Granero and Barclay Rey de Castro, 1995) and biological diversity (Myers et al, 2000; Stattersfield et al, 1998) this area extends more than 600 km along Peru's oldest penetration road to the Amazon (Carretera Central) that connects these disparate areas and myriad culture groups including highland indigenous people (for example, Quechua speaking), lowland indigenous peoples (for example, Shipibo), recent colonists, and long-term settlers (for example, ribereños). Previous research in Peru (Denevan, 1966; Mäki et al, 2001; Sjoholt, 1988; Works, 1985), Brazil (Fearnside, 2002; Laurance, 2000; Laurance et al, 2001; Walker et al, 2000), and the humid tropics generally (Bilsborrow and Hogan, 1999; Rudel, 2002) suggests substantial future LULCC and changes in migration along this and similar access routes given global and local development pressures, and the actions of farmers, colonists, or other resource managers (Phillips et al, 2004; Summers et al, 2004; Walker, 2003).

This paper provides an overview of our research to date, with an explanation of the rationale behind the modeling approach we take, information on the two landscapes evaluated, and preliminary results from the model simulations. We also discuss briefly implications and future research goals.

Study background

The interplay among spatial and temporal patterns and processes collectively shapes and modifies Earth's land use (LU) and land cover (LC). Of possible future outcomes, a given spatiotemporal location is impacted by inherited legacies that are expressed temporally (for example, path dependency), spatially (for example, spatial autocorrelation), or organizationally. Observation of emergent impacts of these contingencies is necessarily scale dependent (Michener et al, 2001). We use dynamic graph-automata models to understand LULCC and population change simultaneously in the study area spanning the Andes to the Amazon. Past LULCC agent-based modeling represents human populations as agents of change acting upon background environmental conditions (Brown et al, 2005). In contrast, we report here on the use of landscape or ecological units acting as agents. It should be noted that, although agency presumes modeling purposive or reactive behavior [as with ants by Haefner and Crist (1994), for genes by Holland (1992), or of ecological units here], this does not imply intent or motive to a given ecological unit (in contrast to Lovelock, 1988). As an example, consider ecological theories of disturbance, in which the interactions between biotic and abiotic factors result in observable system 'reactions', a particular suite of species and characteristics with predictable spatial arrangements or behaviors. However, there is no question of intent or motive here.

It is a standard modeling strategy to represent human agents as vertices of a graph in epidemiology (Meyers et al, 2003; 2005) and in 'generative' models in the social sciences (Epstein, 1999; Epstein and Axtell, 1996). Similarly, individual human agents have been modeled as cells of cellular automata, though this approach has been criticized as simply reinterpreting cellular automata as agent-based models

(Torrens and Benenson, 2005). Dynamic graph automata are models in which agents may be human agents (farmers, heads of household), associations of humans (families, land-tenure holders, communities), or ecological units (remotely sensed and defined patches). The incorporation of a generalized topology (see the next section) and temporal change distinguishes them from cellular automata. In the case study reported here, they are ecological units. Dynamic models allow both agents and their interactions to evolve over time, changing the rules by which they respond to their environment. These models enable the exploration of the effects of scale including, but not limited to, spatial scale. Agent-based models are a generalization of the individual-based models now commonplace in ecology (DeAngelis and Mooij, 2005; Fryxell and Lundberg, 1998; Huston et al, 1988).

By extending such models to both sides of the population – environment interaction, we can assess the usefulness and relative strengths of both approaches in understanding and assessing scale-dependent LULCC as one important example of biocomplexity in natural – human systems (Parker et al, 2003). In generalized agent-based models, it is not necessary to restrict agents to any single type of entity—agents can be defined as individual organisms, human individuals, groups that can act in unison (for example, institutions such as firms), abiotic resources, species, or ecological assemblages as well as ecosystems. (This point does not depend on whether agents are organized as cellular automata or in more general structures such as graph automata).

Representation of different human units (for example, timber concessions, communities, and settlements) as agents is critical to understanding the scale and scope of their impact and organization. Preliminary fieldwork in Peru from 2002 to 2006 suggests that such social agents can each act differently as a function of both general location (lowland versus highland) and culture group (colonist, indigenous, ribereños). Representation of ecological units as agents is a new and important way of conceptualizing ecological organization and its impact on humans and landscapes. Species assemblages found in particular spatial or temporal contexts are among the biophysical features that constitute ecological units in our models. Typically, species that are functionally identical or similar permit generalizations and predictions (Mooney et al, 1996). This analysis uses vegetation studies carried out in Peru over the last two decades but also incorporates methods from landscape ecology and remote sensing to delimit the spatial units corresponding to plant assemblages and other LC types that act with agency in the models.

Dynamic graph automata

In this work, we model all agents and their interactions as dynamic graph automata. Graph automata were introduced as generalizations of cellular automata (Burks, 1970; Gutowitz, 1991) over thirty years ago (Milgram, 1975; Ng et al, 1974a; 1974b; Rosenstiehl et al, 1972; Smith, 1976; Wu, 1978). The basic idea is to connect the cells of cellular automata in a complex network rather than on a regular geometric grid. This mathematical framework has also been called intelligent graphs (Rosenstiehl et al, 1972), polyautomata (Smith, 1976), and web automata (Milgram, 1975; Shah et al, 1973). A slightly more general framework in which each connection is also modeled as an automaton has been called network automata by Rosenfeld (1975). There has been sporadic interest in this framework since its introduction, with its mathematical and computational properties (Rosenfeld, 1975; Rosenstiehl et al, 1972; Wu, 1978) and, typically, its relation to formal language theory being explored (Enshao, 1998; Milgram, 1975; Rosenfeld and Milgram, 1972). The few empirical applications have included reconstruction of serial sections in histology and models of biological self-reproduction

(Tomita et al, 2002). To the best of our knowledge, this is the first use of such a framework in landscape ecology and the study of LULCC.

Part of the generalization of traditional cellular automata to graph automata consists of not restricting all cells to having the same internal transition rules and representation (set or available states), as well as not limiting local geometry to interactions between adjacent cells as specified by some regular two-dimensional geometry. The interactions also need not be symmetric. This means that not all cells are equivalent in the sense of having the same internal rules as well as number and type of interactions as every other cell—this is a more realistic representation of the type of spatial heterogeneity of structure and interactions seen on the landscape or on larger scales. This generalization allows different landscape types to be modeled at the same time, and, more importantly, it allows spatially local interactions to be modeled simultaneously with long-range interactions.

Graph automata are dynamic because of two further generalizations: (i) internal transition rules may evolve and (ii) connectivity between cells can change over time. These generalizations allow representation of temporal heterogeneity. The first generalization also goes beyond the interesting geographical automata systems (GAS) framework proposed recently by Torrens and Benenson (2005). The GAS framework does allow an irregular structure, like graph automata, though connectivity is symmetric. However, because different transition rules may be implemented at different automata, not allowing directionality in the connections is not a serious limitation to what can be modeled in the GAS framework. This framework also allows connectivity to change over time. However, the internal transition rules remain static and spatially contiguous sites are necessarily neighbors even if they do not interact. (The GAS framework also requires spatial locational information as a distinct category, which is part of the definition of an automaton and allows the automaton to change location. In dynamic graph automata, location may be modeled as a state variable and change of location is a change in the value of this variable.) Recently, Syphard et al (2005) used cellular automata that allow rules to change over time to model urban growth in southern California in the sense that some interaction coefficients can vary in their strength (through self-modification). However, their neighborhoods are defined locally on a uniform geometry and do not change with time.

The basic structure of graph automata is that of a directed graph $G = (V, E)$ where V is a (finite) set of vertices (or nodes, or cells) and E is a (finite) set of directed edges, that is, each element $e \in E$ is an ordered pair of vertices, (v_i, v_j), with the v_i, $v_j \in V$ so that e is then interpreted as an edge from v_i to v_j (Diestel, 2005; Harary, 1969). Edges may have weights assigned to them. The number of incident edges at a vertex is called its degree. We assume that each vertex and edge has a label (that establishes its identity for future reference). Each vertex constitutes a (finite-state) automaton with an internal state and transition rules between states. This general definition can be restricted in a variety of ways. In particular, Enshao (1998) requires that the graphs be acyclic, that is, they do not allow a path or continuous sequence of directed edges to begin at a vertex and return to it. Similarly, graphs may be undirected, that is, for every edge (v_i, v_j), there is an edge (v_j, v_i) with the same weight in the opposite direction—in that sense the edges no longer have a directionality associated with them. Tomita et al (2002) require that all vertices have the same degree. In the interest of maintaining generality, we do not impose these restrictions. The more restrictive models can be instantiated within our framework by the features of the vertex and edge sets that are introduced.

Agents, represented by cells in traditional cellular automata, correspond to the vertices of the graph in graph automata. All pairs of vertices connected by edges (in either direction) are 'neighbors' in the sense that they interact with each other.

Due to the freedom of choice in assigning edges between vertices in a graph, specific variable interactions between agents can be incorporated into such models. Any two interacting agents will have an edge between them, irrespective of whether they are spatially contiguous. However, when the graph has a natural spatial interpretation, each vertex will, typically, represent a specific geographical site. As it is a (finite-state) automaton, each vertex has an internal state describing its current features and an internal set of transition rules for the update of this internal state. The states are updated at each time iteration using the internal transition rules, the internal states of all the other vertices connected to it by edges, and the weight of the edge. (Allowing edge weights to be used by the transition rules is a generalization of what is permitted in cellular automata models, which also use internal transition rules and the internal states of neighbors to determine state transitions.) Updating rules are also dynamic and may be deterministic or stochastic. The structure of the graph incorporates our knowledge of the distribution of features on the landscape being modeled. The updating rules incorporate our knowledge of the causal interactions (ecological and social) responsible for changes in the landscape or they are meant to explore particular hypothetical or predicted scenarios.

Beyond this updating protocol, which graph automata share with cellular automata, our graph automata can be dynamic in two other ways. First, the edge set will be potentially modified at each iteration, thus changing which agents interact with each other. Such changes may be due to changing locational context (movement across space by an agent) or ecological context (response to environmental features) or both, and will generally be seen even in short time scales. Formally similar edge modification was considered by Milgram (1975). Second, the vertex set can also change insofar as vertices can disappear, be added, or have their internal rules changed. This characteristic changes the behavior of an agent and is likely to occur on longer time scales. Each vertex, or agent, has a label establishing its identity, therefore, it can be tracked individually over time. While the results reported here do not exploit such dynamism, our future work will explore more complex contexts in which such dynamism cannot be ignored.

Landscape model

Spatial contingencies can be modeled by incorporating different internal updating or transition rules to vertices corresponding to different spatial locations and definitions of neighborhood. Dynamic graph automata allow temporal contingencies to be modeled at two scales—a shorter scale modeled using updates of the edges connecting vertices (corresponding to changes in the set of interacting agents), and a longer scale modeled by changing the vertex set, that is, the internal rules by which agents respond to their environments. Modeled ecological units acting as agents will include dominant functional-vegetation communities and ecosystems with features that determine their ‘behavior’ (for example, recovery rates after disturbance) under the impact of local environmental conditions (for example, soil quality, precipitation) and type of disturbances (including anthropogenic changes). Human agents are defined via modeling of data from community surveys, interviews, and other sources. These behaviors form the internal transition or updating rules at each vertex. As in traditional cellular automata, these internal rules, along with the internal states of connected vertices, will be used to update the internal state of each vertex.

Using this approach, landscapes that are Amazonian (specifically near the rapidly growing city of Iquitos, Peru) and tropical Andean (small towns, rural farming areas), and a protected national park in north-central Peru (the Rio Abiseo National Park, to the east of the Marañon River and to the west of the Huallaga River) were each modeled using as input Landsat TM-derived Level 1 classifications including the classes forest, nonforest vegetation, water, and urban or bare (soil) for the Amazon and forest, scrub, agriculture, and rock or bare for the Andes. Rules were established independently to set conditions for change on the basis of fieldwork including vegetation plots or transects and informal interviews (see below). Additional processing also included extraction of cloud or shadow and stratification (in the Andean site) for improved vegetation discrimination.

These two landscapes are end members in a transect that goes partly along the early exploration routes of Ruiz and Pavón from near Lima towards the Amazon in the 1770s and 1780s (Ruiz, 1998). It also straddles the first Amazon-directed penetration road built in the central Andes over several decades, beginning in the 1940s and continuing into the 1970s. The city of Pucallpa is currently the end of this road, and there are continual attempts to link it someday soon to Brazil. The Ucayali River connects Pucallpa to Iquitos. Although Achard et al (2002) highlighted the deforestation to be found in the eastern part of the study transect (that is, in the western Amazon), few integrated remote-sensing mapping and analysis projects have been undertaken in this area, although there is some information on the actions of colonists and local inhabitants (Bedoya Garland, 1995). The high mountains to the west host ice caps and tropical alpine vegetation (Young et al, 1997). Most of the other mountain LC is rocky slopes, scrublands, or agricultural vegetation (Young and León, 1995; 2001). LU includes tuber and grain agriculture, with varying dependencies on grazing. Eastern-slope pluvial montane forest is found in narrow belts, due to steep slopes, and it is often uninhabited.

Basic graph structure

The graphs used in the landscape simulations reported here had land units as vertices. Each such unit was a 900 m^2 landscape patch, which is the resolution of the TM data. Thus, a vertex corresponds to each pixel of the satellite image. Each such vertex has a (directed) weighted edge, of weight 1, to each of its neighboring ($\leqslant 8$) pixels (forming its Moore neighborhood). The ecological type of a vertex corresponds to the state of a cell in a conventional cellular automata model. A contiguous set of vertices is one in which each vertex is connected to every other vertex in the set through edges of weight 1. The structure so far is that of a cellular automata model interpreted as a graph. However, the additional edges defined below for each individual study region, and the fact that the edge set changes over time, takes us into a nontessellated dynamic framework beyond cellular automata. These additional edges connect each vertex to those vertices that may influence it. Note that all edges are directed from a vertex that is influenced by another, to the one that produces that influence. More detail of each landscape will be given in the next section, which is about transition rules. These rules determine the structure of each graph. In our dynamic framework, connectivity and transition rules come together.

Andean study region

The study region in the Andes consisted of 304 976 ha. The Andes graph contained 6 166 960 vertices, of which 2 778 337 were 'masked' or excluded to make the area evaluated correspond to the western buffer zone of the Rio Abiseo National Park (Kintz et al, 2006). Vertices can be of four types—forest, scrub, agriculture, and rock or bare. First, each forest or scrub vertex is connected by an edge to all vertices that can be reached from it by a path of weight $\leqslant 3$, with the weight of the edge being the length of the path. Note that the edge set will change over time as there are transitions from one type of vertex to another. Second, an additional edge set was introduced for this graph. This edge set was based on estimates of influence on the different vertex types derived from earlier work describing seral and successional stages of vegetation (Young, 1998a; Young and León, 2007), reported and hypothetical climatic shifts (Young and Lipton, 2006), land conversion rates based upon population and labor estimates, and field observations over twenty-two years (Young, 1993a) including about 230 interviews regarding LU and conversion (Kintz et al, 2006; Postigo, 2006; Young, 1993a; Young and Lipton, 2006).

Amazonian study region

The total area of the Amazon study region was 3 237 500 ha. For computational tractability, only a subset of the region was used in these simulations. The subset had an area of 754 961 ha and was chosen at random and modeled as 8 612 624 vertices; of these 224 158 had to be excluded because of cloud cover. Vertices, or cells, can be of four types—forest, nonforest vegetation, water, and urban or bare. Each urban or barren vertex is connected by an edge to all vertices that can be reached from it by a path of weight $\leqslant 5$. This number was based on observed average influence of land units on each other in the study region. An additional edge set supplemented these connectivity relations. Each forest or nonforest vegetation vertex is also connected by an edge to all vertices that can be reached from it by a path of weight $\leqslant 15$. Each water vertex is also connected by an edge to all vertices that can be reached from it by a path of weight $\leqslant 3$. In each case, the weight of the edge is the length of the relevant path. Once again, the edge set will change over time as there are transitions from one type of vertex to another. The additional edge set for this graph was based on estimates of influence derived from vegetation transitions observed in both flooded forests and terra firma forests (Pitman et al, 2001; Salo et al, 1986; Wittmann et al, 2004), agricultural seral and successional stages (Chibnik, 1994; Crews-Meyer, 2006; Pinedo-Vasquez et al, 2002), previous analysis of phenological changes (McCleary et al, 2007), infrastructure growth, population, and labor estimates (Kalliola and Flores-Paitán, 1998; Mäki et al, 2001), 423 semistructured interviews, and 26 years of field observation.

Automata transition rules

For both the Amazon and Andes LULCC simulations in this study, LC-type transitions can occur once per modeling time step (annual interval), and what change occurs at a vertex depends on the types of its neighboring vertices (connected to it by an edge). Variable dependencies on spatial distance between vertices or cells are modeled by the weights of edges that may connect neighboring or distant patches. The transition rules thus specify probabilities of type-specific LC-type change that determine the future LC type of that patch.

Andean transitions

In the topical Andes, landscapes have been altered over millennia by LU (Gade, 1973; Sarmiento, 2003; Young, 1998a). Recently, a landscape-change study was conducted by Kintz et al (2006) to evaluate LULCC along the boundary of Rio Abiseo National Park, located in the northern Peruvian Andes. Previously, Young (1993a) obtained information on the vegetation types and LU systems, in the process delineating four ecological zones across the cordillera where the park and human settlements are located. Highland rules of change for the modeling were derived from those two studies and the classified 1987 TM image, in addition to other observations made elsewhere in the Andes. Further, rather than simply using only those conditions observed in the field or in imagery, a scenario of continued climate shifting towards warmer and dryer conditions as well as greater decentralization (resulting in decreased conservation management) were used to generate the rules.

Recall that vertices, or cells, can be of four types: forest, scrub, agriculture, and rock or bare. LC-type transitions can occur annually and are permitted if a certain cell is within a specified neighborhood of a cell of some type, which has a given number of contiguous neighbor cells of that same type. On the basis of this binary distinction, type-specific probabilities of LC-type change determine the future LC-type of that certain cell. The rules that follow will be stated using 'cells' to make their description correspond as closely as possible to transition rules in the more familiar cellular automata framework.

The following type-specific rules and probabilities governing LC change were used sequentially to determine the transition at each cell.

1. If a cell is forest, and is connected by an edge of weight $\leqslant 3$ to a group of at least sixteen contiguous nonforest cells, the transition probabilities are—forest, 0.94; bare or exposed, 0.02; agriculture, 0.04. Otherwise, the cell will remain forest.
2. If a cell is scrub, and is connected by an edge of weight $\leqslant 2$ to a group of at least four contiguous forest cells, then it has a 0.03 probability of becoming forest. Scrub cells that do not change under this rule, and are connected by an edge of weight $\leqslant 3$ to a group of at least sixteen contiguous agriculture cells, have a 0.05 probability of becoming agriculture. Scrub cells that have not changed under either of the previous two rules have the following transition probabilities—forest, 0.005; scrub, 0.985; bare or exposed, 0.005; agriculture, 0.005.
3. If a cell is agriculture, it will not change.
4. If a cell is bare or exposed, it will not change.

Each iteration used these rules stochastically, reflecting the probabilities of change from one type to another. Note how the nature of the transitions depends on what a vertex (cell) is and also on which vertices are relevant to its future—the geographical range of these depends on each cell's class, thus resulting in a nonuniform geometry for these automata. The transition probabilities were derived from land-conversion rates, which, as noted earlier, were based upon population and labor estimates, and field observations over twenty-two years including interviews (see the subsection entitled Andean study region, above).

Amazonian transitions

The Amazon lowlands are broken by several outer cordilleras of the Andes that reach 2400 m and are capped by cloud forests. The lowlands near Pucallpa were deforested in the 1960s and 1980s for colonization and pasture establishment, then, increasingly, for the planting of coca (Young, 2004). River meandering and associated cutoffs are dramatic biophysical-change agents in the greater Iquitos area (see, for example, Kalliola et al, 1991; Puhakka et al, 1992; Räsänen et al, 1990; Salo et al, 1986; Tuomisto et al, 1994; 2003). In addition, the population of the city and periurban areas of Iquitos continues to increase due to in-migration, while outlying areas change by conversion of forest to agriculture or to the relatively small road network developing to the south of the city.

The most conspicuous consequence, in addition to deforestation, is the growth of Iquitos. There is a direct physical transformation at city margins as pastures, fields, and forests are converted into housing, often by unplanned squatter settlements that are then upgraded over the following decades (Mäki et al, 2001). However, there is also a profound alteration of economic possibilities for even fairly remote rural localities due to the growing urban markets. In some cases, however, urban-based residents might be owners or control decisions out in the rural hinterlands, especially when rural residents do not have land titles or their communities do not have effective control of access to land and resources. For example, commercial fishing operations out of Iquitos and Pucallpa exploit freely fish found in oxbow lakes of the floodplains during the high-water season when boat accessibility is easy and local communities cannot restrict access (Smith et al, 2002).

The rules of change which we used accounted for these shifts, although consequences of some processes were necessarily obscured because of the use of combined classes such as bare soil and urban, or nonforest vegetation. Recall that vertices can be of four types—forest, nonforest vegetation, water, and urban or bare. The following type-specific rules and probabilities governing LC change were used sequentially to determine the transition at each cell.

1. If a cell is urban or bare, and is connected by an edge of weight $\leqslant 5$ to a group of thirty contiguous urban or bare cells, then the cell will remain urban or bare. Otherwise, the probabilities of LC transition are—water, 0.0475; urban or bare, 0.0975; forest, 0.19; and nonforest vegetation, 0.665.
2. If a cell is forest, and is connected by an edge of weight $\leqslant 3$ to a group of fifteen contiguous nonforest vegetation cells, then it has a 0.20 probability of becoming nonforest vegetation. For cells that do not change under this rule, and are connected by an edge of weight $\leqslant 15$ to a group of at least ten contiguous water cells, the transition probabilities are—water, 0.01; urban or bare 0.01; forest, 0.93; nonforest vegetation, 0.05. All other cells have the following transition probabilities: urban or bare, 0.10; forest, 0.85; nonforest vegetation, 0.05.
3. If a cell is nonforest vegetation, and is connected by an edge of weight $\leqslant 3$ to a group of at least fifteen contiguous nonforest vegetation cells, then the cell will remain nonforest vegetation. For cells that do not meet this rule, and are connected by an edge of weight $\leqslant 15$ to a group of at least ten contiguous water cells, the transition probabilities are—water, 0.10; urban or bare, 0.40; forest, 0.40; nonforest vegetation, 0.10. All other cells have the following transition probabilities—urban or bare, 0.18; forest, 0.27; nonforest vegetation, 0.55.
4. If a cell is water, and is connected by an edge of weight $\leqslant 3$ to a group of at least six contiguous nonwater cells, the transition probabilities are—water, 0.889; urban or bare, 0.455; nonforest vegetation, 0.555. An exception to this rule occurs if the cell is also connected by an edge of weight $\leqslant 5$ to a group of at least fifty contiguous forest cells, in which case it will remain water. All other cells have the following transition probabilities—water, 0.96; urban or bare, 0.03; nonforest vegetation, 0.01.

The transition probabilities were derived from observed LC transitions, analysis of phenological changes, and growth estimates as noted earlier (see the subsection entitled Amazonian study region, above).

Computations

All computations used for the above analyses were performed on a Dell PowerEdge 2850 with a 2 GHz Pentium 4 Xeon CPU and 8GB RAM. All software was written in C^{++} and is platform independent (and can be compiled using the GCC compiler collection). The software can be obtained by contacting the authors.

For the Andes, the 15-year simulation (15 equal time intervals) was repeated 1000 times. The average (real) time per simulation per year was 4.96 seconds. In the case of the Amazon dataset, rule complexity in terms of spatial interactions was much higher. Once again, 1000 simulations were carried out for a 15-year period. The average (real) time per simulation per year was 47.76 seconds. In both cases, simulation time increased sublinearly with the size of the dataset.

Results

In both the modeled Amazonian and Andean cases the internal-state transformation of a landscape cell depended probabilistically on the states of all cells within a prescribed radius, not just adjacent cells. Tables 1 and 2 describe the frequency matrix of vertex-type (that is, LC-type) transitions over all 1000 simulations (see, figures 1 and 2).

Table 1. Change matrices for all simulations: Amazonian model. Amazon percentage landscape per change class for all 1000 simulations (bold type indicates stable classes); total change = 37.53% of the landscape.

Initial conditions	Conditions after fifteen years			
	water %	urban or bare %	forest %	nonforest vegetation %
Water	**3.20**	1.20	0.22	0.22
Urban or bare	0.16	**6.92**	5.15	1.35
Forest	1.16	10.34	**45.81**	1.16
Nonforest vegetation	0.21	0.85	2.79	**6.54**

Table 2. Change matrices for all simulations: Andean model. Andes percentage landscape per change class for all 1000 simulations (bold type indicates stable classes); total change = 27.34% of the landscape.

Initial conditions	Conditions after fifteen years			
	forest %	scrub %	rock or bare %	agriculture %
Forest	**7.93**	4.14	2.09	1.30
Scrub	5.96	**63.32**	3.75	2.02
Rock or bare	0.33	4.78	**1.31**	0.27
Agriculture	0.24	2.11	0.34	**0.10**

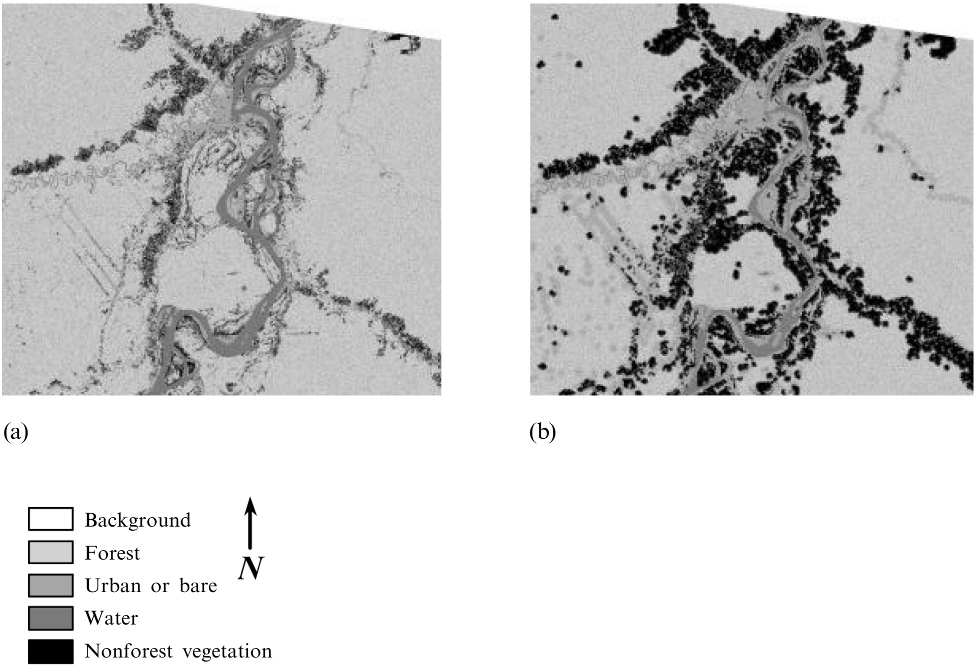

Figure 1. Amazonian change over fifteen years (run 805): (a) initial conditions; (b) fifteen years later.

In general, results to date indicate that LULCC, while more nuanced in the Andean site, poses a serious threat to compositional and configurational landscape stability from the Andes to the Amazon. The frequency of LC-type (that is, composition) and their spatial structure (configuration) change. The Amazonian site exhibited greater areal or compositional change with markedly distinct spatial trends. In contrast, the Andean site showed less overall compositional change but greater structural change (particularly fragmentation). In the not too distant (modeled) future, the Amazonian landscape will become dominated by a landscape matrix of deforested land. In contrast, the Andean change is in some ways both more prevalent and less dramatic. The scrub-cover type will remain dominant, forming the landscape matrix, but land devoted to agriculture or left fallow will spread over much of the modeled area (as no spatial constraints were imposed, for example in relation to the boundaries of the national park).

Figures 1 and 2 show the overall change in one randomly selected simulation for the Amazon and Andes landscapes, respectively. Tables 3 and 4 describes the frequency matrix of vertex-type (that is LC-type) transitions in these simulations. The 805th run (chosen randomly) of the Amazonian model of continued peri-urban expansion and development given shifting river conditions (see figure 1) illustrates the type of marked change observable in many frontier areas of the Amazon (Walsh et al, 2002). Roughly 38% of the landscape was a different category in year 15 than in the initial condition. Just over 45% of the landscape was forested throughout the time steps, with 6 – 7% each in stable agriculture or urban expanses. The three most commonly observed changes were forest to nonforest vegetation (nearly 14%), forest to urban or bare (10% of total landscape), and urban or bare to forest (5%). Almost one quarter of the entire landscape was taken from forest into another use. Importantly, the rules successfully placed

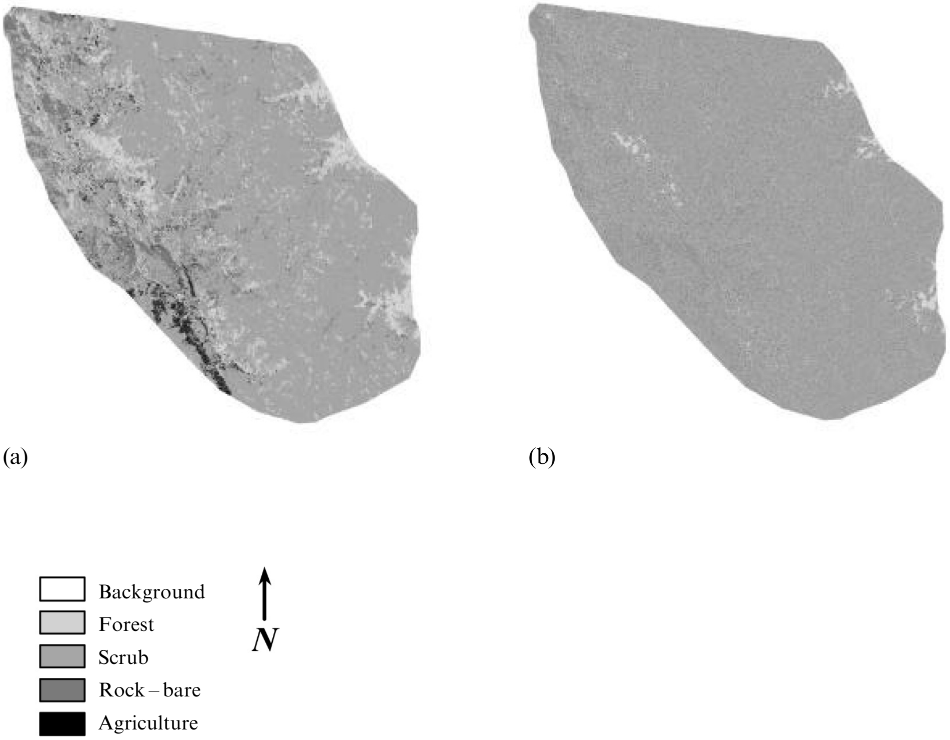
(a) (b)

Figure 2. Andean change over fifteen years (run 221): (a) initial conditions; (b) fifteen years later.

Table 3. Change matrices for randomly chosen simulations: Amazonian model. Amazon hectares and percentage landscape per change class for run 805 (bold type indicates stable classes); total change = 286 133 hectares or 37.9% of the landscape.

Initial conditions	Conditions after fifteen years			
	water %	urban – bare %	forest %	nonforest vegetation %
Water	**23 901/3.2**	9 150/1.2	1 946/0.3	1 729/0.2
Urban or bare	1 286/0.2	**51 988/6.9**	39 597/5.2	10 543/1.4
Forest	8 968/1.2	78 102/10.3	**343 810/45.5**	104 402/13.8
Nonforest vegetation	1 729/0.2	6 821/0.9	21 861/2.9	**49 131/6.5**

Table 4. Change matrices for randomly chosen simulations: Andean model. Andes hectares and percentage landscape per change class for run 221 (bold type indicates stable classes); total change = 84 467 hectares or 27.7% of the landscape.

Initial conditions	Conditions after fifteen years			
	forest %	scrub %	rock or bare %	agriculture %
Forest	**24 127/7.9**	12 836/4.2	6 509/2.1	4 054/1.3
Scrub	18 143/5.9	**191 927/62.9**	11 625/3.8	6 273/2.1
Rock or bare	1 048/0.3	14 671/4.8	**4 084/1.3**	908/0.3
Agriculture	772/0.3	6 529/2.1	1 099/0.4	**371/0.1**

deforestation along emerging agriculture, transportation, and development corridors and also facilitated the spontaneous clearings in deeper areas of the forest commonly observed but more difficult to model. Thus both agricultural extensification and densification (perhaps, though not necessarily, intensification) were adequately simulated. The conversion of urban or bare areas to forest might seem unusual, but in fact are representative of two phenomena observable in many areas of the Amazon. These are (i) the greening of central business district spaces through park planning and streetscaping, and (ii) the succession following a deforestation cycle of clearing and abandonment. An interesting result was the rather spontaneous development (into either agriculture of urban or bare) of remote areas proximate to very small backwater streams, underscoring the importance of resource access in these areas.

The 221st run (chosen randomly) of the Andean model (see figure 2) shows a very differently configured landscape. Though the overall change is lower than that in the Amazonian site (roughly 28% of the landscape changed, as opposed to 38% in the Amazon), the arrangement of landscape elements changed much more in the Andean site. Under the scenario of decentralization and continued warming, the matrix of the landscape is still scrub, with almost 63% of the landscape existing as scrub in both the initial condition and after fifteen years. Roughly 4 – 6% of the landscape switched from scrub to forest and vice versa, with scrub also gaining another 5% of the landscape from rock or bare. Figure 2 illustrates the overall change, where the dissolution of forests is clear (particularly in the conservation areas in the eastern extent), as is the breakdown of the amalgamation of agricultural lands in the western portion. However, what is most striking about this figure is the not entirely predicted rate of fragmentation of all LULC classes in the landscape. Figure 3 shows a subset of one of the protected forest areas from the eastern edge of the image. At this scale, the fragmentation and reorganization of the landscape are easier to see and the likely ecological impact easier to impute (Forman, 1995). The conservation forest, under this scenario,

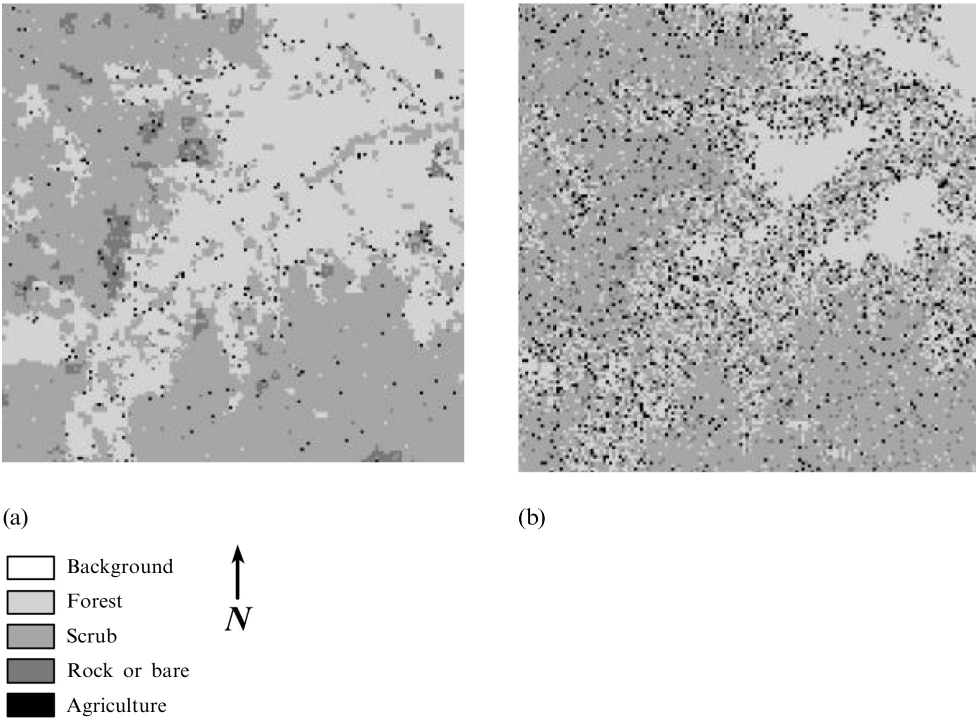

Figure 3. Subset of Andean forest transition over fifteen years (run 221): (a) initial conditions; (b) fifteen years later.

is deteriorating in a spatial manner such that it is mostly remnant patches incapable of providing core forest ecosystem services. Also notable is the manner in which agriculture has spread over the landscape in a disconcerted yet pervasive manner. The rules used in this scenario did, as per the strength of dynamic graph automata, take into account spatial relationships in terms of both proximate and distal neighborhood effects and the representation of treeline (here, 3000 m) derived from a digital elevation model as a proxy for important geomorphic and climatic effects (Walsh et al, 2003; Young and Lipton, 2006). However, the rules were not written explicitly to evoke a particular pattern of fragmentation, and so the result is instructional in considering the emergent properties of a dual scenario of decentralization and continued warming.

Discussion

Our basic framework consists of dynamic graph automata which are generalizations of cellular automata. This generalization enables flexible, dynamic updating of neighborhood relationships, which permits the integration of interactions at widely varying spatial scales and also allows the interactions to evolve over time (though the examples used here do not exploit this capacity). While our use of nonuniform geometry provides us with increased modeling flexibility, it adds to the computational complexity of an already volume-intensive data process. Even though we made significant progress in rapid computation and estimated that computing time only increased sublinearly with the problem size, we predict that a full dataset (with sampled areas subset into nested 50 000 000 cell partitions) with more complex rules can only be simulated (with 1000) runs on a 3 GHz machine with 8 GB RAM and 4 CPUs in roughly 250 hours of computing. Similarly these computations require access to large quantities of data in

RAM which, in the long run, may be the most important constraint on extending further the size of the landscape that can be modeled. However, these technological limitations are not debilitating given the continuing and expected improvements in computer performance. Even our initial results show that modeling landscapes on a continental scale is feasible in this framework. Moreover, the flexibility brought by this framework to allow nonuniform geometry and dynamic updating of both rules and geometry will potentially add realism to these models. Our results illustrate how spatially explicit and distributed dynamic models can be used to model LULCC due to both anthropogenic and natural mechanisms. Such models allow multiple agents with different characteristics to reside in a given area and yet act differently based upon models of their behavior.

Future research will extend this effort, (i) by utilizing remote-sensed data from other sensors, allowing for testing the effect of scale extent and resolution on outcomes, (ii) by making possible further development of this novel approach that models the landscapes as sets of cells that form graph-based automata that allow causal connectivity between geographically nonadjacent cells, and (iii) by comparing those model outcomes with expectations on how spatial and temporal contingencies interact with the social and ecological organization of landscapes along a complex environmental gradient and under differing biophysical and socioeconomic regimes.

The overall study area includes a particularly overlooked portion of the Andes that is crucial because of the high species diversity and turnover (Berry, 1982; Leo, 1980; 1995; von Humboldt and Bonpland, 1818; Young and Reynel, 1997). Although there are continental-scale maps of forest cover (Achard et al, 2002), more regional and local LC mapping efforts are sorely lacking. There are new road building and colonization projects, often funded by international donors, with goals for the economic integration of Ecuador, Peru, and western Brazil. Several large sectors are traditionally used by indigenous groups, while there are other areas designated for formal conservation in the national protected-area system and still others declared for oil or timber extraction.

The overall aim of our modeling effort is to predict the consequences of behaviors such as that of agents migrating, invading, retreating, or integrating with other such agents at different levels of the ecological and spatial hierarchies. The behaviors of different ecological units result in landscape pattern, the observation of which is scale dependent. Multiple aspects of landscape pattern, as a function of time, space, and level are of interest, (i) transformations of community assemblages, corresponding to migration, disappearance and reappearance of specified types of agents—for both ecological units and social units, (ii) fragmentation per se (beyond mere loss) of habitat types (Fahrig, 2003) or human settlement as measured by a variety of indices (McGarigal and Marks, 1995), (iii) landscape perception and management as mitigated by factors such as socioeconomic status as a function of accessibility, and (iv) clustering and dispersion of different habitat, human settlement, and LULC types across the landscape.

This research will complement and enrich recent modeling efforts that involve LULCC and are already exploring the effects of adding spatial constraints (Coppolillo, 2001), temporal controls tied to concurrent climatic and institutional change (de Beurs and Henebry, 2004), landscape metrics (Parker and Meretsky, 2004), and other approaches adapted from landscape ecology and GIScience (Jepsen et al, 2005; Young and Crews-Meyer, 2006), migration and other sociodemographic data (Henry et al, 2003), environmental consequences of different kinds of landscape change (Soares-Filho et al, 2004), behavioral rules (Walker et al, 2004), and management outcomes (Bousquet and Le Page, 2004; Huth et al, 2004). It will also provide another example of a research methodology designed to isolate and identify scale-related and scale-specific phenomena (Evans and Kelley, 2004; Ju et al, 2005; Vermaat et al, 2005).

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