Pattern-Process Relations in Coupled Human-Natural Systems: Modeling LULC Dynamics in the Ecuadorian Amazon

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Introduction

**Some Questions:** What are the rates, patterns, and mechanisms of forest conversion to agriculture, pasture, secondary plant succession, and urban uses? What are plausible scenarios of future land cover change and their policy implications?

**Some Goals:** Spatially simulate and model patterns of landscape change (e.g., deforestation, urbanization, crops/pasture, land fragmentation, change patterns), assess their causes and consequences and derive policy implications.

**Some Approaches:** Generalized Linear Mixed Models, Spatial Regression Models, Multi-Level Models, Neutral Models, and Spatial Simulations using Cellular Automata & Agent Based Models.
Settlement Patterns Affecting Analysis Design

The Ecuadorian “fishbone” or “piano key” settlement pattern is characterized by on-premise management and a distinct linear pattern.
Sample Households & Survey Sectors

1990 & 1999
GIS Data Inventory

Political & Cultural
- Provinces
- Parroquias
- Cantons
- Major Cities in the Oriente
- Cuyabeno Wildlife Reserve
- Yasuní National Park
- Sector boundaries (Sucumbios, Orellana, Napo)


Road Network

Physical Environment
- Rivers & Lakes
- Morphology & Edaphology

Topography
- Elevation and terrain data

Remotely-Sensed Imagery
- Air photos (1990)
- Land Use/Land Cover Classifications (1986 – 2003)
- Hyperion Hyper-spectral (2005)
- Radarsat (2005)
- Digital aircraft Hyper-spatial (2005)
Models of Land Use/Cover Change: Recent Research

(1) Land fragmentation
   Generalized Linear Mixed Model

(2) Spatial simulations - LULC Change
   Cellular Automata

(3) Household adaptations & LULCC
   Agent Based Models
(1) Land Fragmentation

A measure of clumping or aggregation of pixels used to show degree of fragmentation, but is dependent upon pixel adjacency:

- Measurement resolution
- Raster and landcover type orientation
- Variable numbers of LULC classes
Generalized Linear Mixed Model
-- Contagion --

**1990 Model**
- Intercept\(^a\) (55.35)
- Median slope\(^c\)
- Flat (% of fincas)\(^b\)
- Ave. age of head\(^a\)
- # adult females\(^c\)
- Yrs plot established\(^a\)
- Population density\(^b\)
- #subdivisions\(^c\)
- # sub within 3-km\(^a\)
- Per-mon of OFE\(^a\)
- Euclidean distance to Ref. Com\(^b\)
- Residual 112.37, random intercept 42.38, rho 0.27

**1999 Model**
- Intercept\(^a\) (37.23)
- Population density\(^c\)
- Access to electricity\(^b\)
- Euclidean dist. to ref. com\(^c\)
- Distance to water\(^a\)
- Residual 72.09, random intercept 5.48, rho 0.07

“\(^a\)” indicates p-value<0.01; “\(^b\)” indicates p<0.05, “\(^c\)” indicates p<0.10
Selected Findings

- Rapid population growth caused substantial subdivisions of plots, which in turn has created a more complex and fragmented landscape in 1999 than in 1990.

- Key factors predicting landscape complexity are population size and composition of households, plot fragmentation through subdivisions, expansion of the road and electrical networks, age of the plot (1990 only), and topography.
(2) Spatial Simulation of LULC Change & Cellular Automata

**Goal:** Generate LULC simulations based upon actual conditions observed through the satellite time-series and extended in time & space through derived growth rules and neighborhood interactions.

**Approach:** Regular grid of cells, each of which can be in one of a finite number of $K$ possible states, updated synchronously in discrete time steps according to a local, identical interaction rule. The state is determined by the previous states of a surrounding neighborhood of cells, and the rule is specified in the form of a transition function.
Forest to Non-Forest Vegetation

- Travel distance to nearest of 3 major communities; lower, greater change probability; computed as Euclidean distance to the nearest road and then simple distance along network to the community.
- Euclidean distance to nearest road; lower, greater change probability.
- Sector population; higher, greater change probability.
- Slope angle; lower, greater change probability.
- Soil moisture index; lower, greater change probability.
- Parameters: stochastic (0.06), kernel threshold (4 cells), masking threshold (0.4).
Cell Suitability

GIS inputs
Compute cell suitability derived from static & dynamic GIS inputs

Class Growth: stochastic + diffusive

Landsat TM landcover
Year = 1986

Separate classes

Urban
Agriculture
Pasture
For. Succession

Flux classes

Class transition probabilities (sat. time series)

Resolve class competition based on suitabilities

Merge classes
Year +1

Final model year?

No

Yes

Modeled landcover

END
South ISA: Simulation

2010

- **Forest**
- **Agriculture/Pasture**
- **Urban/Barren**
- **Water**
(3) Household Adaptations & Agent Based Models

- Autonomous decision-making entities (agents), an environment through which agents interact, rules that define the relationship between agents and their environment, and rules defining the sequence of actions in the model.

- Complex adaptive systems are self-organized systems that combine local processes to produce holistic systems.

- Macro-level behaviors “emerge” from the actions of individual agents as they learn through experiences and change and develop feedbacks with finer scale building blocks as agents.
Multi-Phasic Response Theory

LULC change is the spatial explicit response of the set of household adaptations to the changing socioeconomic conditions and environmental factors.

The strategies that the household take to improve life conditions are:

- Intensifying land use
- Extensifying land use
- Temporary migration
- Permanent migration to areas with available land
- Fertility decline
Household Life Cycle

1) Young parents who recently arrived in the area initiate forest clearings for subsistence crops.

2) Parents with growing children become engaged in the cultivation of cash crops and pasture.

3) Older parents with teenage children are related to a decrease in the cultivation of annuals and an increase in cattle raising and secondary vegetation.

4) Pasture and perennial crops dominate with increasing proportions of secondary forest as parents age and children reach young adulthood.

5) Children begin to leave the household or subdivide the farm.
Basic Components of the System

- Demographic System
- Agricultural System
- Labor and Mobility System
- Uncertainty System
- Cultural System

Decision-Making

Land Change System

Basic land use classes:
- Primary Forest
- Fallow
- Cash Crops
- Subsistence Crops
- Pasture

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Selected Findings

- Human frontier settlements exhibit self-organized complexity; feedbacks exist between spatial pattern and process.
- Emergent behavior of farmers is seen at macro-level development fronts.
- Changes in land tenancy and the implementation of protective buffers around and within protected areas can increase deforestation and land fragmentation.
- Forest succession and fallow are related to OFE, household assets, male adults, & legal title.
- Spatial structure of LULCC are related to household demographics, labor, change in pop density, year of farm establishment, & farm size.