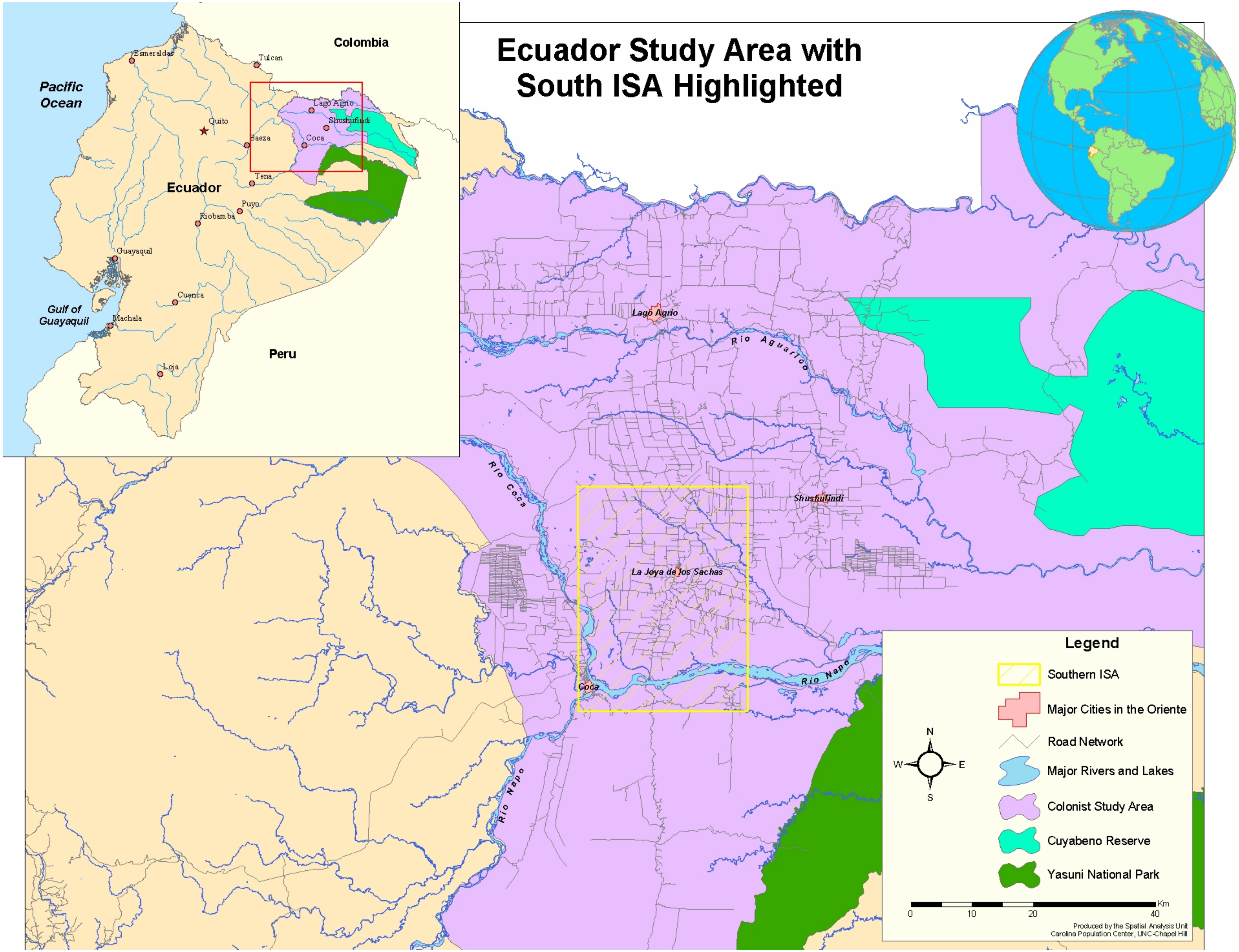
# Modeling the Scale Dependent Drivers of LCLU Dynamics in Northeastern Ecuador

Stephen J. Walsh & Richard E. Bilsborrow, Co-PIs
Dept. of Geography & Biostatistics, Carolina Population Center
University of North Carolina – Chapel Hill, USA

George P. Malanson, University of Iowa, Co-Investigators
Joseph P. Messina, Michigan State University
Galo Medina, EcoCiencia, Quito, Ecuador
Brian Frizzelle, Spatial Analyst, Carolina Population Center
Carlos F. Mena, Christine M. Erlien, Michael Bacon,
Alisson Barbieri, Graduate Research Assistants
William Pan, UNC Post-Doc (now at Johns Hopkins University)

http://www.cpc.unc.edu/projects/ecuador

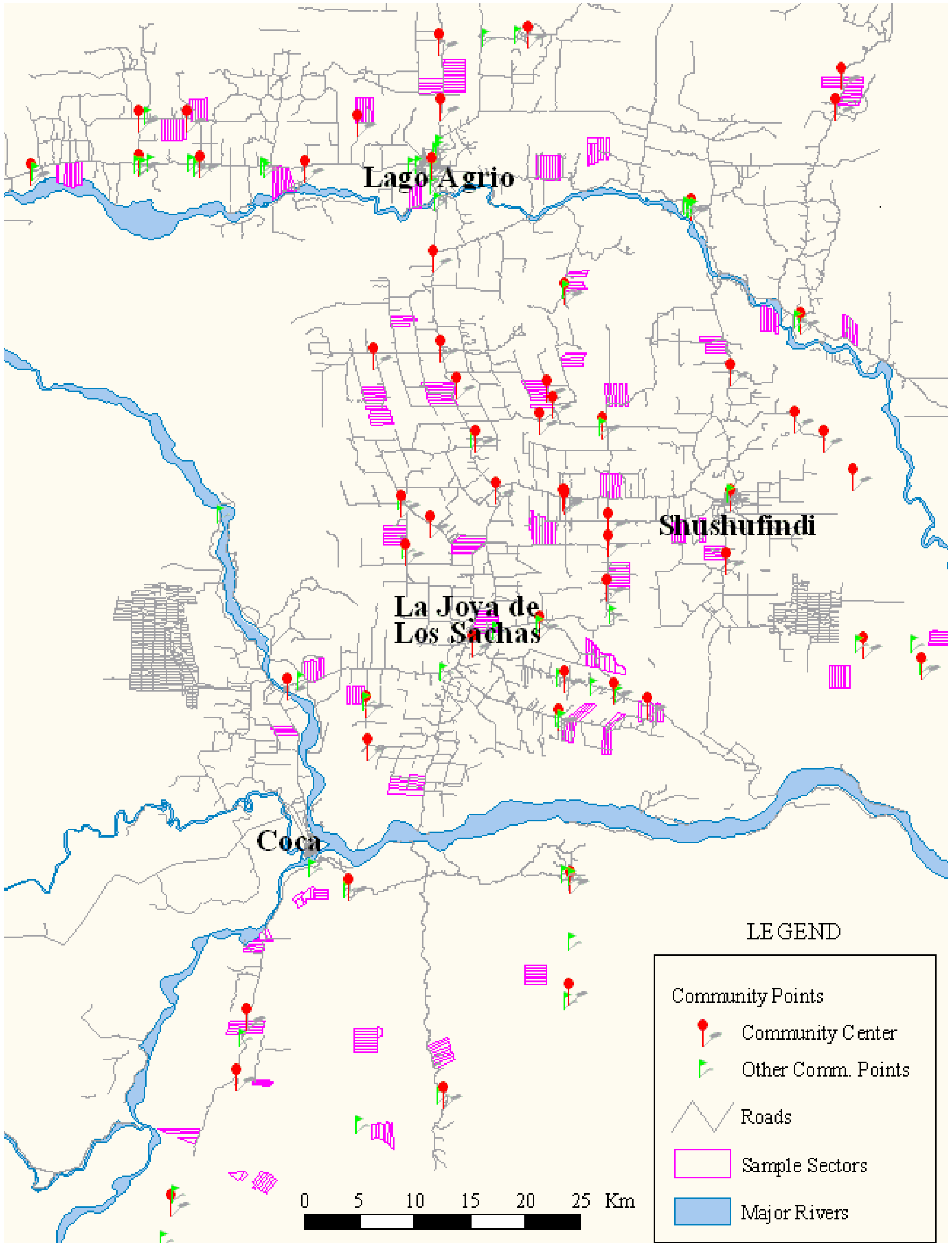


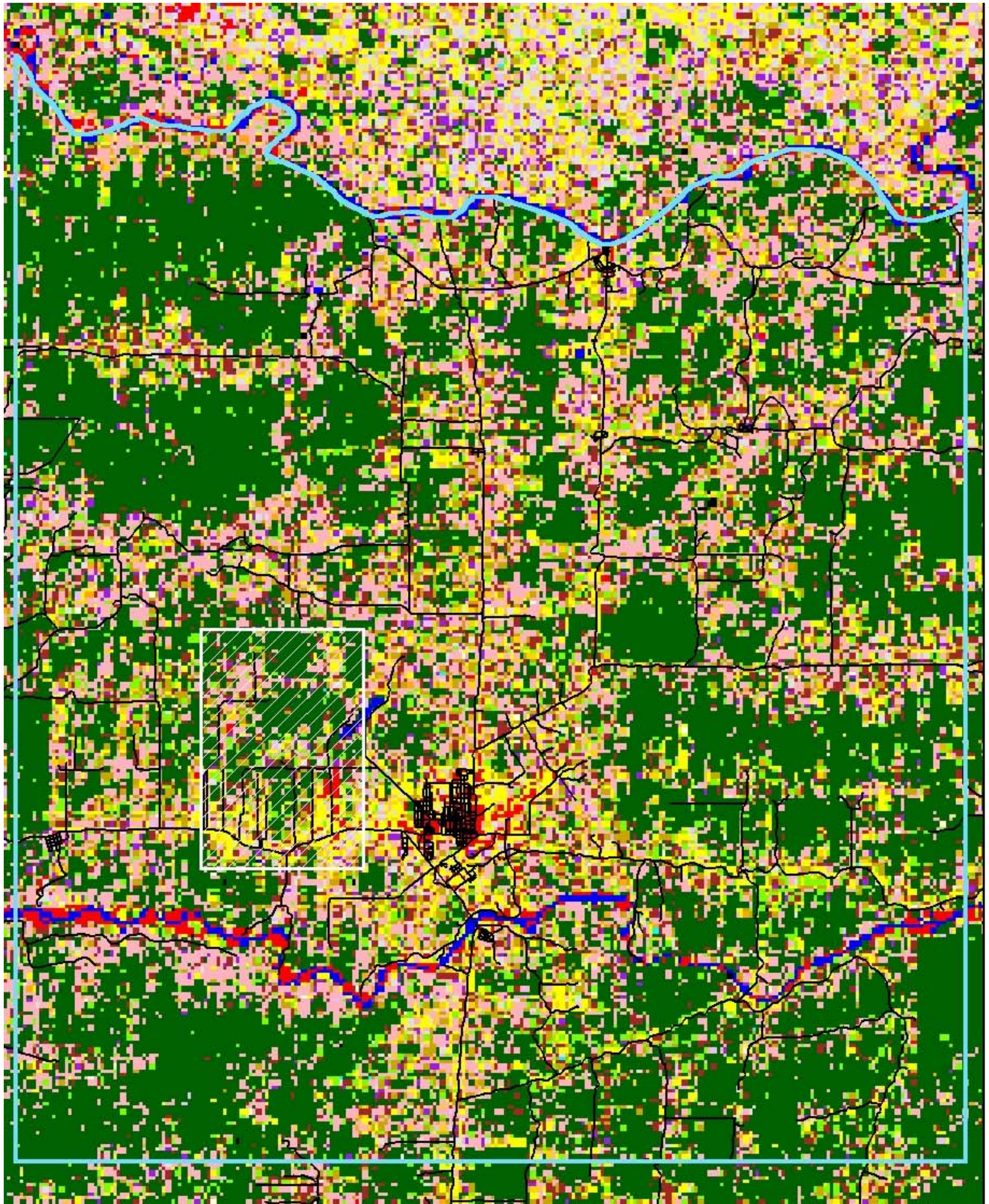
Ecuador Study Area with
South ISA Highlighted
Colombia
Pacific Ocean
Esmeraldas
Tulcan
Quito
Baeza
Lago Agrio
Shushufindi
Coca
Tena
Puyo
Riobamba
Ecuador
Guayaquil
Cuenca
Gulf of Guayaquil
Machala
Loja
Peru
Lago Agrio
Rio Aguarico
Rio Coca
Shushufindi
La Joya de los Sachas
Coca
Rio Napo
Rio Napo
Legend
Southern ISA
Major Cities in the Oriente
Road Network
Major Rivers and Lakes
Colonist Study Area
Cuyabeno Reserve
Yasuni National Park
N
W
E
S
Km
0
10
20
40
Produced by the Spatial Analysis Unit
Carolina Population Center, UNC-Chapel Hill

# 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) and assess their causes and consequences and derive policy implications.
- **Some Approaches:** Spatial simulations & cellular automata, spatial regression models, multi-level statistical models, satellite image change-detections, GIS.

# Sample Households & Survey Sectors



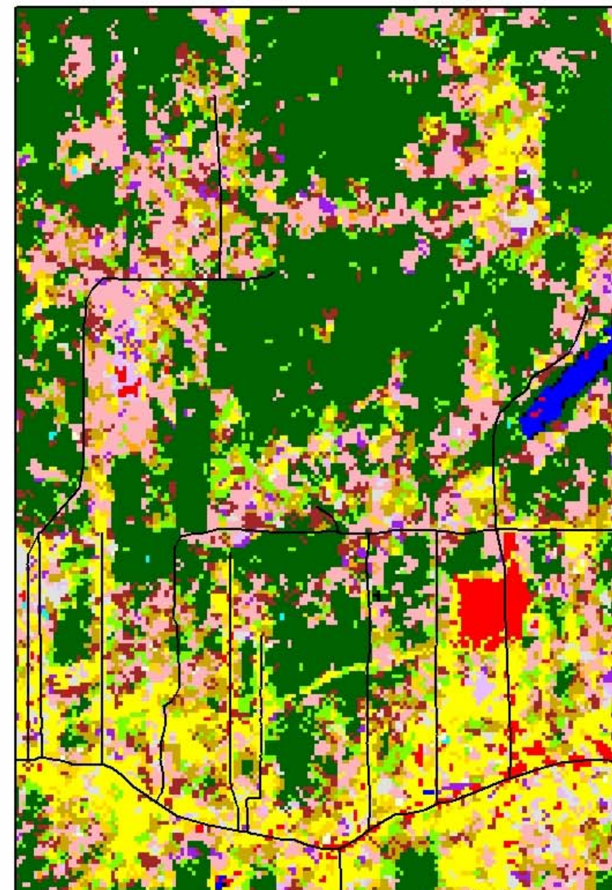


# Detailed LULC Classification Focused on the Northern ISA

12 September 2002

**Classes**

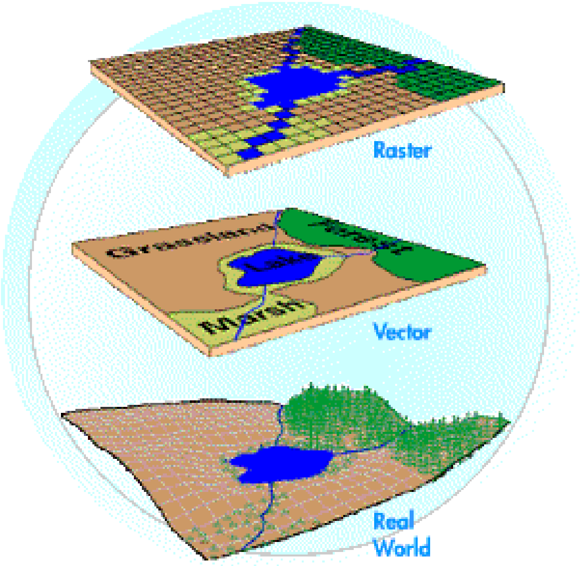
- African Palm
- Banana
- Barren
- Cacao
- Coffee
- Corn
- Palmito
- Pasture Few Trees
- Pasture Many Trees
- Pasture No Trees
- Primary Forest
- Rastrojo
- Secondary Forest
- Swamp
- Unclassified
- Urban
- Water



# GIS Data Inventory

- Political & Cultural
  - Provinces
  - Parroquias
  - Cantons
  - Major Cities in the Oriente
  - Cuyabeno Wildlife Reserve
  - Yasuní National Park
  - Sector boundaries (Sucumbios, Orellana, Napo)
- Sample fincas
- Road Network
- Physical Environment
  - Rivers & Lakes
  - Morphology & Edaphology
- Topography
  - Elevation and terrain data

- Remotely-Sensed Imagery
  - Air photos (1990)
  - Landsat TM Satellite Imagery (1973 – 2003)
  - IKONOS Satellite Imagery (1999 – 2002)
  - Land Use/Land Cover Classifications (1986 – 2003)



# Models of LCLUC: Examples of Recent Research

- (1) Land fragmentation
- (2) Secondary forest succession
- (3) Patterns of land use change
- (4) Conservation forests and land tenure
- (5) Simulations of LCLU change

# (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
- Variables: soils, land use, access, labor, wealth, household characteristics

Pan, W.K.Y., S. J. Walsh, R.E. Bilsborrow, B.G. Frizzelle, C.M. Erlien, F.D. Baquero. 2004. Farm-Level Models of Spatial Patterns of Land Use and Land Cover Dynamics in the Ecuadorian Amazon. *Agriculture, Ecosystems, and Environment*, 101: 117-134.

# 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) Secondary Forest Succession

- Secondary forests has the potential to provide an alternative for the sustainable management of forested ecosystems.
- One of the uncertainties related to the generation of successional vegetation is associated with the socio-economic factors related to the regeneration of forests.
- Objectives of this study are to (a) quantify the proportion of secondary forest and follow, and (b) statistically infer the main factors contributing to the presence and change of successional vegetation at the farm level.

Mena, C.F., Walsh, S.J., Bilsborrow, R.E., 2005. Secondary Forest Succession in the Northern Ecuadorian Amazon: Interactions among People, Place, and Environment. *Regional Environmental Change*, in review.

# Stepwise & Spatial Lag Model

## 1986-1996

- **Fallow**
  - Stepwise: Constant, HH Labor, Income, Roads[a]
  - Spatial Lag Models: HH Labor, Income (Model 1); TPRSUC* (Models 2-3) [a]
- **Secondary Forest**
  - Stepwise: Constant, Education, Walking Distance, Mean Slope[a]
  - Spatial Lag Models: TPRSUC, Constant, Education (Model 1); TPRSUC (Models 2); Constant, Mean Slope, Access (Model 3) [a]

* Spatial Lag AR Parameter

## 1996-2002

- **Fallow**
  - Stepwise: Constant, Flat, Off-farm Labor[a]
  - Spatial Lag Models: Flat (Model 1); TPRSUC (Models 2-3) [a]
- **Secondary Forest**
  - Stepwise: Flat[a]
  - Spatial Lag Models: TPRSUC, Flat (Model 1); TPRSUC, Good Soil (Model 2); TPRSUC (Model 3) [a]

# Selected Findings

- Different combinations of factors contribute to the generation of secondary forest and fallow across different time periods – 1990 & 1999.

- Off-farm employment, household assets, and male adults on the farm are consistently in the models; other important factors include the percentage of the farm under legal title and Euclidean distance to water.

- Factors contributing to a change in the area of secondary forest and fallow between 1986-1996 & 1996-2002 are vehicle access to farms & hired labor.

# (3) Multi-Level Models: Community-Farm Effects & LCLUC Patterns

- Community effects on LCLU patterns at the farm level.
- Plot Complexity: the number of patches in each LCLU change class on the *finca.*
- Hypothesis: Increases in population and population density are related to increased plot complexity over time (with some lag in land cover response); community characteristics influence local land use decisions.


Pan, W.K., and R.E. Bilsborrow, In Press. A Multilevel Study of Fragmentation of Plots and Land Use in the Ecuadorian Amazon. *Global and Planetary Change*.

Bilsborrow, R.E., A. Barbieri, W.K. Pan, In Press. Changes in Population and Land Use over Time in the Ecuadorian Amazon. *Acta Amazonica* 34(4): 635-647.

# Multilevel Model: Constrained Fixed Effects

## Forest

- 0.05 level: Intercept (47.4), Males, Migrants, Educ. of HH Head, Vehicle Access, Distance (Nearest Community & 4 Largest Communities)

## Perennials

- 0.05 level: Intercept (17.9), Migrants, Subdivisions

## Pasture

- 0.05 level: Migrants, Hired Labor, Title, Vehicle Access, Distance to Lago, Civil Registrar

## Annuals

- 0.05 level: Children, Shops & Restaurants

# Multi-Level Models: Pattern of LCLU Dynamics

**1986-1996**

- Intercept (15.80)
- Total hectares
- Years *finca* established since 1990
- Months of hired labor 1990
- Km to civil registrar

**1996-1999**

- Intercept (29.44)
- Total hectares
- Years *finca* established since 1990
- Change in population density 1986-96
- Months of hired labor 1990
- Km to civil registrar

# Selected Findings

- Communities with a civil registrar appear to play a larger role in influencing the number of patches on a *finca;* less fallow land because of market opportunities at nearby towns.

- Contextual factors at the community affect LCLUC at the farm level.

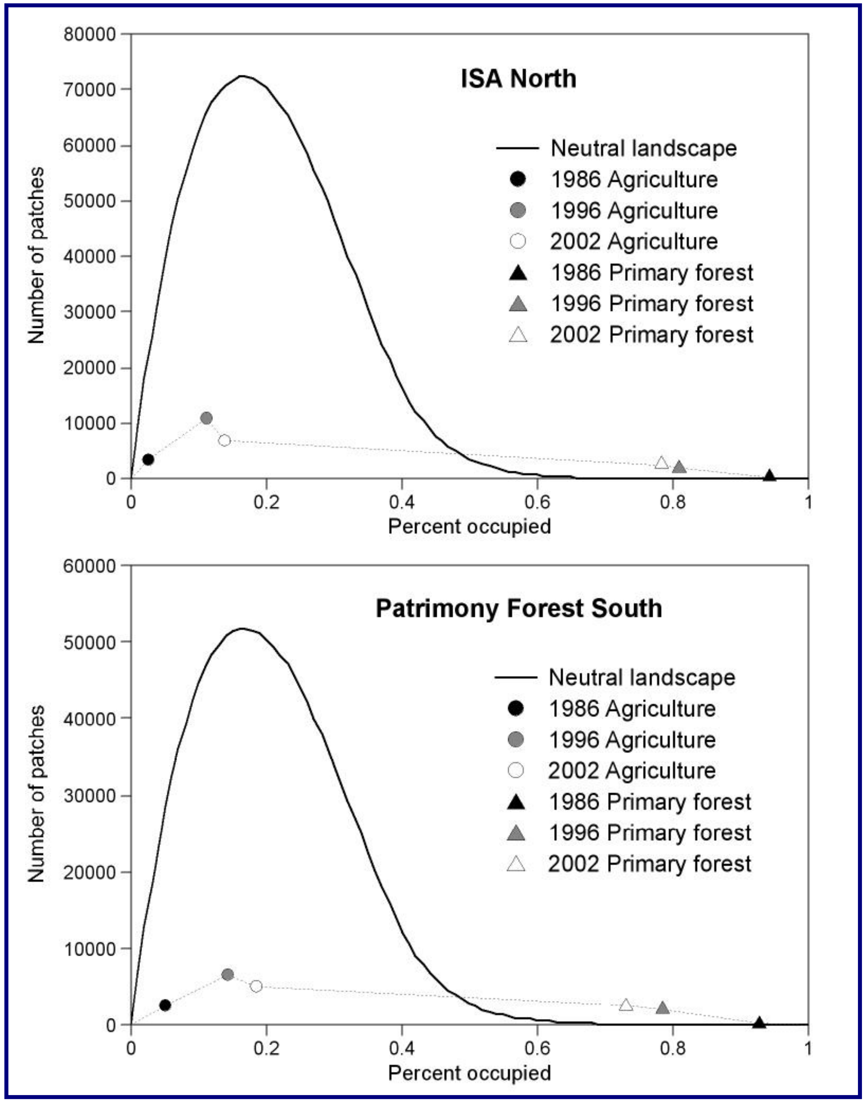
- Months of hired Labor, size of the farm, year of farm establishment, and change in population density are important factors in the pattern of LCLU change at the farm-level.

# (4) Land Tenure and Deforestation: Conservation Forests

- Cuyabeno Wildlife Reserve: LCLUC within the context of conflicts attributed to the emergent land tenure systems surrounding the Cuyabeno.
- Patrimony forests: a restricted land use category on lands surrendered to colonists who had settled in the Reserve; allowed colonization and communal land titles.
- Communities further exacerbated LCLUC patterns in direct and indirect ways.

Messina, J.P., Walsh, S.J., Mena, C.F., Delamater, P.L., 2005. Land Tenure and Deforestation Patterns in the Ecuadorian Amazon: Conflicts in Land Conservation in a Frontier Setting. *Applied Geography*, in review.

# Deviation from Neutral Plots: Study Area & Patrimony Forests



# Selected Findings

- Changes in land tenancy and the implementation of protection buffers have increased the process of deforestation and forest fragmentation.

- Neutral models are an approach to compare the quantification characteristics of a unique landscape relative to a theoretical landscape; deviation from neutral is the true distance between the pattern metric values of the sample landscape and those values of the neutral landscape.

- Pattern metrics used to generate a description of spatial organization of LCLU types for the neutral landscapes.

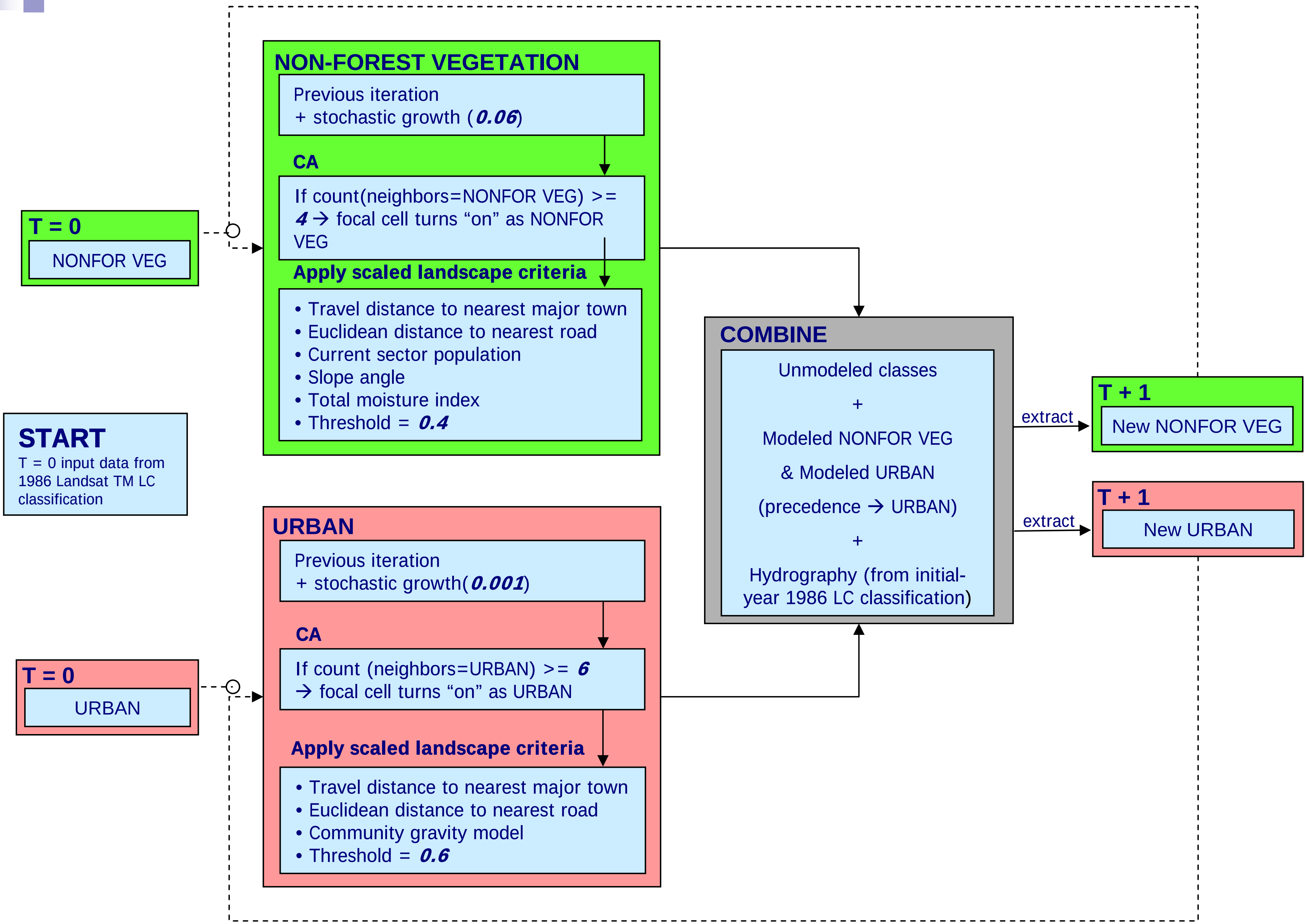
# (5) Spatial Simulation & Cellular Automata

- **<u>Goal</u>**: 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.

- **<u>Approach</u>**: CA consists of a 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 usually specified in the form of a transition function.

Messina, J.P. and Walsh, S.J., 2005. Dynamic Spatial Simulation Modeling of the Population-Environment Matrix in the Ecuadorian Amazon. *Environment and Planning B*, in press.

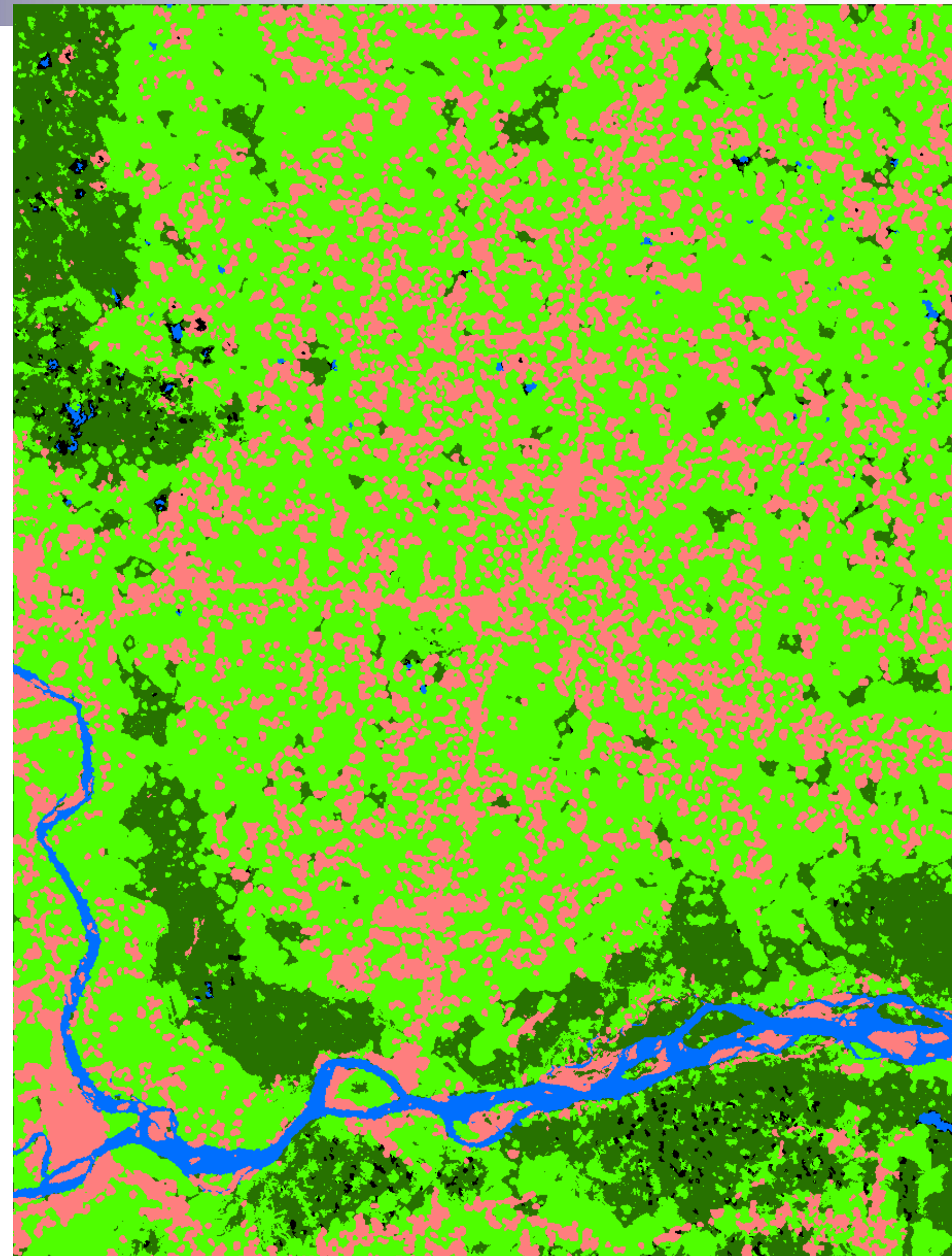
Messina, J.P. and S.J. Walsh, 2001. 2.5D Morphogenesis: Modeling Land use and Land cover Dynamics in the Ecuadorian Amazon. *Plant Ecology*, 156(1): 75-88.


NON-FOREST VEGETATION
Previous iteration
+ stochastic growth (0.06)
CA
If count(neighbors=NONFOR VEG) >= 4 → focal cell turns "on" as NONFOR VEG
Apply scaled landscape criteria
• Travel distance to nearest major town
• Euclidean distance to nearest road
• Current sector population
• Slope angle
• Total moisture index
• Threshold = 0.4
T = 0
NONFOR VEG
START
T = 0 input data from 1986 Landsat TM LC classification
COMBINE
Unmodeled classes
+
Modeled NONFOR VEG
& Modeled URBAN
(precedence → URBAN)
+
Hydrography (from initial-year 1986 LC classification)
extract
T + 1
New NONFOR VEG
extract
T + 1
New URBAN
URBAN
Previous iteration
+ stochastic growth(0.001)
CA
If count (neighbors=URBAN) >= 6
→ focal cell turns "on" as URBAN
Apply scaled landscape criteria
• Travel distance to nearest major town
• Euclidean distance to nearest road
• Community gravity model
• Threshold = 0.6
T = 0
URBAN

# South ISA: CA Simulation

2010

- Forest
- Agriculture/Pasture
- Urban/Barren
- Water



# Selected Results

- *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 protection buffers around and within protected areas can increase deforestation and land fragmentation.
- Forest succession and fallow are related to off-farm employment, household assets, male adults, & legal title.
- Spatial structure of LCLU and LCLUC patterns are related to household demographics, labor, change in pop density, year of farm establishment, & farm size.

- *Future Directions*:
- Spatial and temporal dynamics of population mobility.
- Growth of communities and their affects on LCLUC on farms and in protected forests.
- Spatial models and simulations using agent based models and cellular automata approaches for addressing nonlinear systems with feedbacks to integrate people, place, and environment, and to consider policy implications of LCLUC.
- Integration of multiple stakeholder groups (i.e., colonists, indigenous groups, communities, oil interests, and government) and a dynamic environment using spatial simulations and nonlinear systems approaches.