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

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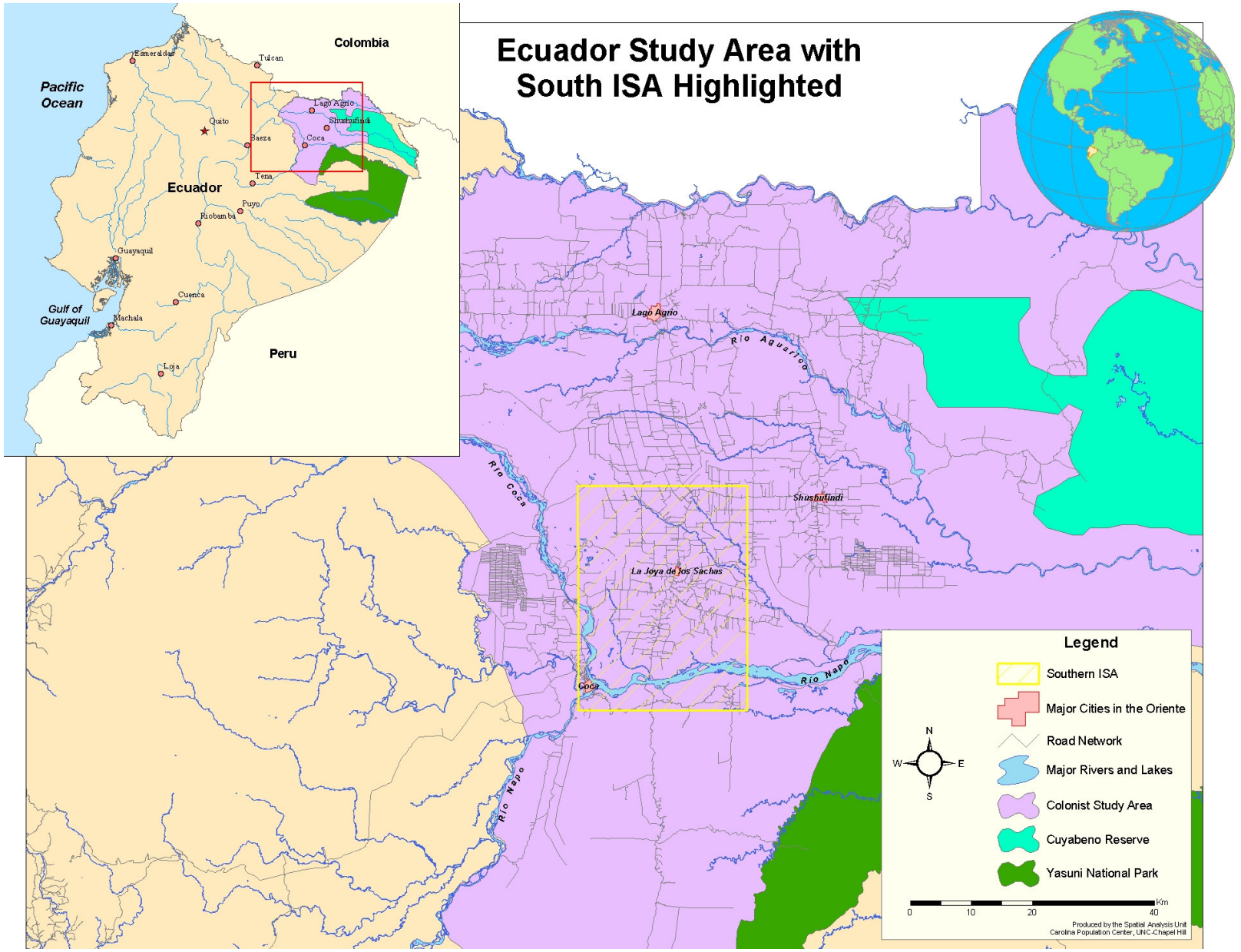

Ecuador Study Area with South ISA Highlighted
Colombia
Pacific Ocean
Ecuador
Peru
Gulf of Guayaquil
Esmeraldas
Tulcan
Quito
Baeza
Lago Agrio
Shushufindi
Coca
Tena
Puyo
Riobamba
Guayaquil
Cuenca
Machala
Loja
Lago Agrio
Rio Aguarico
Rio Coca
Shushufindi
La Joya de los Sachas
Coca
Rio Napo
Rio Napo
Legend
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
0
10
20
40
Km
Produced by the Spatial Analysis Unit
Carolina Population Center, UNC-Chapel Hill

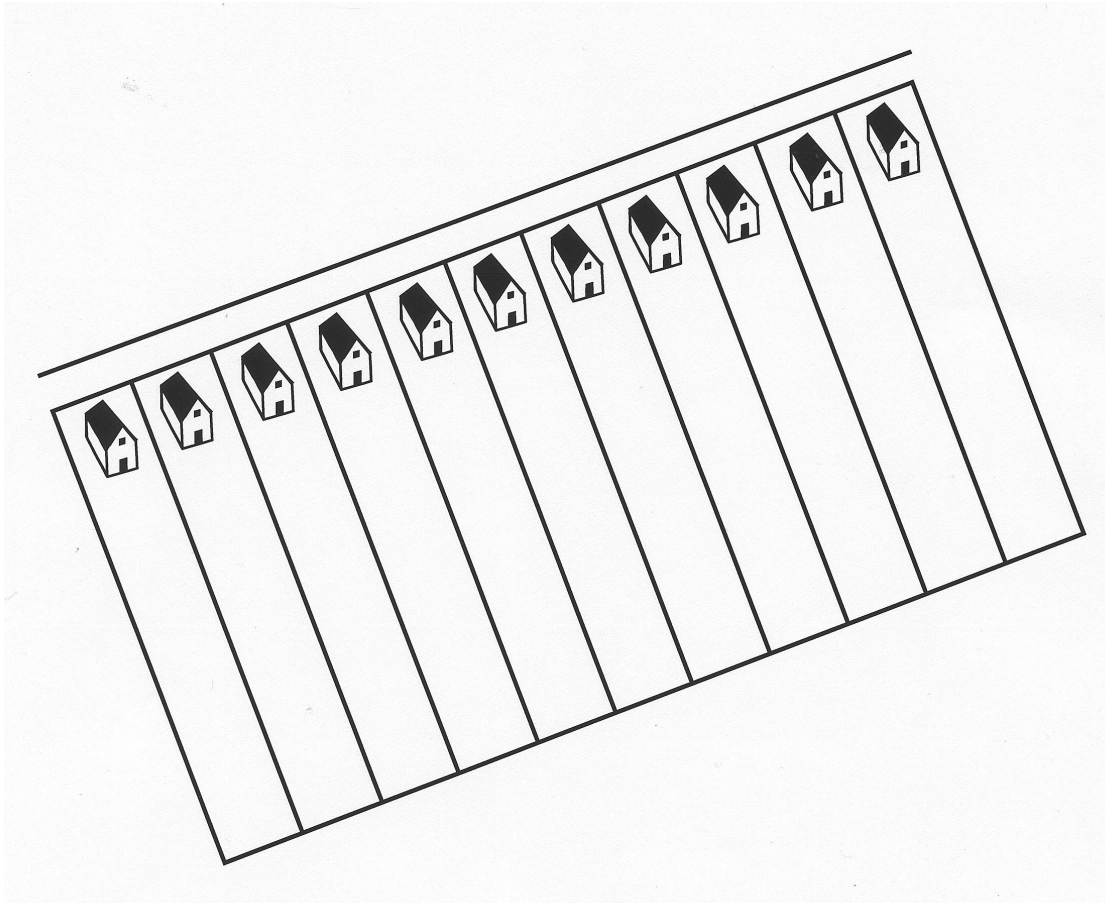
Introduction

- **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), 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.

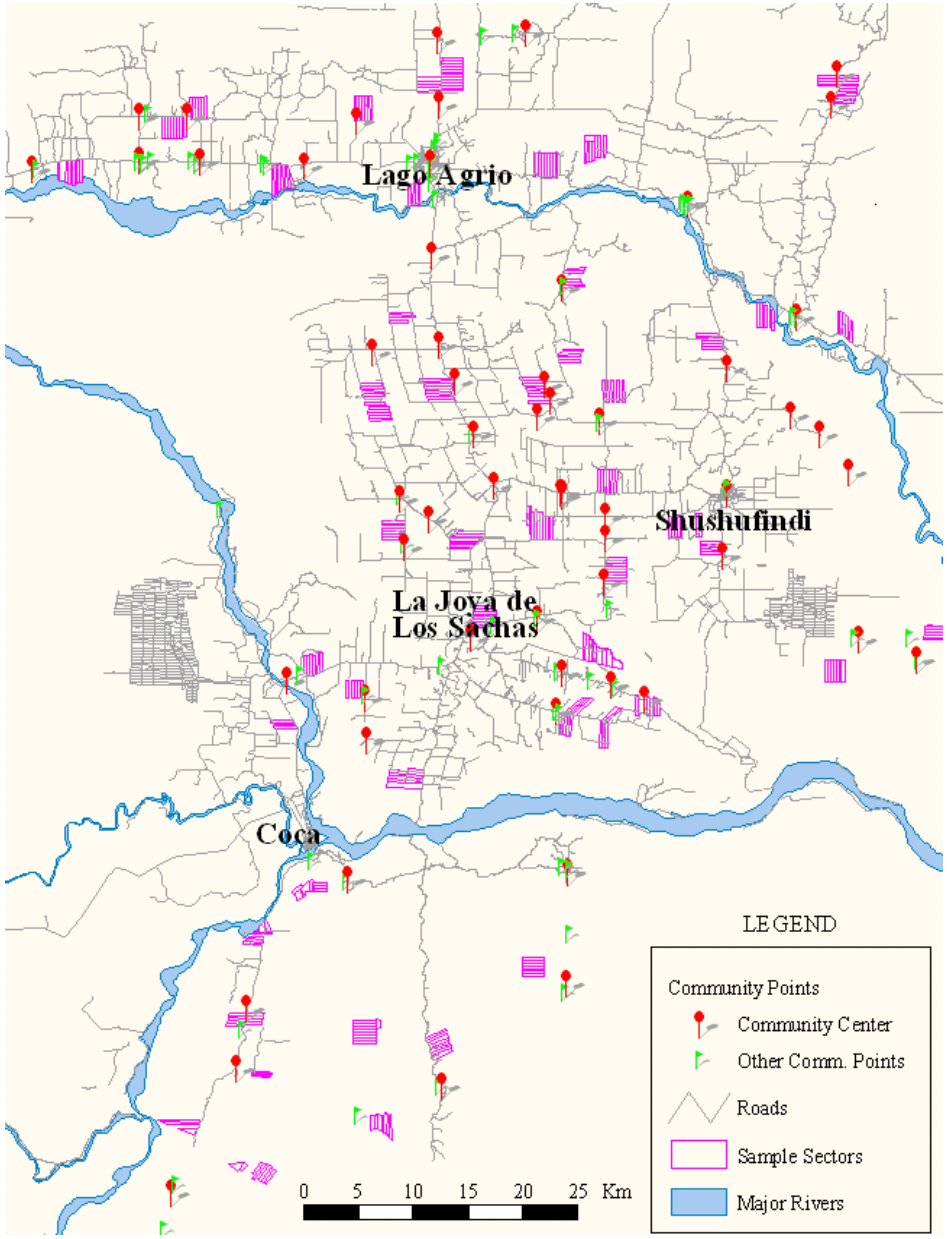
Settlement Patterns Affecting Analysis Design



The Ecuadorian “fishbone” or “piano key” settlement pattern is characterized by on-premise management and a distinct linear pattern

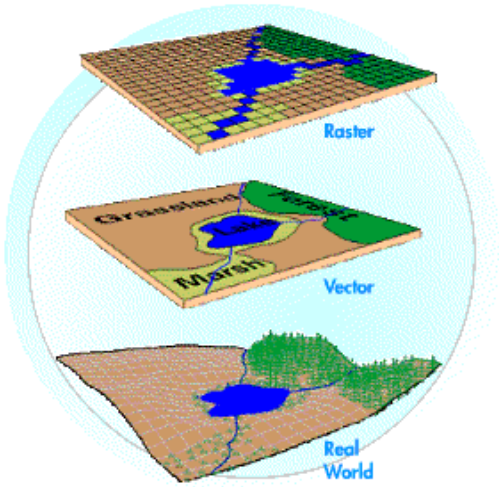
Sample Households & Survey Sectors

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)
- Social Surveys: Fincas (1990 & 1999), Communities (2000), Indigenous Groups (2001)
- 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)
  - 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.

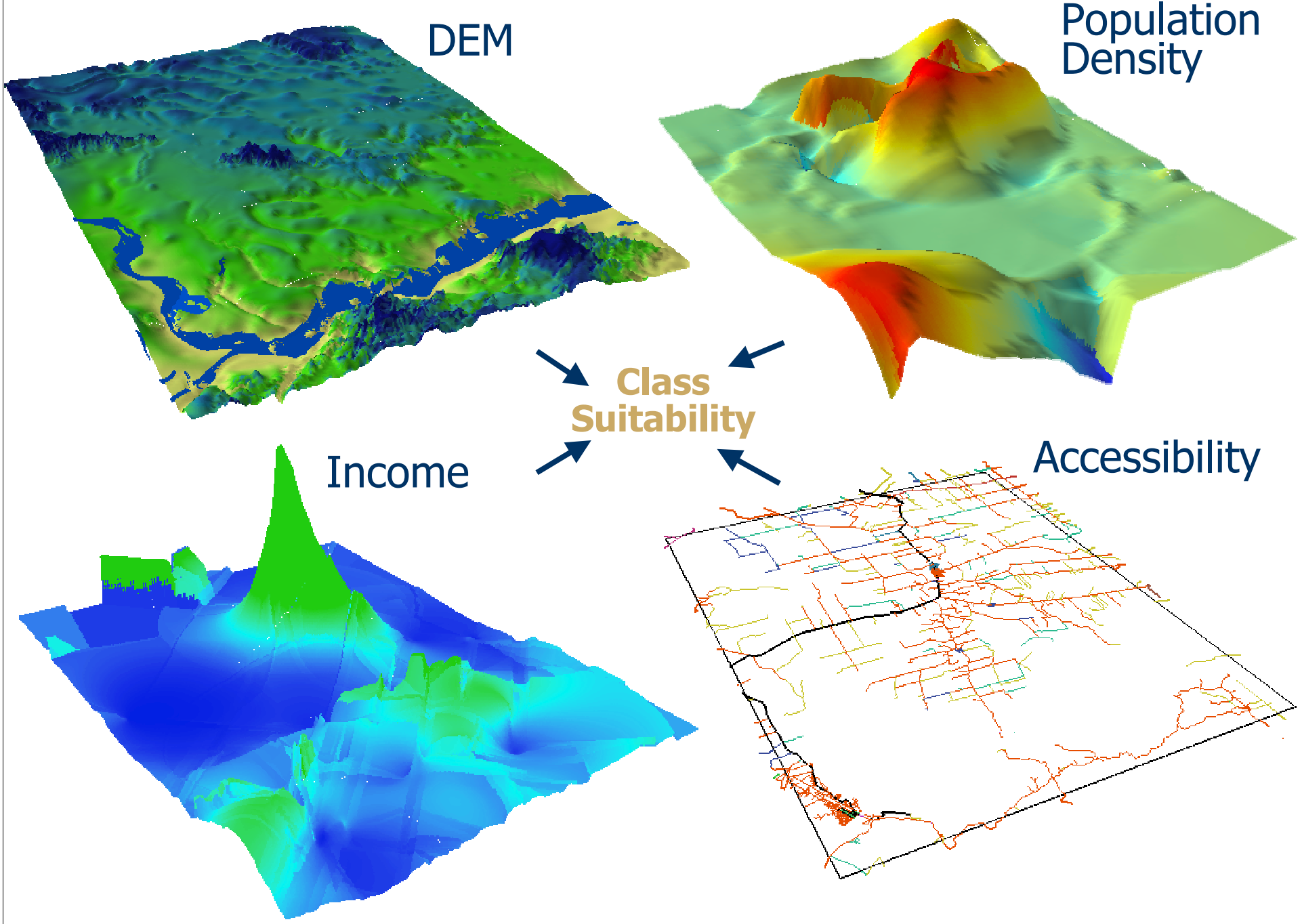
(2) Spatial Simulation of LULC Change & Cellular Automata

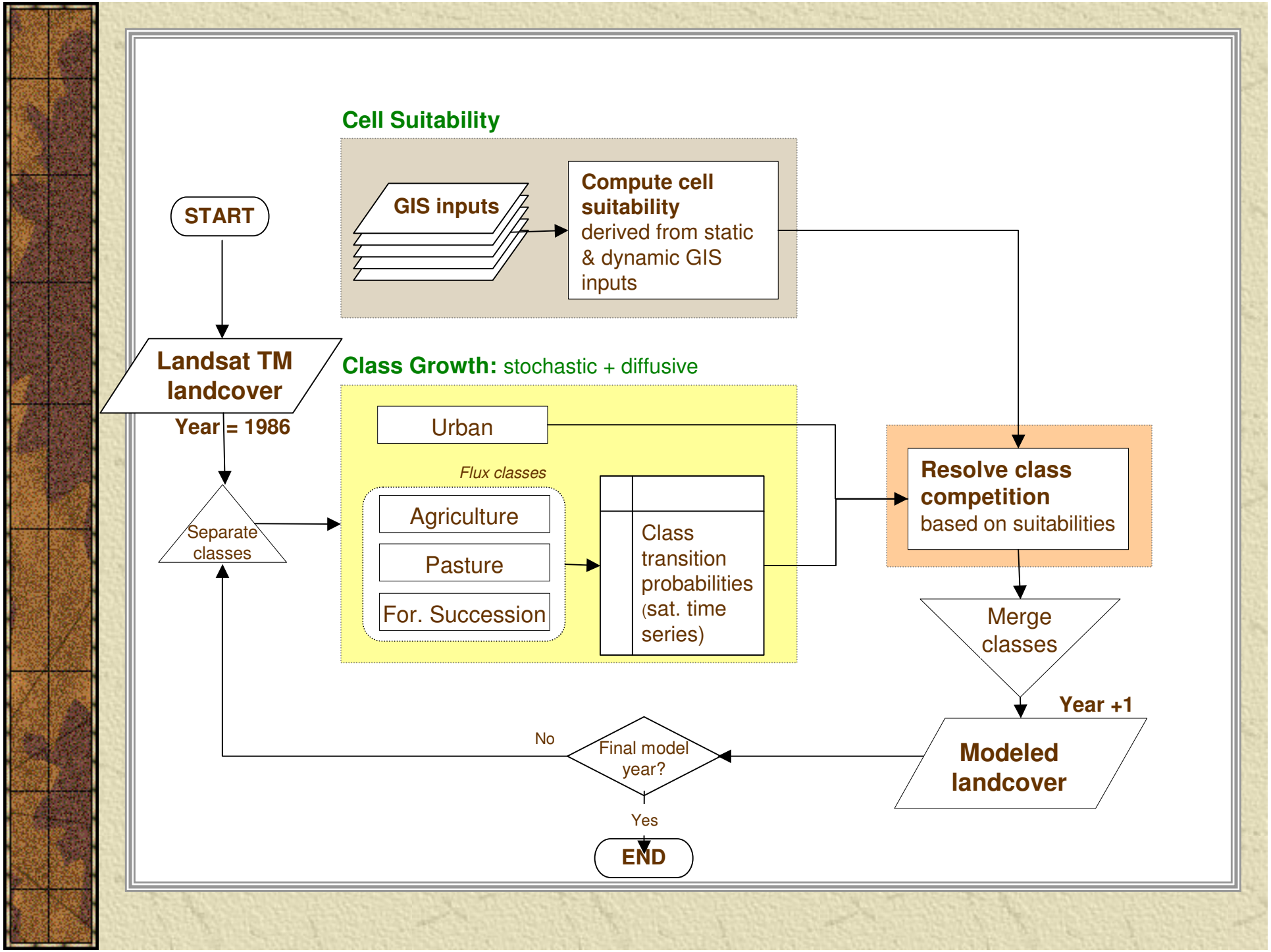
- **Goal: Generate LULC simulations based upon actual conditions observed through the satellite time-series and extended in time & space through derived growth rules and neighborhood interactions.**

- **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

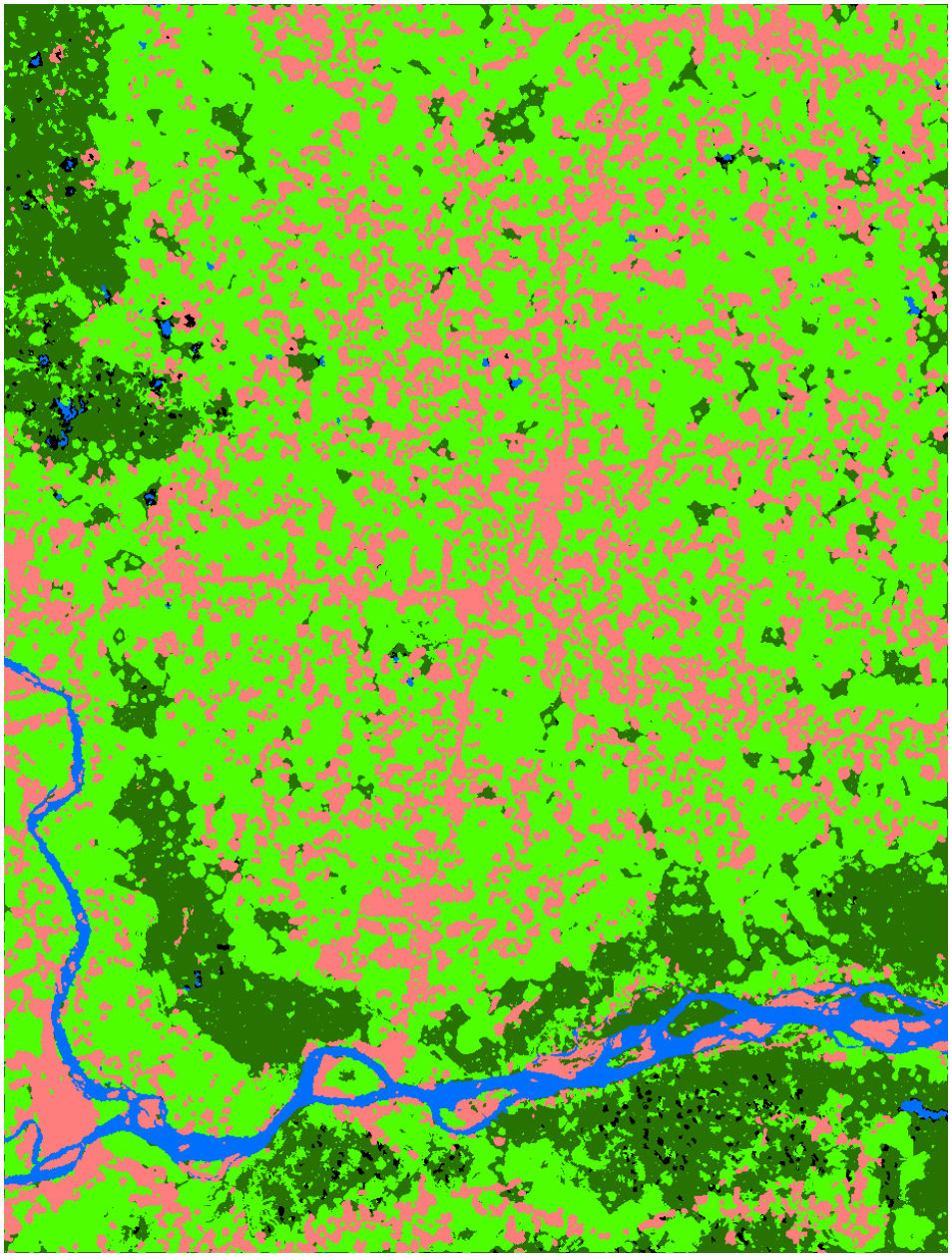
- Travel distance to nearest of 3 major communities; lower, greater change probability; computed as Euclidean distance to the nearest road and then simple distance along network to the community.
- Euclidean distance to nearest road; lower, greater change probability.
- Sector population; higher, greater 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).


DEM
Population Density
Class Suitability
Income
Accessibility


Cell Suitability
START
GIS inputs
Compute cell suitability derived from static & dynamic GIS inputs
Landsat TM landcover
Year = 1986
Class Growth: stochastic + diffusive
Urban
Flux classes
Agriculture
Pasture
For. Succession
Class transition probabilities (sat. time series)
Separate classes
Resolve class competition based on suitabilities
Merge classes
Year +1
Modeled landcover
Final model year?
No
Yes
END

South ISA: Simulation

2010



(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.

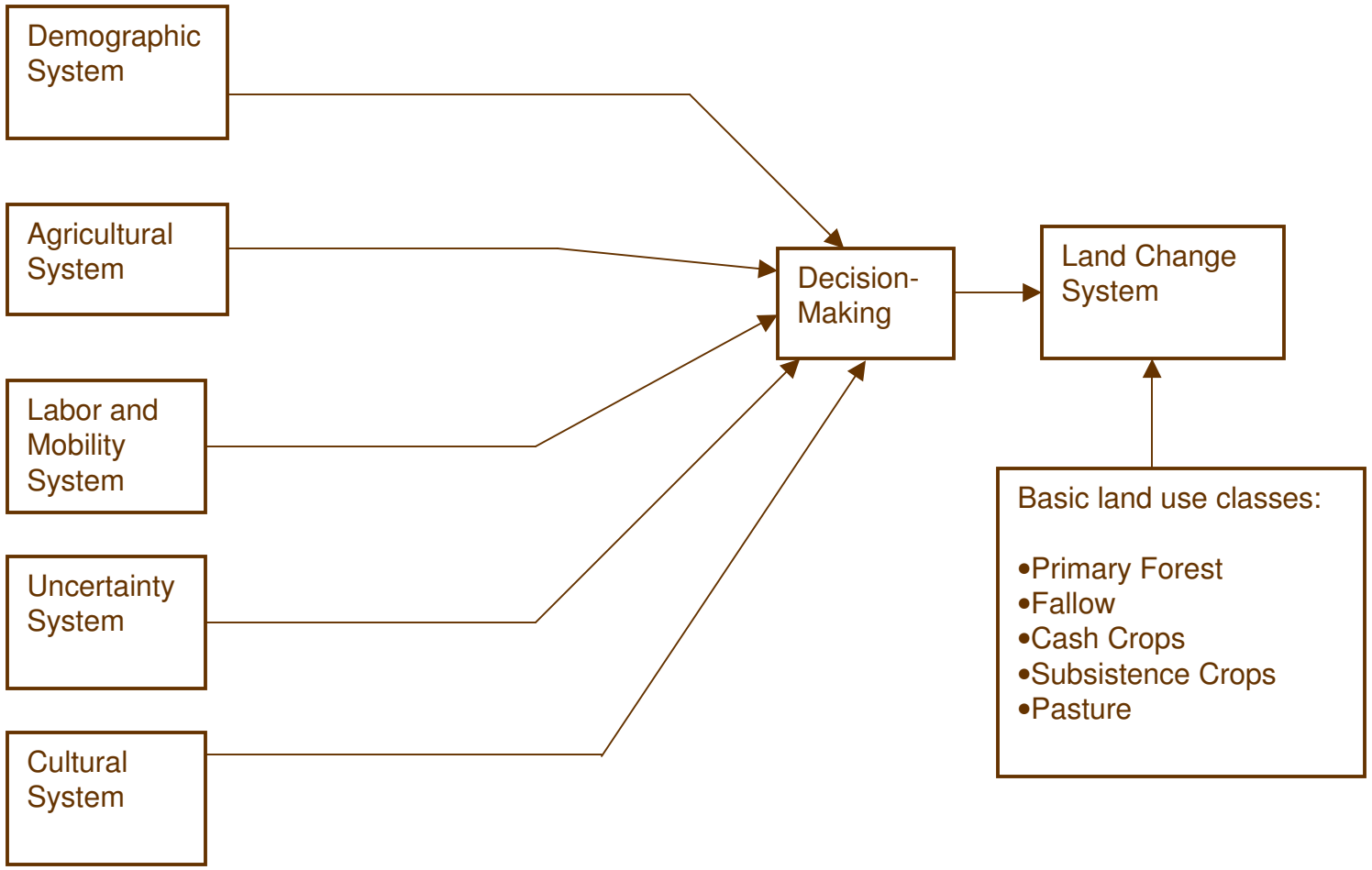
The strategies that the household take to improve life conditions are:

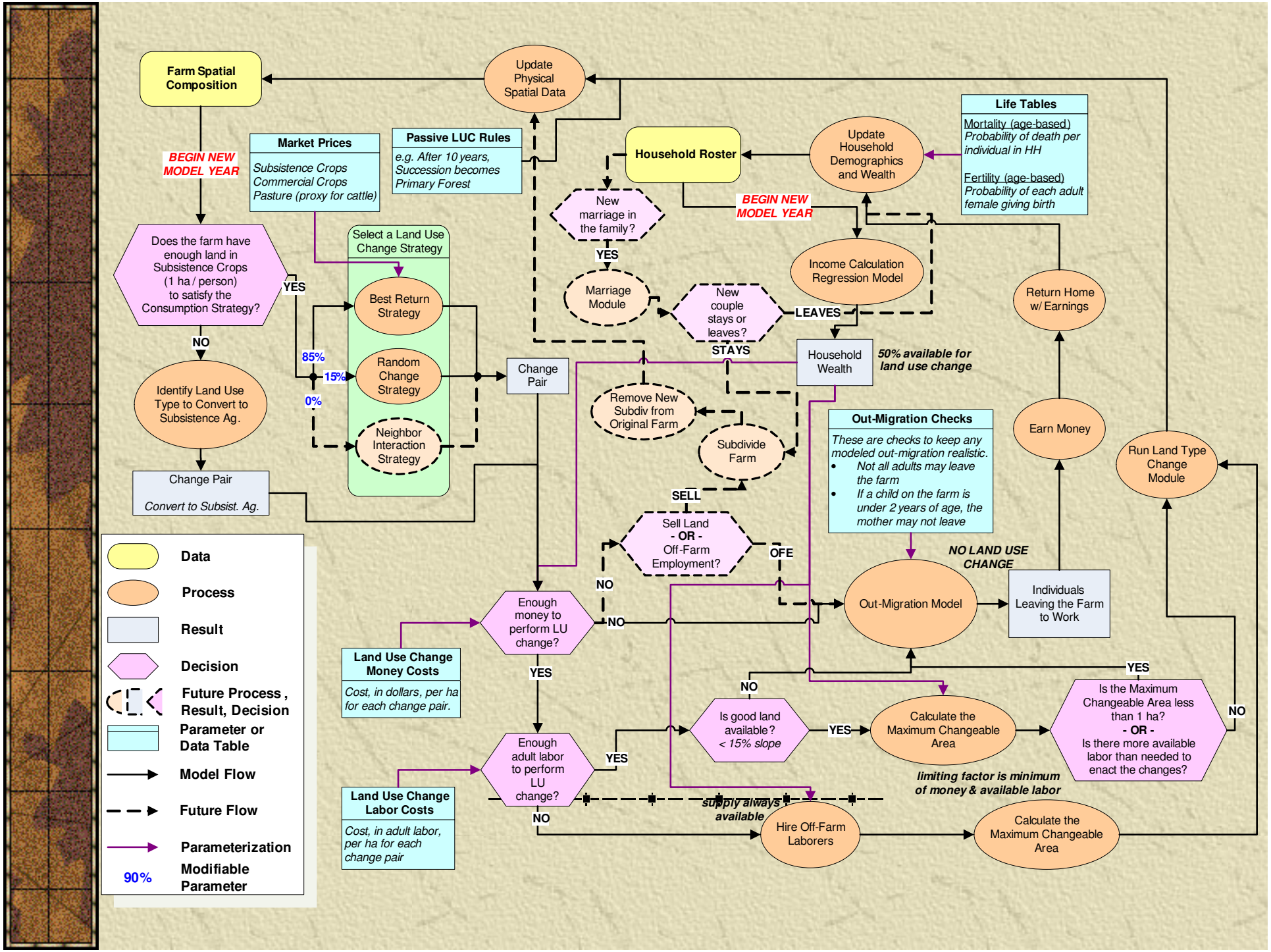
- Intensifying land use
- Extensifying land use
- Temporary migration
- Permanent migration to areas with available land
- Fertility decline

Household Life Cycle

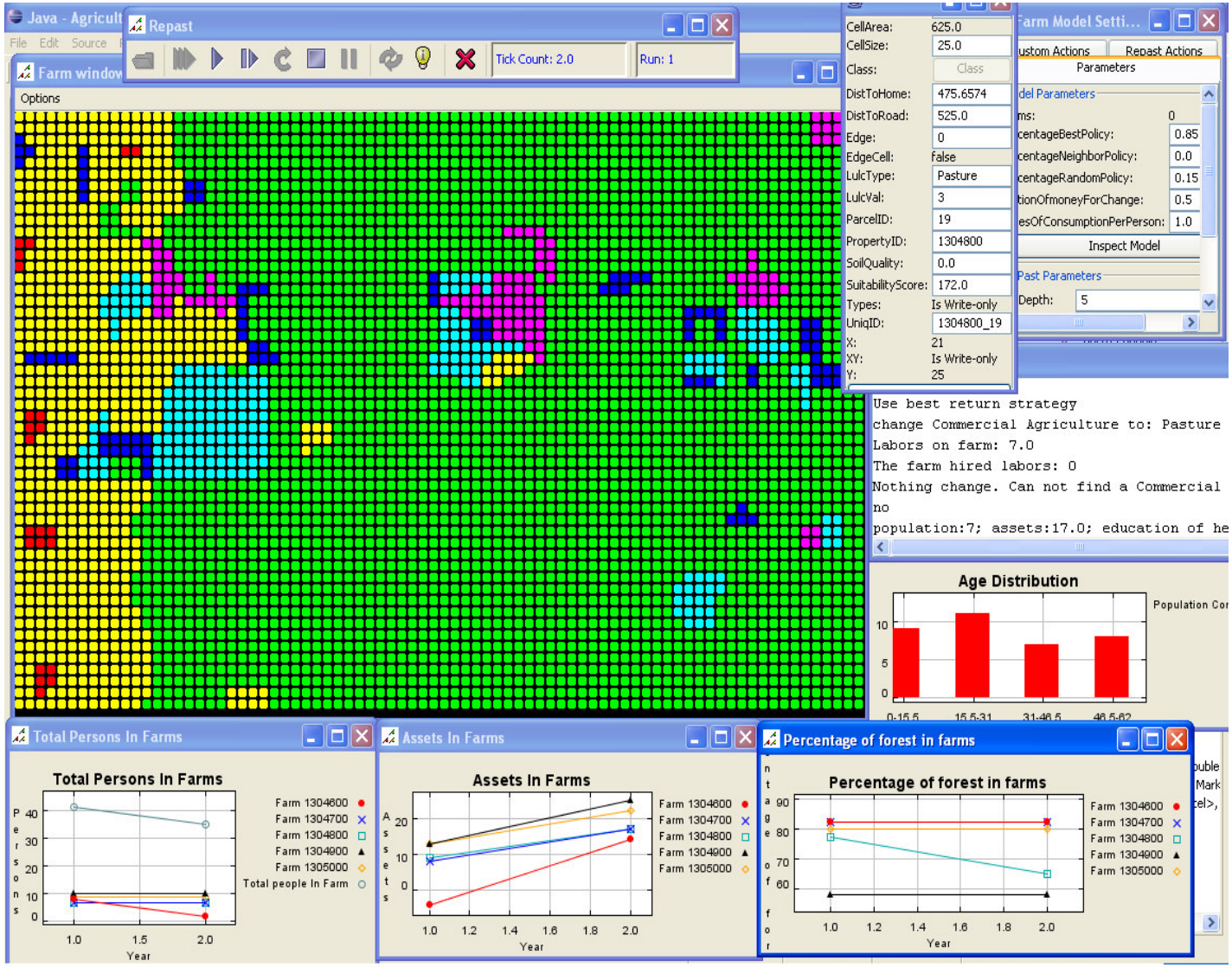
1) Young parents who recently arrived in the area initiate forest clearings for subsistence crops.
2) Parents with growing children become engaged in the cultivation of cash crops and pasture.
3) Older parents with teenage children are related to a decrease in the cultivation of annuals and an increase 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

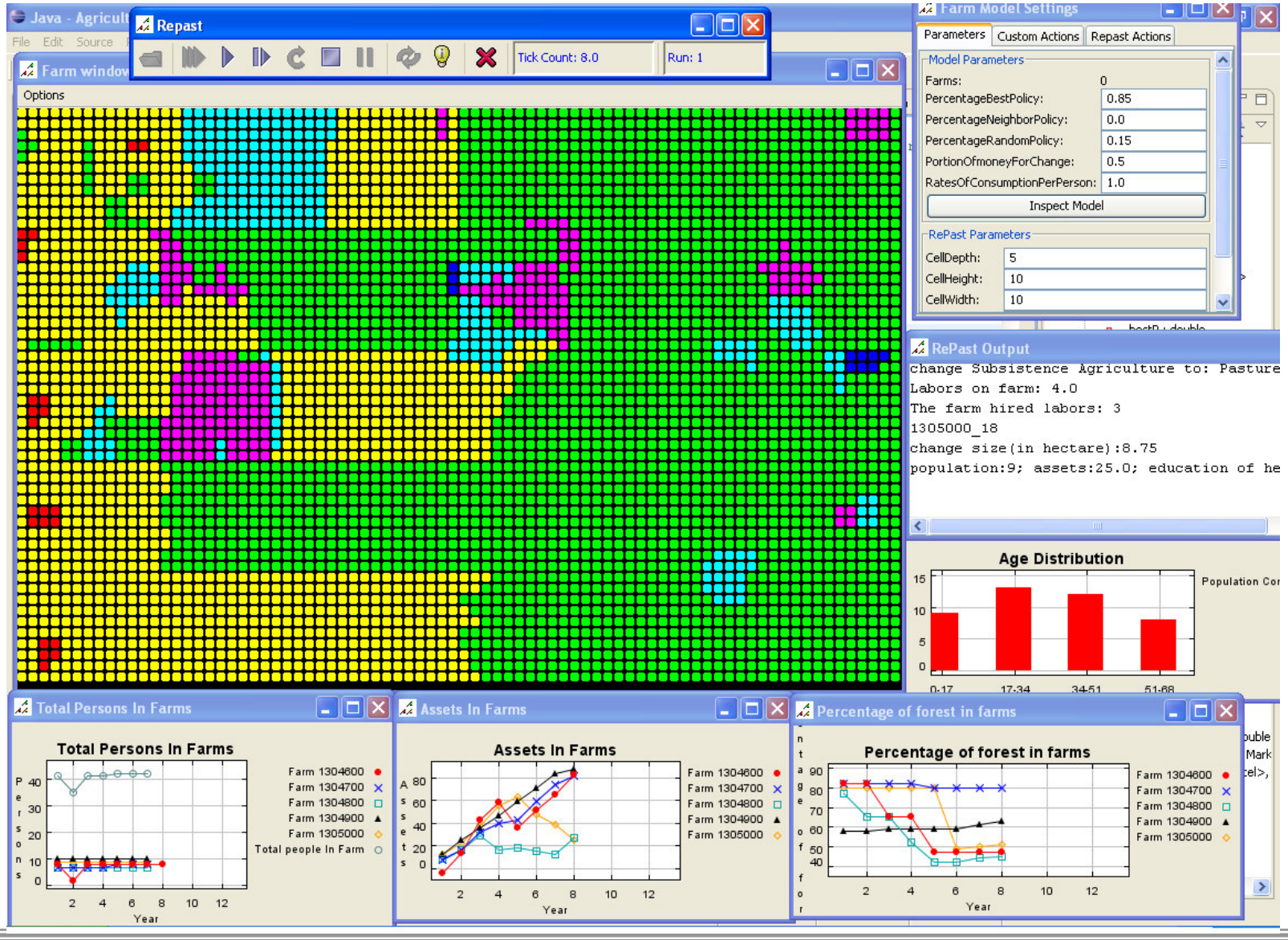



Farm Spatial Composition
Update Physical Spatial Data
BEGIN NEW MODEL YEAR
Market Prices
Subsistence Crops
Commercial Crops
Pasture (proxy for cattle)
Passive LUC Rules
e.g. After 10 years, Succession becomes Primary Forest
Household Roster
Update Household Demographics and Wealth
Life Tables
Mortality (age-based)
Probability of death per individual in HH
Fertility (age-based)
Probability of each adult female giving birth
New marriage in the family?
YES
BEGIN NEW MODEL YEAR
Does the farm have enough land in Subsistence Crops (1 ha / person) to satisfy the Consumption Strategy?
YES
NO
Select a Land Use Change Strategy
Best Return Strategy
Random Change Strategy
Neighbor Interaction Strategy
85%
15%
0%
Marriage Module
New couple stays or leaves?
LEAVES
STAYS
Income Calculation Regression Model
Return Home w/ Earnings
Household Wealth
50% available for land use change
Change Pair
Remove New Subdiv from Original Farm
Subdivide Farm
Identify Land Use Type to Convert to Subsistence Ag.
Change Pair
Convert to Subsist. Ag.
Out-Migration Checks
These are checks to keep any modeled out-migration realistic.
Not all adults may leave the farm
If a child on the farm is under 2 years of age, the mother may not leave
Earn Money
Run Land Type Change Module
SELL
Sell Land - OR - Off-Farm Employment?
OFE
NO LAND USE CHANGE
Out-Migration Model
Individuals Leaving the Farm to Work
Enough money to perform LU change?
NO
YES
Land Use Change Money Costs
Cost, in dollars, per ha for each change pair.
Is good land available? < 15% slope
YES
NO
Calculate the Maximum Changeable Area
Is the Maximum Changeable Area less than 1 ha? - OR - Is there more available labor than needed to enact the changes?
YES
NO
limiting factor is minimum of money & available labor
Enough adult labor to perform LU change?
YES
NO
Land Use Change Labor Costs
Cost, in adult labor, per ha for each change pair
supply always available
Hire Off-Farm Laborers
Calculate the Maximum Changeable Area
Data
Process
Result
Decision
Future Process, Result, Decision
Parameter or Data Table
Model Flow
Future Flow
Parameterization
90%
Modifiable Parameter

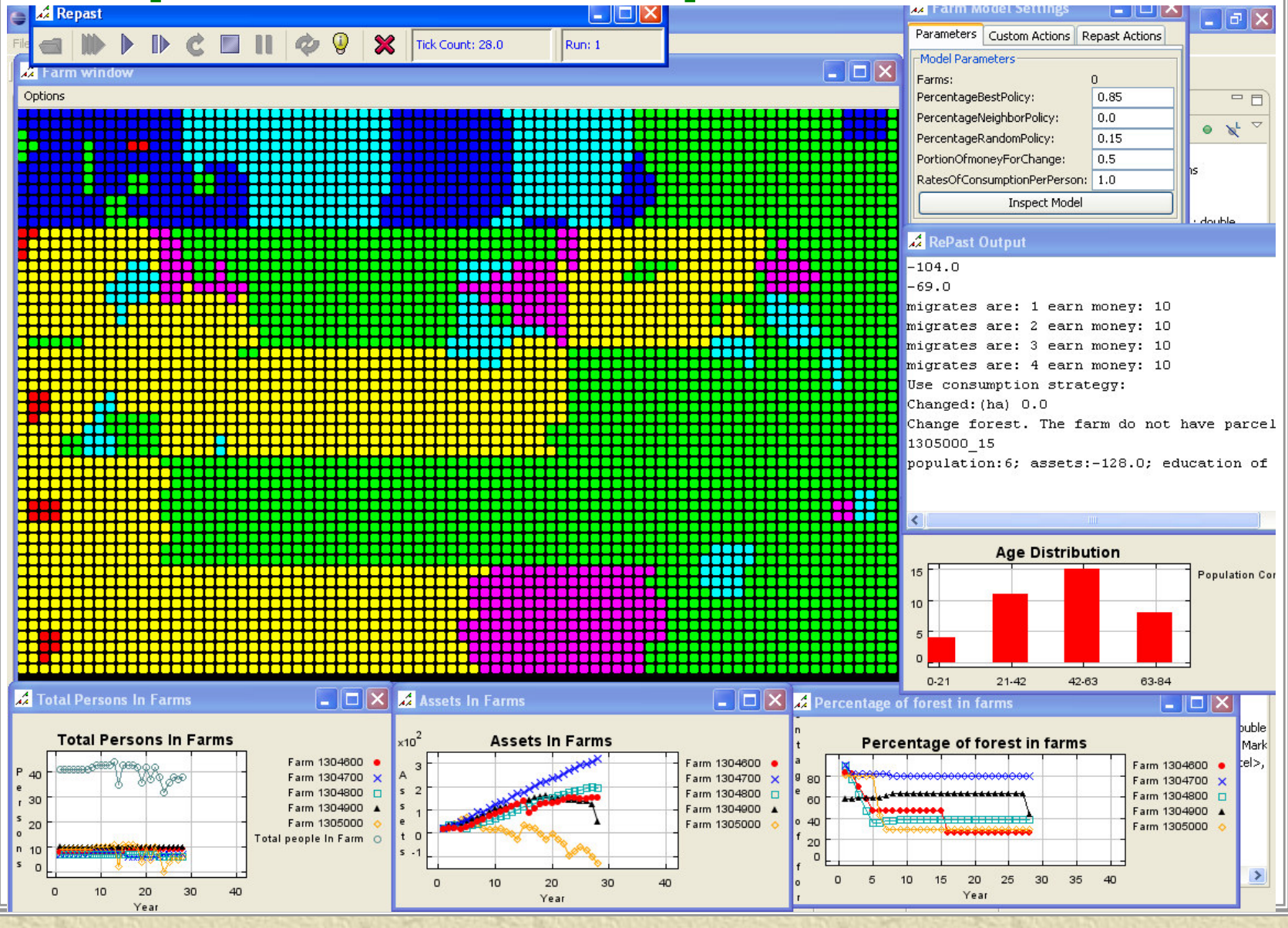
Repast Screen Capture: Year 2



Repast Screen Capture: Year 8



Repast Screen Capture: Year 28



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.