AGENT-BASED MODELS OF COMPLEX SOCIO-ECOLOGICAL SYSTEMS: DEFORESTATION, HOUSEHOLD VULNERABILITY AND ROAD-BUILDING IN THE SW AMAZON

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MODELING PLATFORMS FOR EVALUATION OF COMPLEX SOCIAL-ECOLOGICAL SYSTEMS

- Construction of models of complex social-ecological systems depends on understanding of said systems
- Theoretical frameworks and plenty of data inform model design for evaluation of outcomes
- **We need systematic approaches to the analysis of output from dynamic simulation models**
- One example: NSF CNH 1114924, “Global Sensitivity & Uncertainty Analysis for Evaluation of Ecological Resilience: Theoretical Debates over Infrastructure Impacts on Livelihoods & Forest Change”

MODELING PLATFORMS FOR EVALUATION OF COMPLEX SOCIAL-ECOLOGICAL SYSTEMS

- **The Challenge:**
- New infrastructure has manifold impacts on social-ecological systems
- Multiple research literatures report various empirical findings
- Road ecology: mostly negative ecological impacts
- Development economics: mostly positive economic impacts
- Social science (various): mostly negative social impacts

MODELING PLATFORMS FOR EVALUATION OF COMPLEX SOCIAL-ECOLOGICAL SYSTEMS

- **The Case:**
- The Inter-Oceanic Highway in the southwestern Amazon
- Part of IIRSA, the Initiative for Integration of Regional Infrastructure in South America

Source: CEPEI 2002

MODELING PLATFORMS FOR EVALUATION OF COMPLEX SOCIAL-ECOLOGICAL SYSTEMS

- **The Case:**
- Paving during the 2000s in the tri-national "MAP" Frontier where Bolivia, Brazil and Peru meet
- Highly biodiverse forests, many rivers
- High social diversity in terms of countries, ethnic groups, land tenure

MAP

Madre de Dios - Acre - Pando

PERU - BRASIL - BOLÍVIA

Estrada do Pacífico
GOVERNO FEDERAL
ACRE
Assis Brasil 60 Km
Cuzco / Peru 800 Km
Lima / Peru 1.931 Km
Oceano Pacifico 1.530 Km
Estrada do Pacífico / BR-317
Acre, Brazil

Madre de Dios, Peru


Pando,
Bolivia


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Trans-boundary infrastructure and land cover change: Highway paving and community-level deforestation in a tri-national frontier in the Amazon

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ABSTRACT

Economic globalization manifests in landscapes through regional integration initiatives involving trans-boundary infrastructure. While the relationships of roads, accessibility and land cover are well-understood, they have rarely been considered across borders in national frontier regions. We therefore pursue an analysis of infrastructure connectivity and land cover change in the tri-national frontier of the southwestern Amazon where Bolivia, Brazil and Peru meet, and where the Inter-Oceanic Highway has recently been paved. We integrate satellite, survey, climate and other data for a sample of rural communities that differ in terms of highway paving across the tri-national frontier. We employ a suite of explanatory variables tied to road paving and other factors that vary both across and within the three sides of the frontier in order to model their importance for deforestation. A multivariate analysis of non-forest land cover during 2005–2010 confirms the importance of paving status and travel times, as well as land tenure and other factors. These findings indicate that integration affects land cover, but does not eliminate the effects of other factors that vary across the frontier, which bears implications for the study of globalization, trans-boundary infrastructure, environmental governance and land cover change.

MODELING PLATFORMS FOR EVALUATION OF COMPLEX SOCIAL-ECOLOGICAL SYSTEMS

- **Our Approach:**
- Two key concepts: connectivity and resilience
- Evaluate highway paving in a forest frontier…
- …in terms of changes in market accessibility for rural producers…
- …who depend on natural resources for their livelihoods…
- …with a focus on social outcomes (like wealth) and ecological outcomes (like forest cover)

MODELING PLATFORMS FOR EVALUATION OF COMPLEX SOCIAL-ECOLOGICAL SYSTEMS

- **The Theoretical Approach:**
- Biophysical characteristics of the resource base and location…
- …along with changes in connectivity due to paving and market growth…
- Influences decisions to modify the resource base (forest degradation, clearing, soil degradation)…
- …and yield socioeconomic outcomes (food security, wealth)
- Various feedbacks from previous decisions influence resilience
- Ongoing changes in connectivity, market prices, resource characteristics

MODELING PLATFORMS FOR EVALUATION OF COMPLEX SOCIAL-ECOLOGICAL SYSTEMS

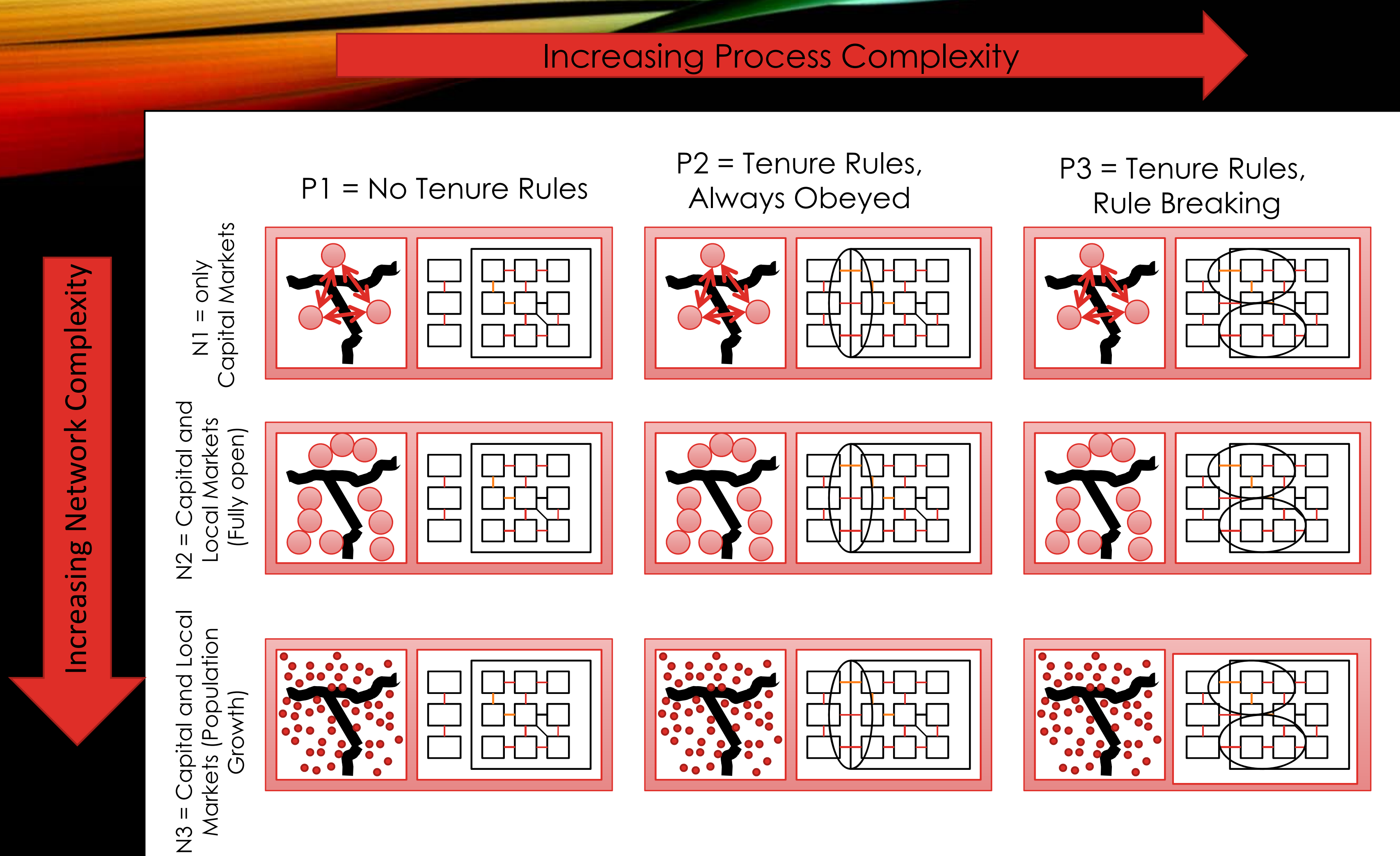
- **Competing theoretical ideas:**
- Connectivity:
- Producers face tradeoffs in marketing produce in larger (but often more distant) markets with more buyers…
- …or smaller (and often closer) markets with fewer buyers
- Land tenure:
- Some theories (e.g. the evolutionary theory of land rights) assume homogeneous private property rights…
- …but many developing regions exhibit diverse tenure models with distinct bundles of rights

MODELING PLATFORMS FOR EVALUATION OF COMPLEX SOCIAL-ECOLOGICAL SYSTEMS

- **Analytical approach, part 1:**
- Evaluate theories using a flexible modeling platform
- Develop different model instantiations that correspond to competing theoretical expectations
- In this case, vary the model design in terms of connectivity (network structure) and land tenure (process complexity)
- Three network instantiations (N1-3) and three process (P1-3), for nine total

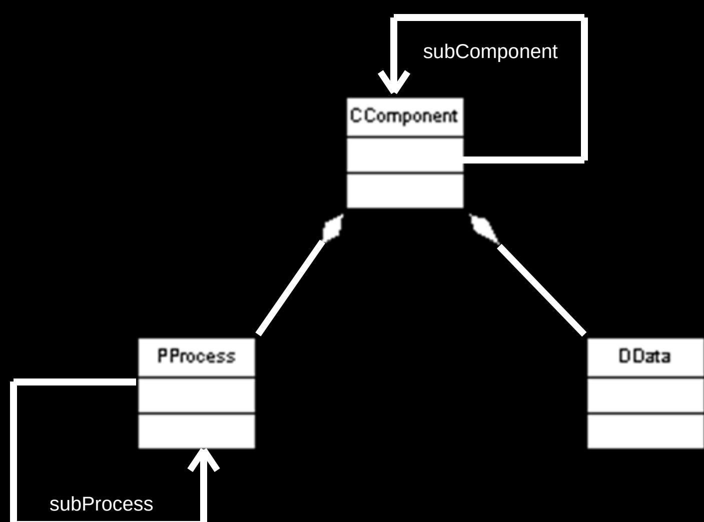
MODELING PLATFORMS FOR EVALUATION OF COMPLEX SOCIAL-ECOLOGICAL SYSTEMS

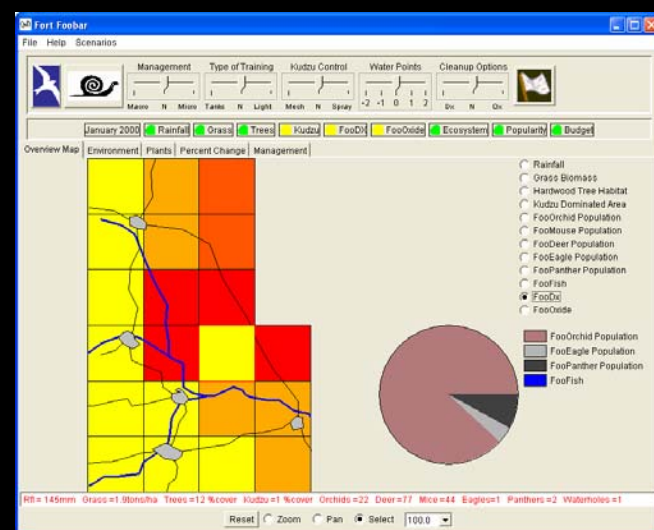
- **Analytical approach, part 1:**
- N1 = only sell to regional capitals, if profitable
- N2 = sell to nearest market, including local towns
- N3 = optimize site of sale by proximity and probability of buyer
- P1 = homogeneous bundles of rights, no rules
- P2 = diversified bundles of rights and rules, all rules followed
- P3 = diversified bundles of rights and rules, rules broken if profitable even with fines


Increasing Process Complexity
Increasing Network Complexity
P1 = No Tenure Rules
P2 = Tenure Rules, Always Obeyed
P3 = Tenure Rules, Rule Breaking
N1 = only Capital Markets
N2 = Capital and Local Markets (Fully open)
N3 = Capital and Local Markets (Population Growth)

MODELING PLATFORMS FOR EVALUATION OF COMPLEX SOCIAL-ECOLOGICAL SYSTEMS

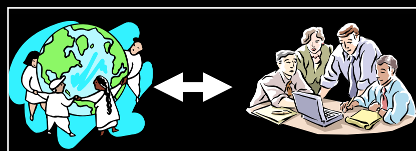
- **Platform 1: “Questions and Decisions” (QnD)**
- At each time step, QnD consumes geodata (DData) and applies processes with rules (PProcess) to objects with specific operations (CComponent)





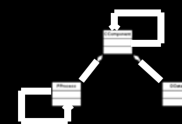
QnD’s flexibility permits development of model instantiations iteratively via consultations with collaborators and stakeholders

Preliminary Stakeholder Dialogue



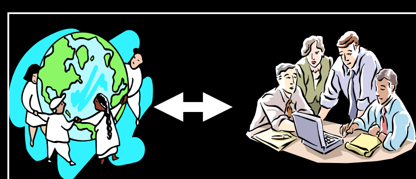
- Define the objectives of the model
- Develop the key proceses and components
- Compile input data
- Discuss applications of the model

Preliminary Version of Model



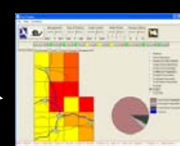
- Initial data, processes and objects
- Simple networks, basic processes, and limited data
- Initial calibration

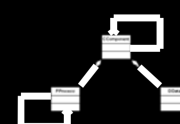
Periodic Iterative Dialogues



- Revise assumptions, model structure
- Identify and elaborate alternative instantiations of the model
- Revise the presentation of model output

Multiple Instantiations of the Model

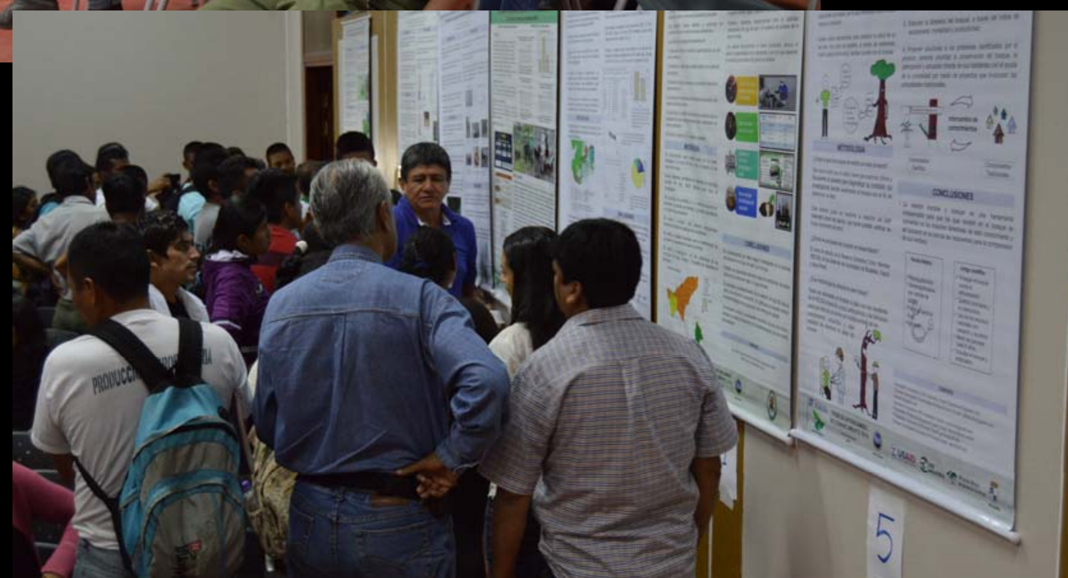




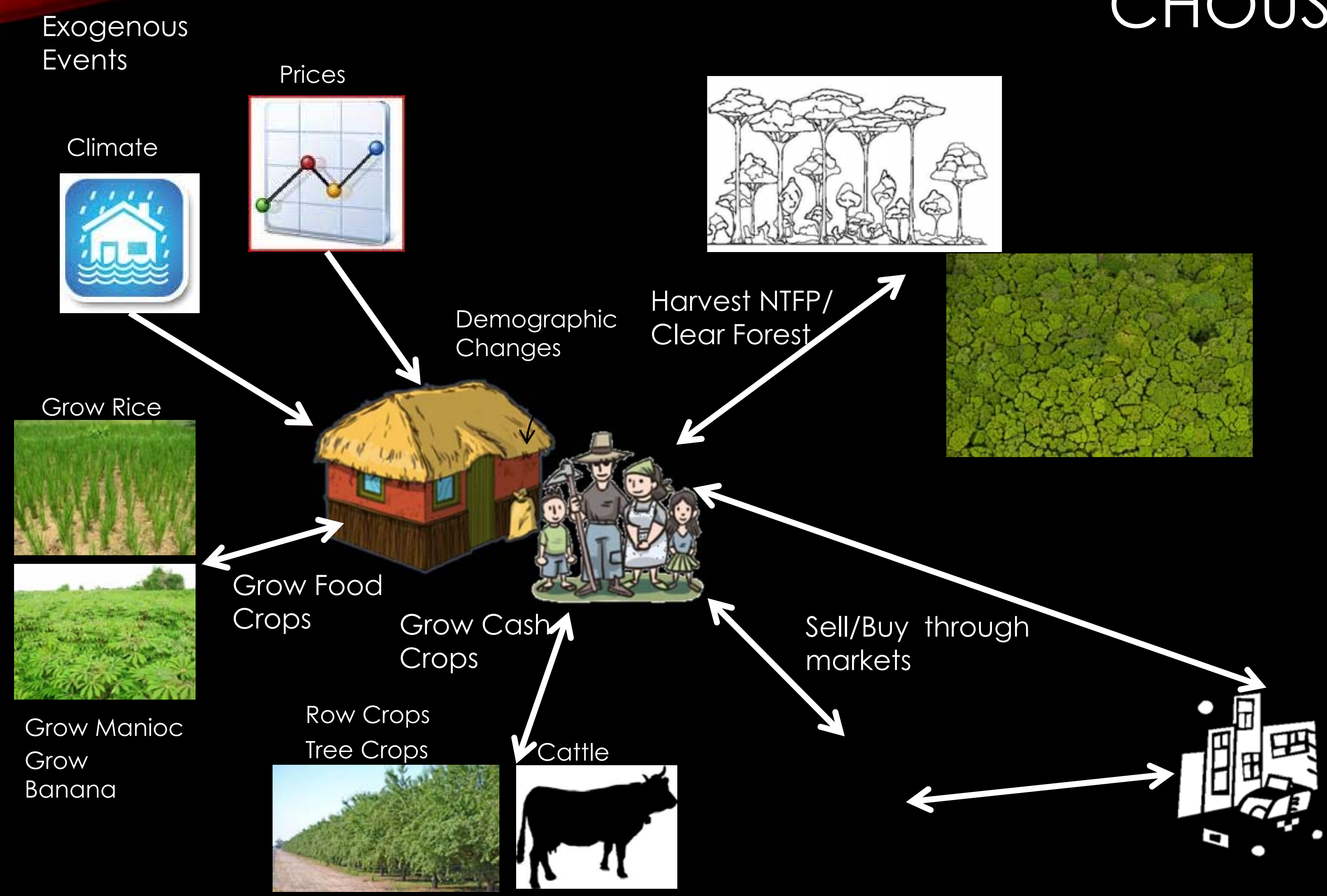
- More detailed data, processes, and objects
- Various instantiations permit comparisons and theoretical testing

Participatory workshops on model development with in-country colleagues, 2013-2014

Workshops to report model output to local stakeholders, 2016



PRIMARY QND:MAP OBJECT/AGENT CHOUSEHOLD



QND:MAP OBJECT DESIGNS – CHOUSEHOLD AND SPACE

HOUSEHOLD CALENDAR

Limitations: Land, Labor & Capital

	Forest		Rice			Manioc			Other row crops			Bananas			Other tree crops			Cattle	Castanha	Wage work
	Clearing	Burning	Planting	Weeding	Harvesting	Planting	Weeding	Harvesting	Planting	Weeding	Harvesting	Planting	Trimming	Harvesting	Planting	Trimming	Harvesting	Culling	Harvesting	
May	X						X	X					X	X						X
June	X						X	X					X	X				X		X
July	X						X	X					X	X				X		X
Aug		X					X	X					X	X						X
Sept		X					X	X					X	X						X
Oct		X	X			X	X	X	X			X	X	X	X					X
Nov			X	X		X	X	X	X	X		X	X	X	X					X
Dec				X			X	X		X			X	X		X			X	X
Jan				X			X	X		X			X	X		X			X	X
Feb				X			X	X		X			X	X		X			X	X
Mar				X	X		X	X		X	X		X	X			X			X
Apr					X		X	X			X		X	X			X			X

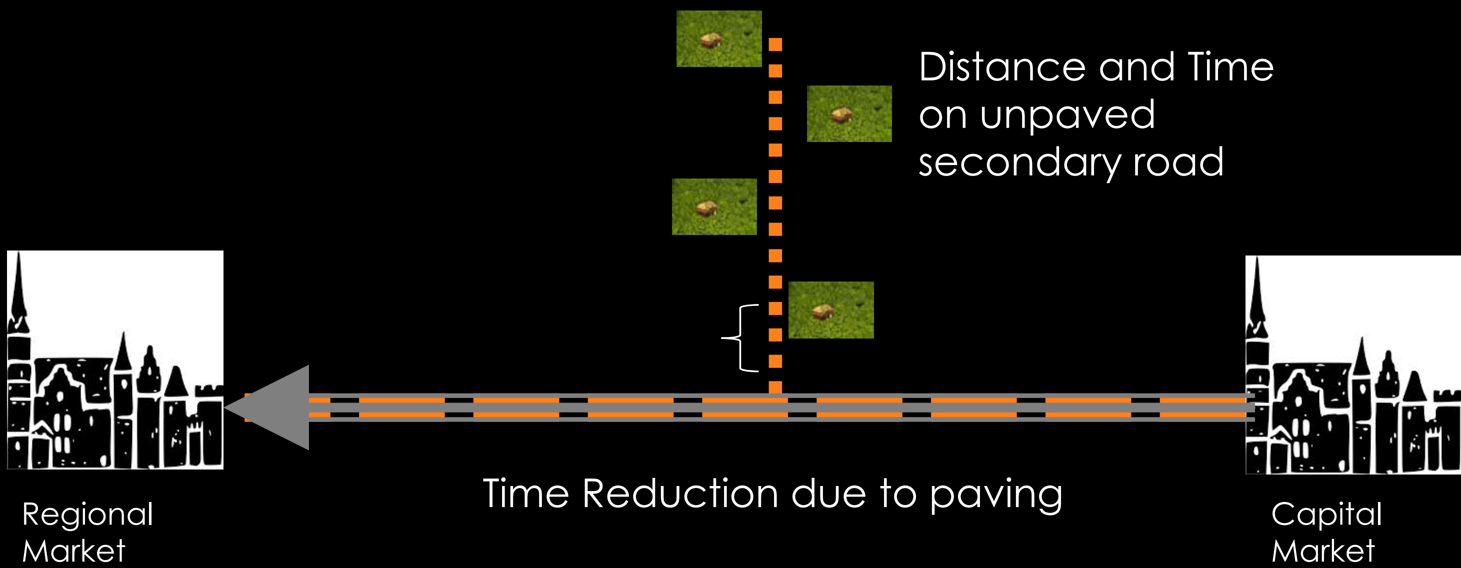
$$LaborAvl_{month} = \sum \left(LaborAvl_{ageGender}\ x\ \#_{ageGender}\right)$$

$$LaborReq_{month} = \sum\left(LaborReq_{crop}\ x\ Area_{crop}\right) + LaborReq_{clear\&burn}$$

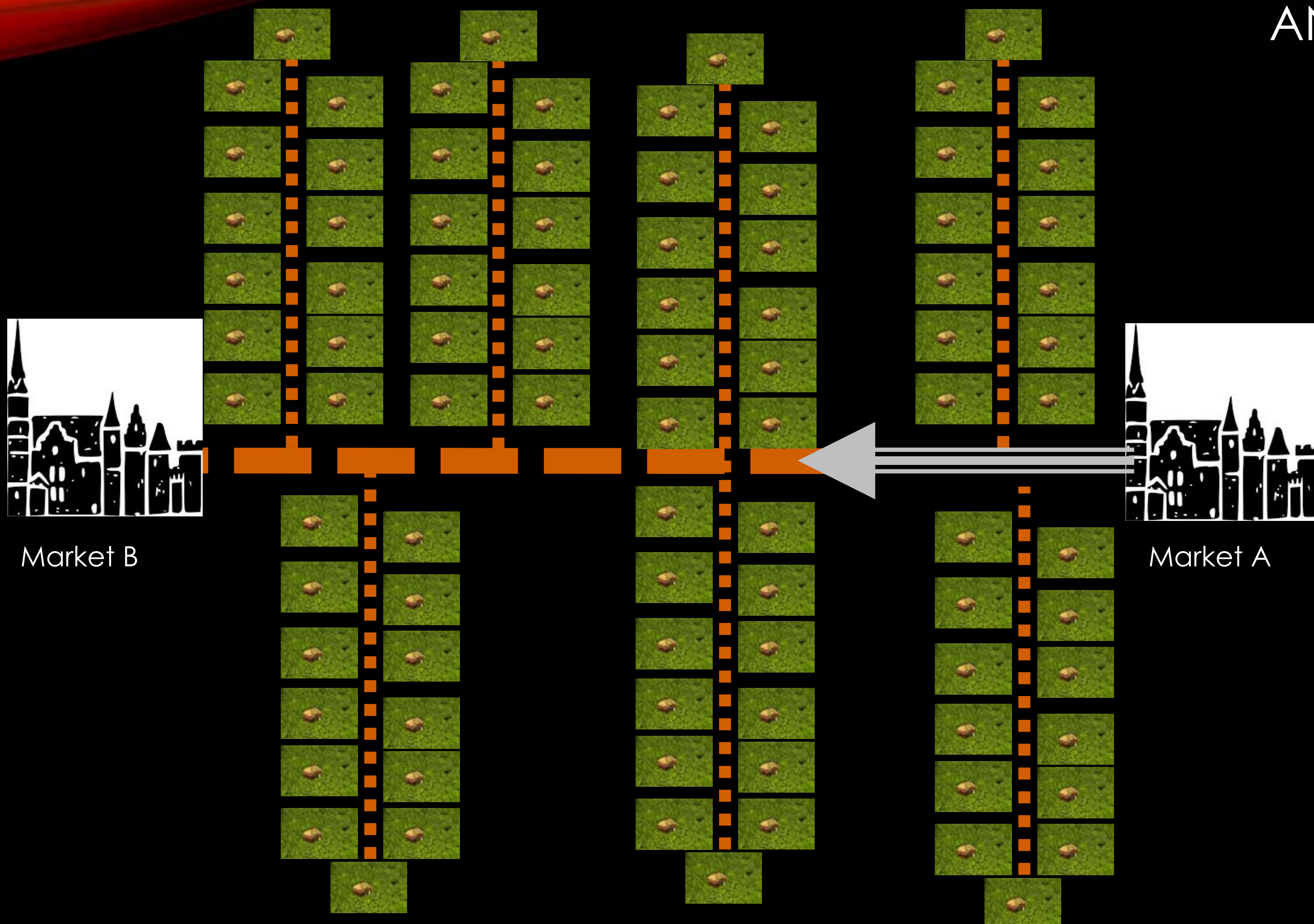
$$FoodSecurity_{month} = \sum\left(Store_{FoodCrop} + Purchase_{FoodCrop} - \ Consume_{FoodCrop}\right)$$

$$Wealth_{month} = \sum\left(AmtToSell_{crop}\ x\ Price_{crop} - TransCost_{crop}\right)$$

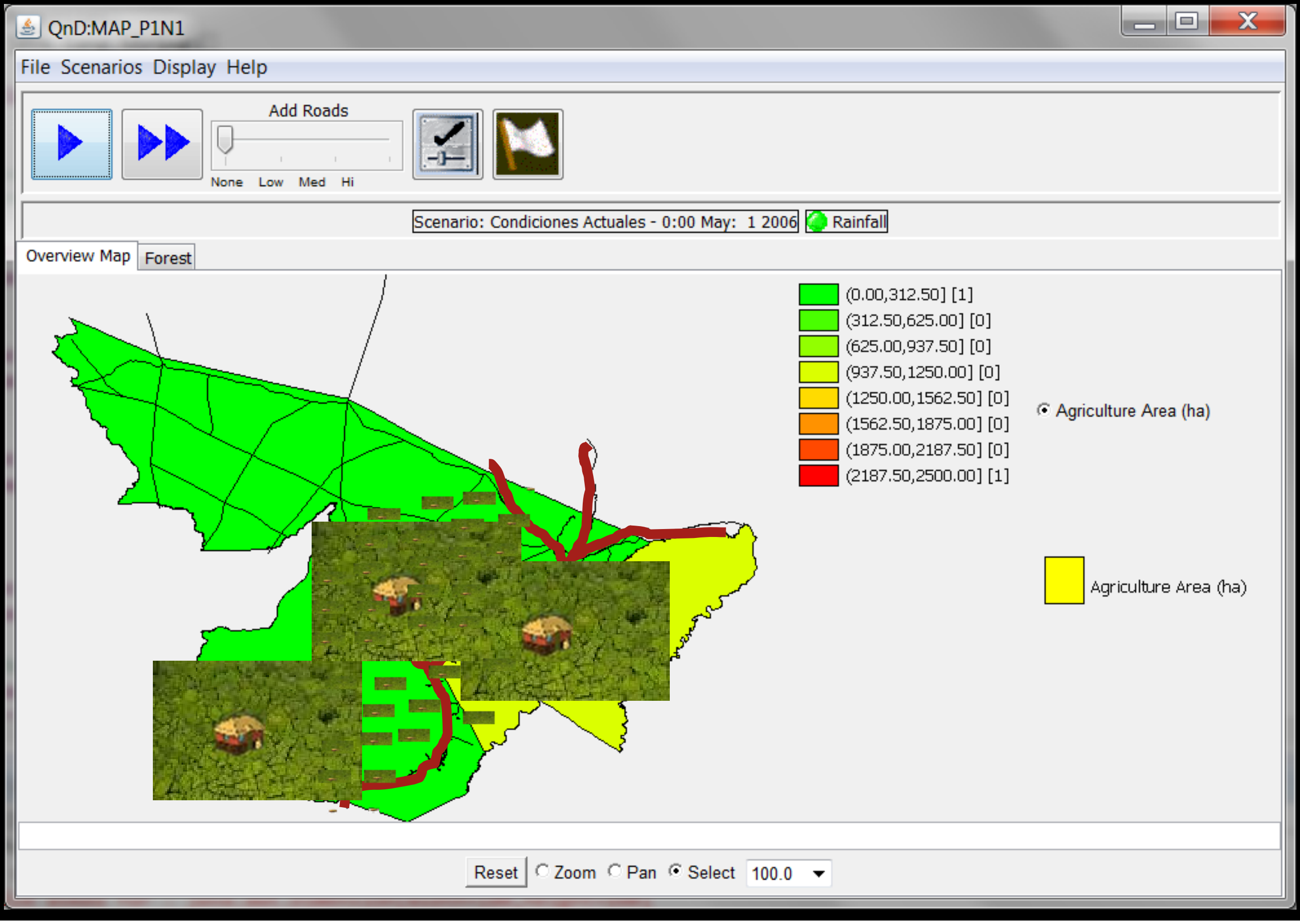
HOUSEHOLD INTERACTIONS WITH ROADS AND MARKETS



GROUPS OF HOUSEHOLDS ARRANGED ALONG ROADS AND MARKETS



HOUSEHOLD OBJECTS ARE STOCHASTICALLY REPLICATED INTO 99 POLYGONS OF INTEREST

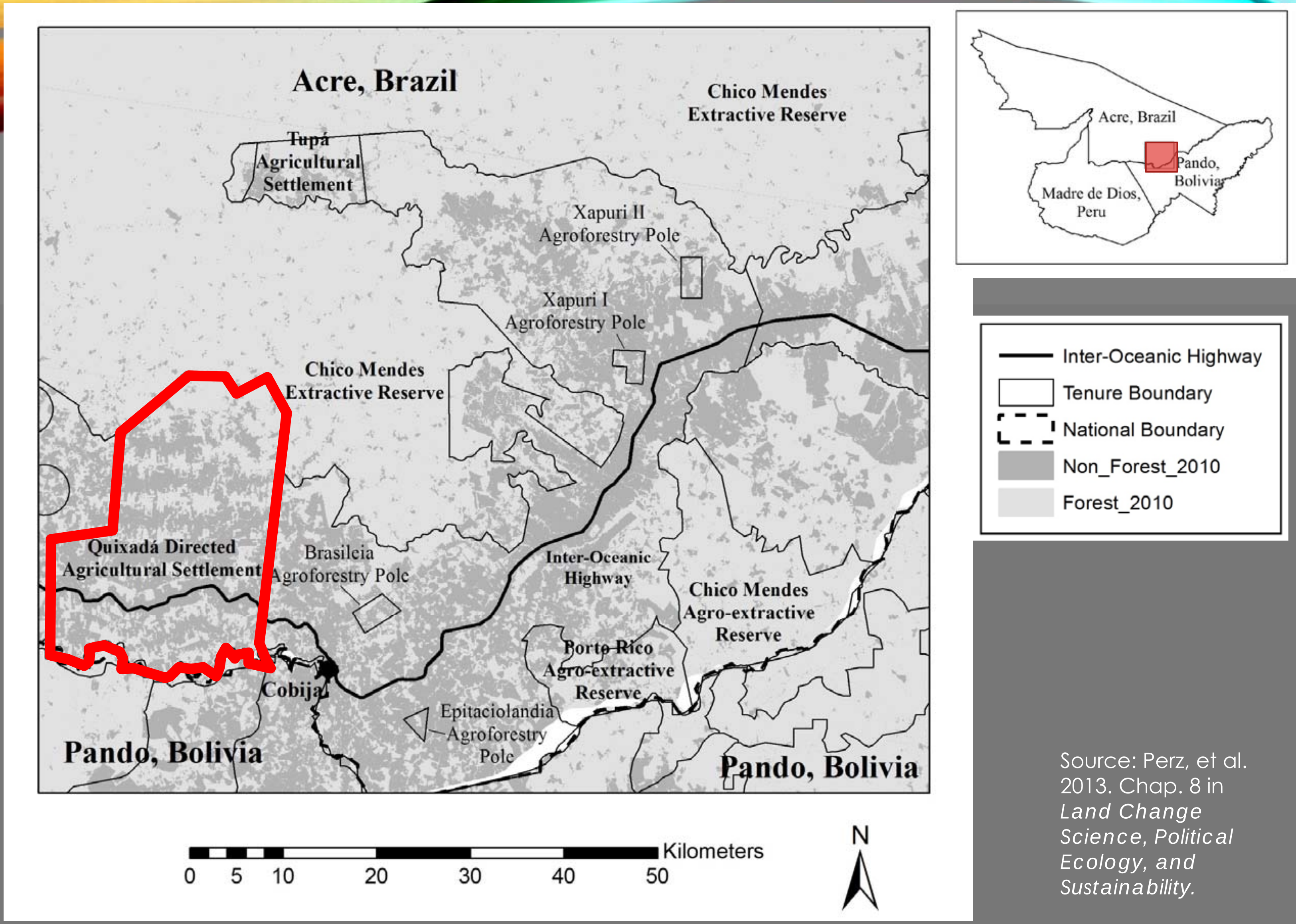


99 Spatial Communities with internal HH agents

- Spread along road system in Brazil, Peru and Bolivia
- Varying land allocations per HH (10 ha to 500 ha)
- Varying education and wealth levels for each HH
- Varying access to markets & road paving
-
- Varying forest types within each community

Quixada

- 50 ha/HH
- Capital Market: 310 min (1985) to 164 min (2002)
- Secondary Market: 32 min (1985) to 20 min (2002)
-



Source: Perz, et al. 2013. Chap. 8 in *Land Change Science, Political Ecology, and Sustainability.*

P1 = No Tenure Rules

P2 = Tenure Rules, Always Obeyed

P3 = Tenure Rules, Rule Breaking

PAD Quixadá, Acre, Brazil

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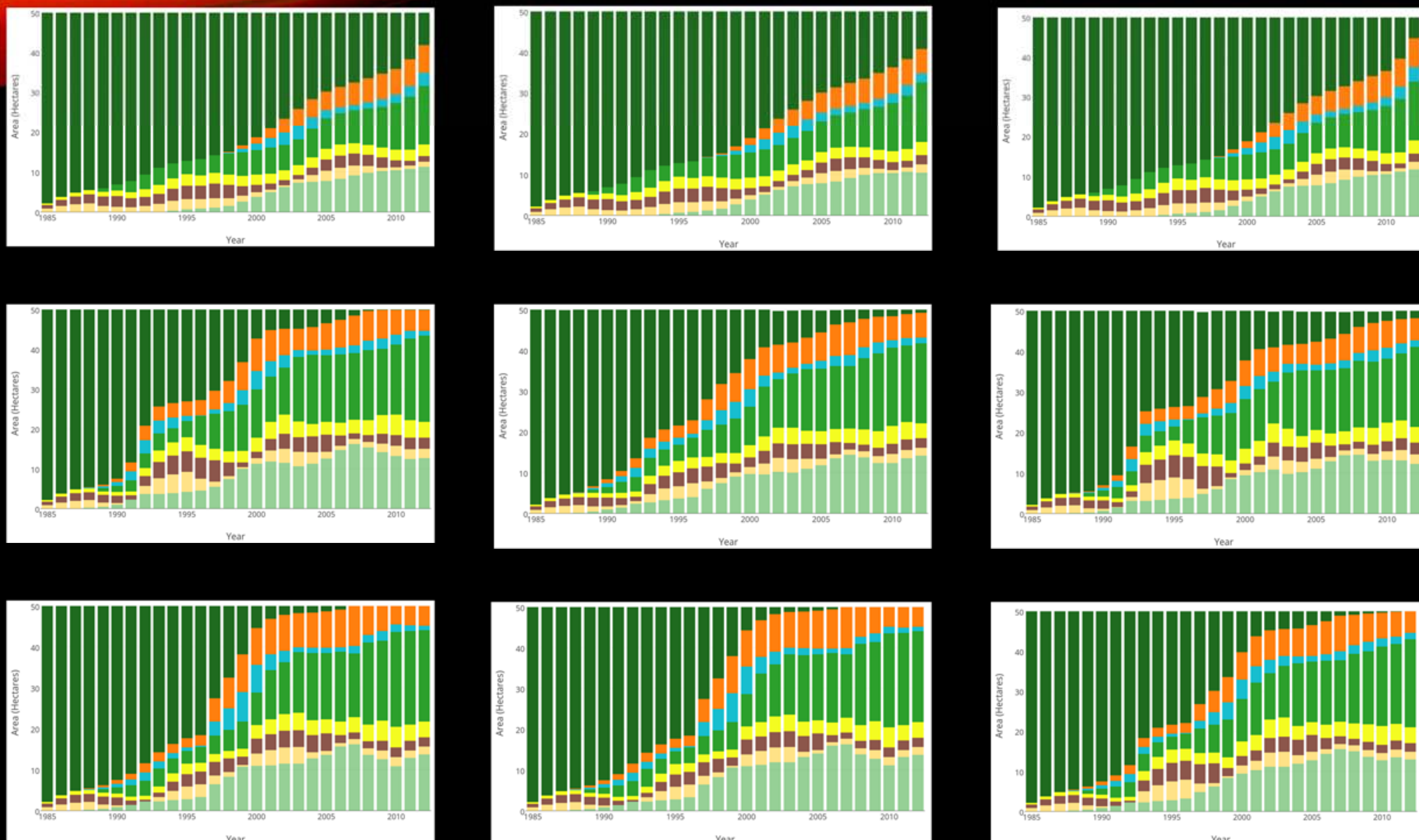
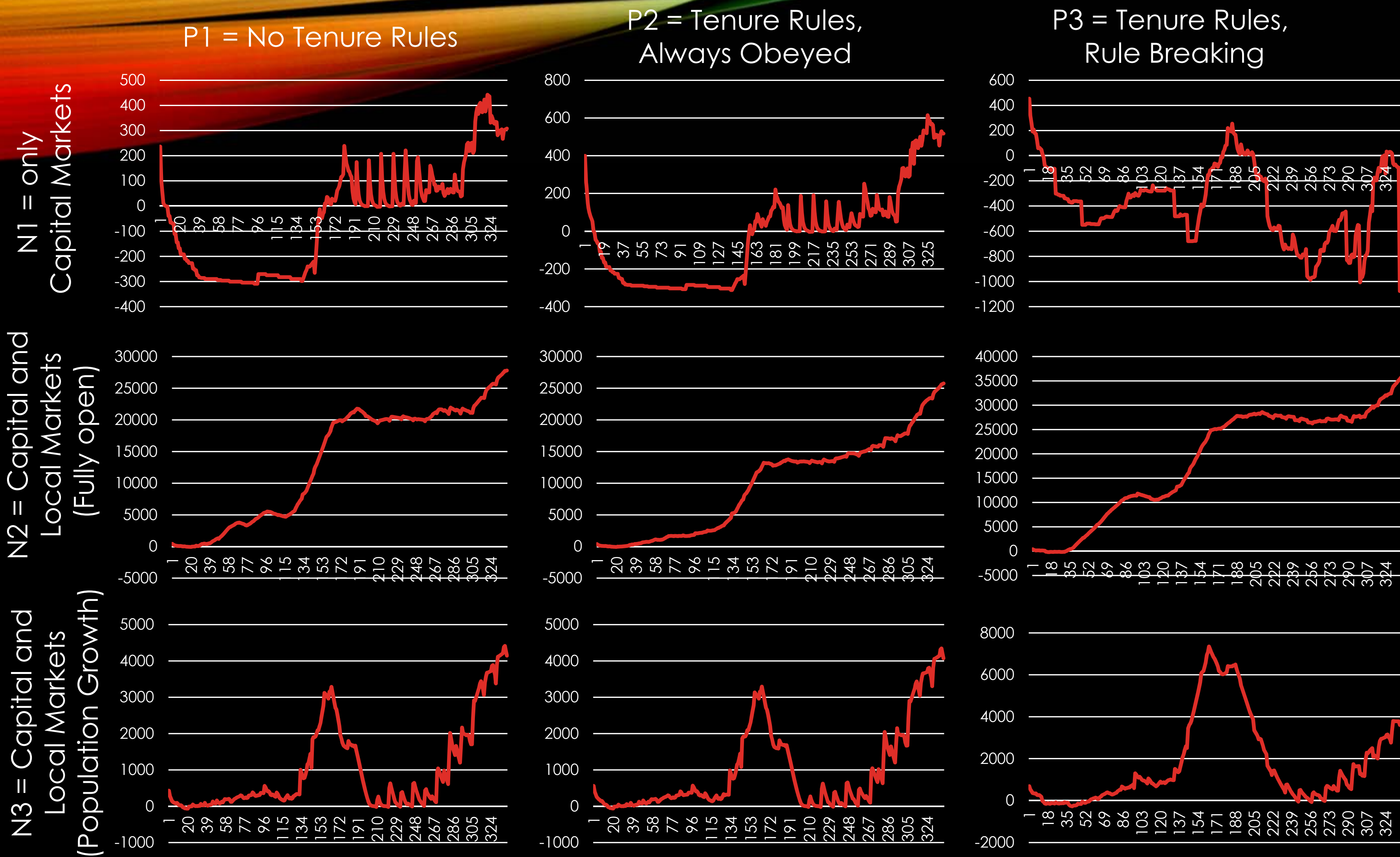


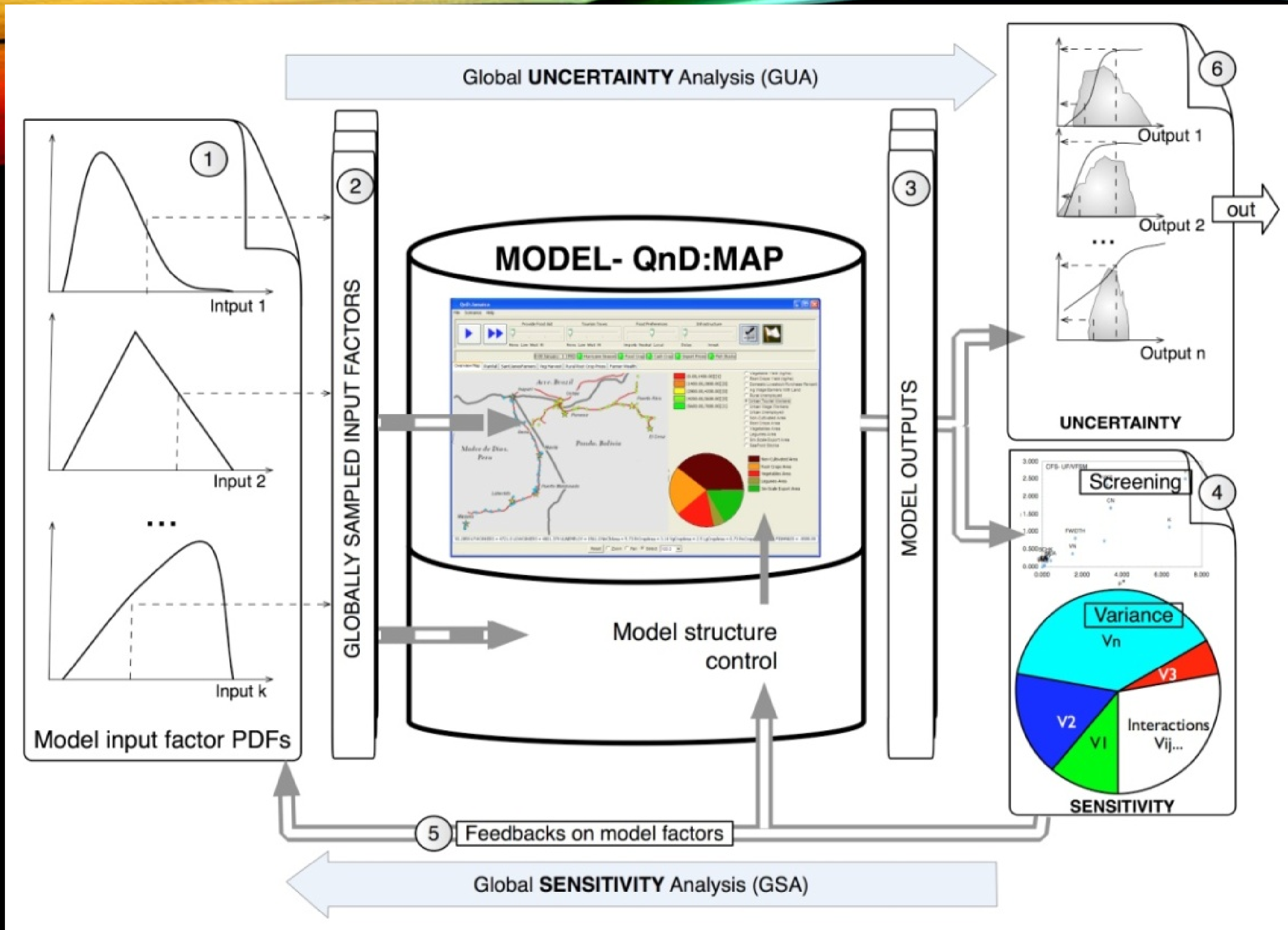


PAD Quixadá, Acre, Brazil

Average household Wealth (US$)

MODELING PLATFORMS FOR EVALUATION OF COMPLEX SOCIAL-ECOLOGICAL SYSTEMS

- **Analytical Approach, part 2: GSA/UA**
- We also need systematic approaches to evaluation of model output
- All models are just representations, and thus “incorrect”
- But it is useful to quantify model sensitivity to sources of uncertainty
- Global sensitivity and uncertainty analysis (GSUA) permit systematic evaluation of model performance (Saltelli, et al. various)
- To which model inputs, each with their uncertainties, is model output most sensitive?


Global UNCERTAINTY Analysis (GUA)
1
Intput 1
Input 2
...
Input k
Model input factor PDFs
2
GLOBALLY SAMPLED INPUT FACTORS
MODEL- QnD:MAP
Model structure
control
3
MODEL OUTPUTS
6
Output 1
Output 2
...
Output n
out
UNCERTAINTY
Screening
4
Variance
Vn
V3
V2
V1
Interactions
Vij...
SENSITIVITY
5
Feedbacks on model factors
Global SENSITIVITY Analysis (GSA)

MODELING PLATFORMS FOR EVALUATION OF COMPLEX SOCIAL-ECOLOGICAL SYSTEMS

- **Platform, part 2: Simlab**
- Global uncertainty analysis relates sources of uncertainty among inputs to variability in model outputs…
- …and global sensitivity analysis identifies the inputs to which the output is most sensitive
- Both require systematic random variation in the values of all input factors
- Requires repeated runs of the simulation on a supercomputer (HiPer Gator!)
- For more complicated models with more inputs, more runs required

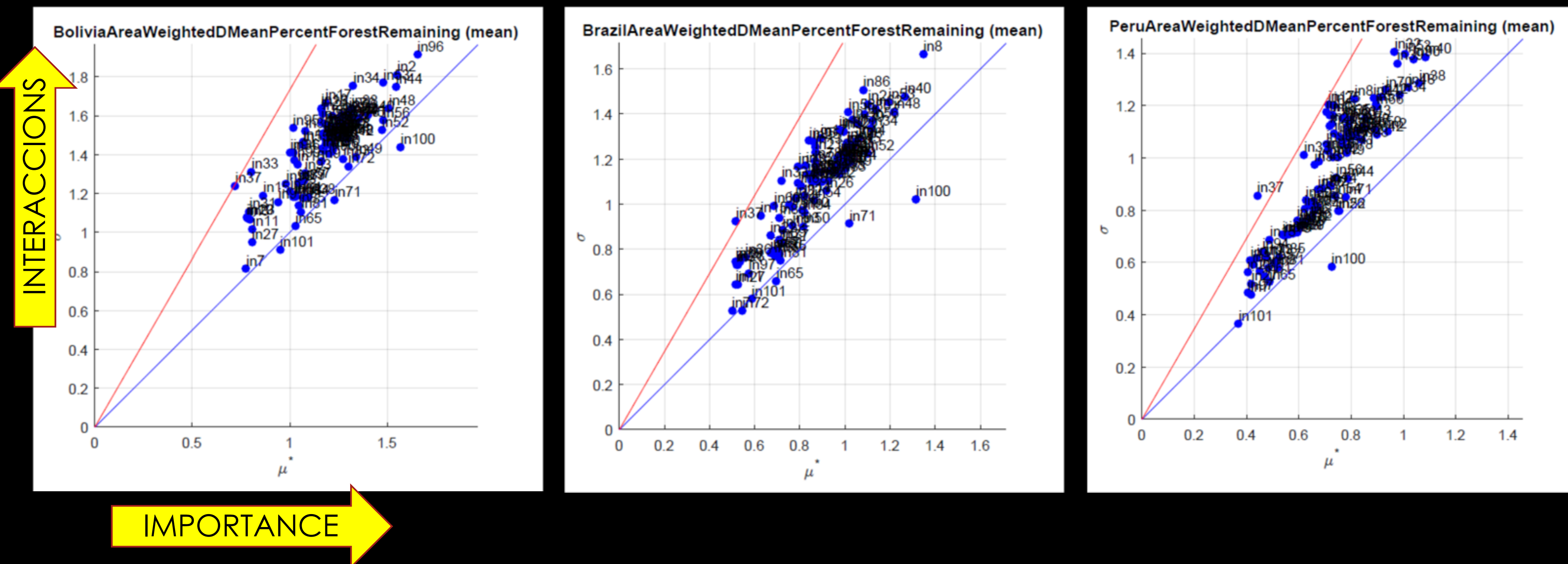
MODELING PLATFORMS FOR EVALUATION OF COMPLEX SOCIAL-ECOLOGICAL SYSTEMS

- **Platform, part 2: Simlab**
- GSA/UA has multiple steps and yields multiple forms of findings
- In GUA, the Morris screening method relates model inputs to output:
- μ^* indicates the importance of the input for the output
- Permits identification of the key inputs, helps simplify GSA

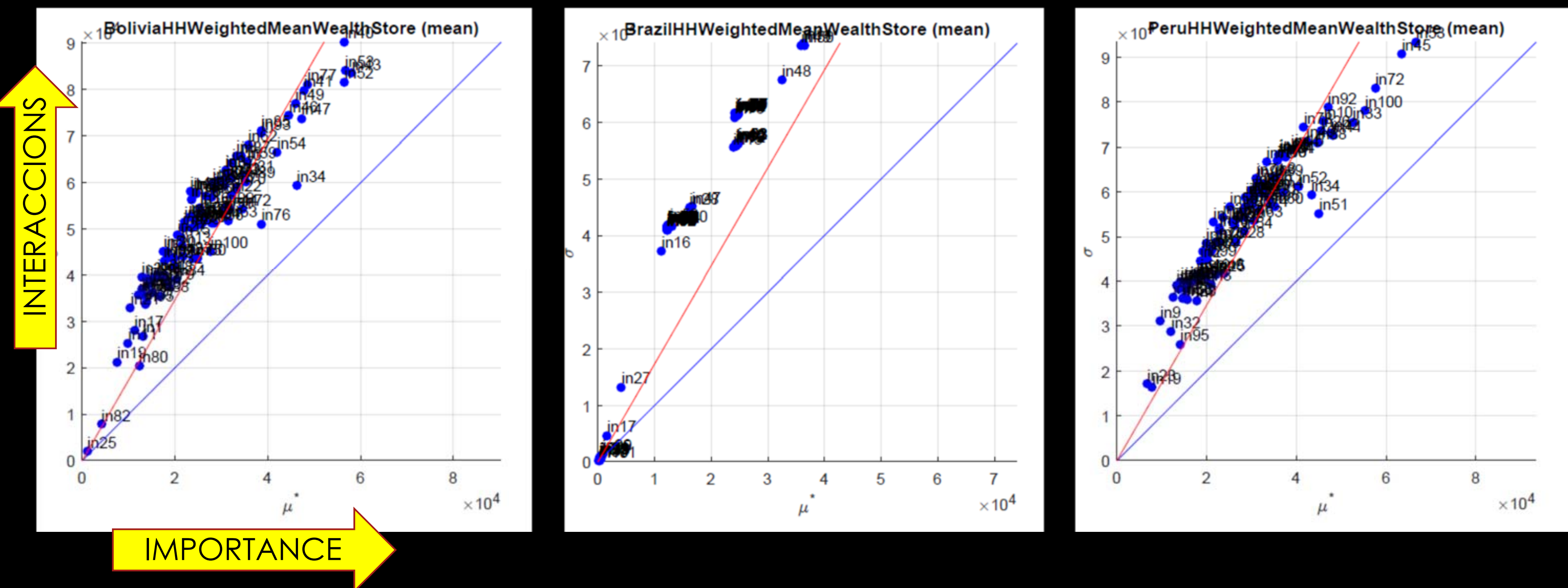
MODELING PLATFORMS FOR EVALUATION OF COMPLEX SOCIAL-ECOLOGICAL SYSTEMS

- **Platform, part 2: Simlab**
- GUA also accounts for interactions among inputs:
- σ indicates the strength of its interactions with other inputs
- Goes beyond local or "OAT" techniques of UA; hence "global" UA

MODELING PLATFORMS FOR EVALUATION OF COMPLEX SOCIAL-ECOLOGICAL SYSTEMS



MODELING PLATFORMS FOR EVALUATION OF COMPLEX SOCIAL-ECOLOGICAL SYSTEMS

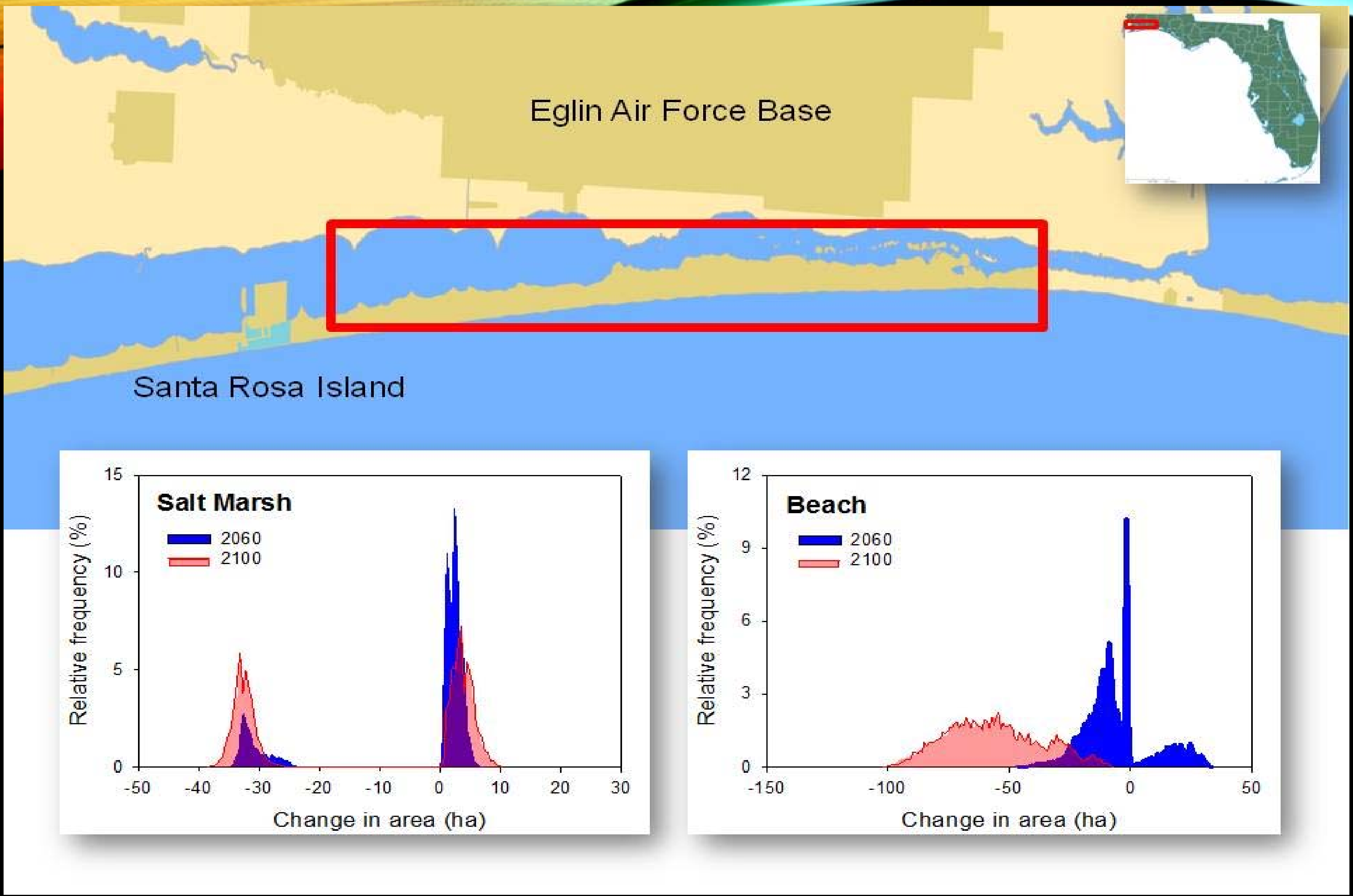


MODELING PLATFORMS FOR EVALUATION OF COMPLEX SOCIAL-ECOLOGICAL SYSTEMS

- **Platform, part 2: Simlab**
- Important inputs might be social or ecological factors
- They might also be theoretically important or more mundane
- Led to debates among the project team over their interpretation
- The bottom line: GUA is a powerful diagnostic tool for identifying the key input factors behind variability in model output

MODELING PLATFORMS FOR EVALUATION OF COMPLEX SOCIAL-ECOLOGICAL SYSTEMS

- **Platform, part 2: Simlab**
- Part 2 of GSA/UA focuses on model sensitivity
- Simlab produces PDFs of model output across many repetitions of the model with variations in the input factor values
- The form that output PDFs take indicates sensitivity and the likely values in the model outputs
- GSA still in the works as we finalize the P3 model instantiations
- But results from other model applications are intriguing



Source: Chu-agor 2011, Perz, et al. 2013

MODELING PLATFORMS FOR EVALUATION OF COMPLEX SOCIAL-ECOLOGICAL SYSTEMS

- **Platform, part 2: Simlab**
- PDFs can be interpreted in terms of ecological resilience (Perz, et al. 2013)
- Ecological resilience highlights shifts in systems among multiple possible states

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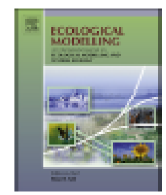

Review

Evaluating ecological resilience with global sensitivity and uncertainty analysis

CrossMark

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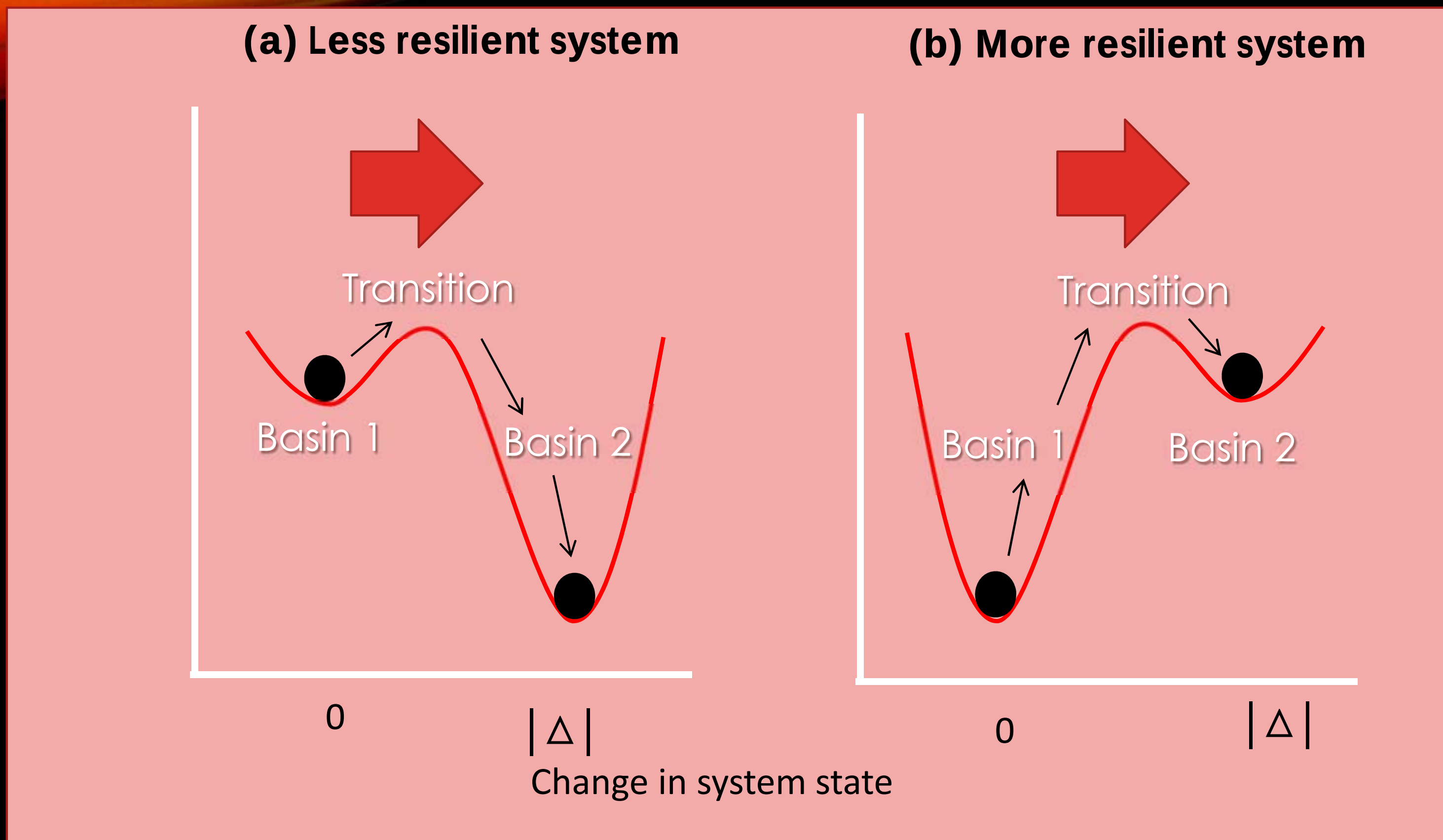
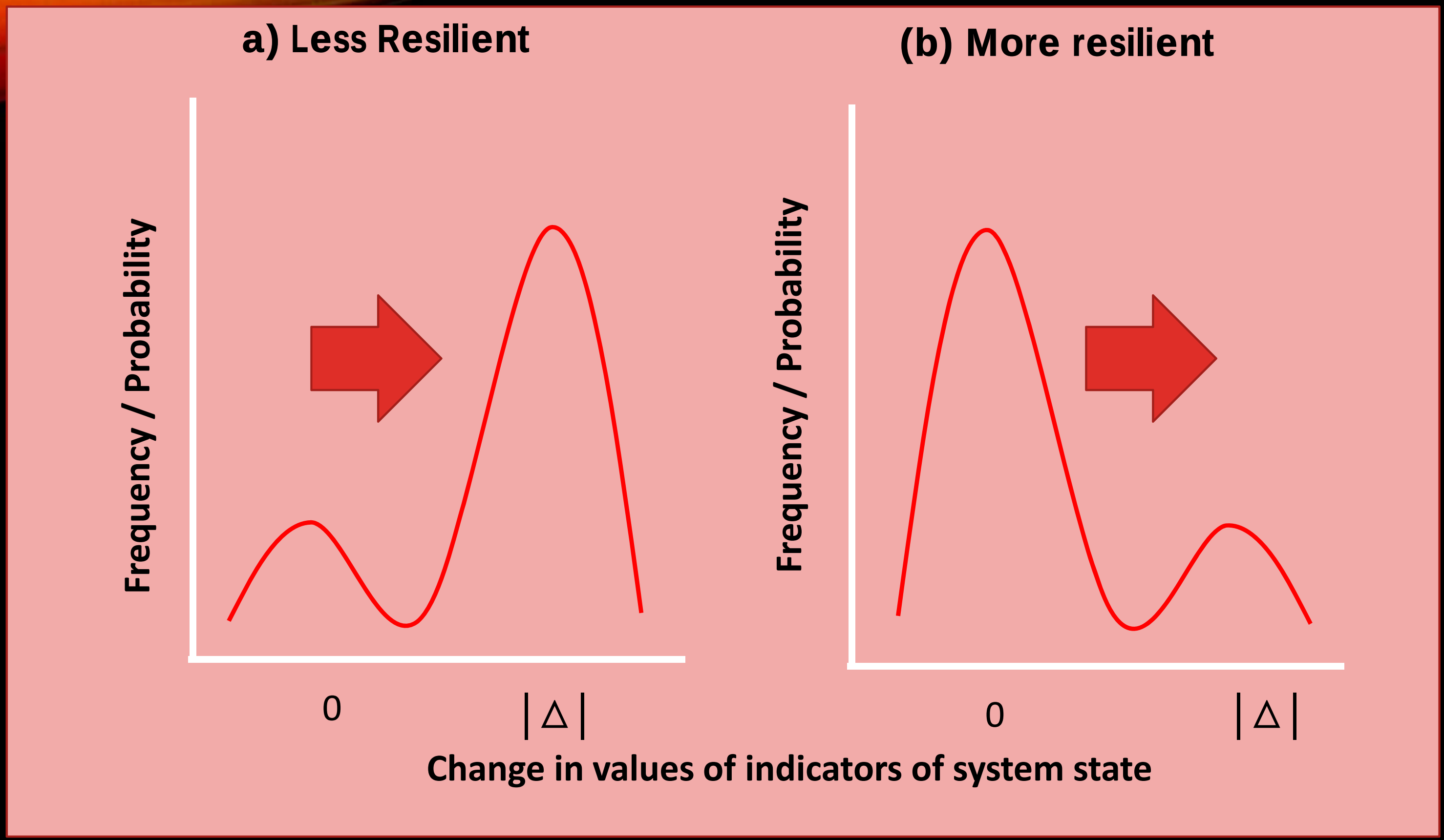
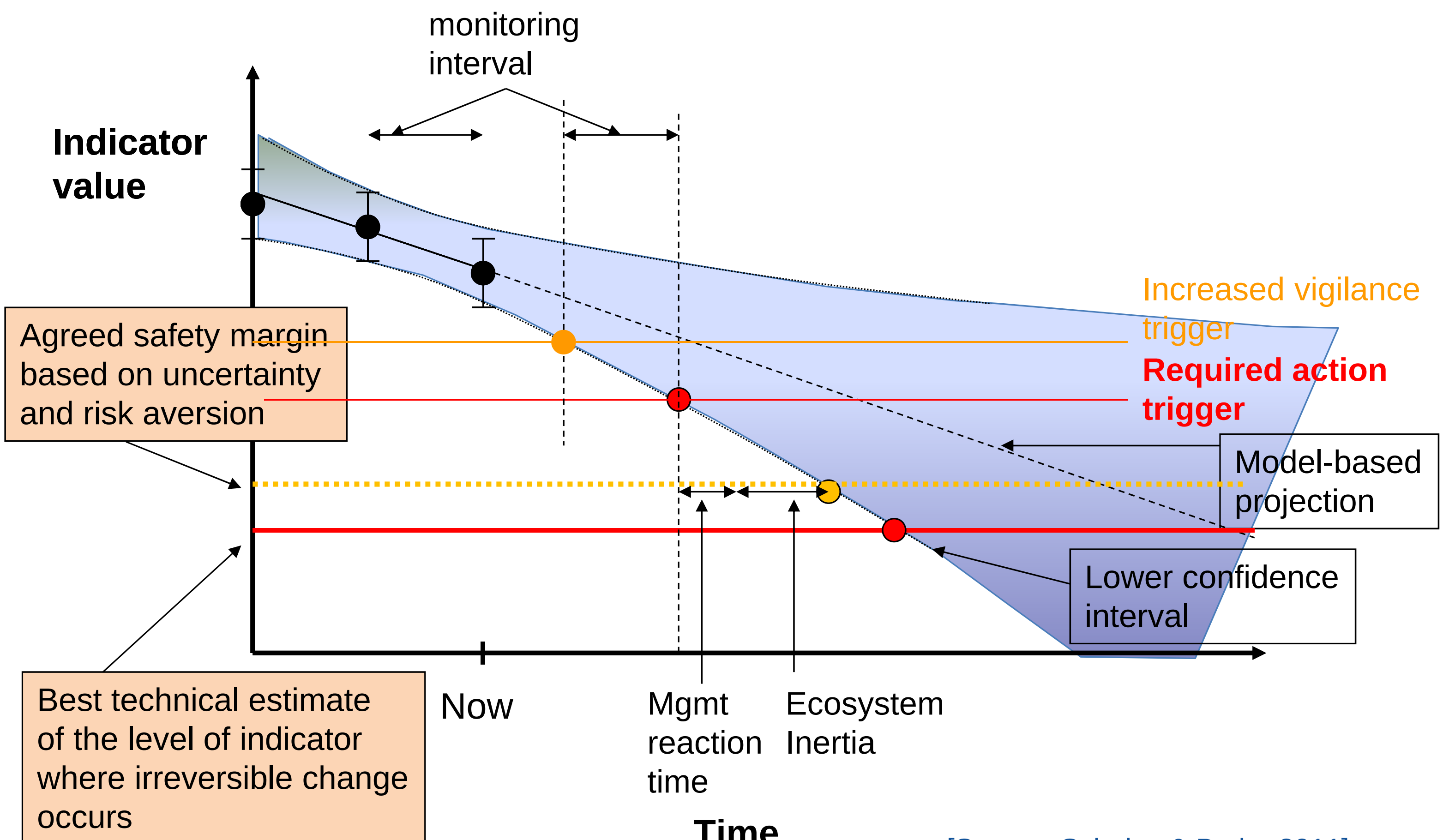
MODELING PLATFORMS FOR EVALUATION OF COMPLEX SOCIAL-ECOLOGICAL SYSTEMS

- **Platform, part 2: Simlab**
- PDFs can be interpreted in terms of ecological resilience (Perz, et al. 2013)
- Ecological resilience highlights shifts in systems among multiple possible states
- PDFs quantify the probability that a system will be in a certain state
- Indicated by the PDF of values for the model output as an indicator of system state


(a) Less resilient system
Transition
Basin 1
Basin 2
0
|Δ|
(b) More resilient system
Transition
Basin 1
Basin 2
0
|Δ|
Change in system state


a) Less Resilient
(b) More resilient
Frequency / Probability
Frequency / Probability
0
|∆|
0
|∆|
Change in values of indicators of system state

Integrating Monitoring, Modeling and Uncertainty into Decisions



[Source: Scholes & Botha,2011]

MODELING PLATFORMS FOR EVALUATION OF COMPLEX SOCIAL-ECOLOGICAL SYSTEMS

- **Conclusions**
- A modeling platform with high flexibility like QnD allows multiple instantiations to compare theories and evaluate model complexity
- Plans in the works to incorporate additional information on plant diversity and ecosystem services
- Species-specific data on carbon stocks; evaluate regarding plant communities and PES programs
- Plans also underway to incorporate climate change and variability; our study region was in the epicenter of the 2005 and 2010 Amazon droughts

MODELING PLATFORMS FOR EVALUATION OF COMPLEX SOCIAL-ECOLOGICAL SYSTEMS

- **Conclusions**
- A diagnostic tool like GSA/UA permits systematic evaluation of the sources of uncertainty and their consequences for model output
- Analysis of PDFs from GSA has additional theoretical applications in the evaluation of ecological resilience

MODELING PLATFORMS FOR EVALUATION OF COMPLEX SOCIAL-ECOLOGICAL SYSTEMS

- **Conclusions**
- Establishing specific ranges in for inputs in GSA/UA also has policy and management applications
- A policy that prohibits or prevents a key factor from going beyond a certain value can be evaluated in terms of sensitivity of model output, and thus the efficacy of the policy

QUESTIONS?

Acknowledgements: NSF CNH 1114924, "Global Sensitivity & Uncertainty Analysis for Evaluation of Ecological Resilience: Theoretical Debates over Infrastructure Impacts on Livelihoods & Forest Change"