"Integrated Assessment Modeling" of Coupled Natural and Human Systems in LCB

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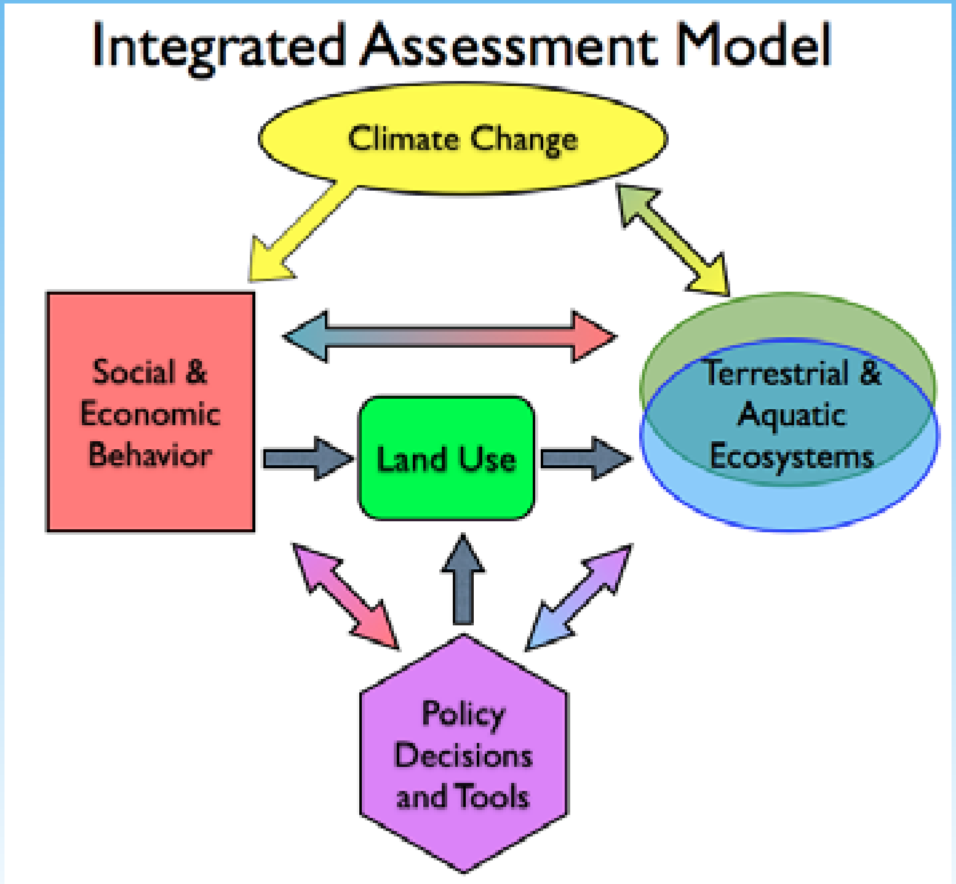
RACC's IAM Research Approach

- Three Working Groups Meet 6-8 times per year
  - Cascading IAM working group
  - Hybrid IAM working group
  - Data Management working group
- Annual day-long retreats
- Numerous side meetings between all specific sub-groups
- Truly an interdisciplinary and collaborative working experience

The Overarching RACC Question

How will the interactions of climate change and land use alter hydrological processes and nutrient transport from the landscape, internal processing and eutrophic state within the lake, and what are the implications for adaptive management strategies?



Three Distinct Approaches to IAMs

- **Cascading Models**
  - E.g. MIT's IGSM; GB-Quest (Carmichael et al 2005)
- **Bayesian Networks and System Dynamic Models (Hybrid Models)**
  - E.g. World3 (Meadows et al 2003); IIASA's GAINS model; IIASA's EPIC model
- **Impact Assessment Models**
  - Synthesis-Based
    - E.g., Millennium Ecosystem Assessment (MEA) 2005; Rottmans and Van Asselt approach to "Integrated Assessment"
  - Multi-Criteria Decision Analysis (MCDA)
    - E.g. Conservation and Development Planning (Zia et al. 2011 *Ecology and Society*); Energy and Environment Planning etc.

Comparing Cascading and Hybrid IAMs of LCB

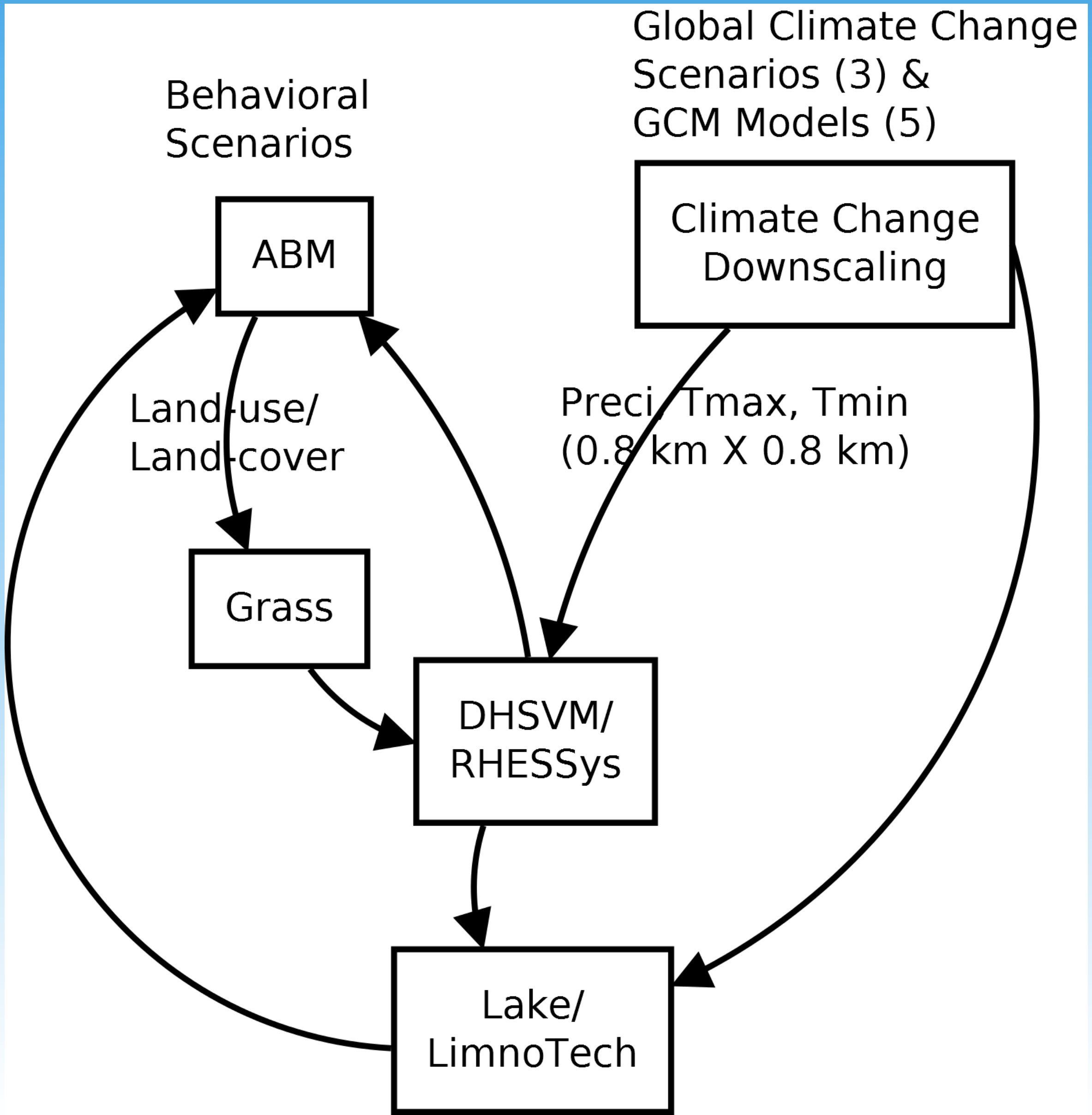
Cascading IAM

- High spatial resolution (30m x 30m)
- High temporal resolution (nested from hourly to daily and annual)
- Limited scope (only Missisquoi and Winooski watershed)
- Highly process-based
- Difficult to adjust and re-calibrate
- May take many days and perhaps weeks to run a scenario!
- Platform: PEGASUS

Hybrid IAM

- Low spatial Resolution (watershed scale)
- Low temporal resolution (nested from weekly to annual and decadal)
- Broader scope (all VT-LCB watersheds)
- Dynamic but less emphasis on process
- Flexible adjustments and easier re-calibration
- May take minutes to run a scenario!
- Platform: AnyLogic Professional

Current Architecture of RACC's Cascading IAM



Cascading IAM: Multi-Discipline Modeling

- Select the best practices for modeling each component of a complex system
  - Land Use Management and Prediction
  - Atmospheric/Weather/Climate Prediction
  - Watershed Hydrological Flow Analysis
  - Lake Water Quality

- Integrate by Building Connections between Dependent Models
  - Consistent land region of study
  - Isolate Parameters that Affect Other Models
  - Bridge Between Models with Necessary Data Manipulations
  - Create a Framework to House and Direct Data Between Models

Cascading IAM Overview

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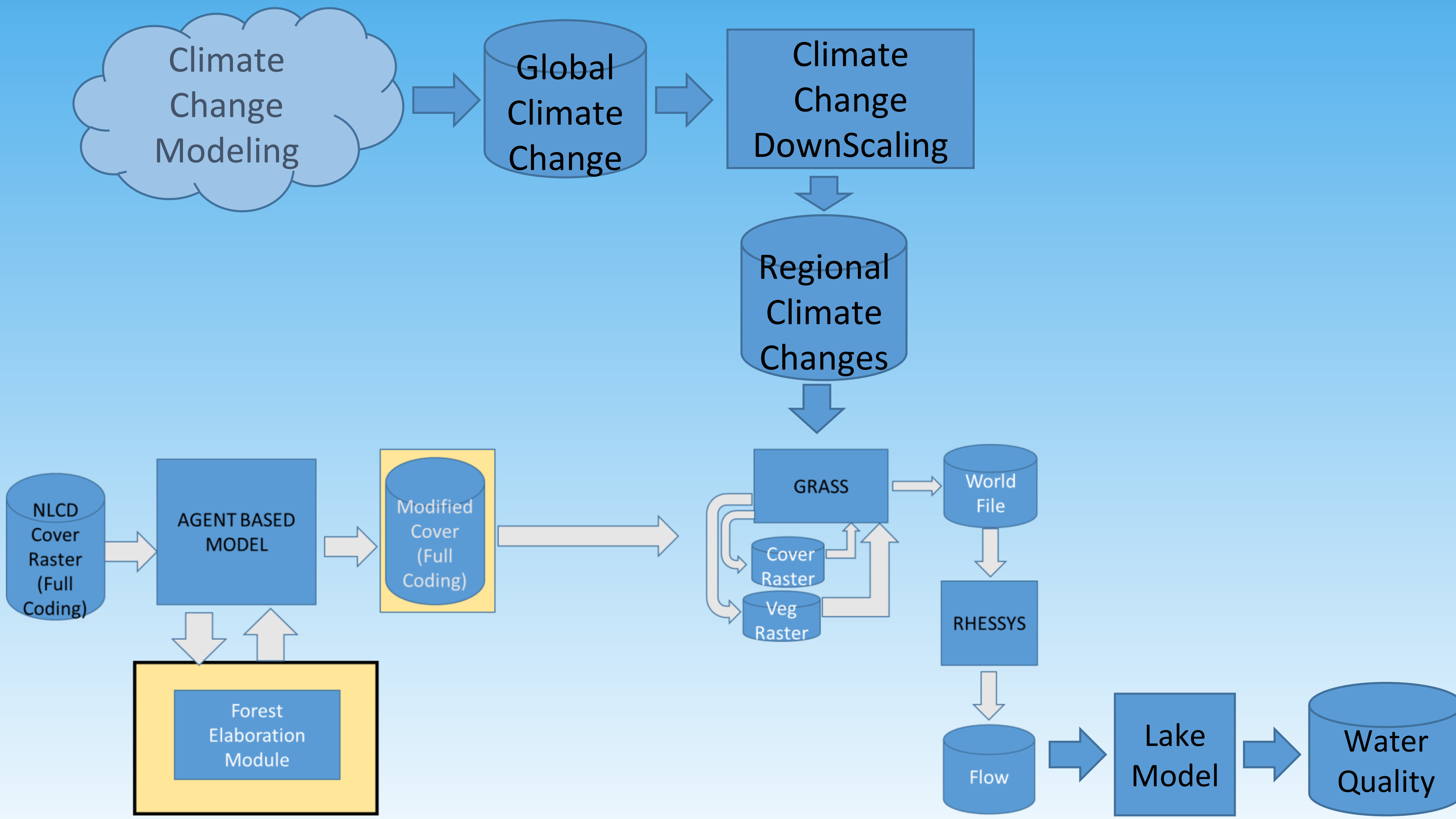
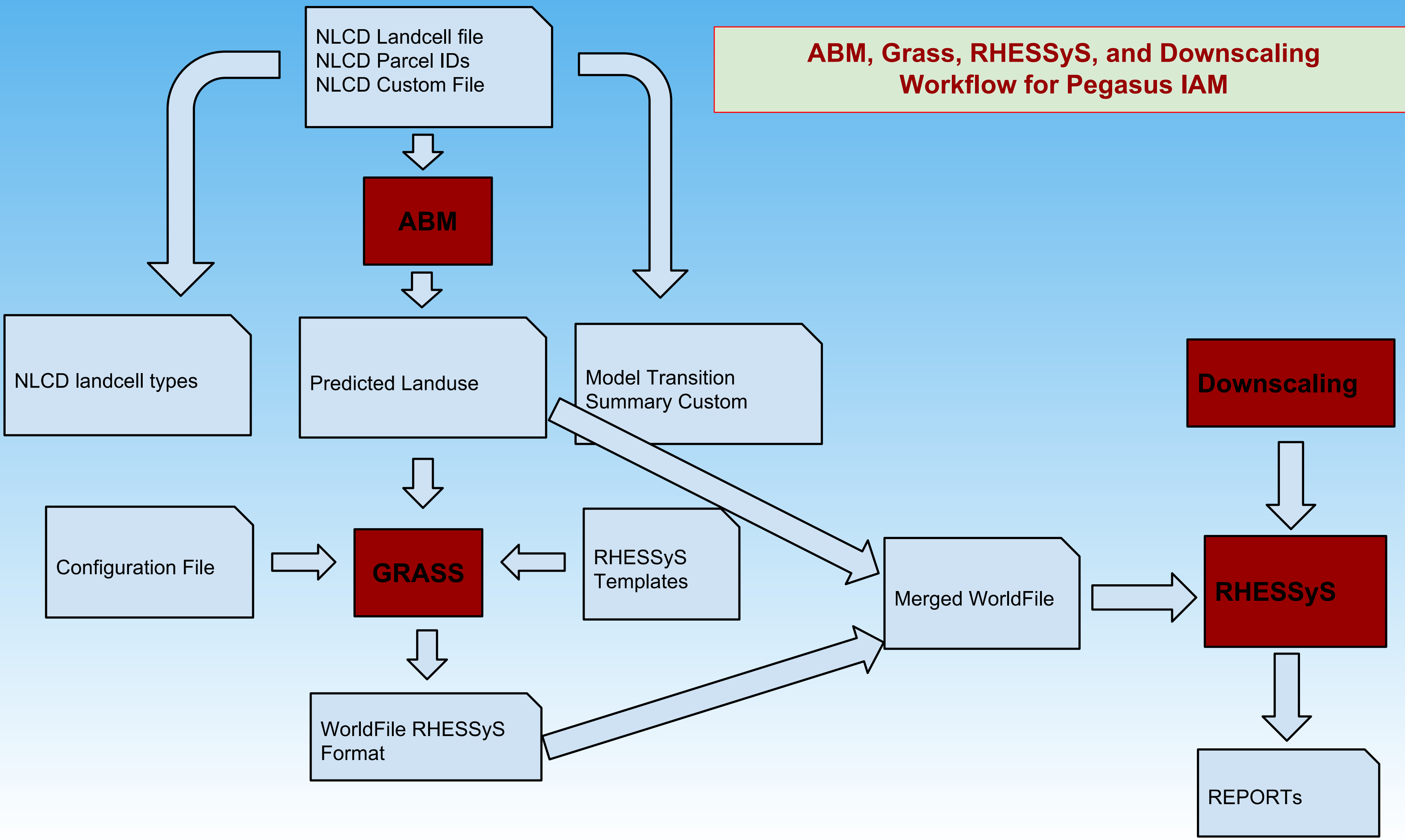
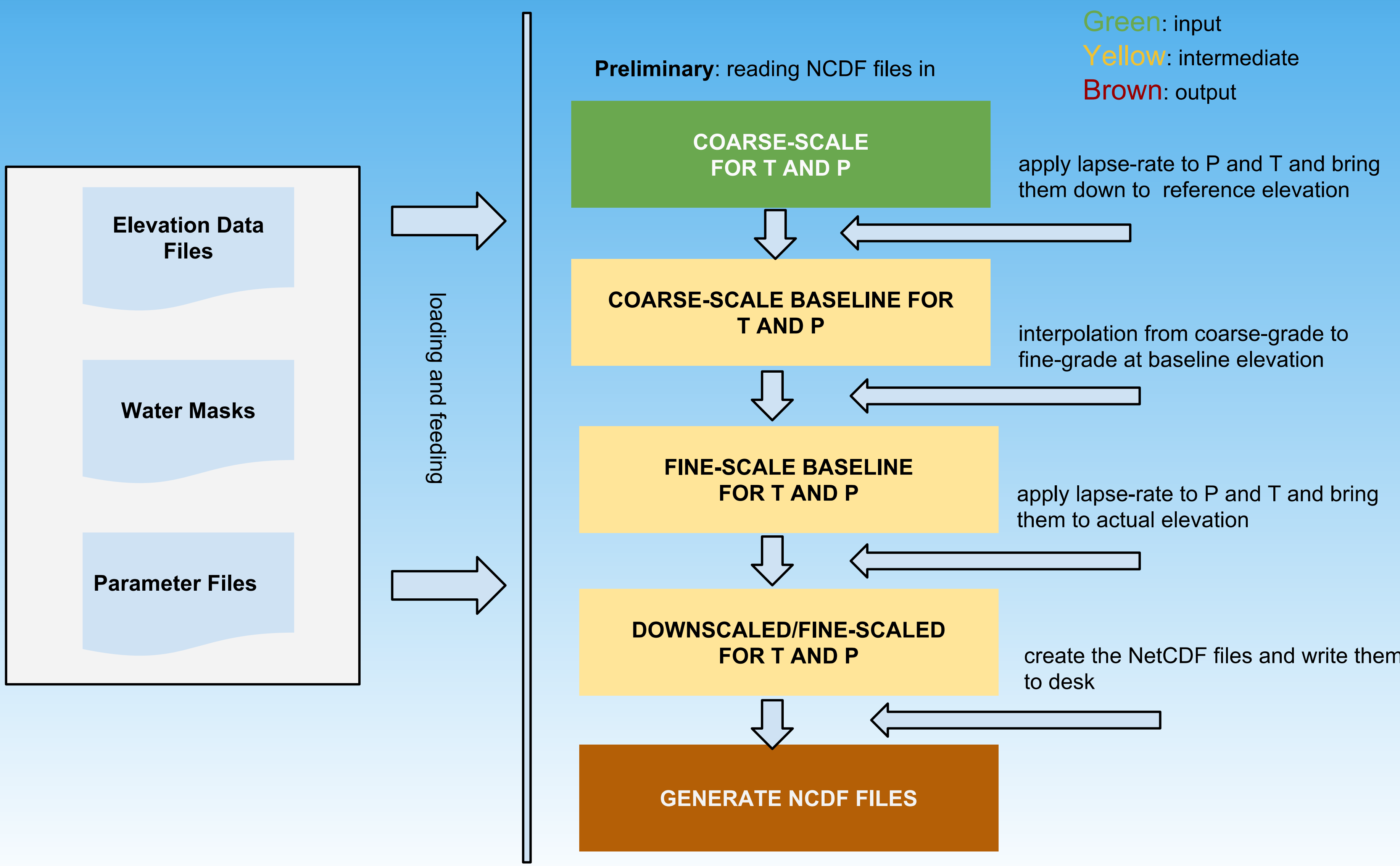


Phase I: Automating Climate, Land Use and Hydrology Scenario Runs



Pegasus Workflow for Climate Downscaling



Progress on Integrating ILUTABM and Downscaled Climate Scenarios with RHESSyS

- IAM working group chose three land-use ABM scenarios and two GCM scenarios to manually run six (3x2) demonstrative scenarios on RHESSyS

- Detailed workflow for automation in PEGASUS will be developed in the IAM retreat on August 19, 2014 (28 participants expected to attend)

Uncertainties surrounding ecological, economic and policy drivers of LULCC are mostly ignored in these baseline projections!

Projected Land Covers (2010-2050)

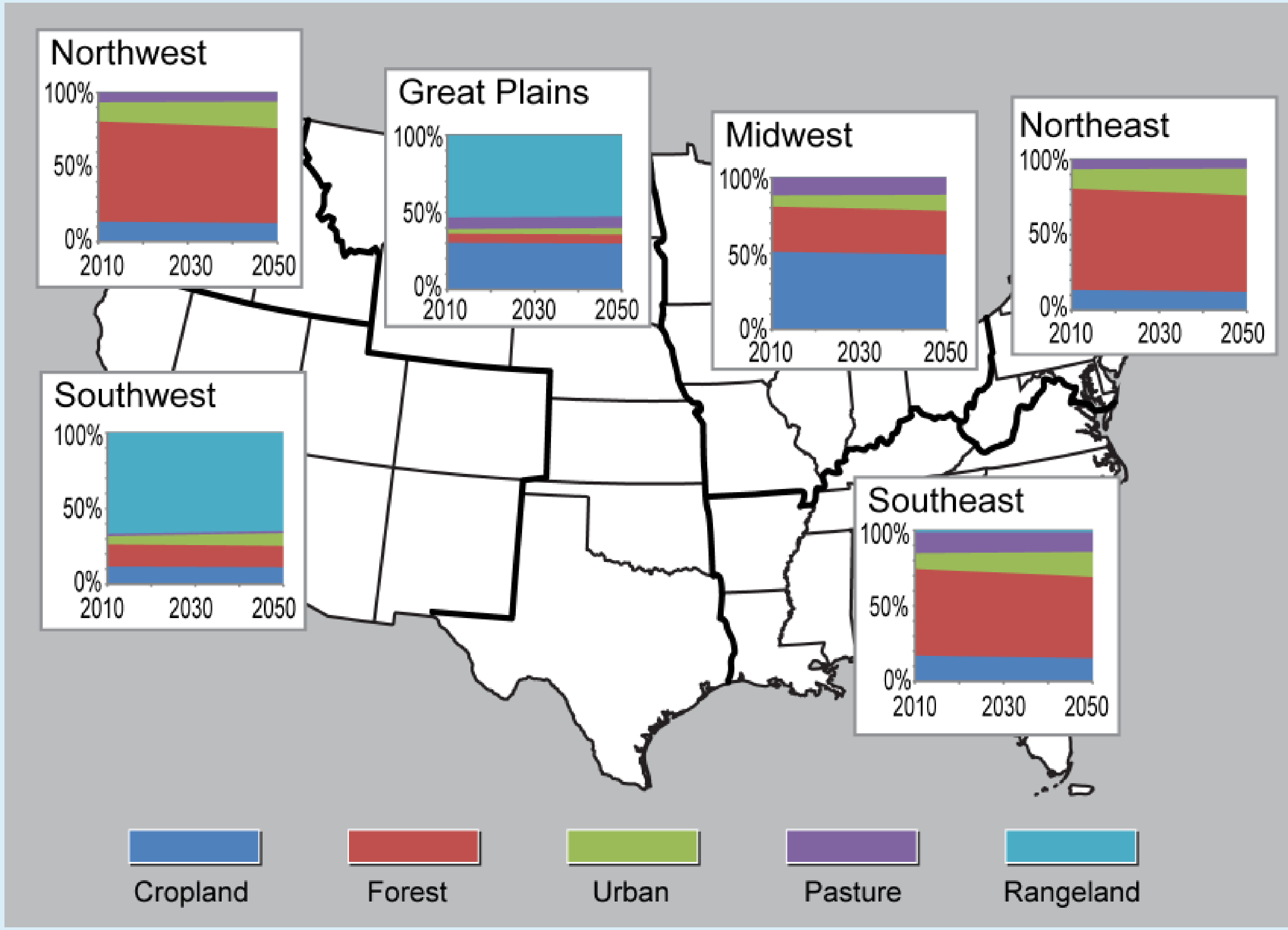


Figure 13.3. Projected percentages in each land-cover category for 2050 compared with 2010, assuming demographic and economic growth consistent with the high-growth emissions scenario (A2) (Data from USDA).

Brown et al. (2014) LULCC, National Climate Assessment

Overarching ABM Design

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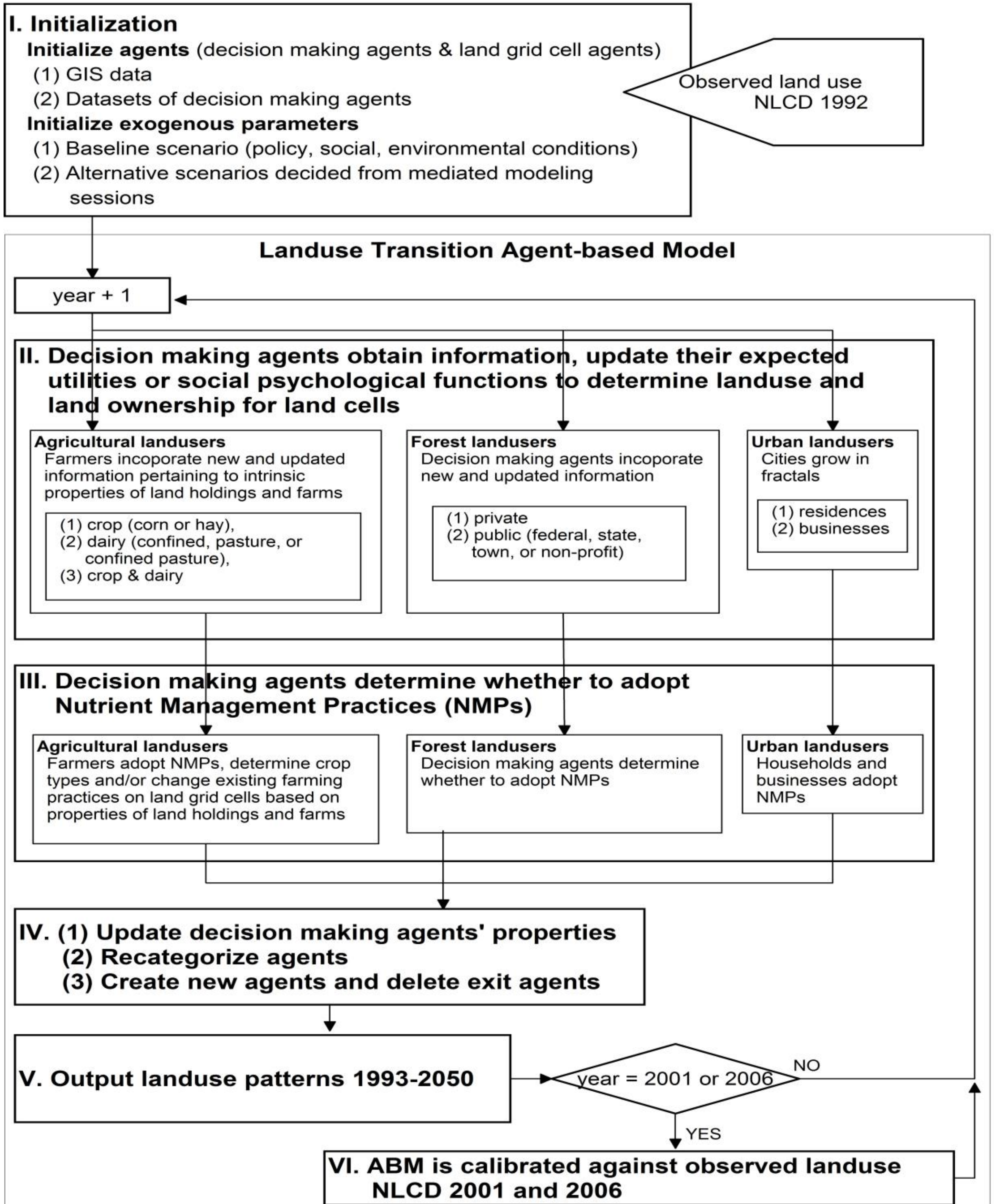

Interactive Land Use Transition Agent-based Mode (ILUTABM)

- Human agents (landowners) make land use decisions based on their expected utility and returns of productivity from their lands to maximize their livelihood (expected utility)

- Landowner types:
  - Farms
  - Urban Business
  - Urban Residence

Farmer: Expected Utility & Land use Decisions

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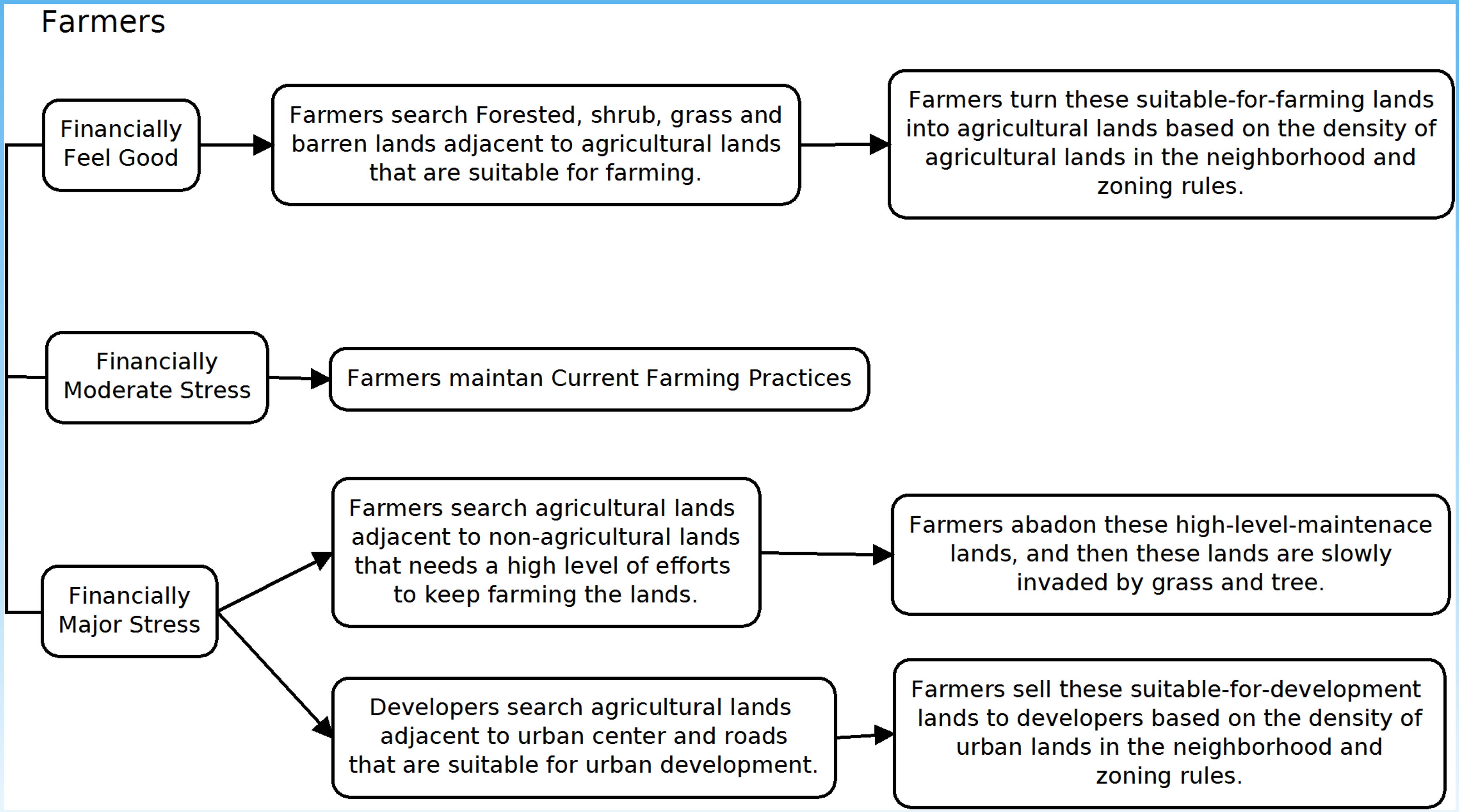
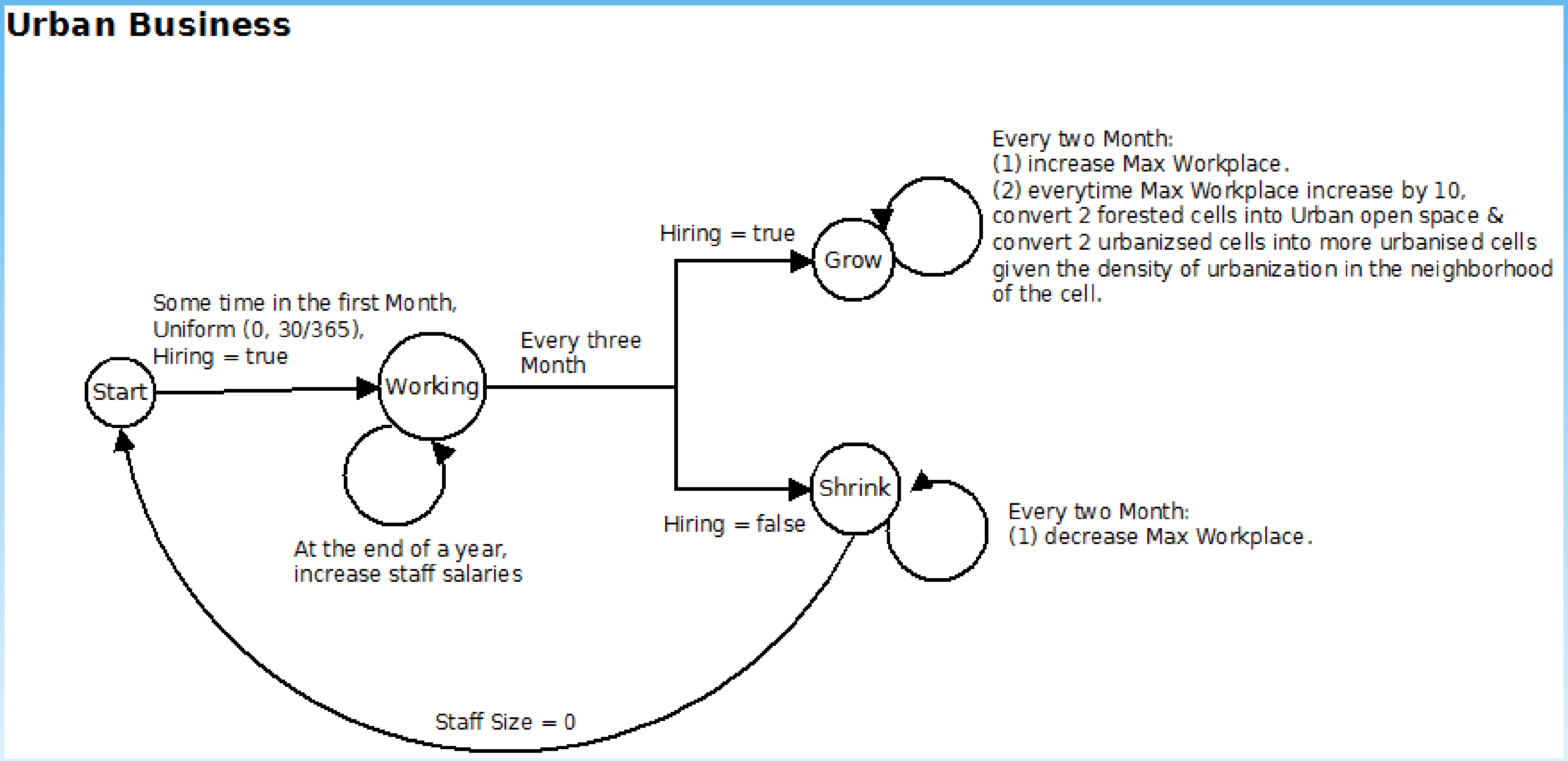
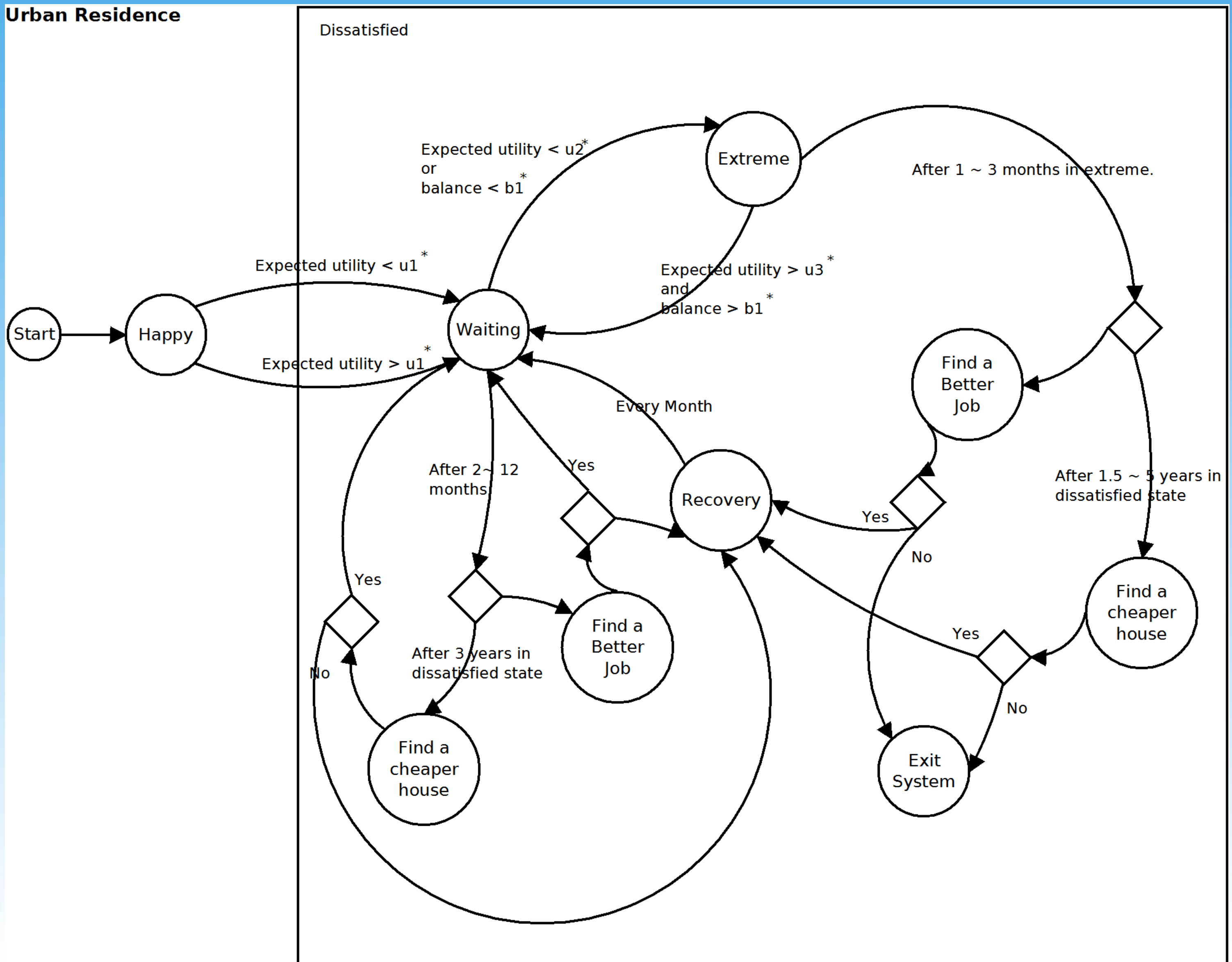


Urban Business: State & Land Use Decisions



Urban Residence: State & Land Use Decisions



Estimation of Land Use Suitability

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- Example 1: if a farmer is financially feeling good
  - Search land cells that are suitable for farming based on the land use of neighboring cells by using
  - Logistic function, which gives (e.g. to pasture or crop):
  - If > {
  If >
        Turn into crop
  Else if >
        Turn into pasture
}

Estimation of Land Use Suitability

- Example 2: if a farmer is financially major-stressful
  - Abandon land cells at the edge of the farm lands based on the land use of neighboring cells by using
  - Logistic function, which gives (e.g. From ag to grass or shrub):
  - If >

    Turn into grass

    Else if >

    Turn into shrub
  - Logistic functions also apply to from barren to grass, from shrub to forest, from ag to urban

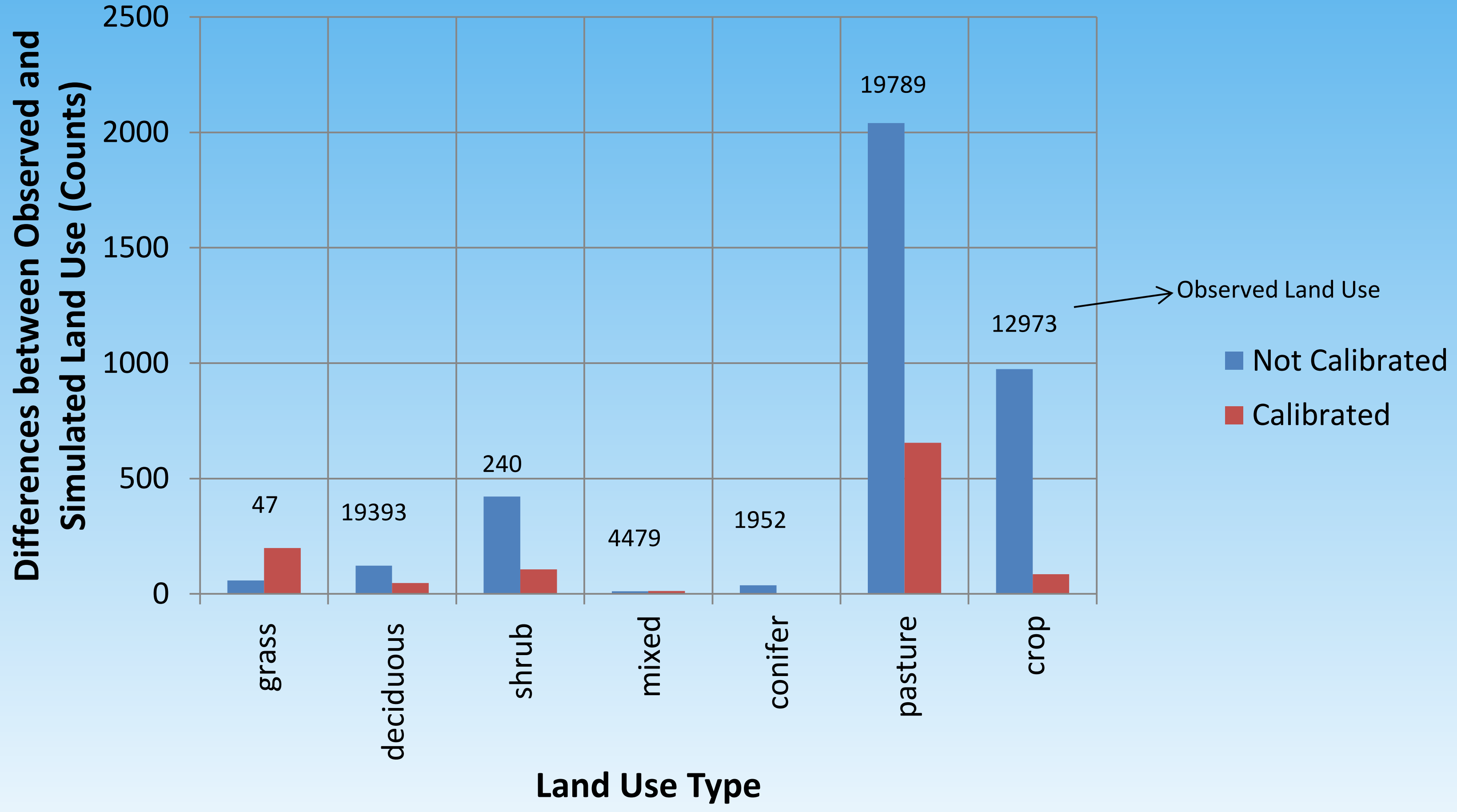
From Agriculture to urban parcels

- If the number of urban residences who do not occupy a parcel > a threshold
- Then, pasture & crop lands in Ag parcels that
  - Are closer to a Urban center or roads, and
  - The landowners are financially major-stressful
  - Are located in zones where urbanization are not restricted
- Are converted into
  - Urban open spaces, urban low intensity, mid intensity, or high intensity
  - Depending on the urbanization level of the neighborhood

ILUTABM: Calibration

- Stepwise
- Calibrated to NLCD 2011
- Calibrated by minimizing land cell counts for
  - Grass, shrub,
  - Deciduous, mixed and evergreen forest,
  - Crop and pasture/hay

ILUTABM Calibration Results



Preliminary Simulation
Calibrated & Under Scenario IP

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Preliminary Simulation
Calibrated & under Scenario IP

Canada, North of the Missisquoi Bay

Highgate & Franklin

Preliminary Simulation
Pro Forest Growth & Under IP

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Preliminary Simulation
Pro Crop Growth & Under LAP

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ILUTABM Scenarios

- Cali-gr-sh-fo-ag-IP
  - Parameters are calibrated to minimize discrepancy between observed and simulated land use in 2011 for
    - Grass, shrub
    - Deciduous, mixed and evergreen forest
    - Crop and Pasture/hay
  - socio-economic conditions: Increase Poverty (IP)
- Pro-Crop-LAP
  - Parameters are set to trigger crop land expansion
  - Socio-economic conditions: Largely Alleviate Poverty (LAP)
- Pro-Forest-IP
  - Parameters are set to trigger forest growth
  - Socio-economic conditions: Increase Poverty (IP)

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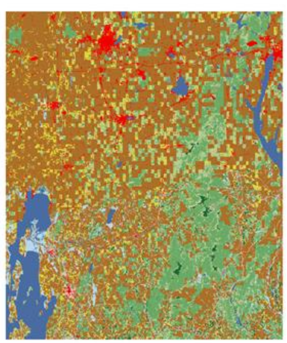
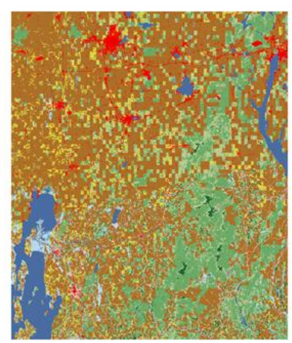
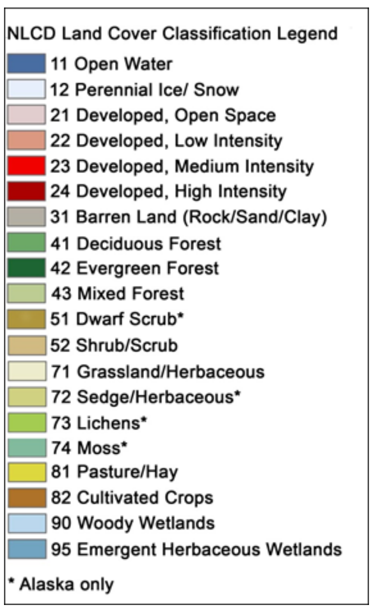
Observed Land Use 2001	Simulated Land Use 2011	Simulated Land Use 2041
	 Calibrated, IP	 Calibrated, IP
	 Pro-Forest, IP	 Pro-Forest, IP
	 Pro-Crop, LAP	 Pro-Crop, LAP



ILUTABM Scenarios: Parameters Setting

	Scenarios		
Parameters	Cali-gr-sh-fo-ag-IP	Pro-Crop-LAP	Pro-Forest-IP
lag_barren2grass	3	3	3
lag_grass2shrub	2	2	2
lag_shrub2trees	3	3	3
coef_2Grass	0.5	0.5	**4.5**
coef_2Forest	1.1	0.1	6
coef_2Shrub	5	5	5
coef_2Desiduous	4	4	5.5
coef_2Mixed	2.5	2.5	5.5
coef_2Conifer	3	3	5.5
coef_2Ag	3	4.5	1.2
coef_2Crop	3.5	5	0.9
coef_2Pasture	3.5	5	0.8
min_prob_2Grass	0.7	0.7	0
min_prob_2Forest	0.37	0.37	0
min_prob_2Shrub	0.6	0.6	0
min_prob_2Deciduous	0	0	0
min_prob_2Mixed	0.8	0.8	0
min_prob_2Conifer	0.8	0.8	0
min_prob_2Ag	0.5	0	0.3
min_prob_2Crop	0.6	0	0.3
min_prob_2Pasture	0.6	0	0.5

Comparing 2000 LULC with 2041 Scenarios

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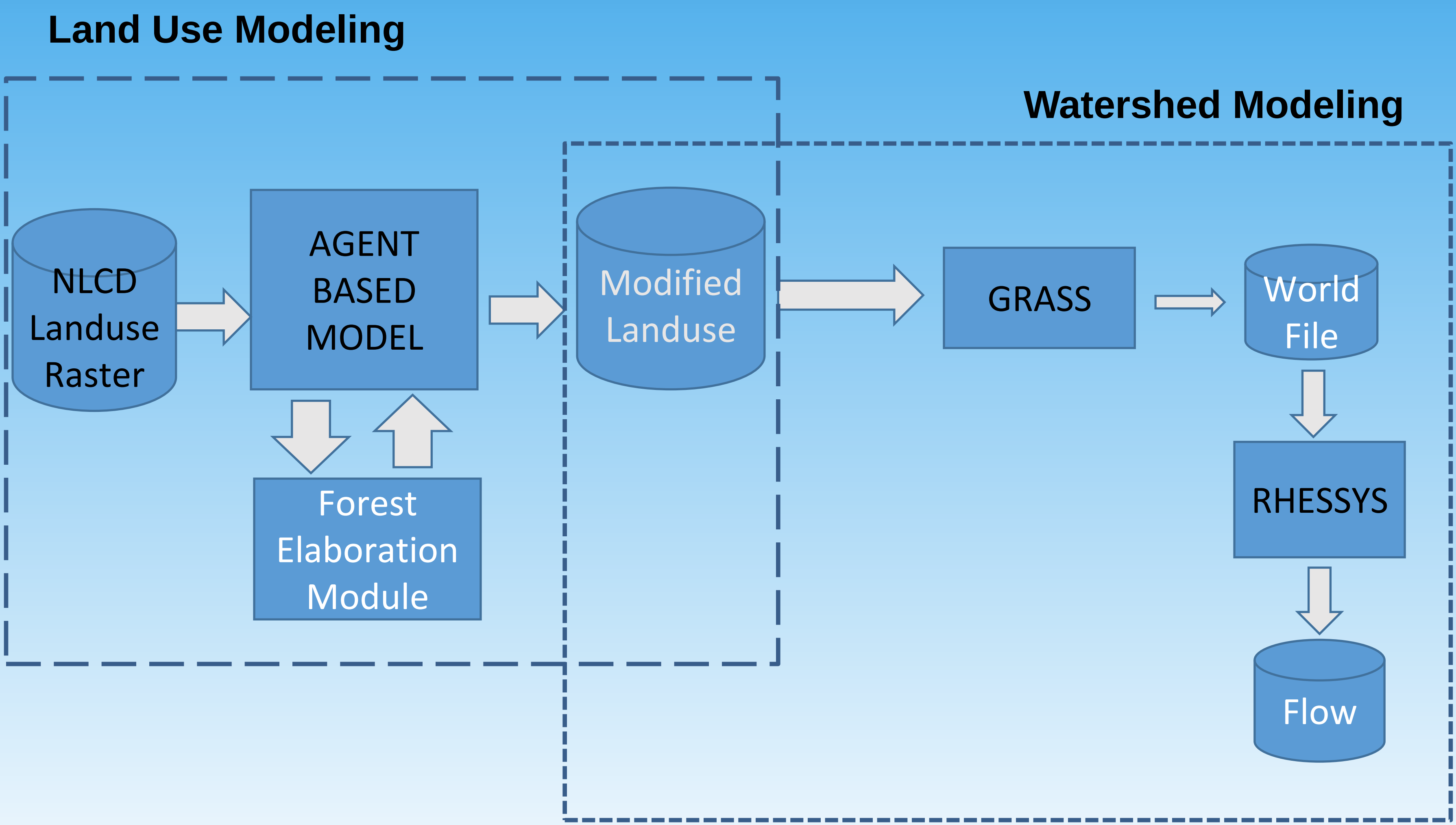
		cali-gr-sh-fo-ag	pro-crop-LAP	pro-forest-IP
Type	Origin 2000 (%)	IP 2041 (%)	LAP 2041 (%)	IP 2041 (%)
Shrub	1.22	0.58	0.5	0.56
Grass	0.57	0.45	0.22	1.15
No Vegetation	26.26	27.63	55.8	15.92
Mixed Forest	24.97	24.57	13.67	24.61
Coniferous Forest	8.4	7.88	3.8	7.91
Deciduous Forest	38.58	38.89	26	49.84

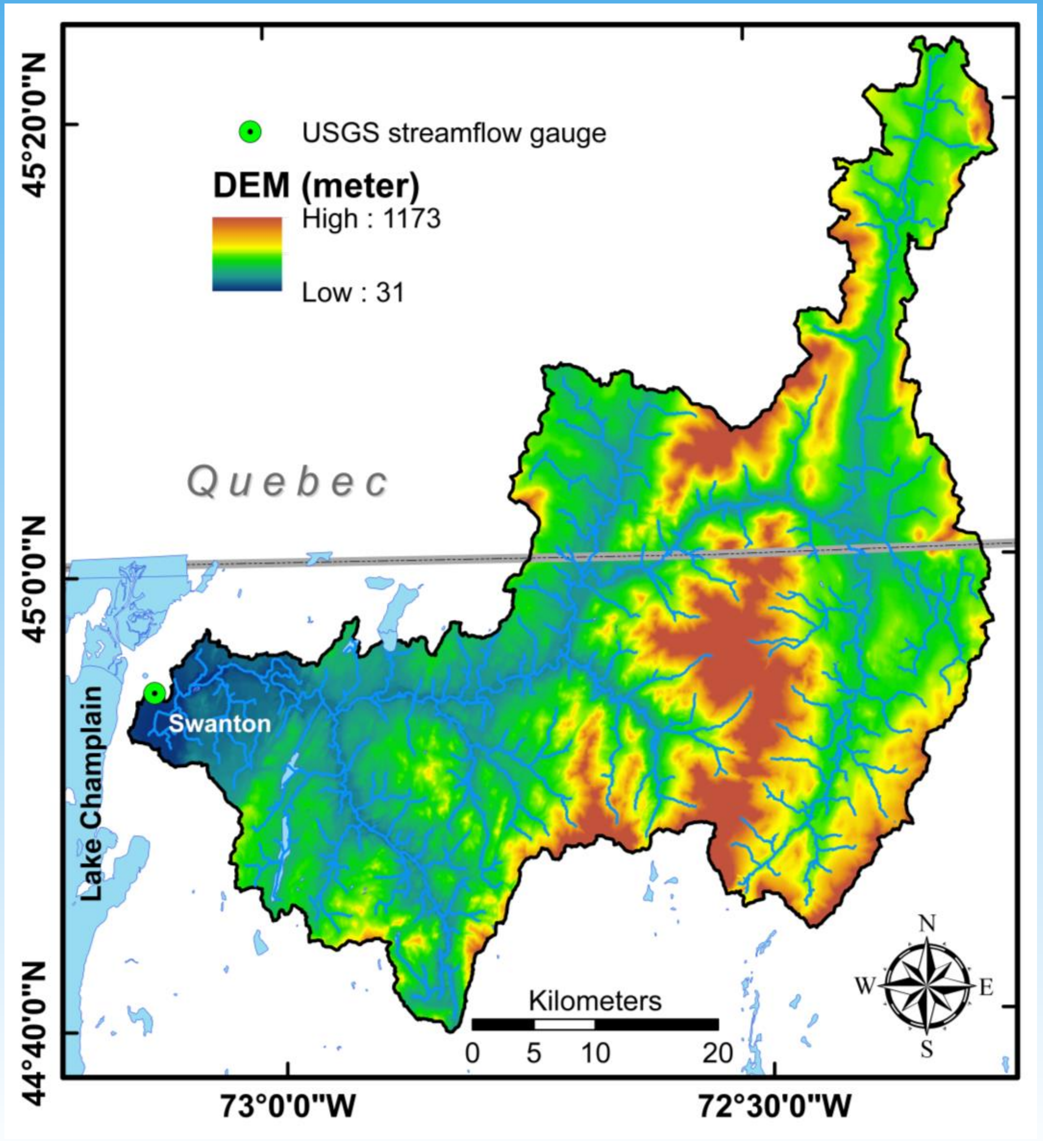
Watershed drainage area is 2,200 km^2

Cascading Landuse to Flow

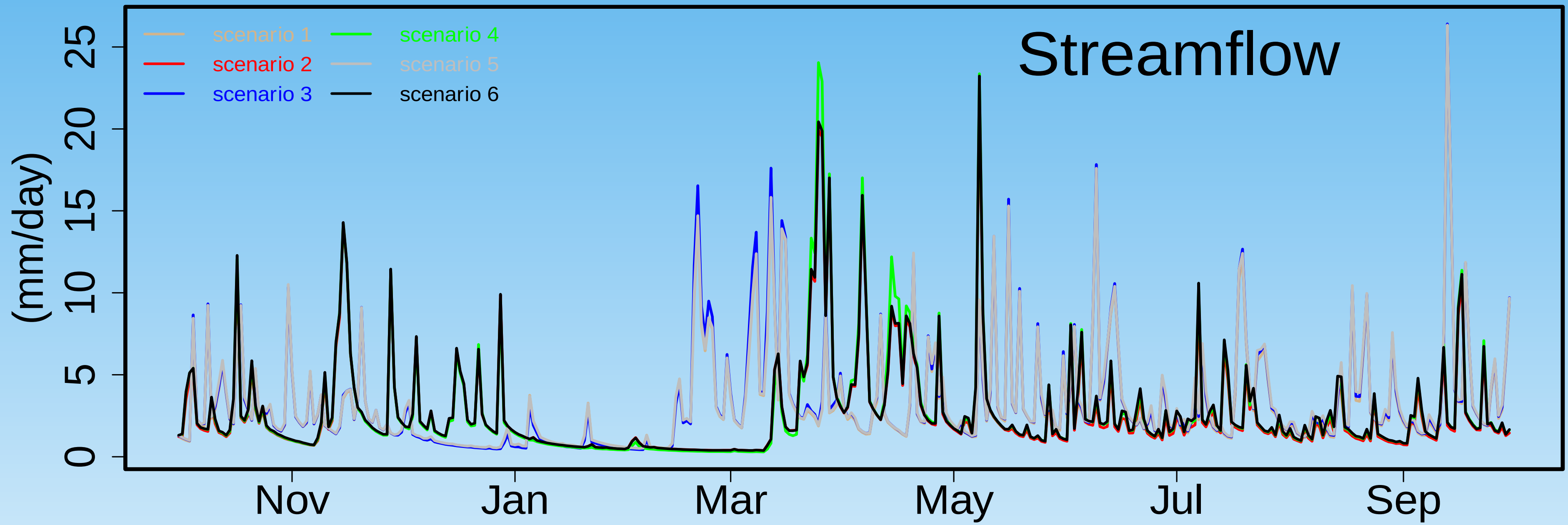


Missisquoi River Watershed @Swanton

- Drainage area 2,200 km^2
- Watershed outlet has streamflow records since 1990 (USGS gauge # 04294000)
- Average annual runoff 745 mm
- Distributed Hydrological Model (RHESSys)

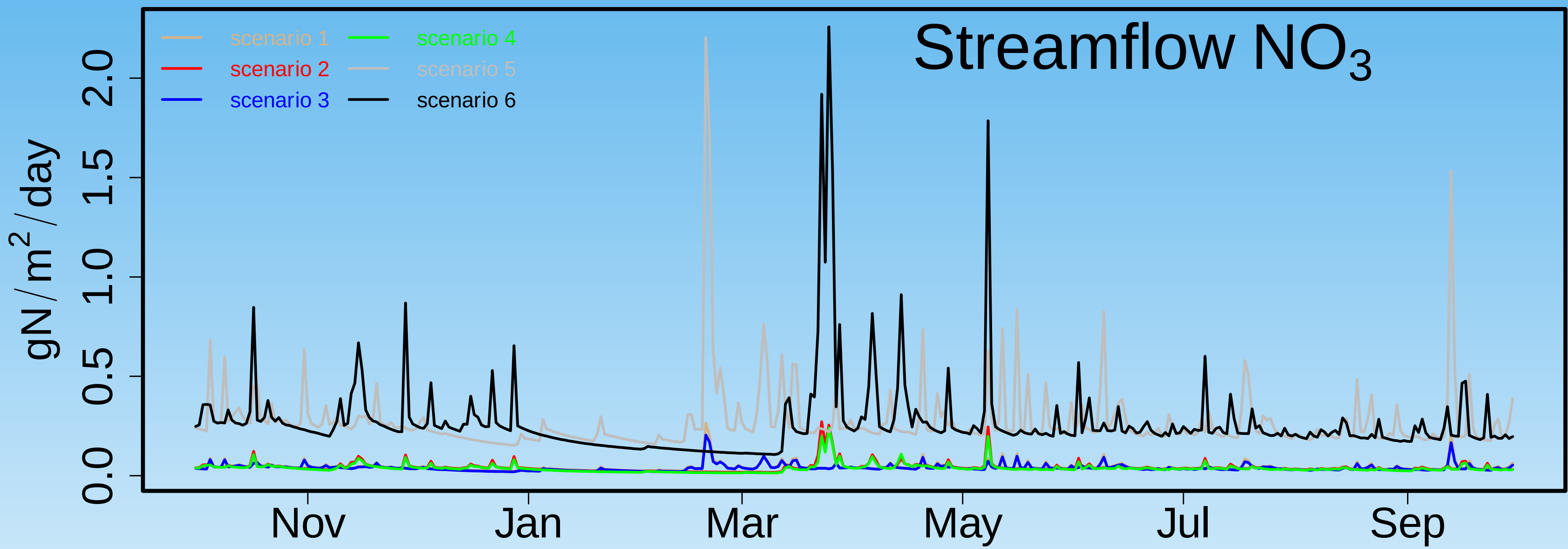


Streamflow hydrograph
Missisquoi River at Swanton



- **cali_gr_sh_fo_ag_IP & BNU_ESM rcp85 = scenario 1**
- **cali_gr_sh_fo_ag_IP & CESM1_BGC rcp85 = scenario 2**
- **pro-crop-LAP & BNU_ESM rcp85 = scenario 3**
- **pro-crop-LAPP & CESM1_BGC rcp85 = scenario 4**
- **pro-forest-IP & BNU_ESM rcp85 = scenario 5**
- **pro-forest-IP & CESM1_BGC rcp85 = scenario 6**

Un-calibrated Streamflow Nitrate hydrograph Missisquoi River at Swanton



- **cali_gr_sh_fo_ag_IP & BNU_ESM rcp85 = scenario 1**
- **cali_gr_sh_fo_ag_IP & CESM1_BGC rcp85 = scenario 2**
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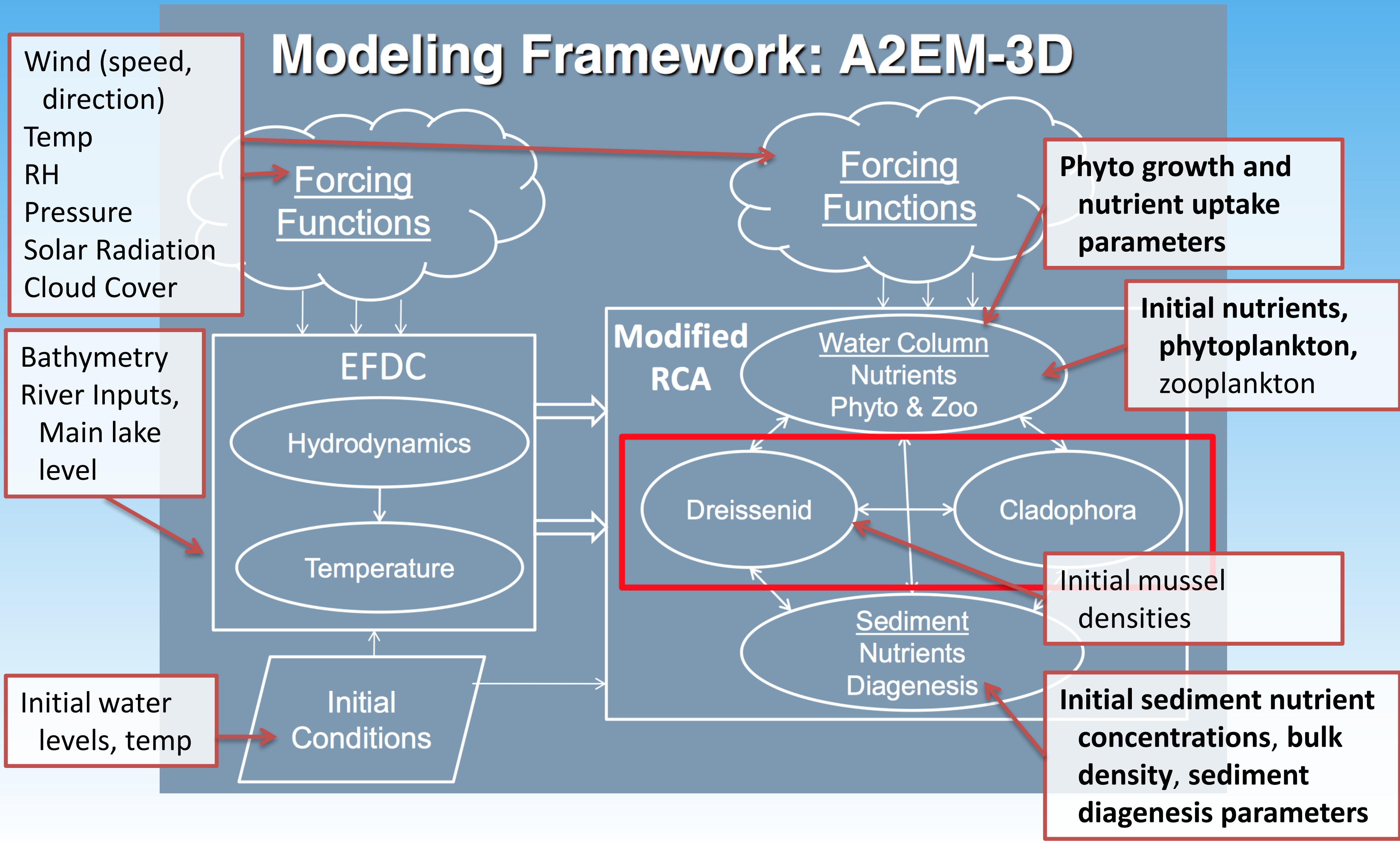
- **pro-forest-IP & BNU_ESM rcp85 = scenario 5**
- **pro-forest-IP & CESM1_BGC rcp85 = scenario 6**

Phase 2 (2014-15): Integration of DHVSM/RHESSYS with Lake Model (A2EM)

A2EM Architecture

Background: A2EM (Advanced Aquatic Ecosystem Model)



Integrating A2EM with RHESSYS

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- Anticipated steps to Integrate A2EM into the IAM framework
  - Develop preprocessor to translate RHESSYS/DHSVM output into input file formats for EFDC and RCA (text-delimited files)
  - Develop script to automate EFDC→ RCA → EFDC… batch runs (integrating watershed model)
    - Current framework uses an Access database and a semi-proprietary interface, but that mostly facilitates the development of input files; that could be done manually
  - Come up with a method of estimating meteorological variables not being downscaled (**solar radiation, cloud cover, wind**, RH, pressure)

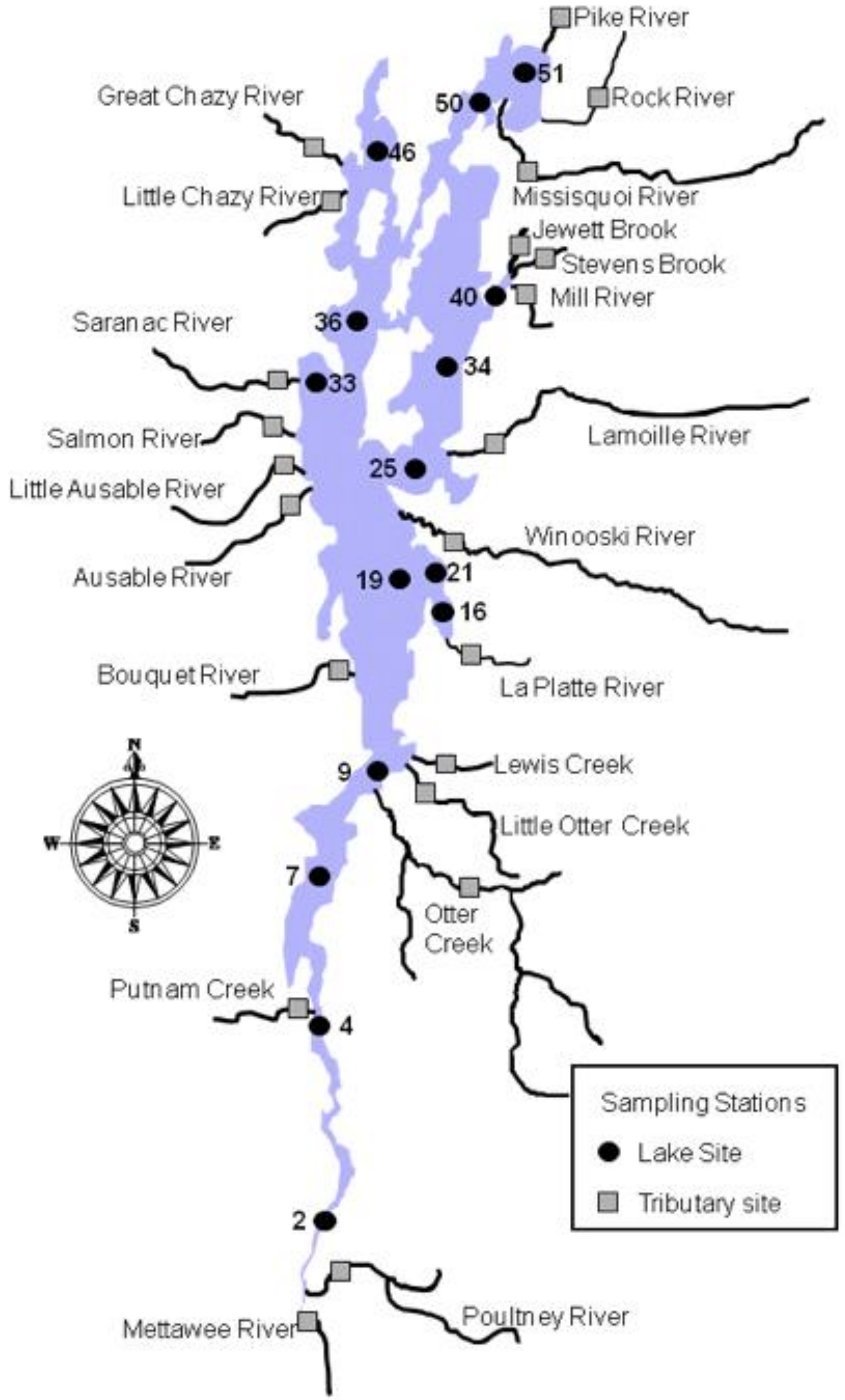
RACC Hybrid IAM Architecture

Hybrid Modeling Approach

- Focus on developing a “hybrid” integrated assessment model that integrates P and N fluxes from watersheds as well as climate change scenarios in predicting Harmful Algal Blooms (HABs) in the lake Segments.

- A Bayesian Network Model is being developed to integrate dynamic P and N fluxes at biweekly time-scale in predicting the likelihood of algal blooms in the lake segments where LCB monitoring sites are located (starting with Missisquoi, South Lake, Winooski and so forth)

LCB Monitoring System



Why Bayesian Networks? Assessment and Management of Uncertainty

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- Understanding the impacts of anthropogenic climate change on water quality, such as formation and persistence of harmful algal blooms (HABs), requires **quantification of uncertainty** that is introduced in assuming future trajectories of N and P fluxes as well as water and atmospheric temperature gradients.

- Forecasting the location and timing of critical transitions in fresh water lake systems
  - Empirical Focus on Missisquoi Bay
  - LCBP and USGS monitoring data from 1992-2010 is aggregated at bi-weekly timescale to train the models

Dynamic Forecasting of Critical Transitions

[Dakos et al. (2012) PLoS One (7)7: e41010]

Table 1. Early warning signals for critical transitions.

		Phenomenon		
	Method/Indicator	Rising memory	Rising variability	Flickering
metrics	Autocorrelation at-lag-1	x		
	Autoregressive coefficient of AR(1) model	x		
	Return rate (inverse of AR(1) coefficient)	x		
	Detrended fluctuation analysis indicator	x		
	Spectral density	x		
	Spectral ratio (of low to high frequencies)	x		
	Spectral exponent	x		
	Standard deviation		x	x
	Coefficient of variation		x	x
	Skewness		x	x
	Kurtosis		x	x
	Conditional heteroskedasticity		x	x
	BDS test		x	x
models	Time-varying AR(p) models	x	x	
	Nonparametric drift-diffusion-jump models	x	x	x
	Threshold AR(p) models			x
	Potential analysis (potential wells estimator)			x

ARIMA Model

Consider a first-order autoregressive moving-average process. Then `arima` estimates all the parameters in the model

$$\begin{aligned} y_t &= \mathbf{x}_t\boldsymbol{\beta} + \mu_t && \textit{structural equation} \\ \mu_t &= \rho\mu_{t-1} + \theta\epsilon_{t-1} + \epsilon_t && \textit{disturbance}, \text{ARMA}(1,1) \end{aligned}$$

where

ρ	is the first-order autocorrelation parameter
θ	is the first-order moving-average parameter
ϵ_t	$\sim$ *i.i.d.* $N(0,\sigma^2)$, meaning that ϵ_t is a white-noise disturbance

You can combine the two equations and write a general ARMA(p,q) in the disturbances process as

$$\begin{aligned} y_t = \mathbf{x}_t\boldsymbol{\beta} &+ \rho_1(y_{t-1} - \mathbf{x}_{t-1}\boldsymbol{\beta}) + \rho_2(y_{t-2} - \mathbf{x}_{t-2}\boldsymbol{\beta}) + \cdots + \rho_p(y_{t-p} - \mathbf{x}_{t-p}\boldsymbol{\beta}) \\ &+ \theta_1\epsilon_{t-1} + \theta_2\epsilon_{t-2} + \cdots + \theta_q\epsilon_{t-q} + \epsilon_t \end{aligned}$$

It is also common to write the general form of the ARMA model more succinctly using lag operator notation as

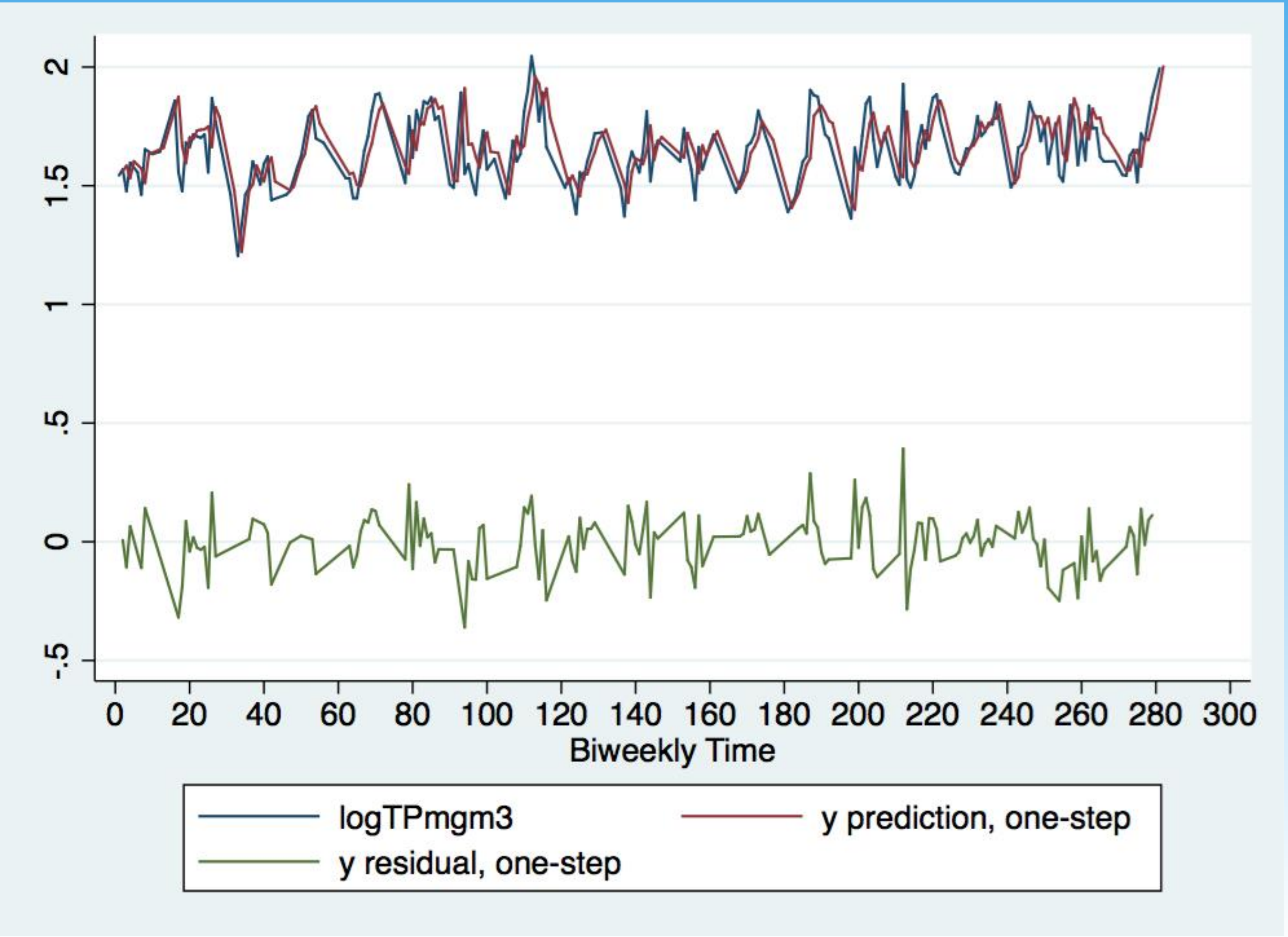
$$\boldsymbol{\rho}(L^p)(y_t - \mathbf{x}_t\boldsymbol{\beta}) = \boldsymbol{\theta}(L^q)\epsilon_t \qquad \text{ARMA}(p,q)$$

where

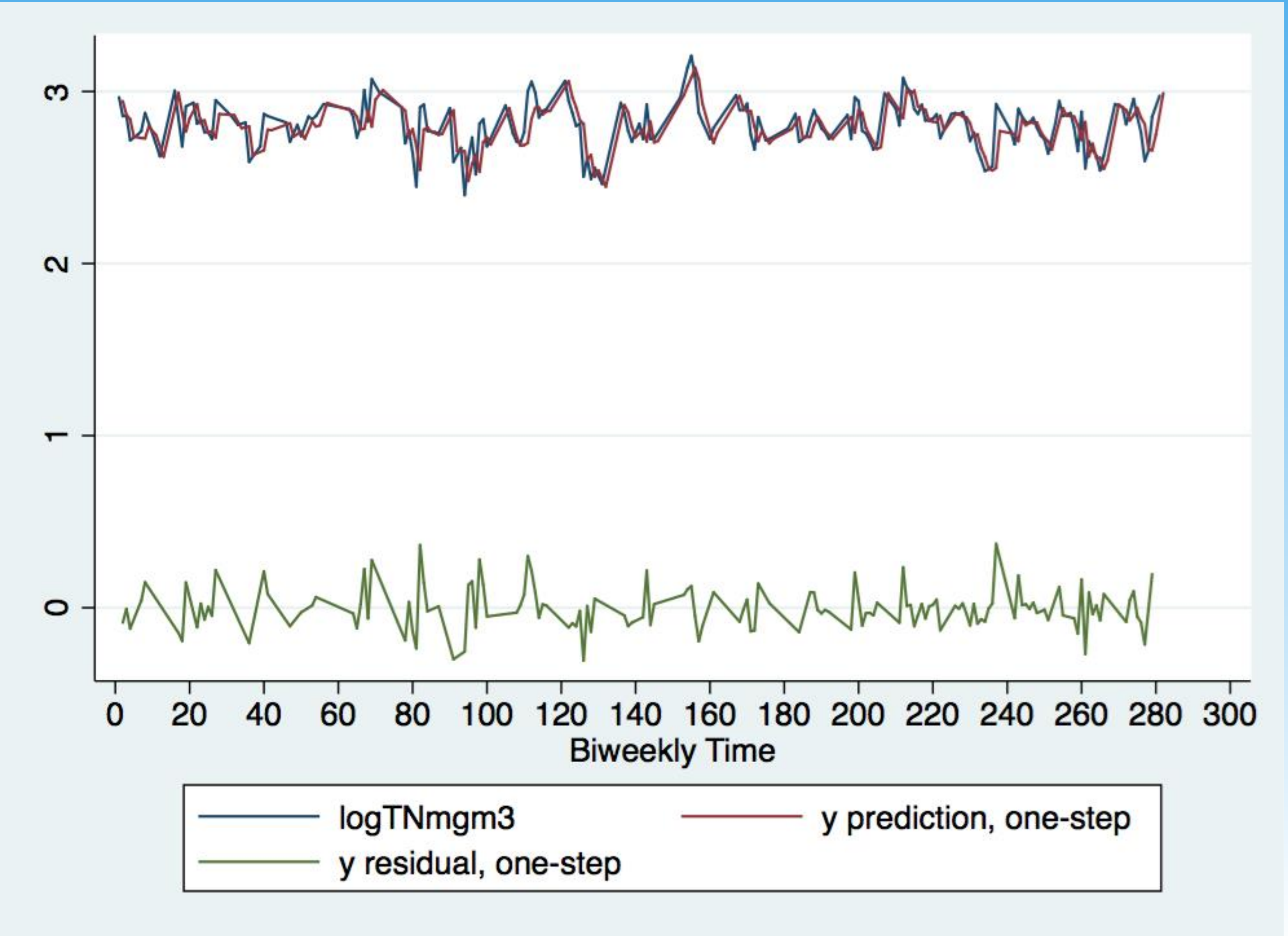
$$\begin{aligned} \boldsymbol{\rho}(L^p) &= 1 - \rho_1 L - \rho_2 L^2 - \cdots - \rho_p L^p \\ \boldsymbol{\theta}(L^q) &= 1 + \theta_1 L + \theta_2 L^2 + \cdots + \theta_q L^q \end{aligned}$$

and $L^j y_t = y_{t-j}$.

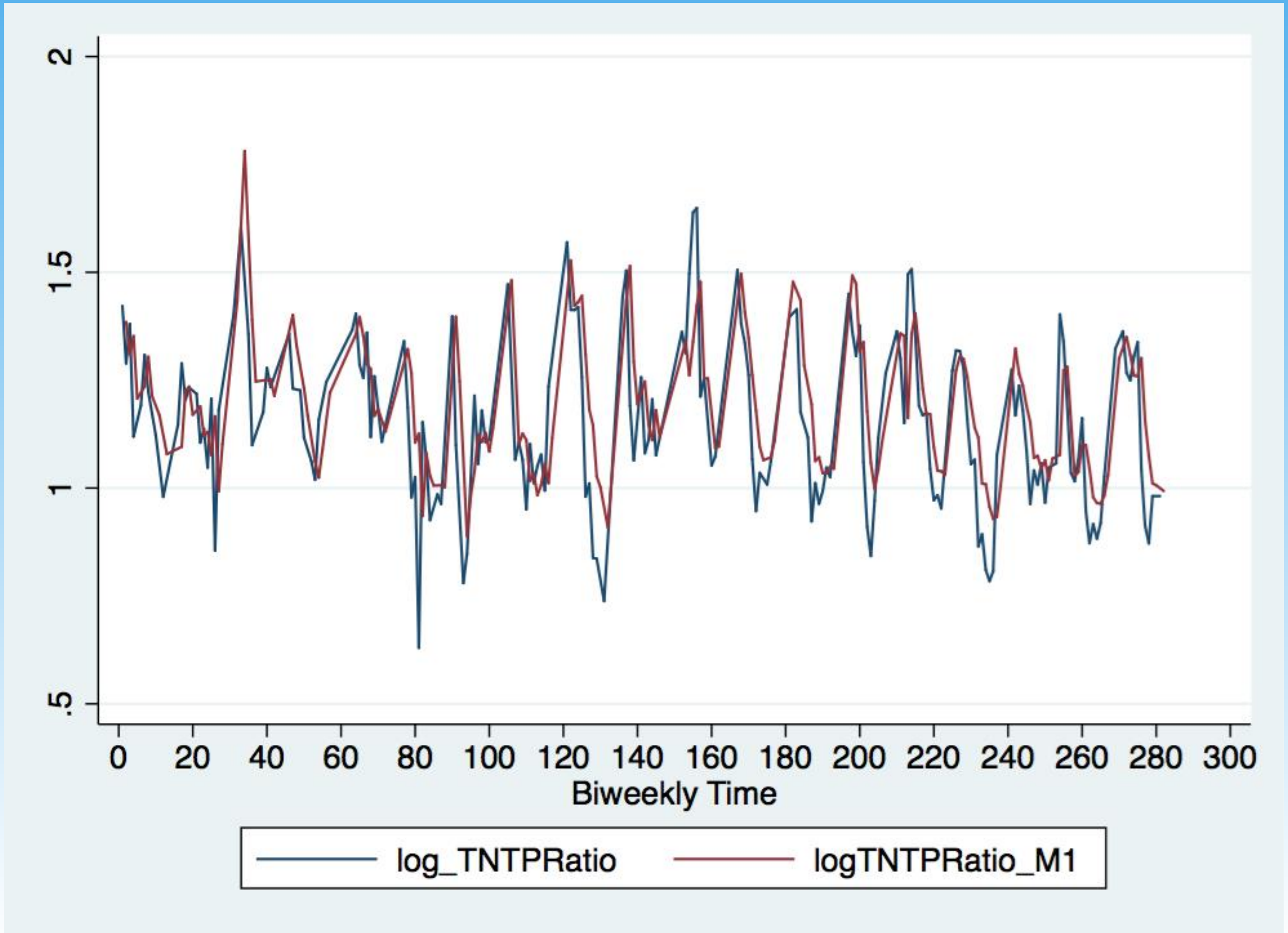
Observed versus predicted TP (ARIMA Model 1)



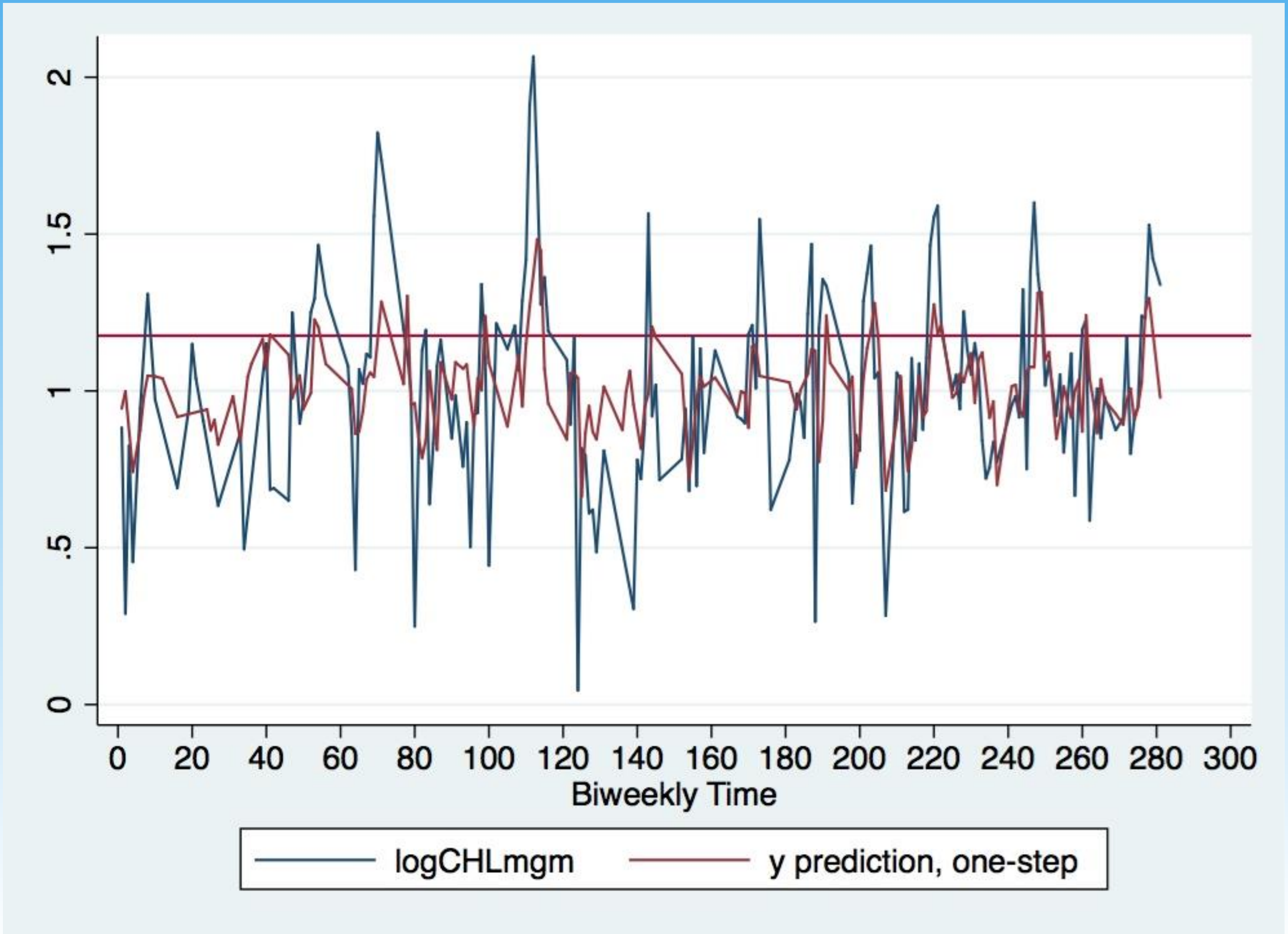
Observed versus predicted TN (ARIMA Model 2)

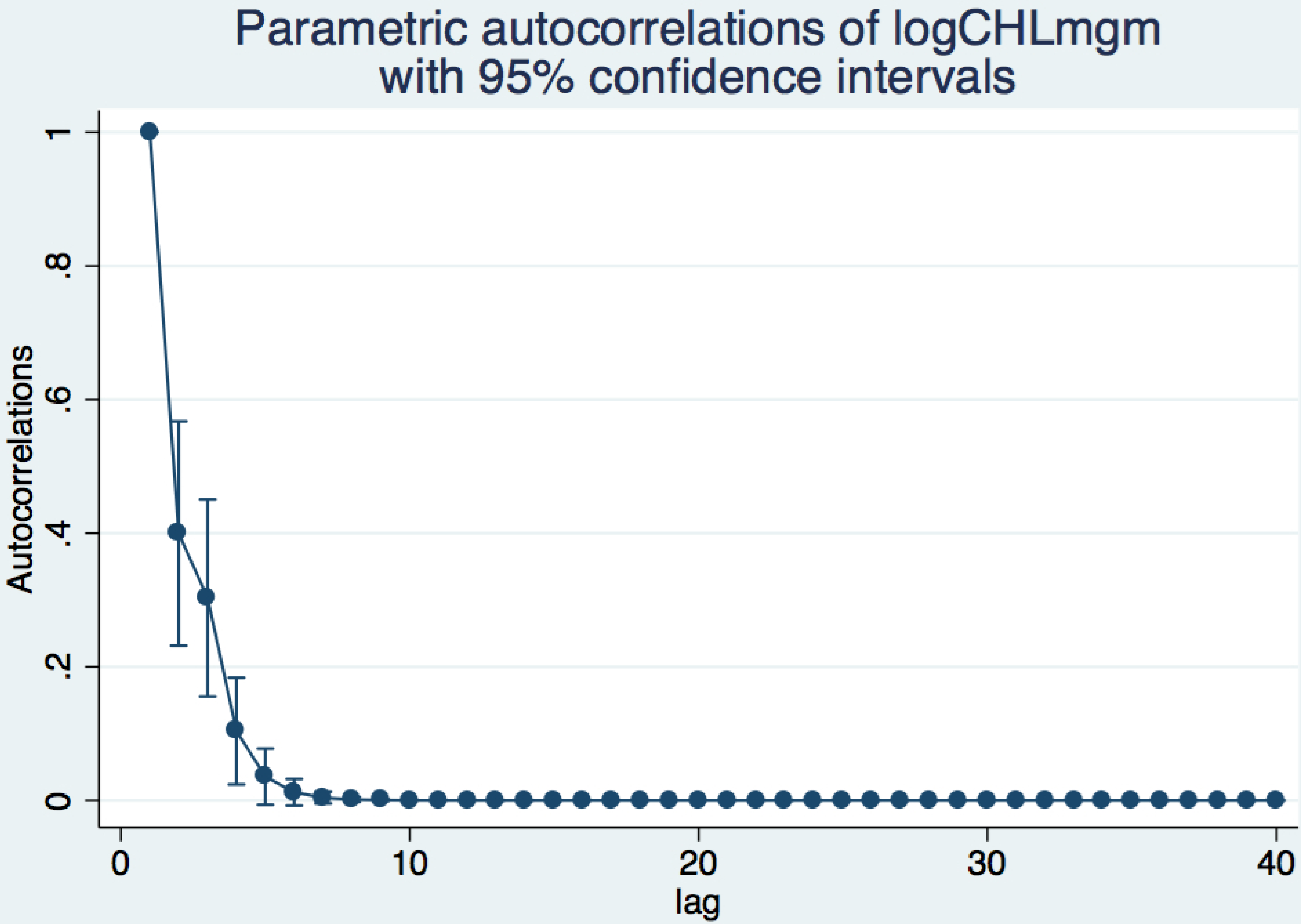


Observed versus predicted TN/TP



Observed versus predicted ChlA (ARIMA Model 3)




Parametric autocorrelations of logCHLmgm
with 95% confidence intervals
Autocorrelations
0
.2
.4
.6
.8
1
0
10
20
30
40
lag

Next Steps: Hybrid IAM Development

- LCBP (1992-2010) Long-term monitoring and USGS datasets as training datasets, and 2011-14 as calibration datasets for Bayesian network model development

- In addition, downscaled GCM/statistical scenarios for temperature, precipitation and solar radiation

- **ARIMA Models (1, 2 and 3) presented above are being used to connect P and N fluxes with climatic scenarios, predict TN/TP ratios, and in turn predict HABs [Focus on critical transitions and alternate stable states]**

- Calibrated model will be used to predict TN/TP ratios and ChlA (2011-2050) under different climate change, hydrological land-use land cover change and policy & governance scenarios

What will IAMs do? Assess the Effectiveness of Policy Solutions

- A crowdsourcing Delphi survey of 100+ experts and civil society stakeholders led to the identification of more than 60+ unique policy and technical solutions

- Stakeholder driven policy solution scenarios can be run on the IAMs to assess the P, N and HAB reduction effectiveness, given different climate change scenarios and land-use scenarios

Adaptive Co-Management of Critical Transitions

- **“Foresight”** in the face of uncertainties
  - When will critical transitions take place?
- **Value Pluralism**
  - What to do in the face of conflicting values?
- **Experimental Interventions**
  - What type of social and policy learning is taking place from real-world experimental policy and management interventions?

THANK YOU

Research on Adaptation to Climate Change

- For more information: Asim.Zia@uvm.edu

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