Adaptation to Climate Change in Lake Champlain Basin: Integrated Assessment Modeling of Climate Change, Land-Use Change, Hydrology and Lake Biogeochemistry Interactions

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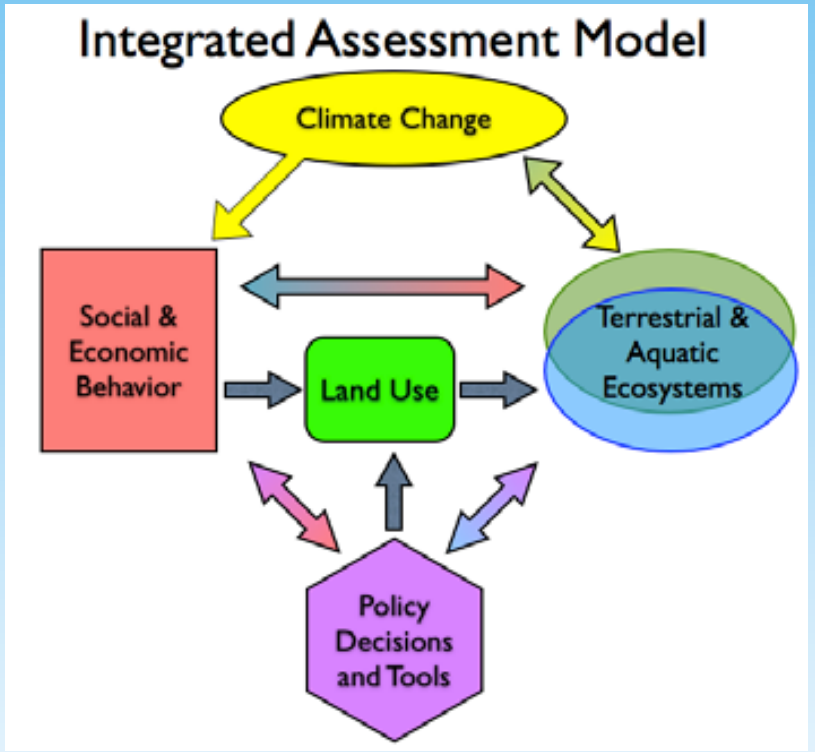
The Overarching RACC Question (from NSF funded proposal)

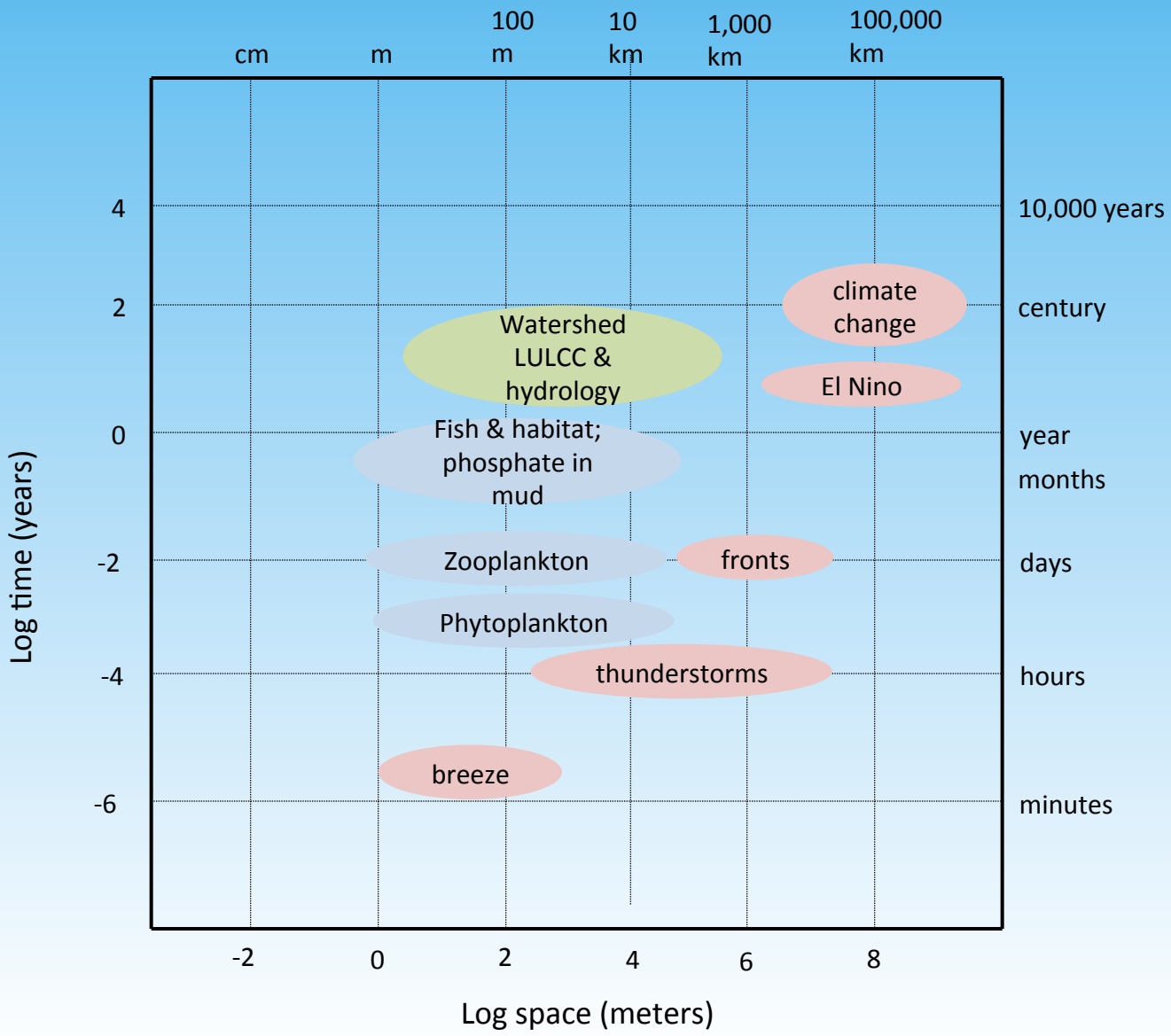
How will the interactions of climate change and land use alter hydrological processes and nutrient transport from the landscape, internal processing and eutrophic state within the lake, and what are the implications for adaptive management strategies?

Social Ecological System (SES) science goals

Adaptive management goals



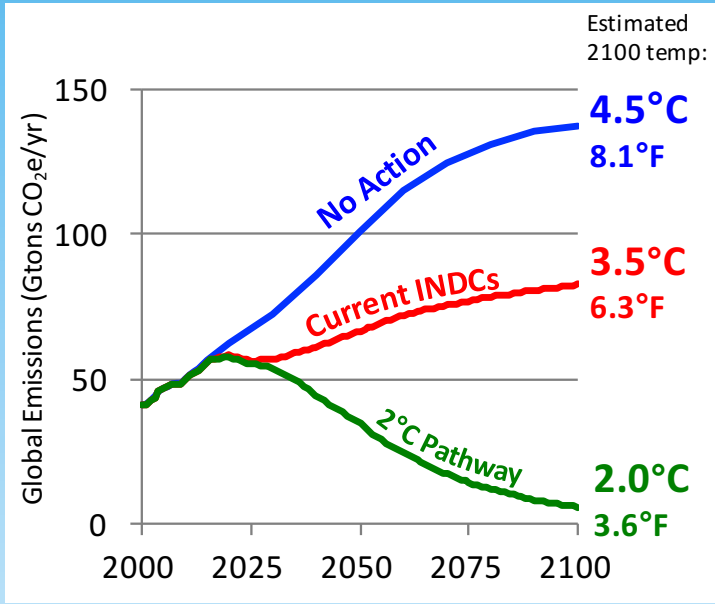
Complexity of modeling cross-scale interactions in Social Ecological Systems (SES)

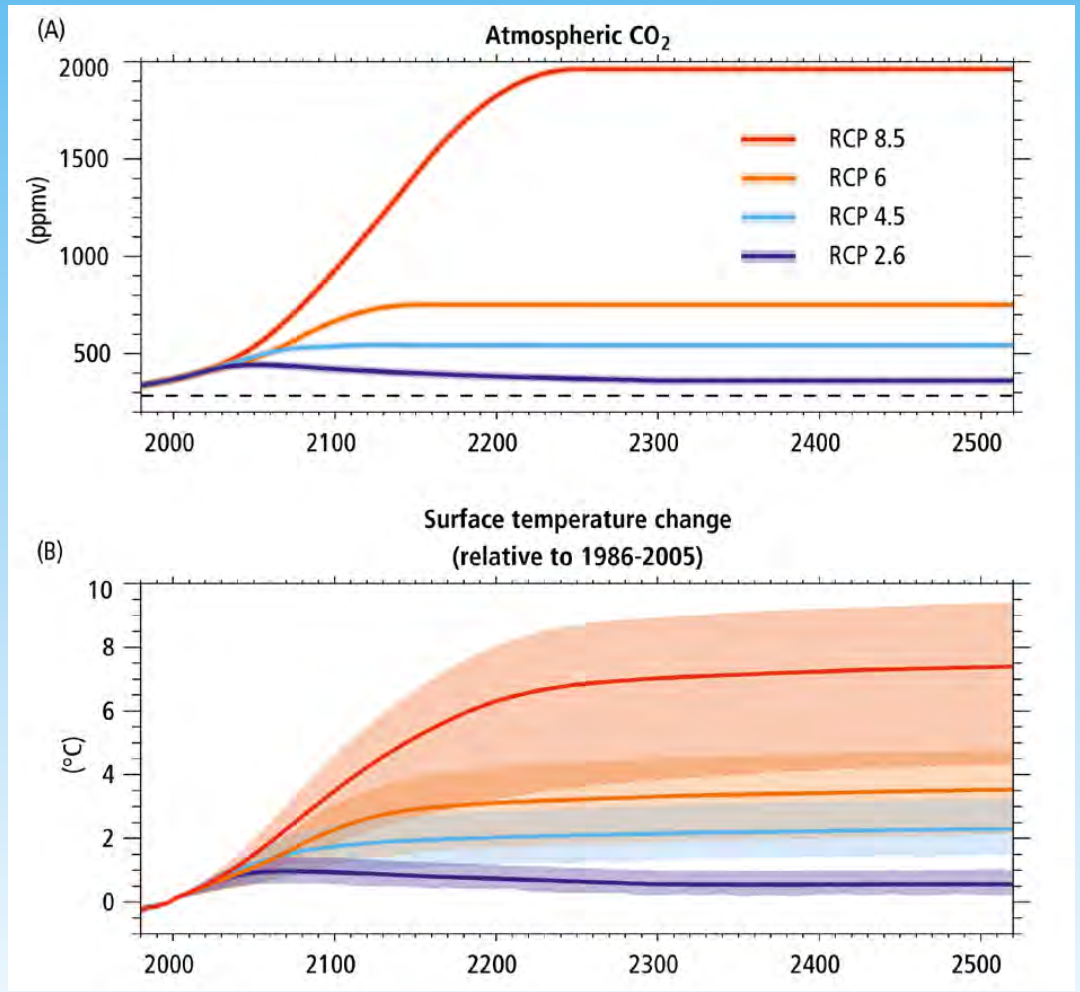


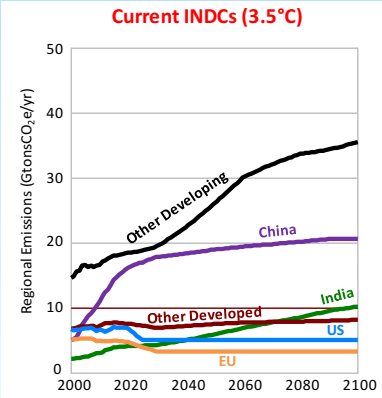
Relatively **slow** turn over rates

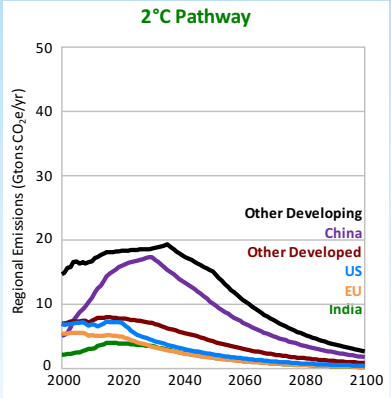
Relatively **fast** turn over rates

Uncertainty in Global Climate Trajectories: Paris Treaty expectations and global scale collective action problems!









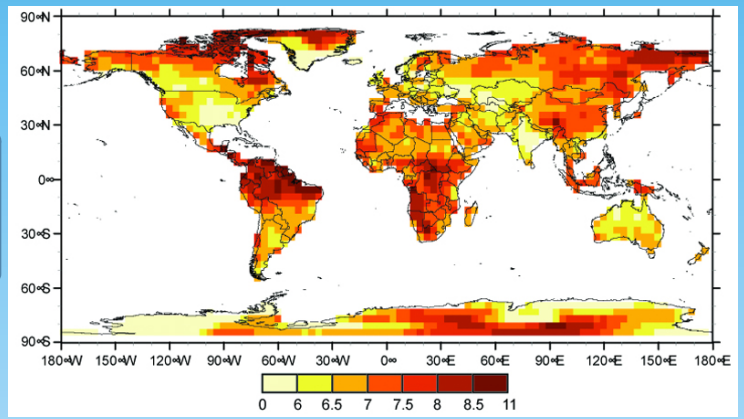
Source: Climate Interactive

IPCC 2014

Scaling down global climate change scenarios to regional/basin levels: more uncertainty

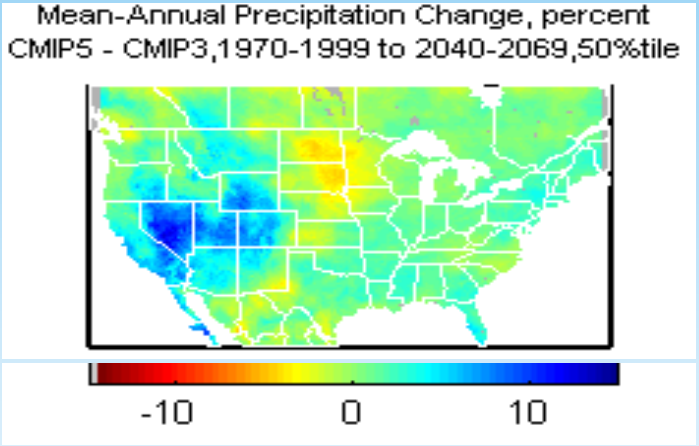
General Circulation Models

Climate ~100 Km



CMIP5 Intermediate Downscaling

Climate ~12 Km



Fine Downscaling

Climate ~ 1km

Existence of non-linearities, thresholds, lags and alternate stable states in social ecological systems

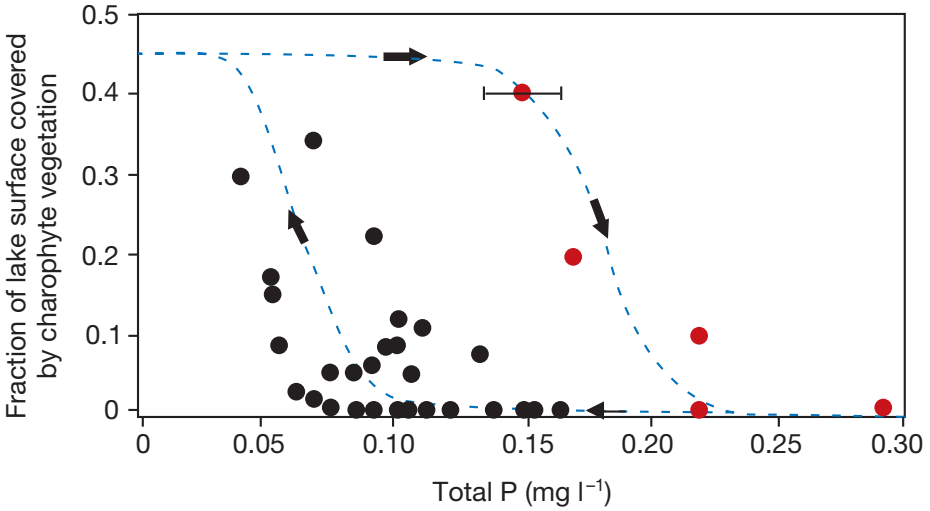
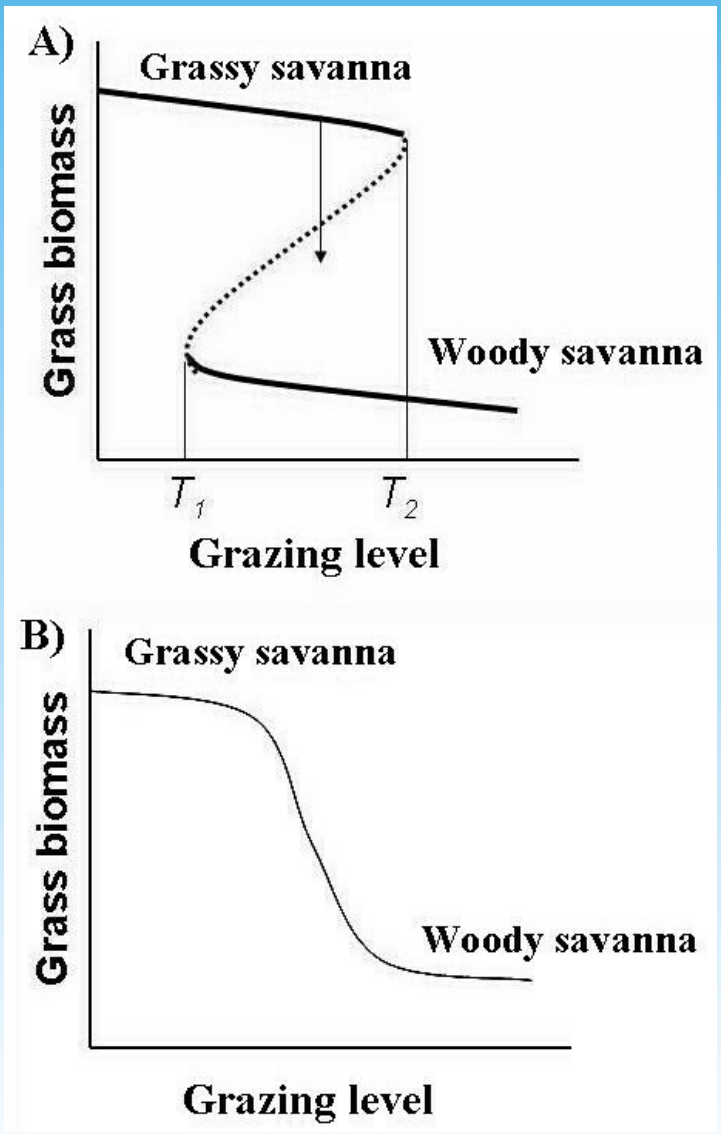


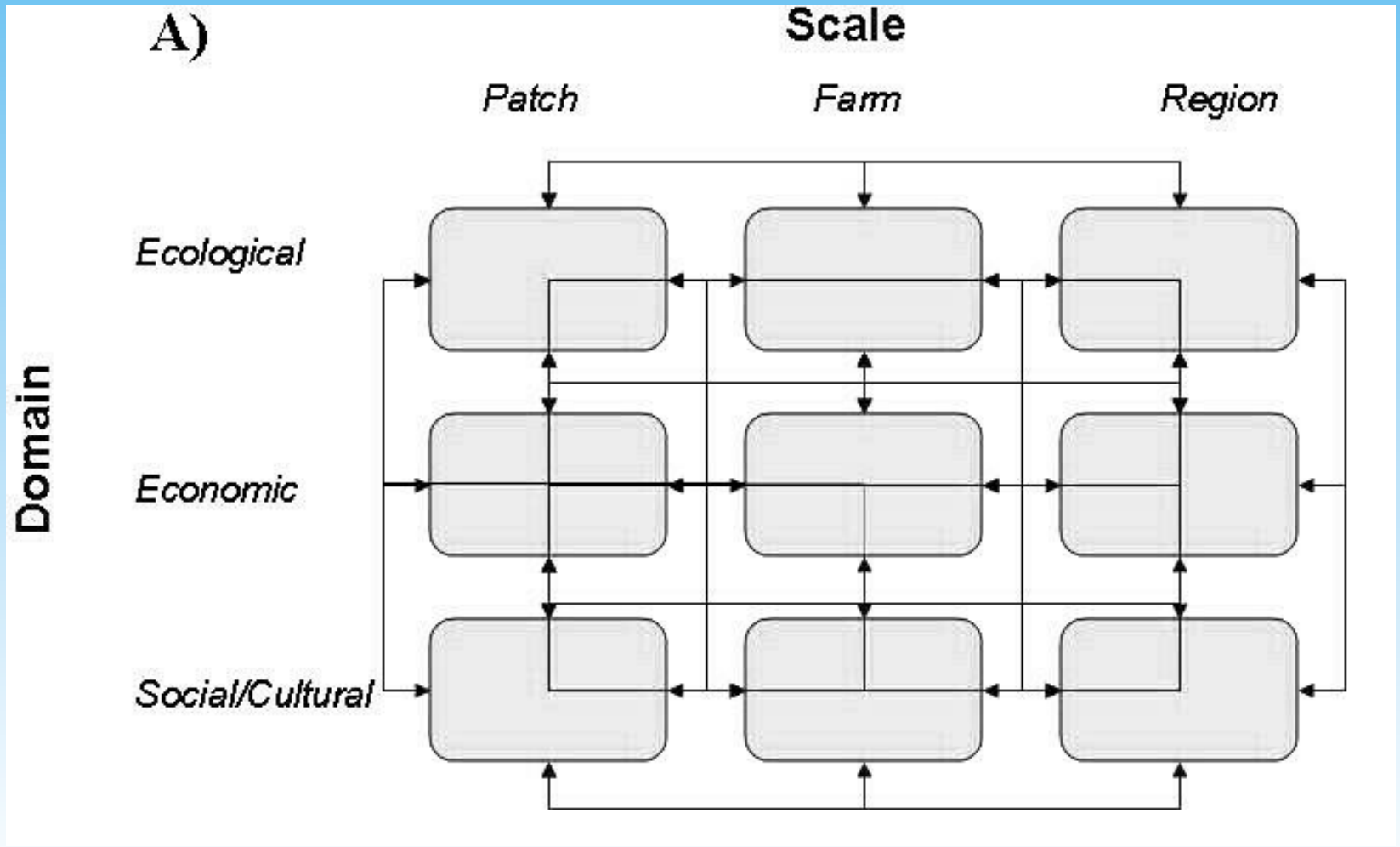
Figure 4 Hysteresis in the response of charophyte vegetation in the shallow Lake Veluwe to increase and subsequent decrease of the phosphorus concentration. Red dots represent years of the forward switch in the late 1960s and early 1970s. Black dots show the effect of gradual reduction of the nutrient loading leading eventually to the backward switch in the 1990s. From ref. 59.

Scheffer et al. 2001 *Nature*



Kinzig et al. 2006 *Ecology & Society*

Cascading Interactions of alternate stable states in social ecological systems: NP Hard Computational Complexity

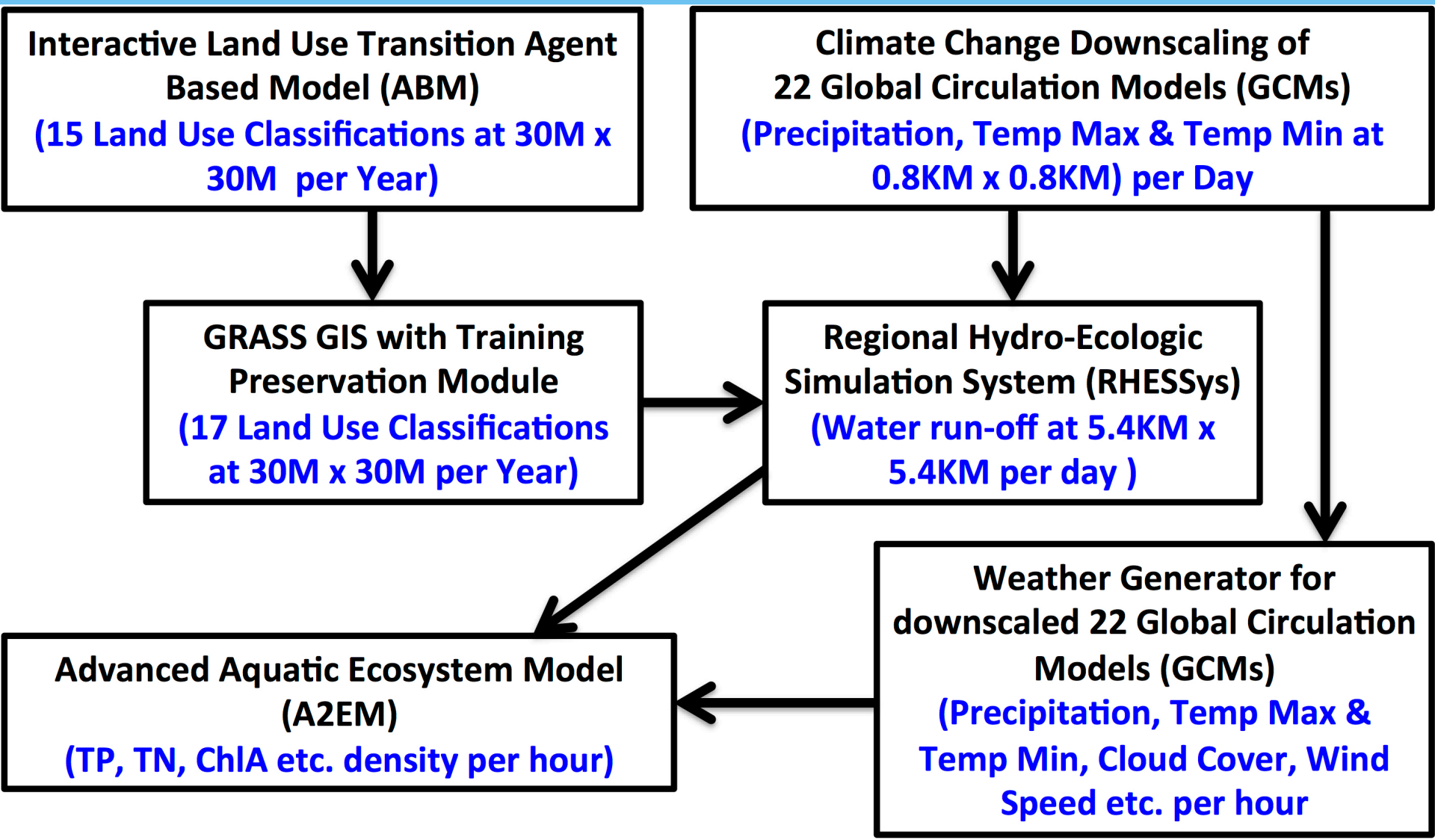


Kinzig et al. 2006 *Ecology & Society*

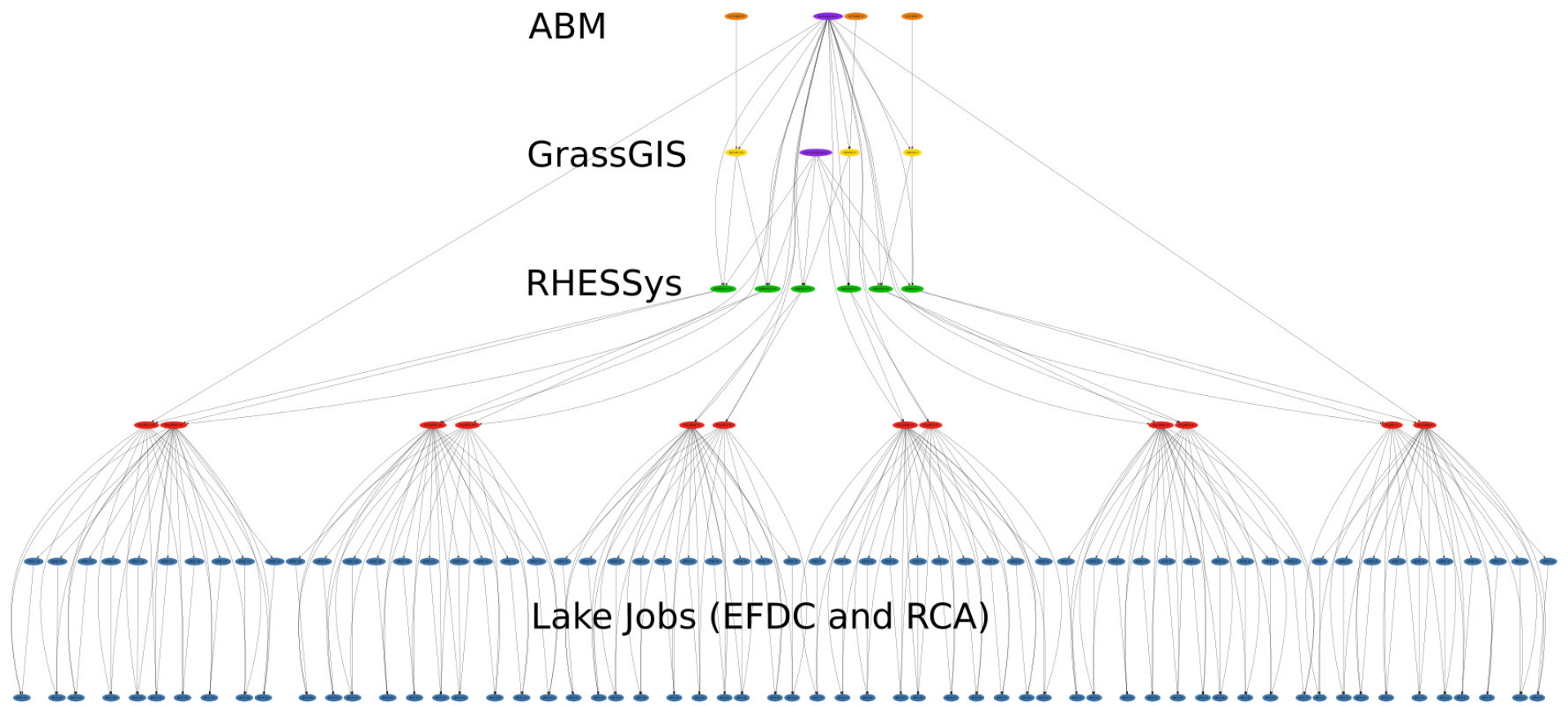
Adaptive Management IN Social Ecological Systems

- Social Ecological Systems are characterized by:
  - Cross-scale interactions
  - uncertainty in behavior across space and time,
  - non-linearities, thresholds, lags, alternate stable states
  - cascading interactions
- "Command and Control" or "Optimization" type of management approaches do not work with complex adaptive systems such as LCB SES
- Adaptive Management approach is needed to tackle the problem of adaptation to climate change in LCB
- RACC's Cascading Integrated Assessment Model (IAM) aims at deploying a complex adaptive systems computational approach to model cross-scale drivers of global climate change as well as social, policy and governance drivers of land-use land cover change at watershed/basin scales, responses of the hydrological systems to these drivers of change and the effects on the alternate stable states of Lake Champlain (segments).
- Cascading IAM can be used for: (a) SES hypotheses testing; (b) **Scenario testing for facilitating adaptive management in the medium to long run**

High Resolution Forecasting of Global Climate Change Impacts on Watersheds and Lakes: Integrating Climate, Land-Use, Hydrological and Limnology Models



PEGASUS Job Tree example for High Resolution Forecasting of Global Climate Change Impacts on Fresh Water Lakes



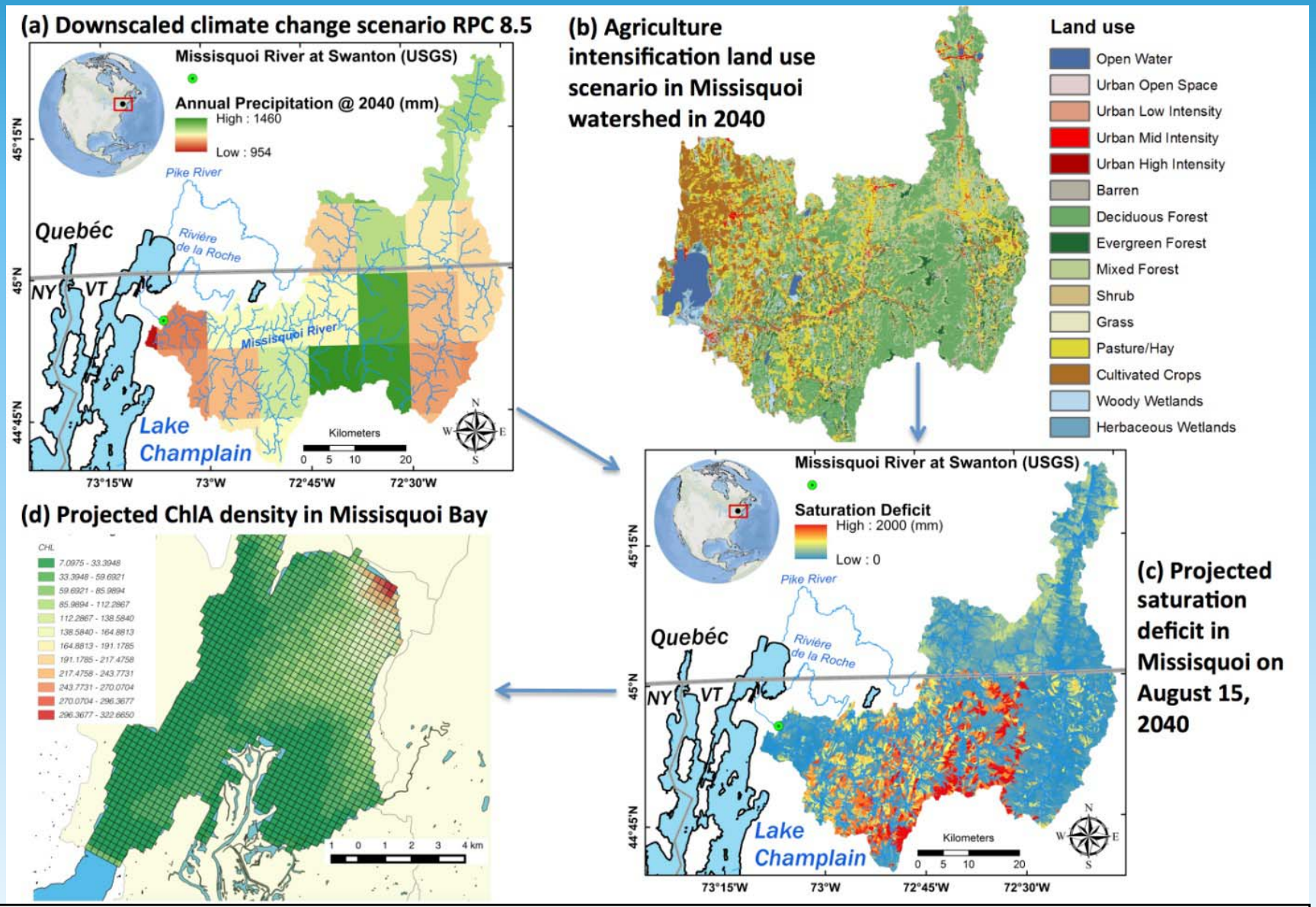


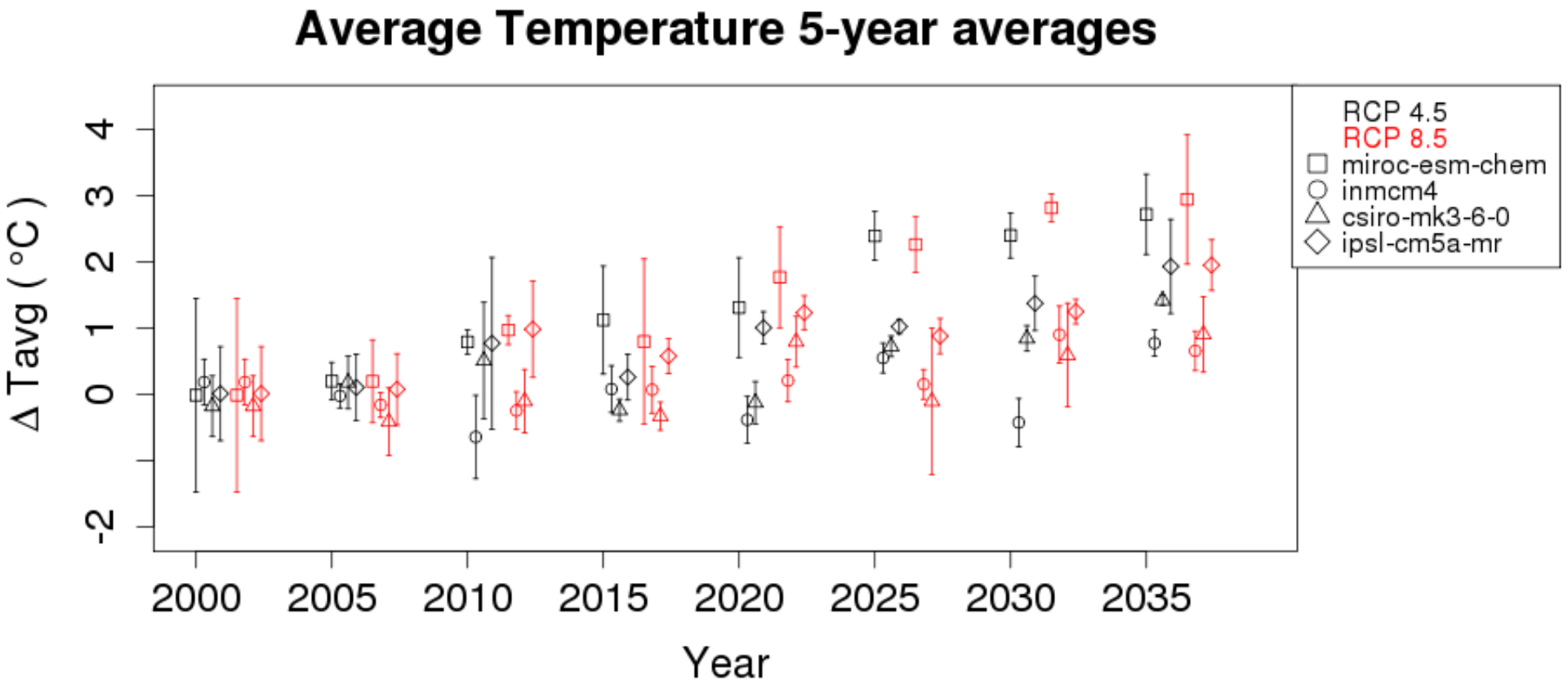
Figure 8. Output from cascading current Track-1 IAM that will be replaced by the BREE IAM: Output reveals (a) Projected precipitation by GCM BNU_ESM.1.rcp85 in 2040; (b) Projected Land-Use by Agent Based Model in 2040; (c) Projected hydrological scenario by RHESSys on August 15, 2040; (d) Projected Chlorophyll A (proxy for algae) concentration by A2EM on August 15, 2040.

Scenario Settings for Missisquoi for ongoing cascading IAM runs to predict alternate stable states of Missisquoi Bay and response of the watershed hydrology to changing climate and land-use

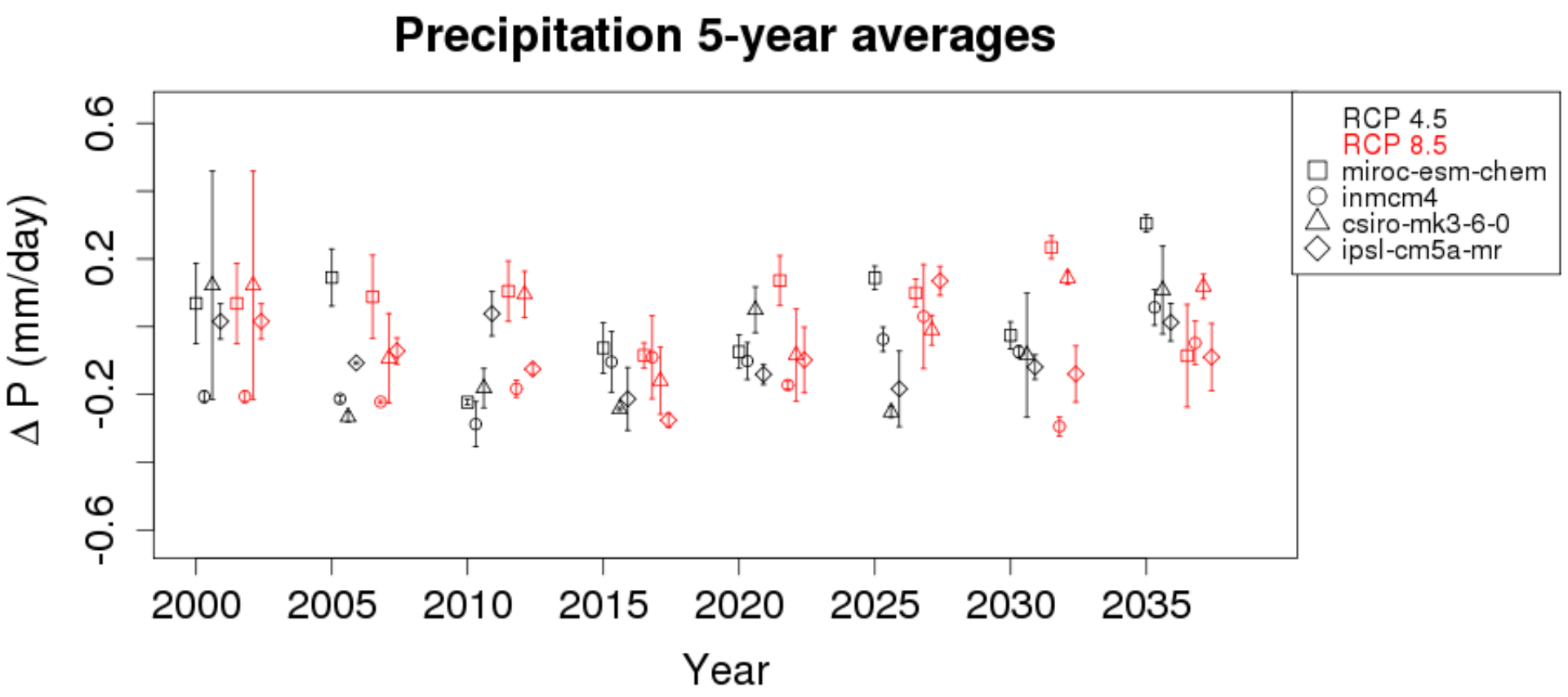
- Climate Scenario: RCP 45 and RCP 85
  - Four GCMs (miroc-esm-chem; inmcm4; csiro-mk3; ipsl-cm5a) are used for both scenarios
- LULCC ABM Scenarios: BAU, Pro-forest, Pro-Ag, Urbanization
- Running 2001 through 2041
- We're using the coarse gridded lake models

LULCC ABM	RCP 4.5	RCP 8.5
Business As Usual	$ChlA^{11}$, $Temp^{11}$, …..	$ChlA^{12}$, $Temp^{12}$, …..
Pro-forest	$ChlA^{21}$, $Temp^{21}$, …..	$ChlA^{22,}$, $Temp^{22}$, …..
Pro-Ag	$ChlA^{31}$, $Temp^{31}$, …..	$ChlA^{32}$, $Temp^{32}$, …..
Urbanization	$ChlA^{41}$, $Temp^{41}$, …..	$ChlA^{42}$, $Temp^{42}$, …..

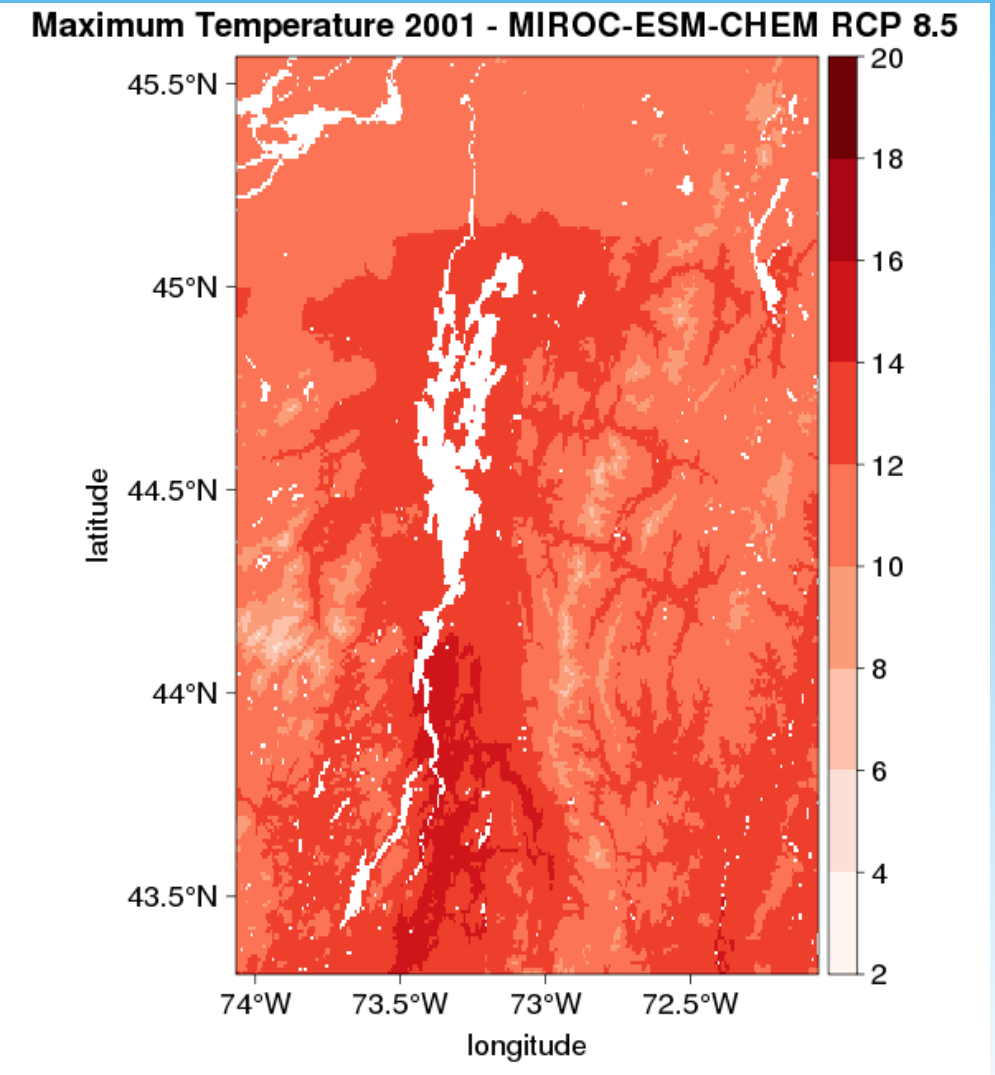
Large Uncertainty Across Four GCM Projections for Temperature (El Nino effects are not included in these projections)



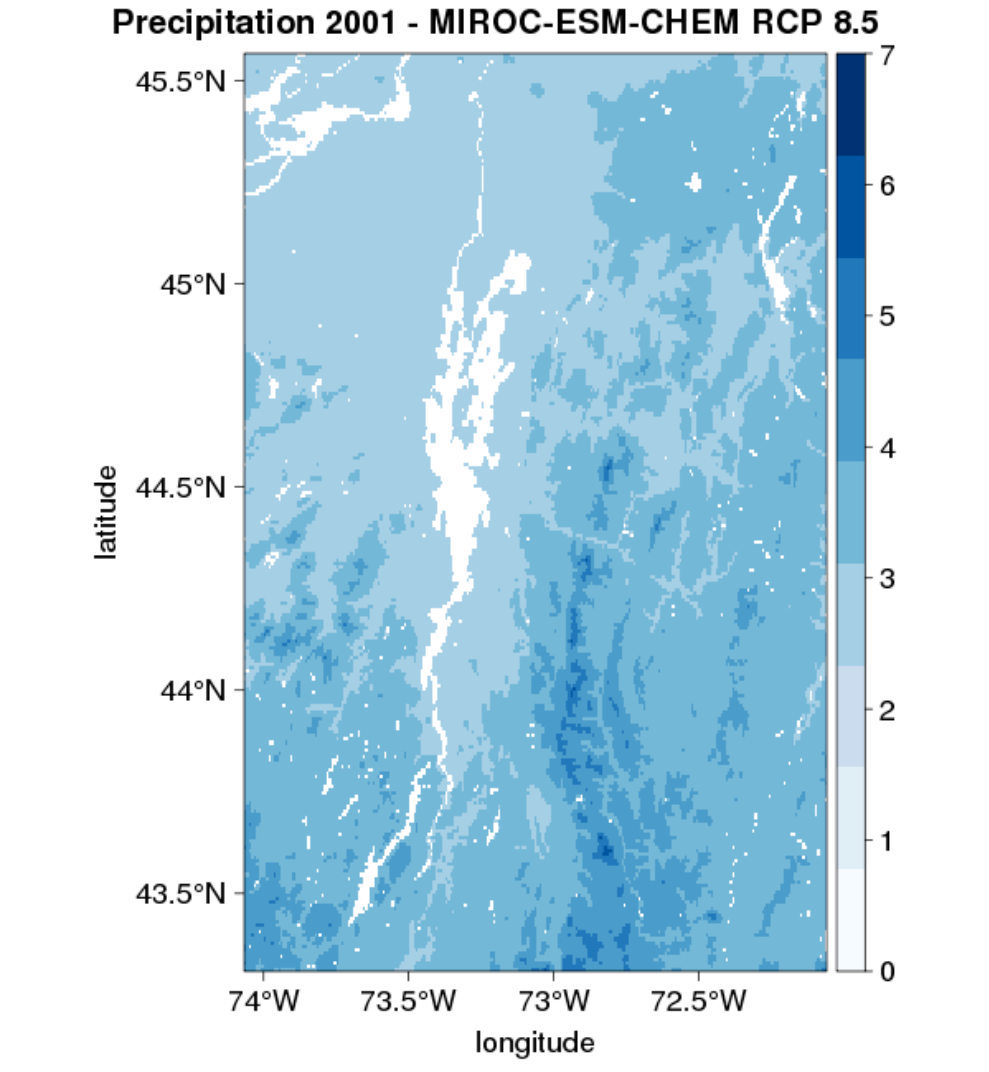
Large Uncertainty Across Four GCM Projections for Precipitation (Extreme events are not included in such SMOOTHED projections)



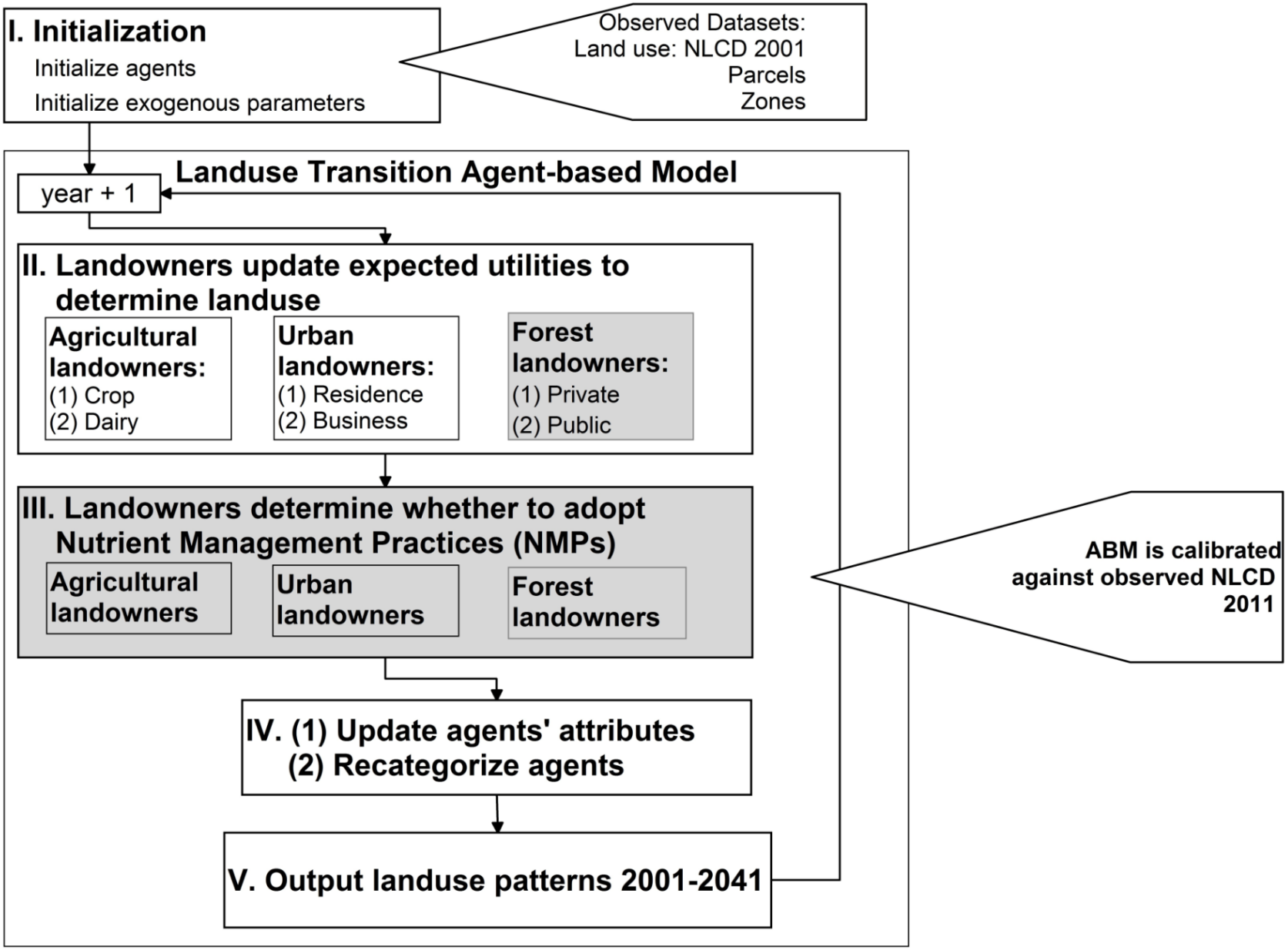
Cascading IAM can generate high resolution temperature projections for alternate climate scenarios and GCMs for LCB



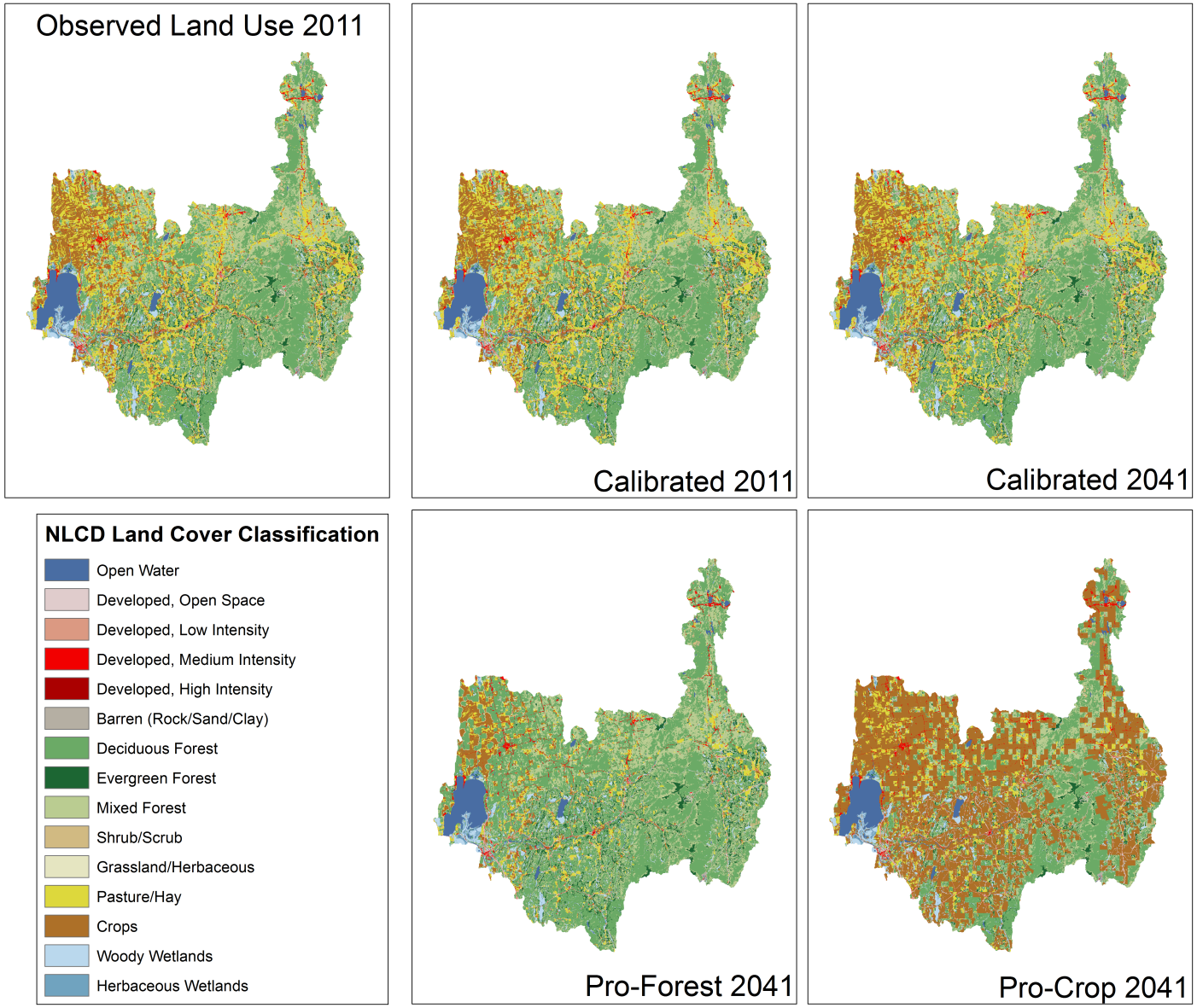
Cascading IAM can generate high resolution precipitation projections for alternate climate scenarios and GCMs for LCB



LULCC Agent Based Model (ABM) Design



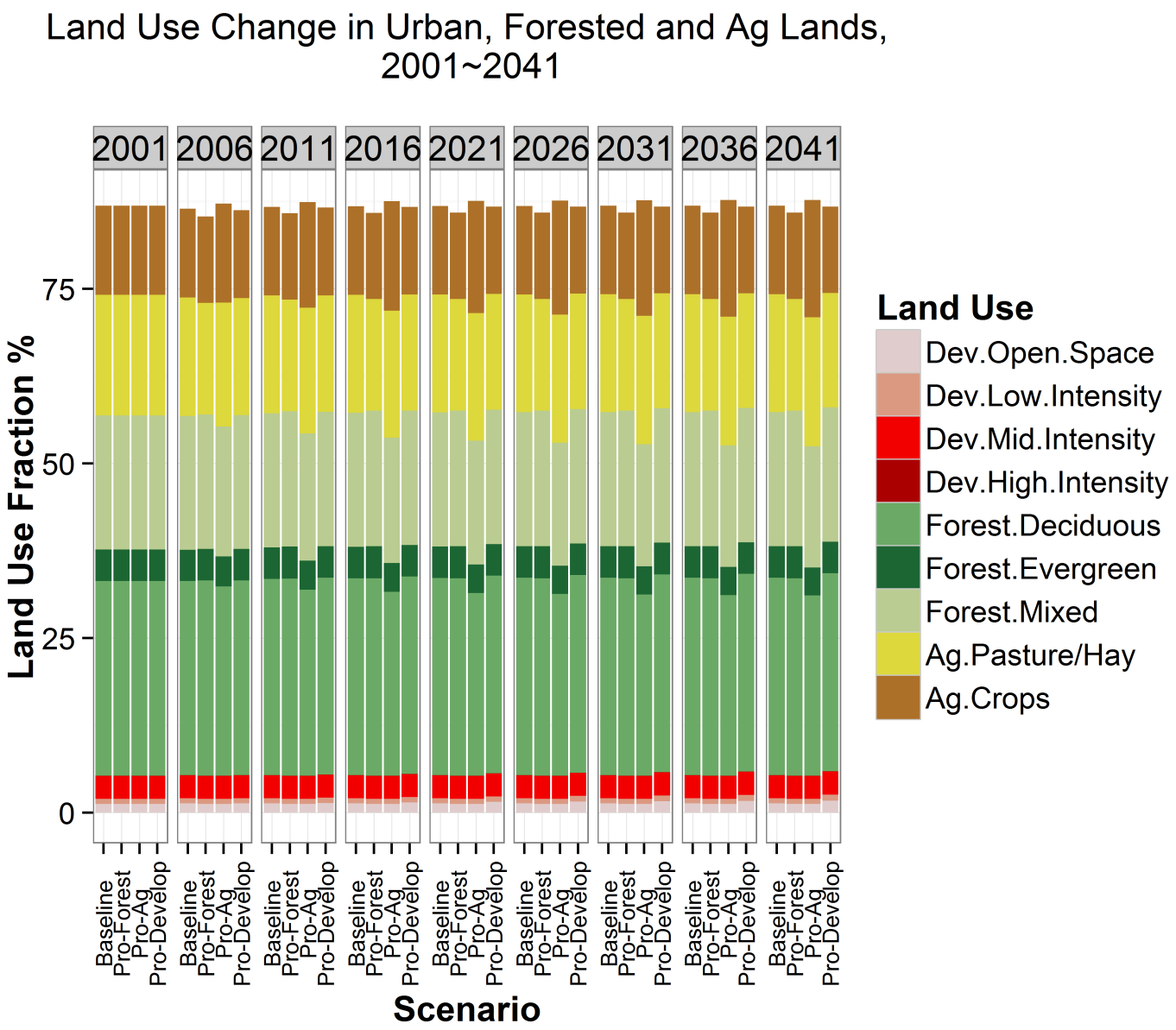
Calibrated version of land use transition agent based model can generate high- resolution scenarios at watershed scales for 15 National Land-Cover (NLCD) classifications



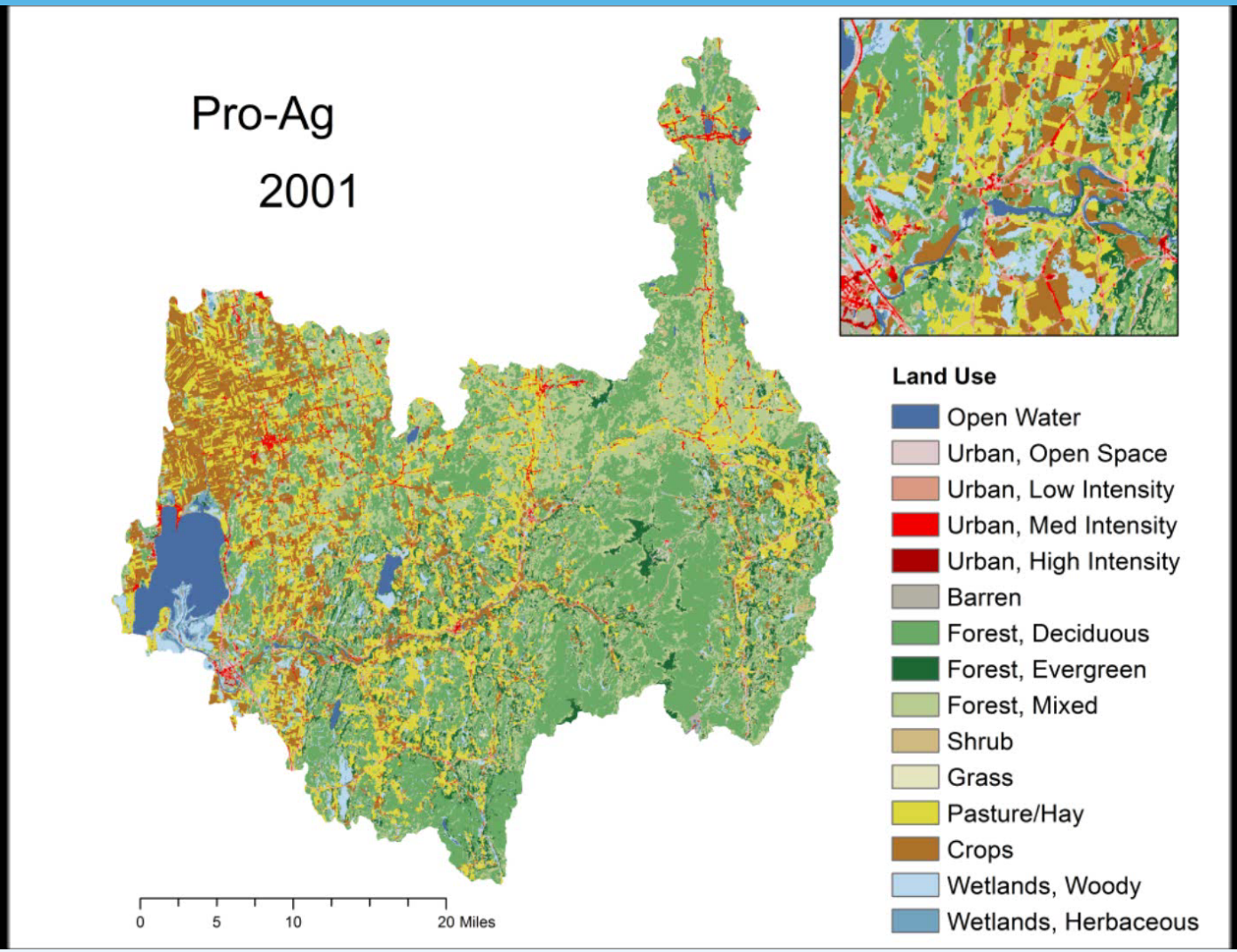
Pro-crop, pro-forest and urbanization scenario families have been developed to test hypotheses about the impacts of alternate stable states in landscapes that emerge in response to different land use, agriculture and economic development policies

Scenario	Conserve Act 250	Maintain farmer subsidies	Promote economic development
BAU	yes	yes	no
Pro-forest	yes	no	no
Pro-ag	no/modify	yes	no
Urbanization	no/modify	no	yes

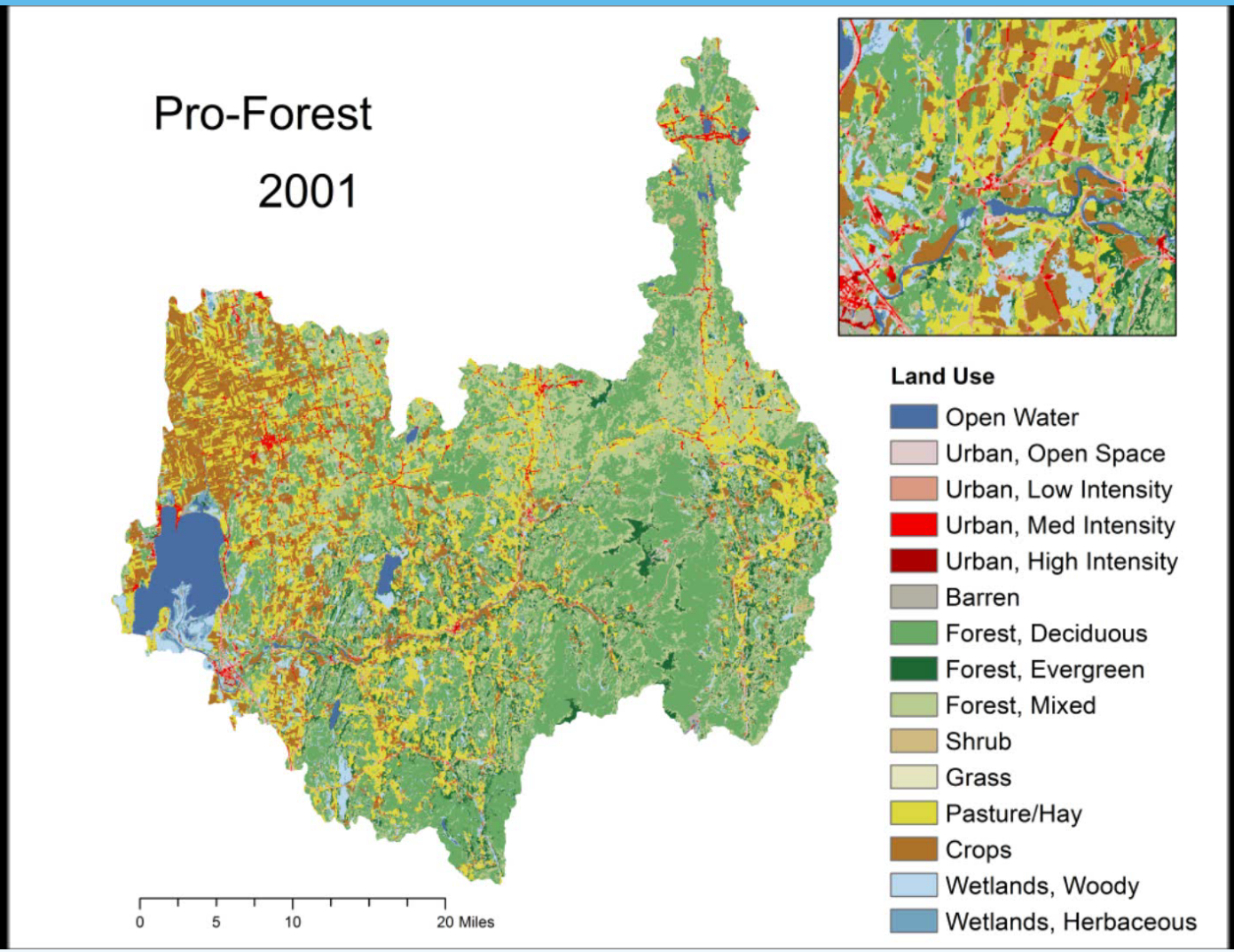
Aggregate comparison of four LULCC scenarios



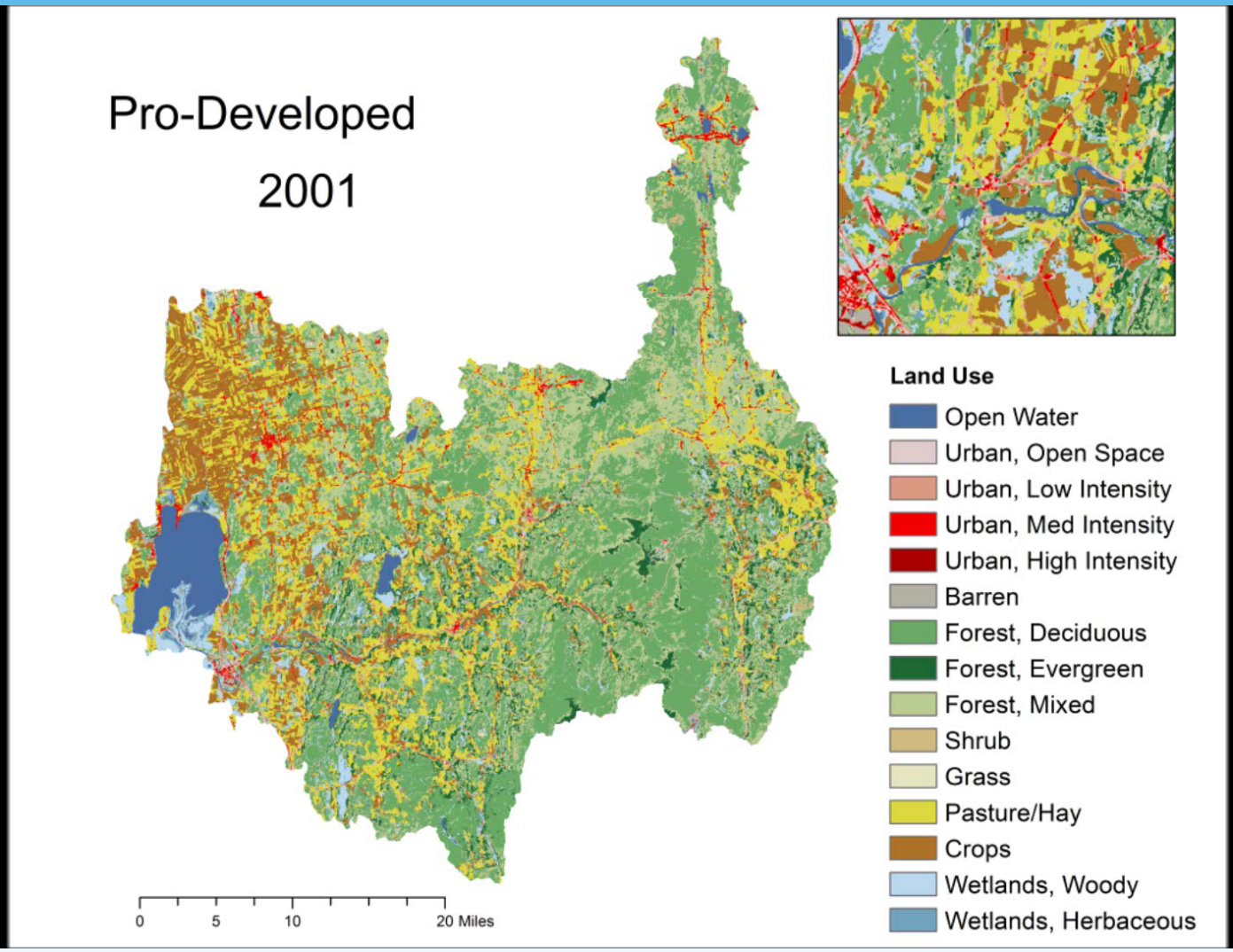
Agriculturally dominant landscape scenario



Forest dominated landscape scenario



Urbanized landscape scenario

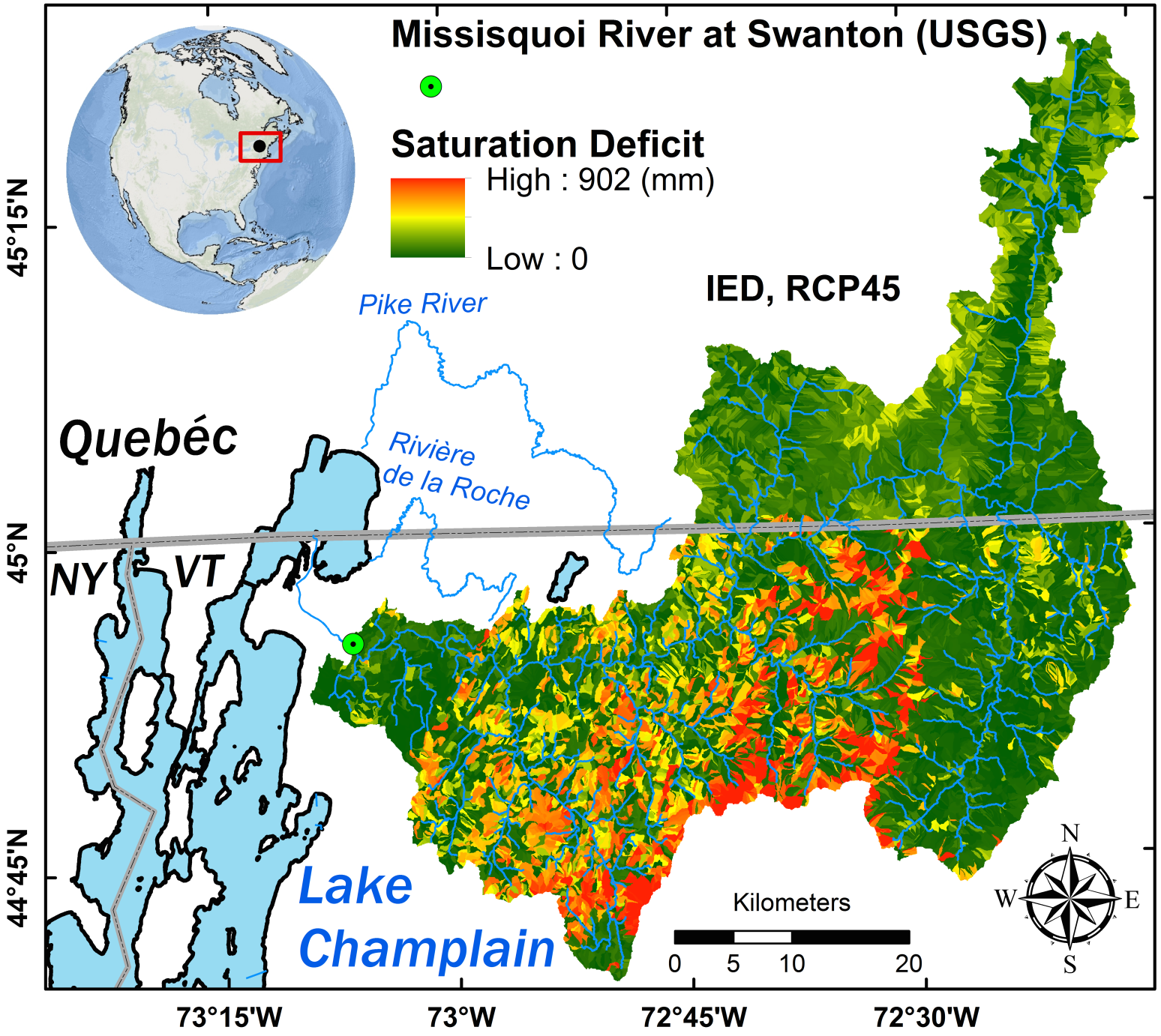


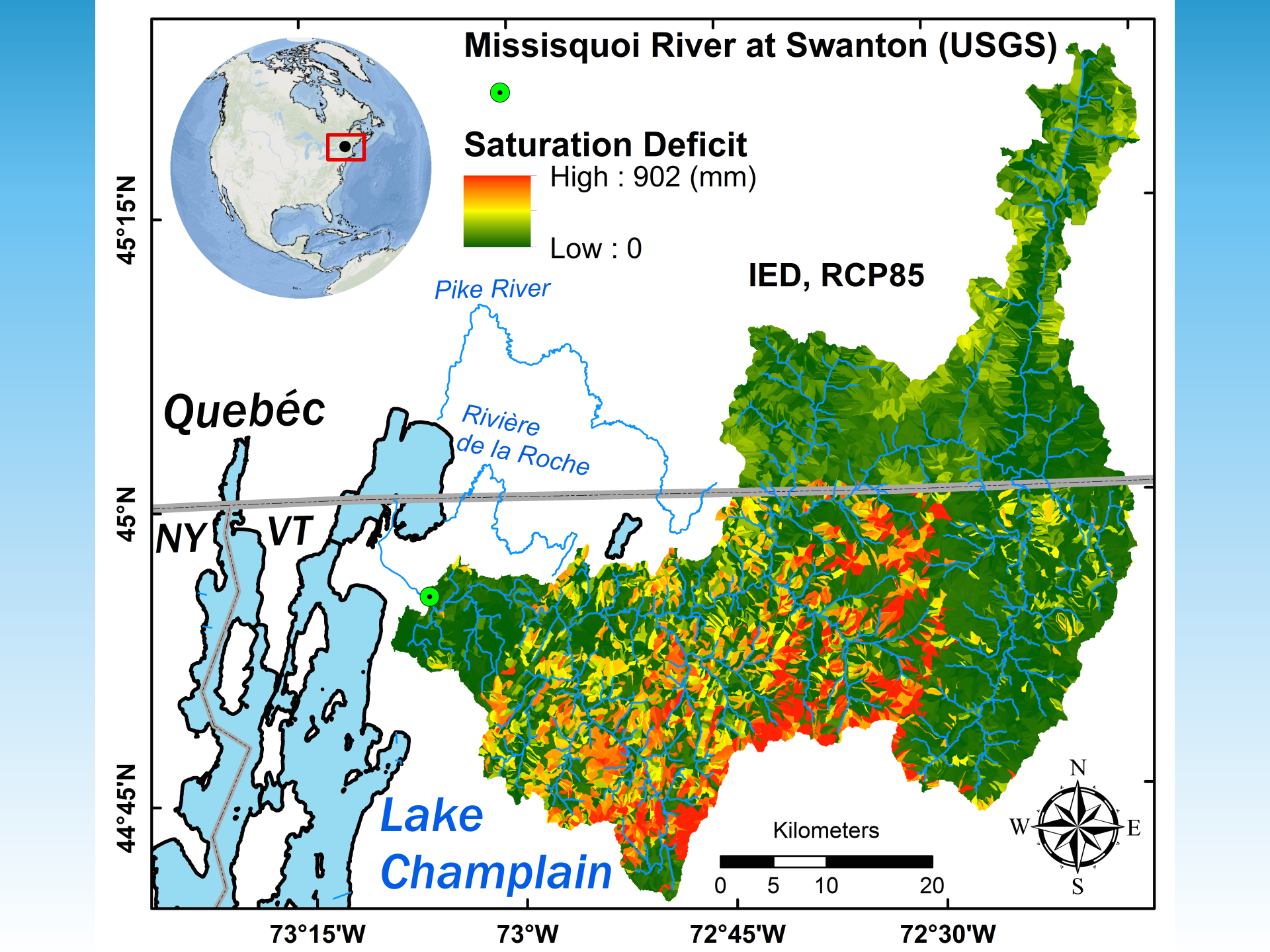
In Progress: Predicting NMP Adoption Under Alternate Policy and Behavioral Scenarios

- A pilot-tested 22-page 43-question panel survey instrument implemented by NASS, USDA on a stratified random sample of farmers in two watersheds: first wave in 2013, second wave in 2015
- A pilot-tested 4-page 16-question survey instrument implemented through mail to a stratified random sample of households in LCB: first wave in 2015
- Bounded-rational (Conjoint Analysis) approach to estimate the likelihood of NMP adoption under alternate policy incentives and regulations
- Theory of Planned Behavior approach to estimate the likelihood of NMP adoption under different behavioral and social norm conditions

LULCC ABM Highlights and Extensions

- The LULCC ABM is generalizable with NLCD and other similar remote sensing data bases
- Endogenous interactions between farmer aggregate utilities and land cell ecosystem service gradients generate emergent dynamics
- Work in progress: Disaggregating farmer and land-cell ecosystem service functions
- Work in progress: Assignment of land value for urban, forest and agricultural parcels using ANNs
- Feedbacks from lake and hydrological models are being developed


Missisquoi River at Swanton (USGS)
Saturation Deficit
High : 902 (mm)
Low : 0
IED, RCP45
Pike River
Rivière de la Roche
Quebéc
NY
VT
Lake Champlain
45°15'N
45°N
44°45'N
73°15'W
73°W
72°45'W
72°30'W
Kilometers
0 5 10 20
N
W
E
S


Missisquoi River at Swanton (USGS)
Saturation Deficit
High : 902 (mm)
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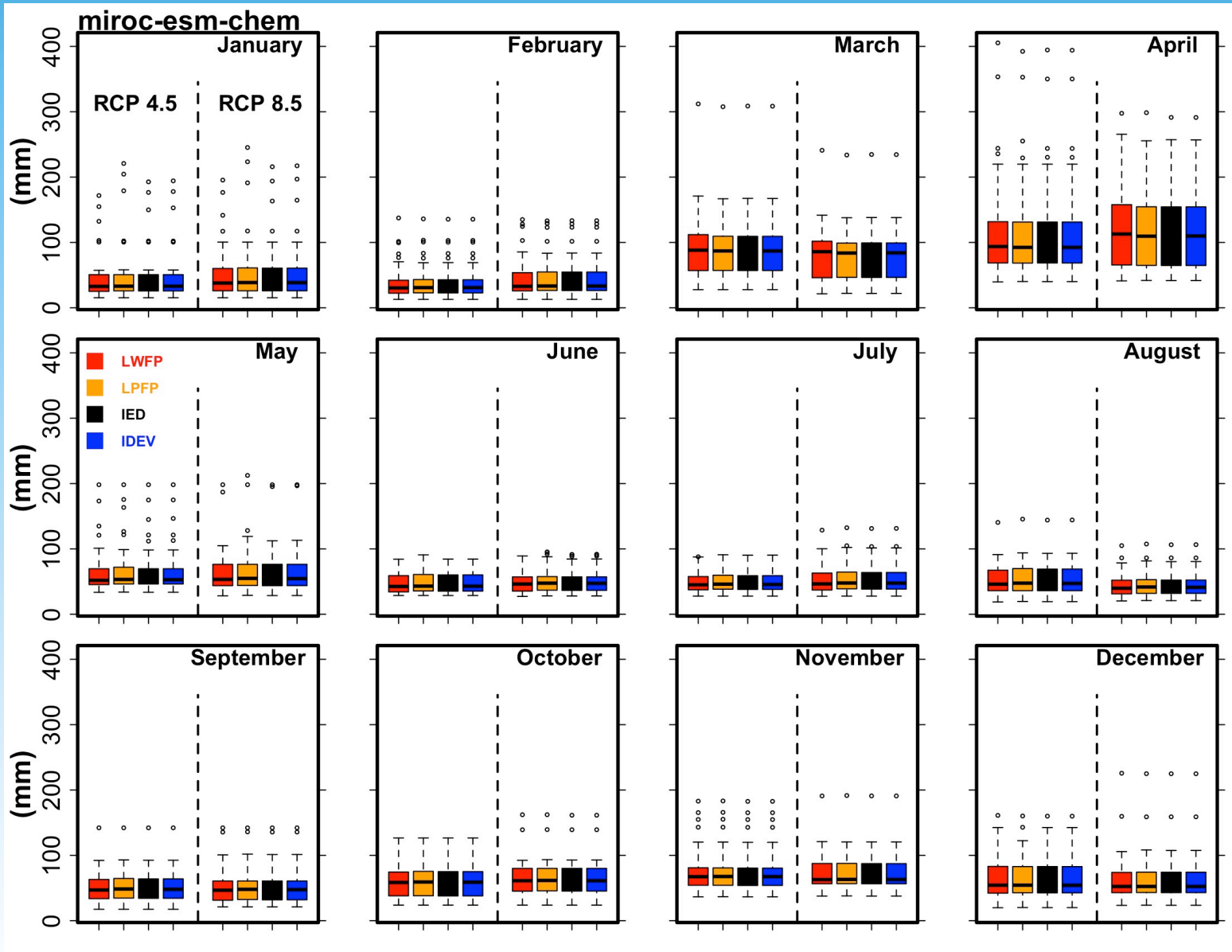
Quebéc
NY
VT
Lake Champlain
Kilometers
0 5 10 20
N
W
E
S
45°15'N
45°N
44°45'N
73°15'W
73°W
72°45'W
72°30'W

Projected Monthly Streamflow in Missisquoi (2001-2041)

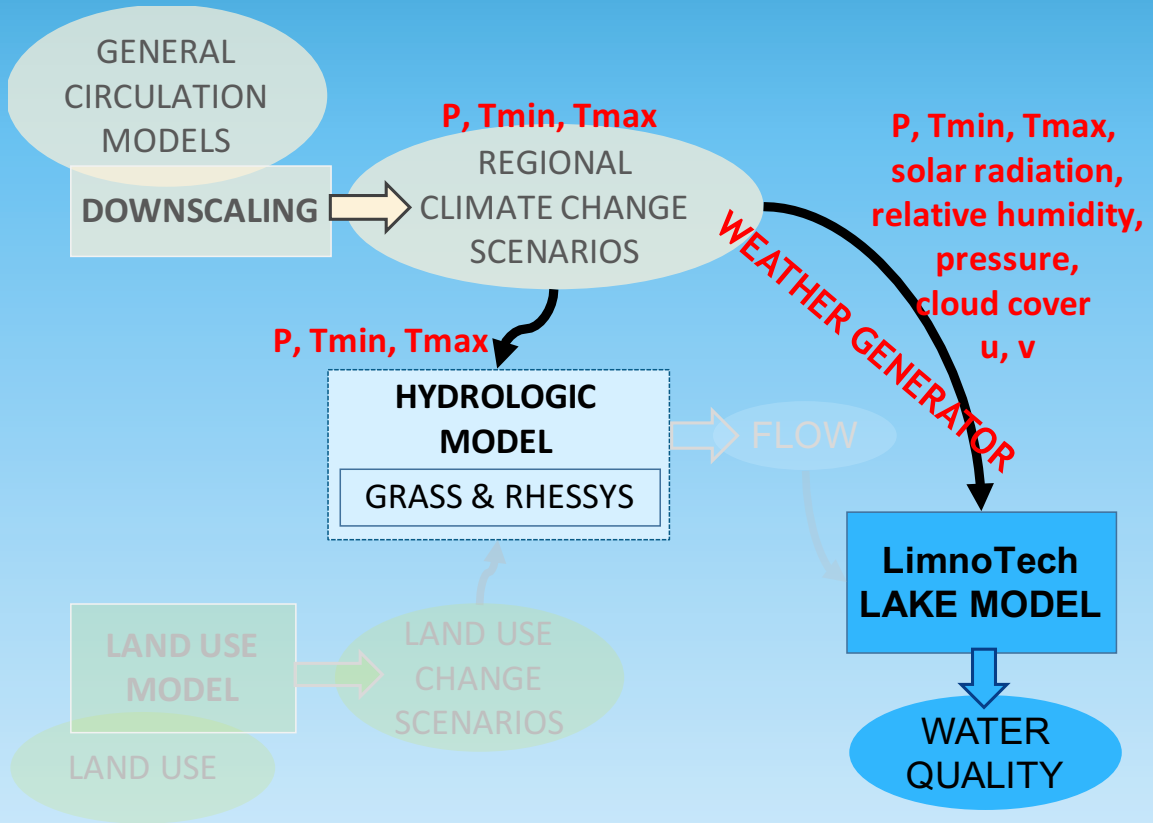


RHESSys Extensions in progress

- While RHESSys model is responding to changing climate signal, a tighter coupling of LULCC ABM with RHESSys is being worked upon to both improve the LULCC signal in terms of changes in 15 land use classifications as well as adoption of BMPs by land-users

- BSTEM integration with RHESSys will improve cascading IAM ability to model extreme events, simulate the effects of BMP adoption and improve the estimates of nutrient fluxes in the lake model

Weather generator resampling approach



For each future daily T and P

Find a matching pair of T and P in historic NARR

Steps:

1. Search the historic data under ***two conditions***:
   A. time: near selected date
   B. value: close T and P values
2. Collect a set of ***nearest T and P neighbors***
3. ***Randomly*** select one neighbor

daily weather sequence of all climate variables

Downscaled GCM

T and P

Daily, 1950 - 2099

NARR

T, P, u, v, RH, Pressure, Solar Radiation, Cloud Cover

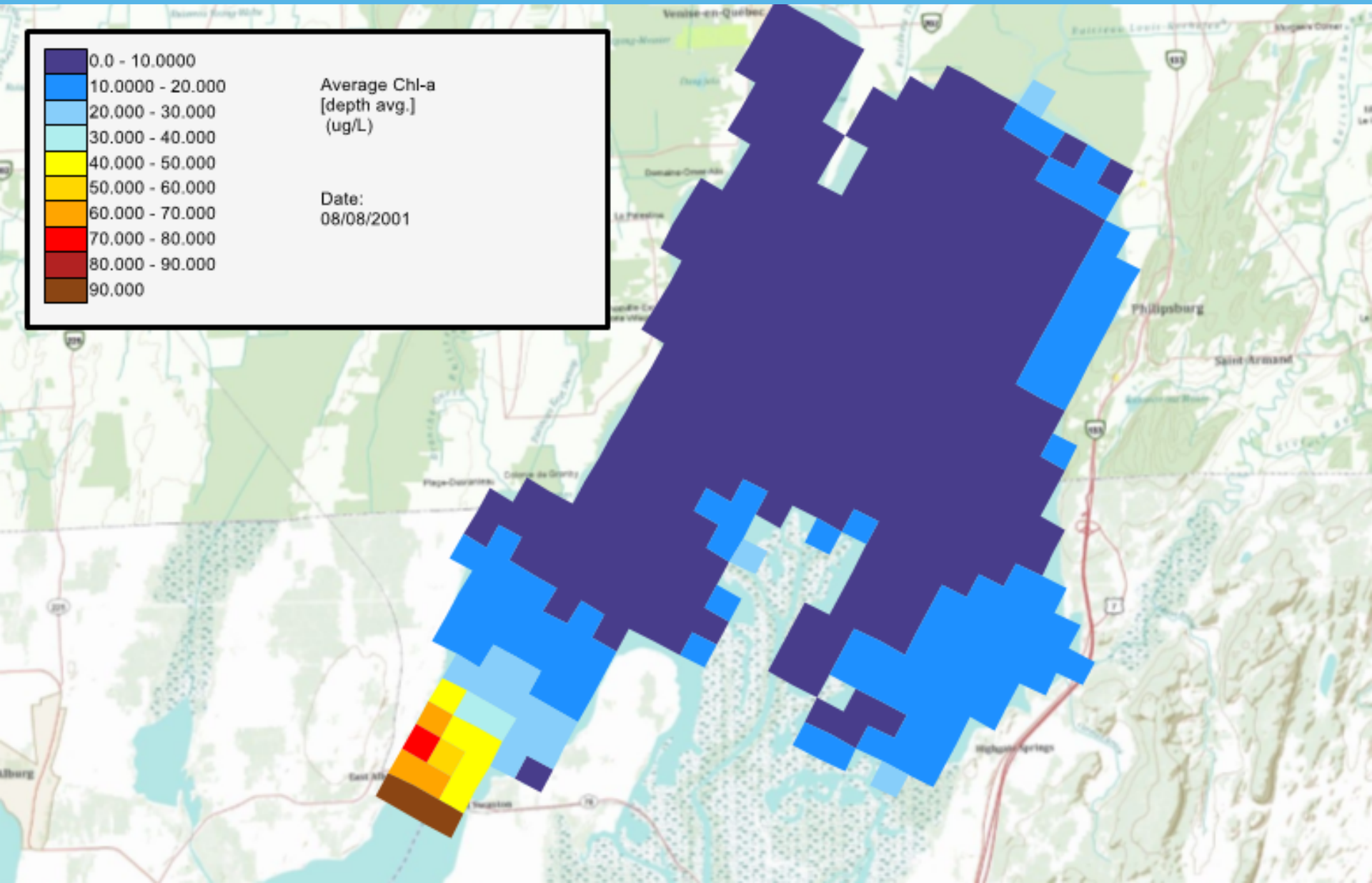
Daily, 1979 - 2014

North American Regional Reanalysis (NARR)

32 km grid resolution, daily from 1979 – 2014

http://www.esrl.noaa.gov/psd/data/gridded/data.narr.html

Cascading IAM can project alternate stable states in Missisquoi Bay for alternate climate and land-use scenarios: Example of Pro-forest & RCP 4.5 Miroc-ESM



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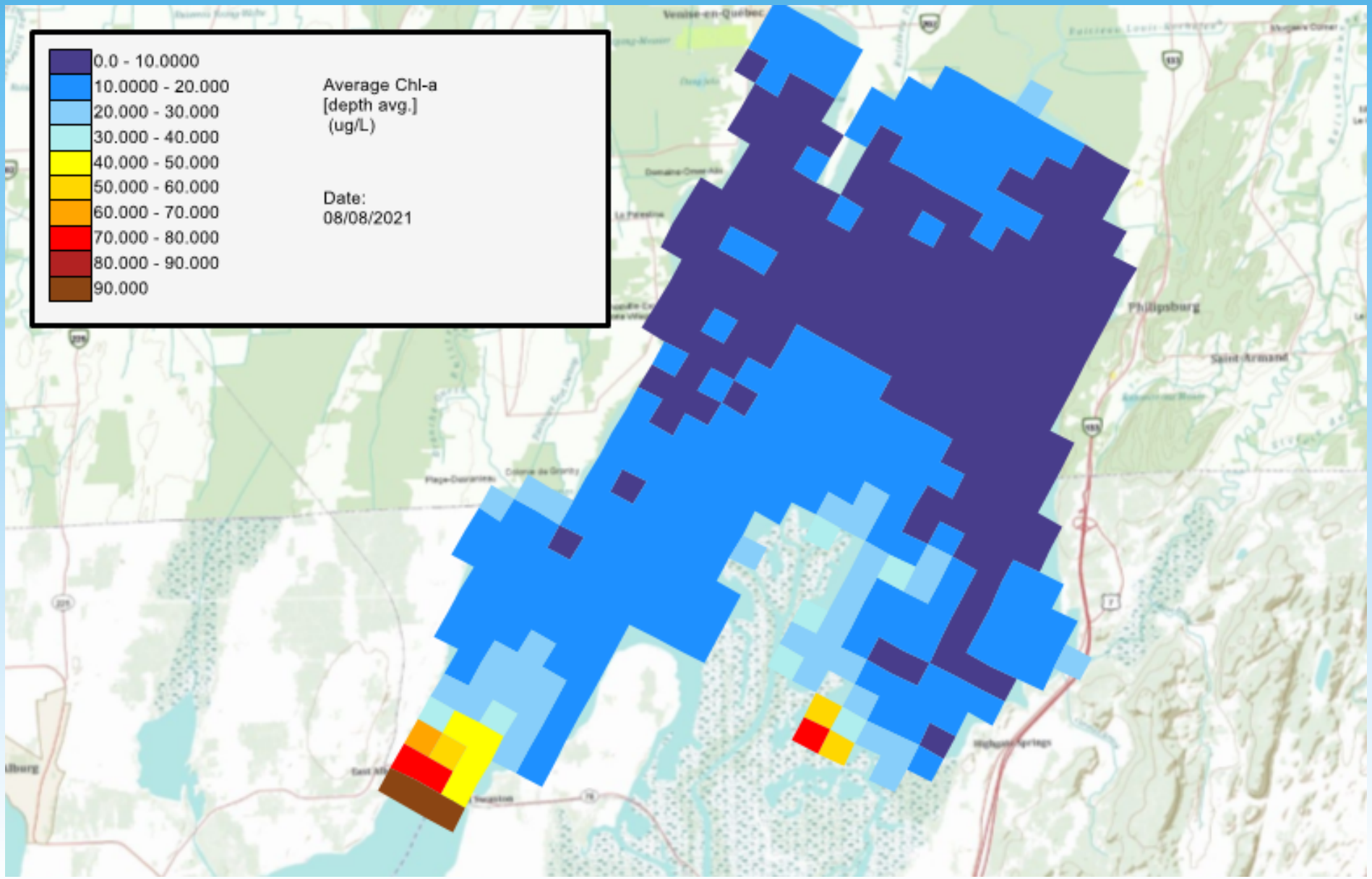

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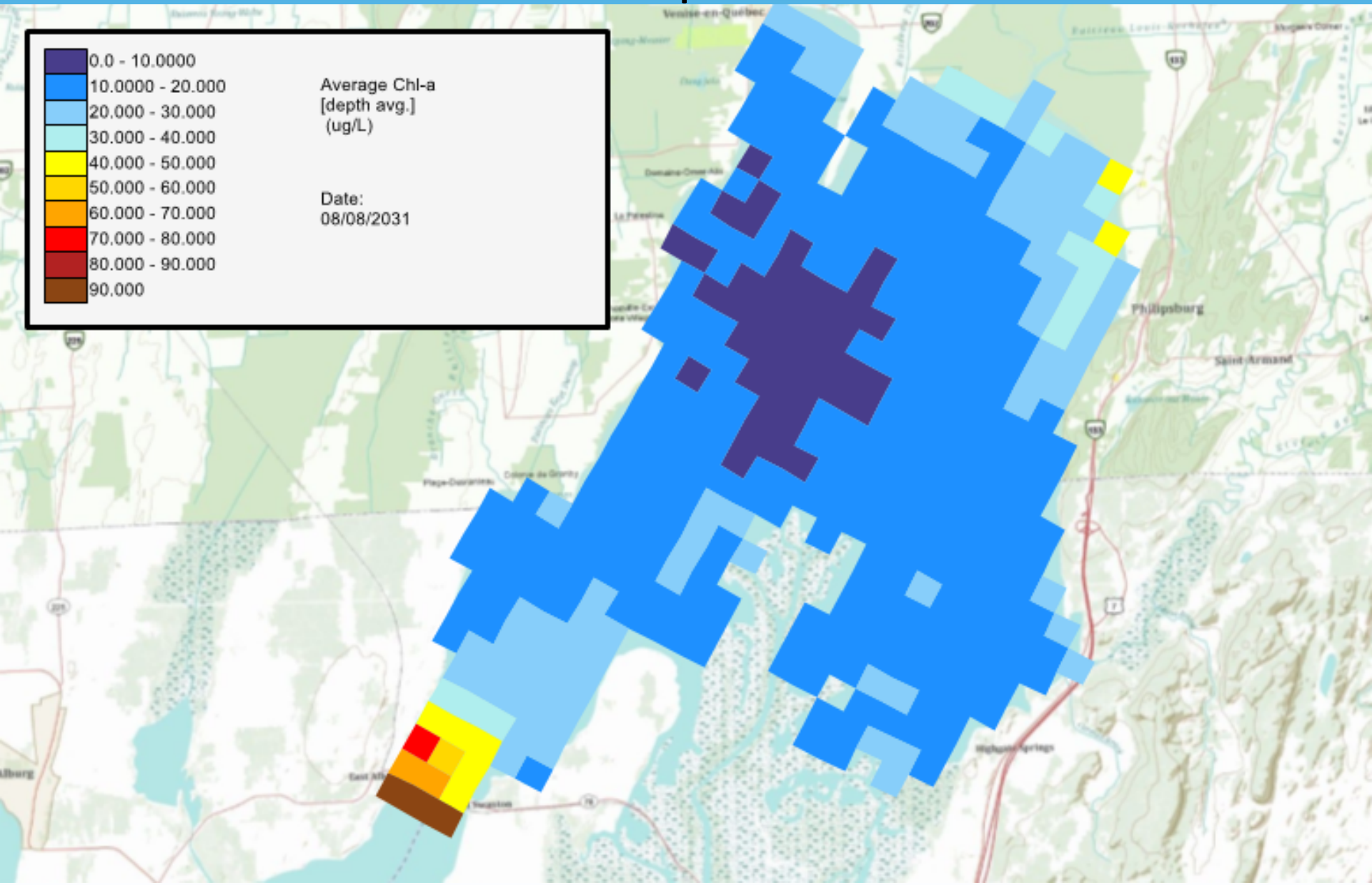
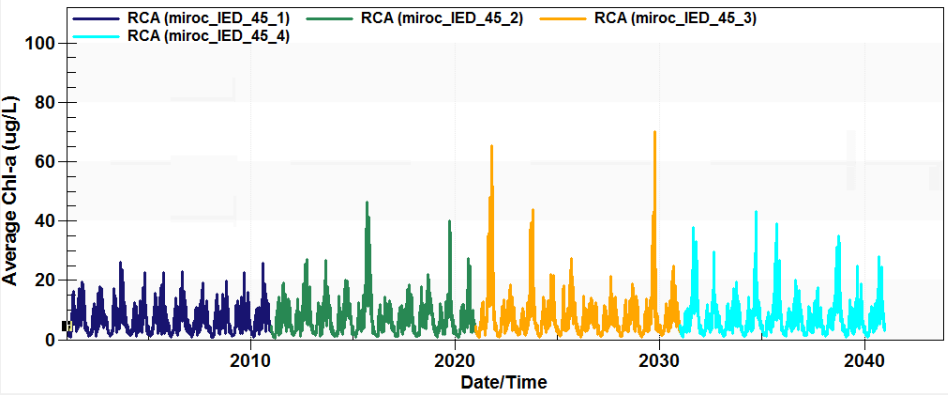


Layer: 1.00, Pool 1 (I=19, J=22, K= 1)



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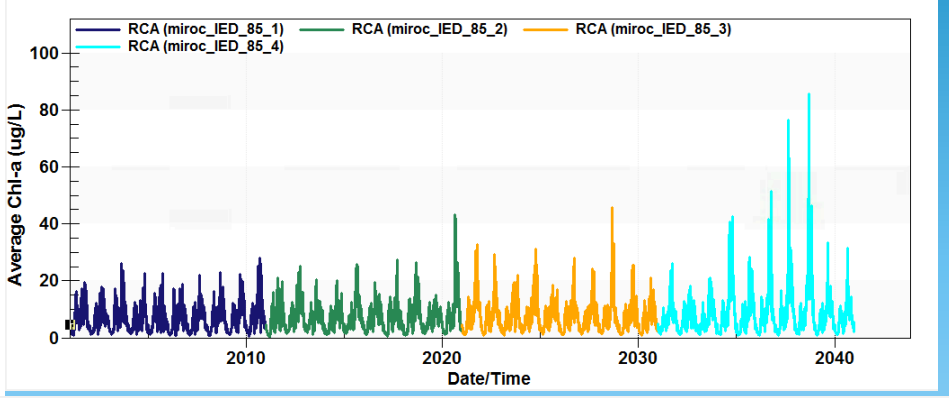

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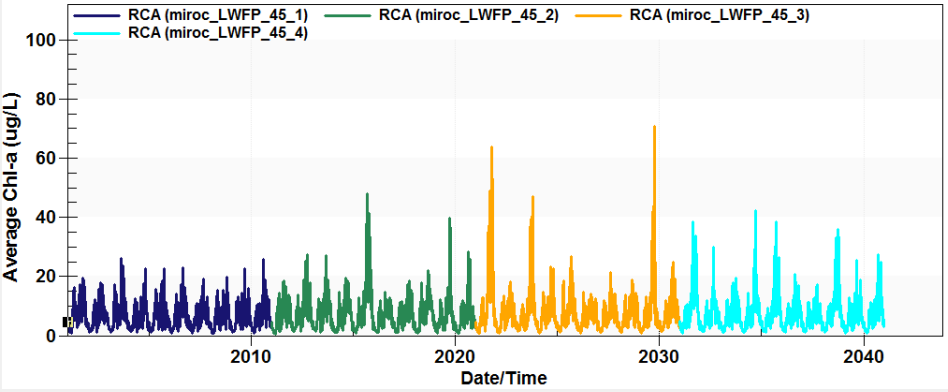

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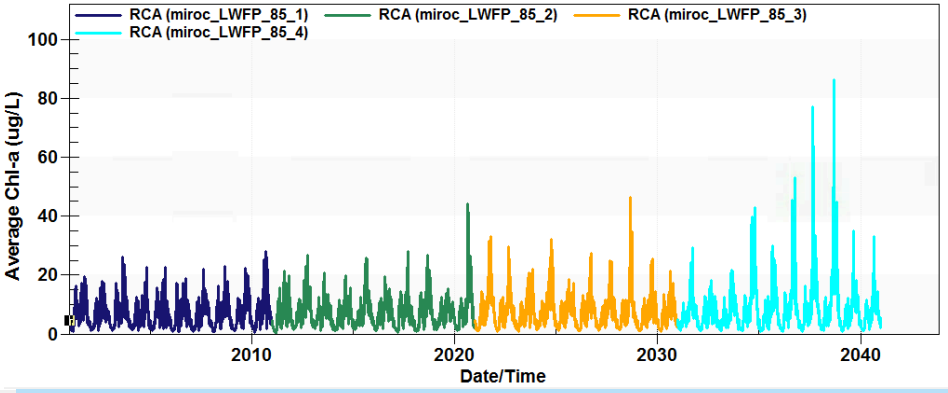

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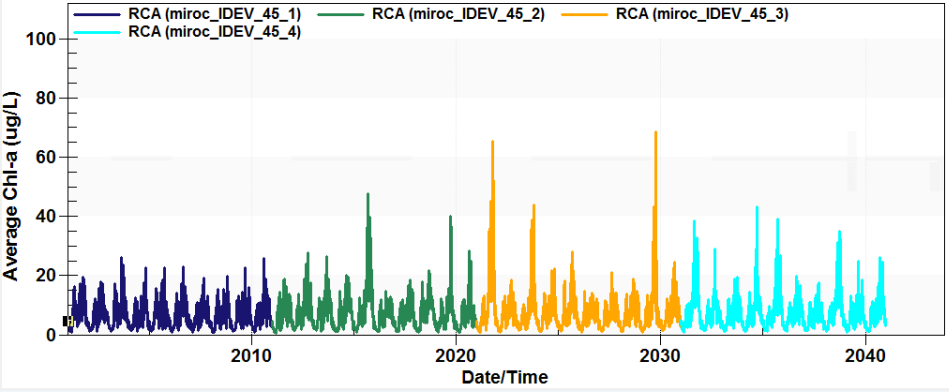

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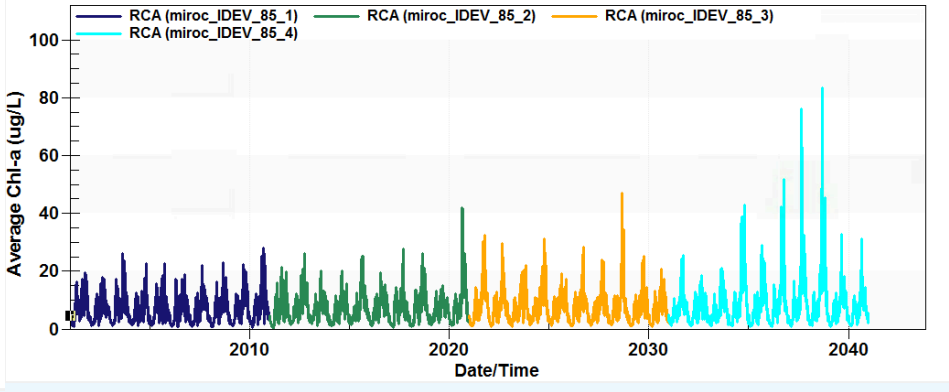

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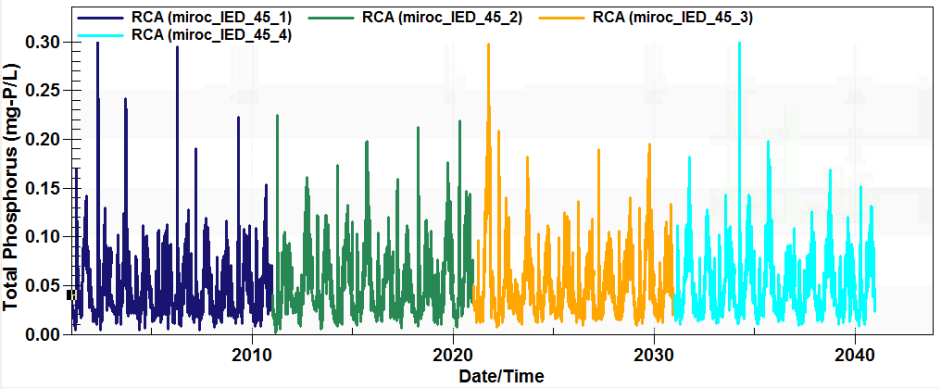

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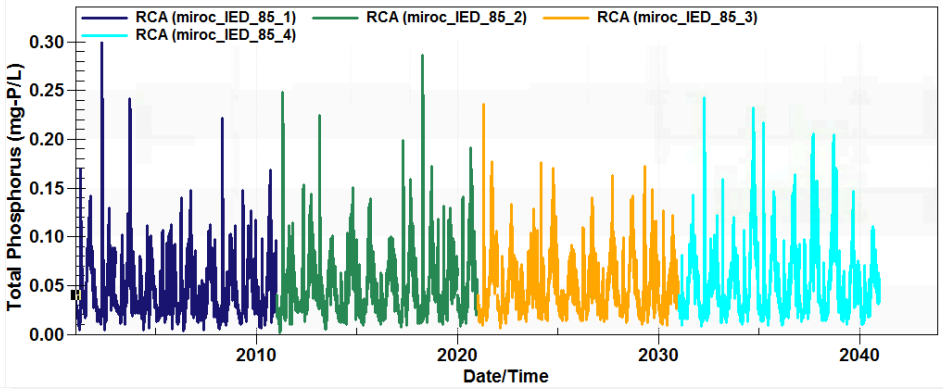

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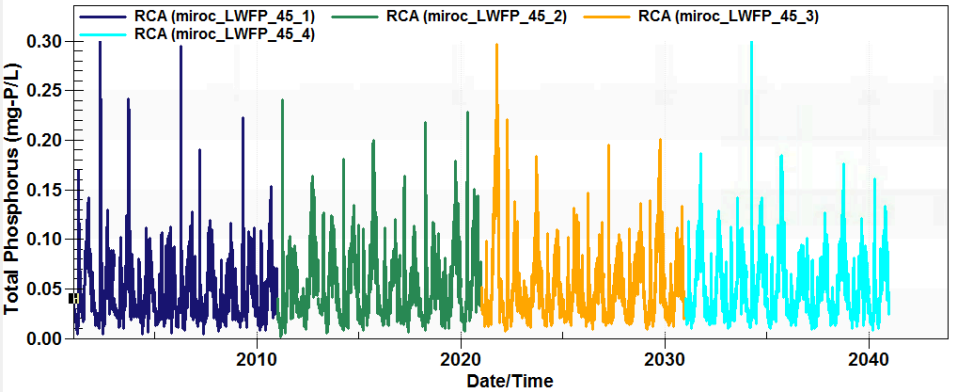

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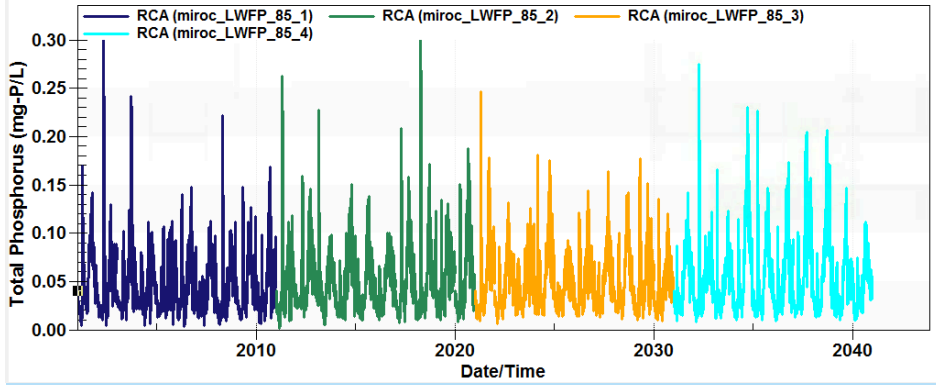

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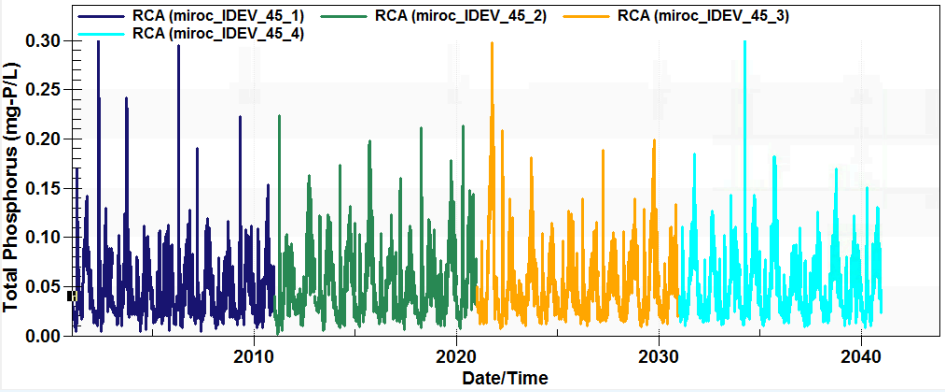
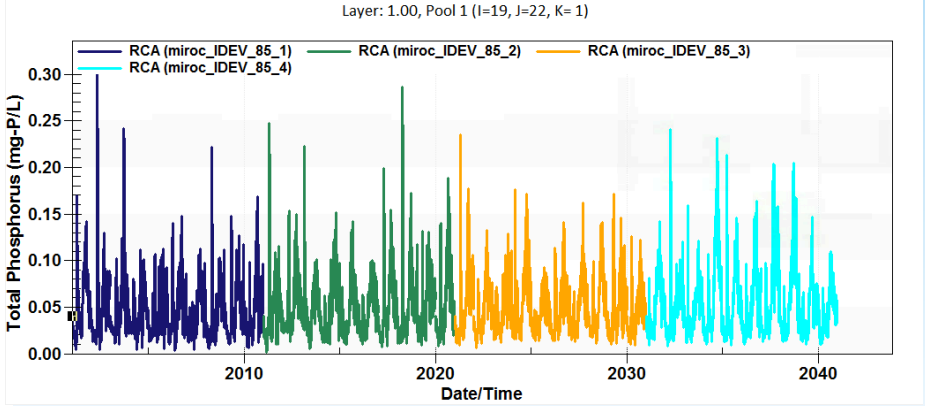


Layer: 1.00, Pool 1 (I=19, J=22, K= 1)



IAM applications for SES science and adaptive management goals

- **Develop IAM capability to simulate the impacts of adaptive interventions on water quality conditional upon climate change and land-use scenarios (RACC)**

- **Test Alternate Lake States (RACC)**

- **Facilitate stakeholder designed scenario testing (RACC)**

- Test feedback loop dominance (RACC and BREE)
- Quantify uncertainty propagation (RACC and BREE)
- Simulate adaptive decision making by Land-use agents (BREE)
- Estimate the risk benefit ratios for policy investments through BMP adoption incentives and regulations (Potential application)

Possible Cascading IAM Structure beyond RACC (2011-2016): currently under review for BREE 2016-2021 at the earliest!!

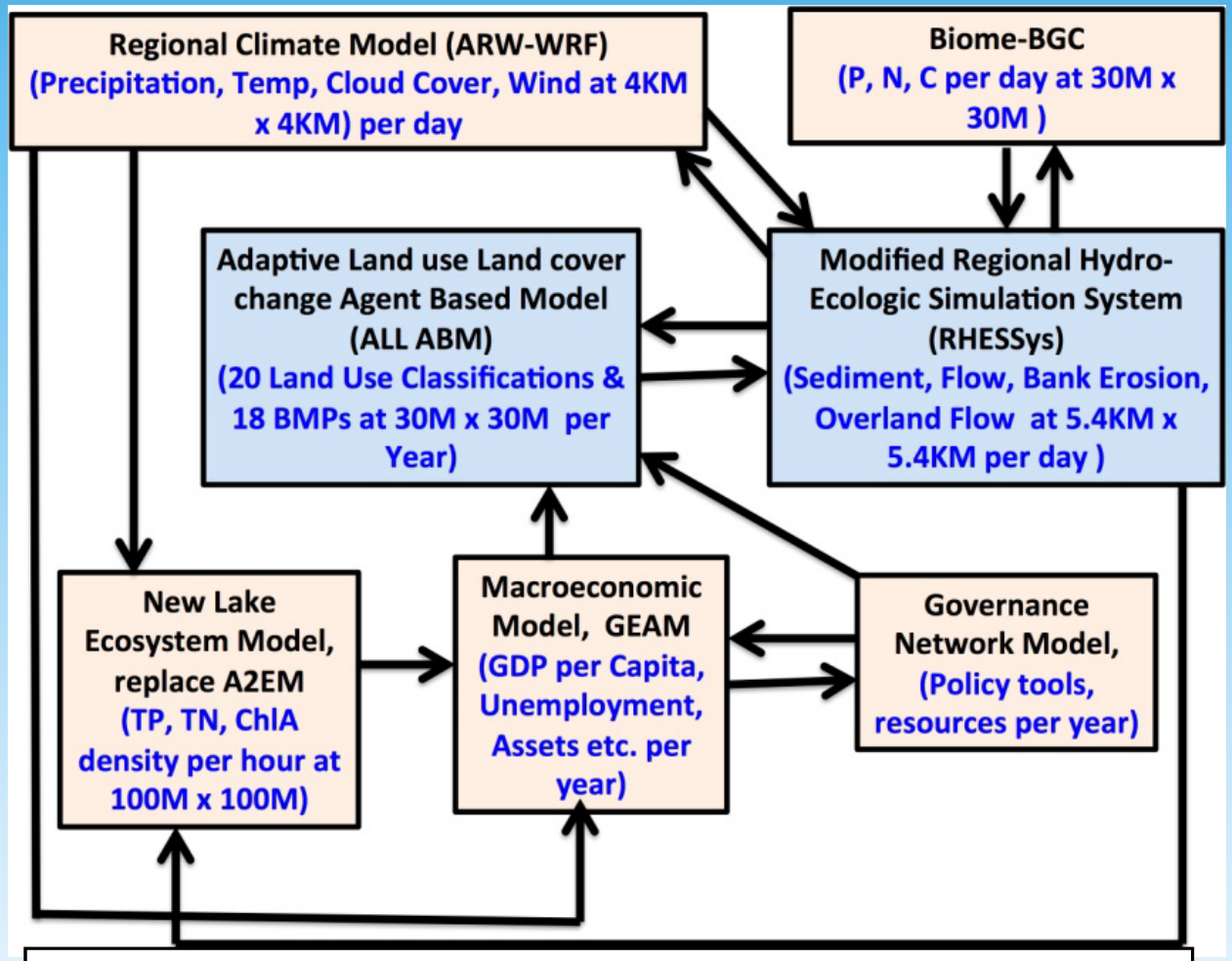


Figure 7: The BREE Integrated Assessment Model (IAM) of coupled social ecological systems for understanding the cascading impacts of climate change induced extreme events at watershed scales; tan = new model; blue = expanded existing model; WRF: Weather Research and Forecasting; ALL: Adaptive Landuse Land cover agent based model: GEAM: General Equilibrium Analysis Model

What can cascading IAM do? Facilitate adaptive management and support decision making under risk and uncertainty

- A crowdsourcing Delphi survey of 100+ experts and civil society stakeholders led to the identification of more than 60+ unique adaptive (management) interventions

- By May 2016, we expect IAM to be able to simulate 16 of these interventions to assess the P, N and HAB reduction effectiveness, under alternate climate change and landscape scenarios

- Extensions of cascading IAM can be develeped as targeted Decision Support Systems (DSS) for facilitating decision making and adaptive management at watershed and basin wide scales

Expected/possible extensions in Cascading IAM

- **Embed BSTEM in RHESSys to simulate sedimentation flows (May 2016); and BiomeBGC in RHESSys to simulate C, N, P fluxes in streams (BREE)**

- **Replace flow based P regression equations in A2EM with sedimentation (May 2016) and C,N, P fluxes (BREE)**

- **Add 3-5 agricultural BMPs (May 2016) and additional ag and urban BMPs (BREE) in LULCC ABM**

- **Feedbacks from the lake to LULCC ABM, in particular impact of water quality in LCB on property values (May 2016), public opinion reflected in surveys, news media and social media (BREE), governance network (BREE), and macro-economic indicators (BREE)**

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