# 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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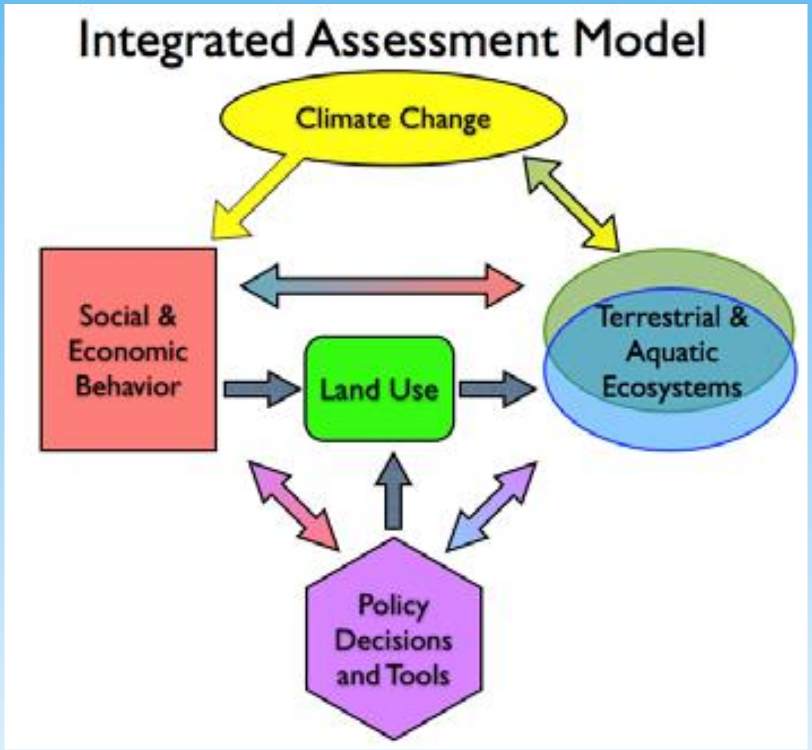
# The Overarching RACC Question (from NSF funded proposal)

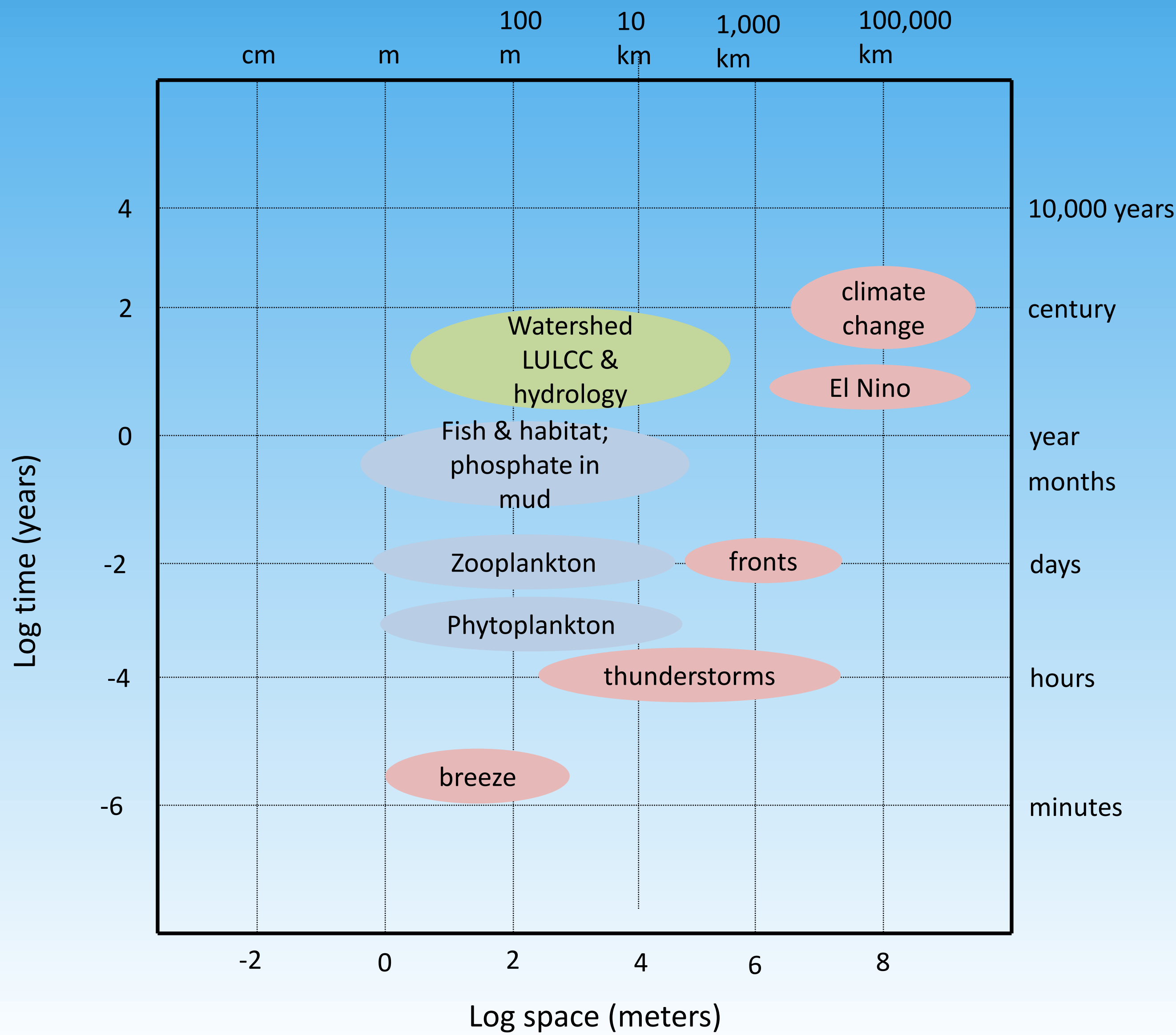
**How will the interactions of climate change and land use alter hydrological processes and nutrient transport from the landscape, internal processing and eutrophic state within the lake, and what are the implications for adaptive management strategies?**

Social Ecological System (SES) science goals

Adaptive management goals



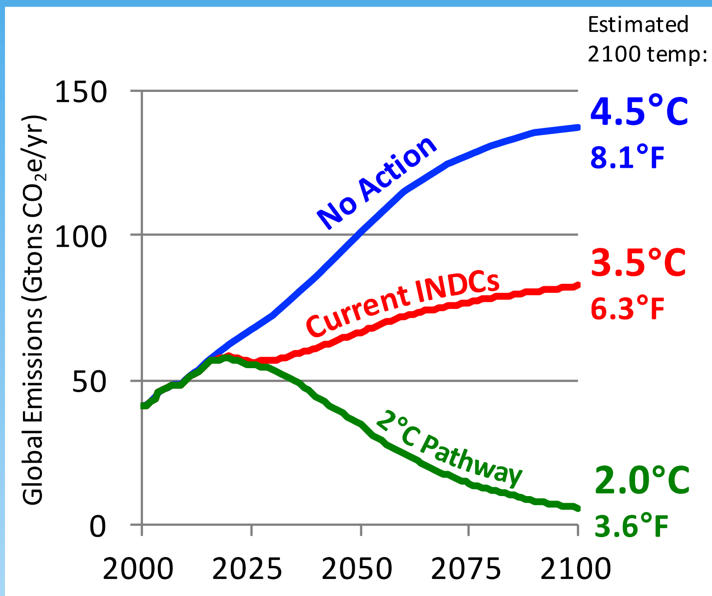
# Complexity of modeling cross-scale interactions in Social Ecological Systems (SES)

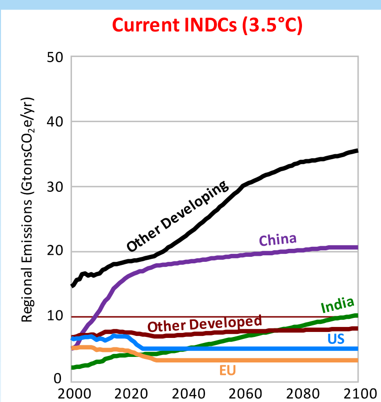


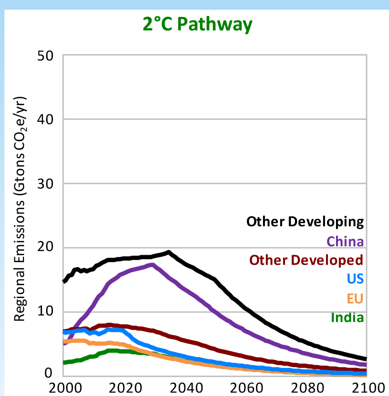

Relatively **slow** turn over rates

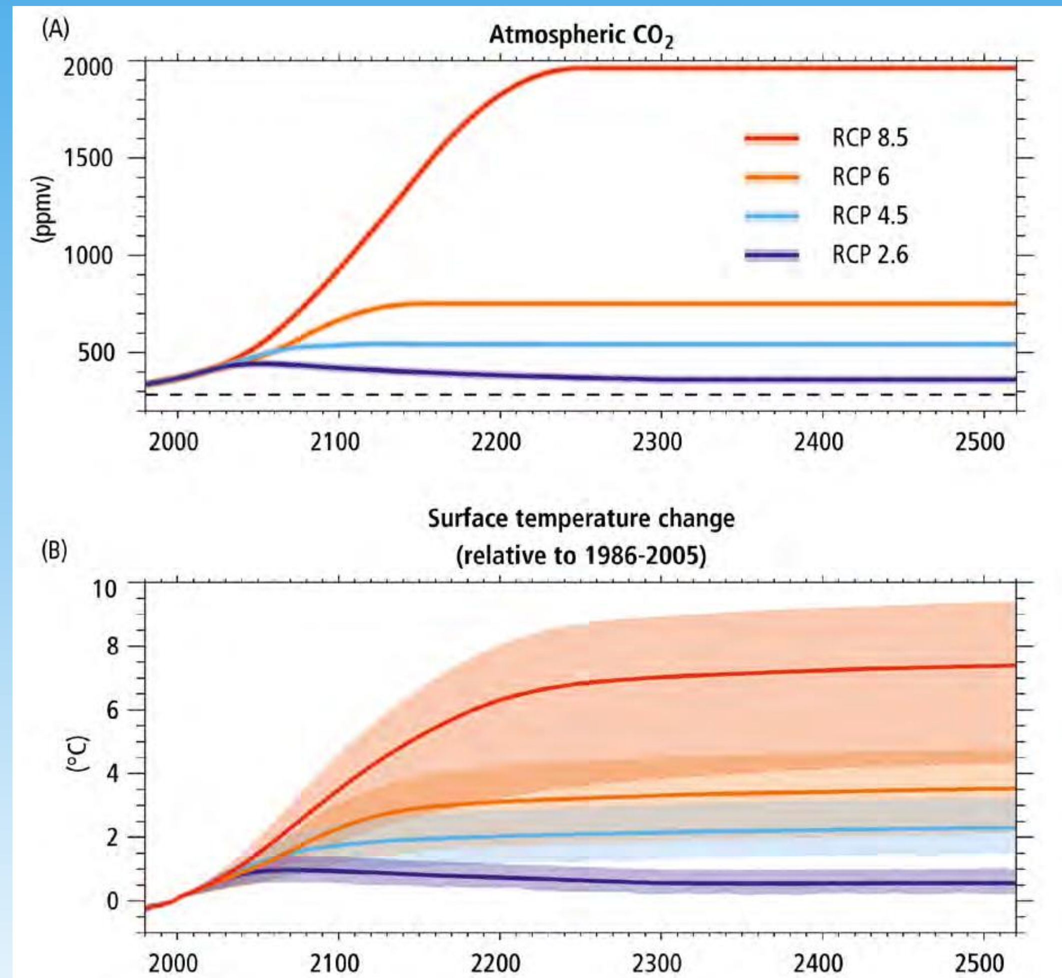
Relatively **fast** turn over rates

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



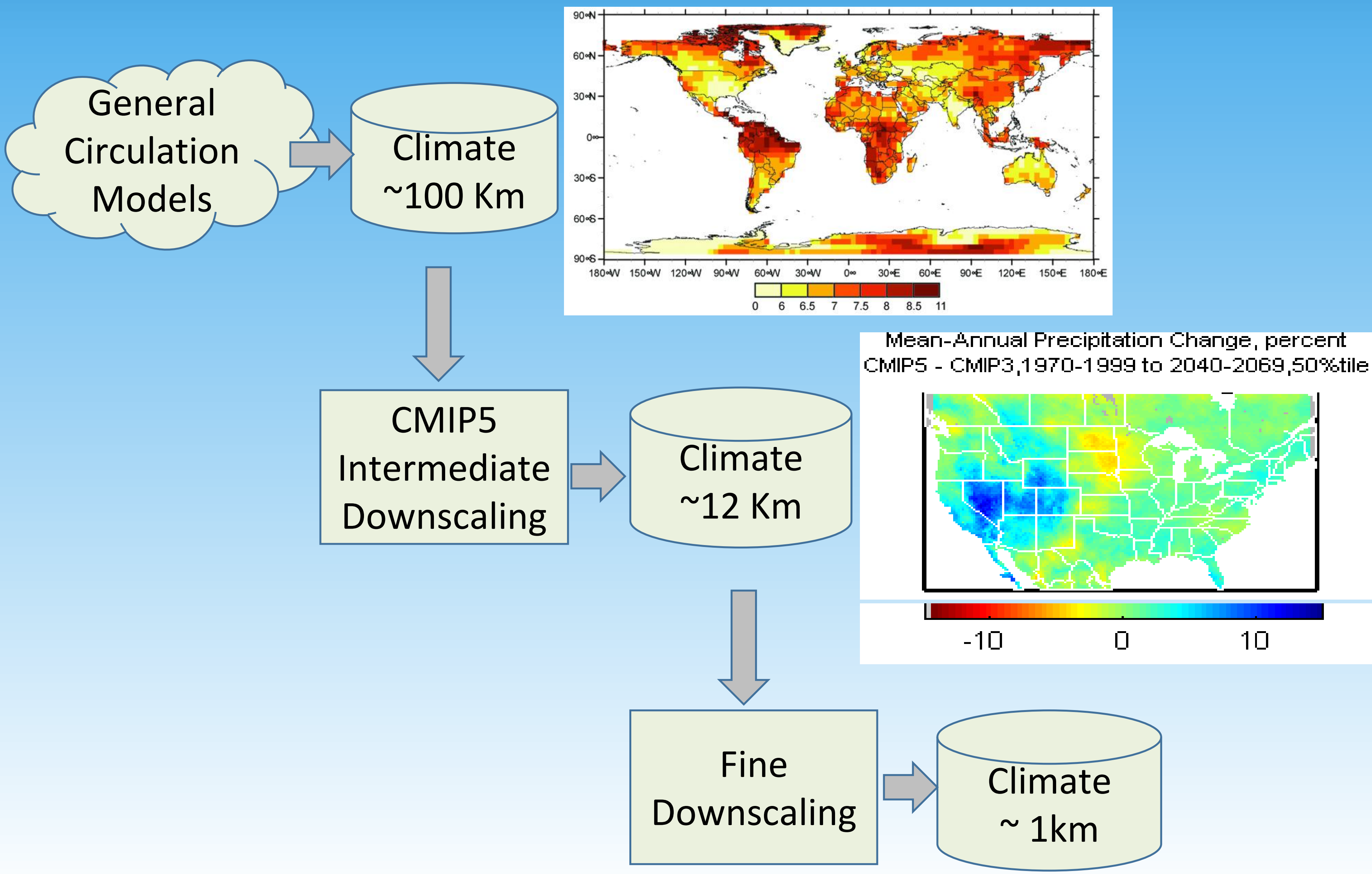




Source: Climate Interactive

IPCC 2014

# <u>Scaling</u> down global climate change scenarios to regional/basin levels: more <u>uncertainty</u>



# Multi-scale policy landscape

EPA (2015) uses SWAT and Bathtub models, along with a spreadsheet analysis, to determine nutrient load reductions. Land use change is assumed constant; Limnotech model used in Missisquoi!

Land use varies across watersheds

EPA (2015)

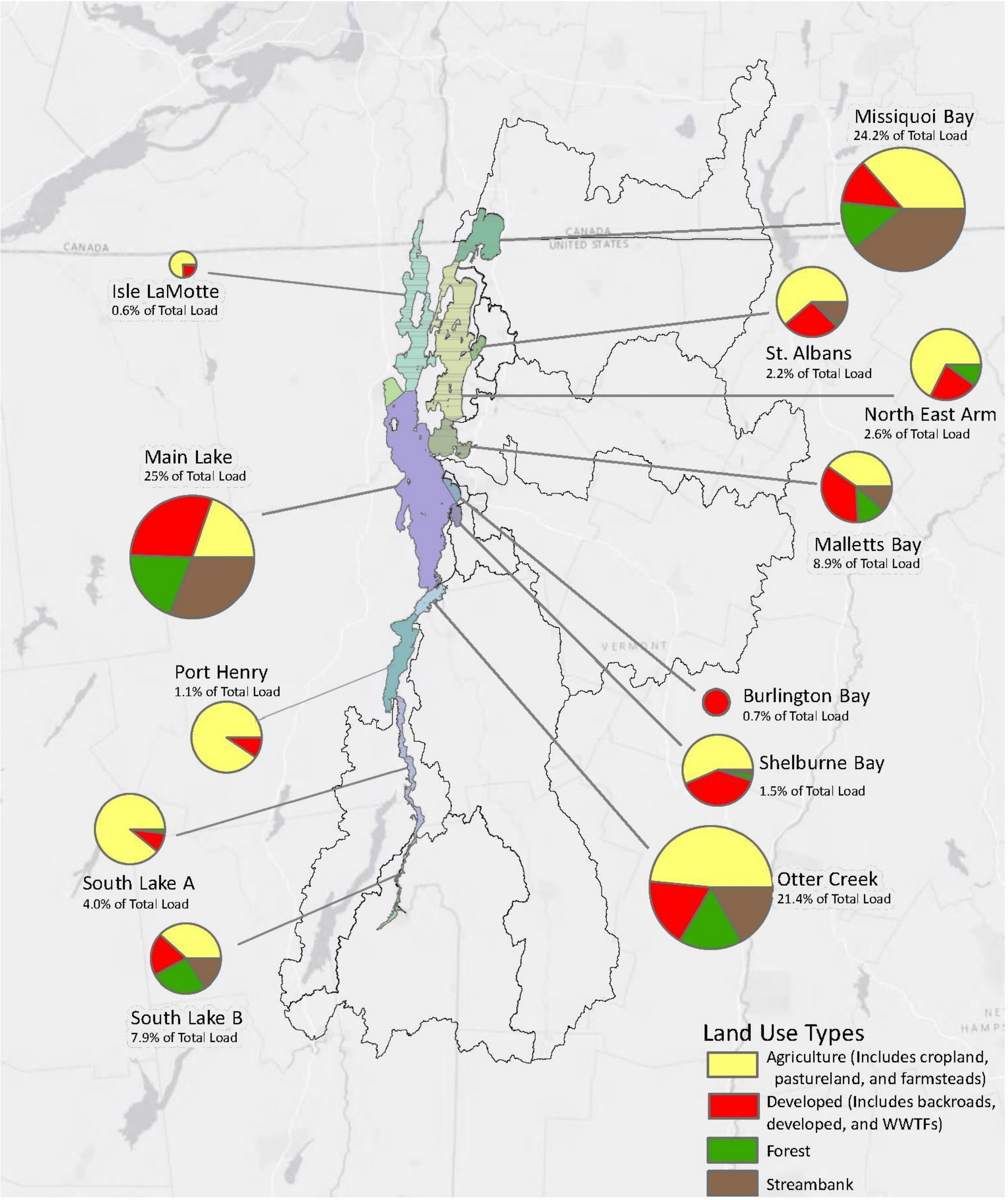


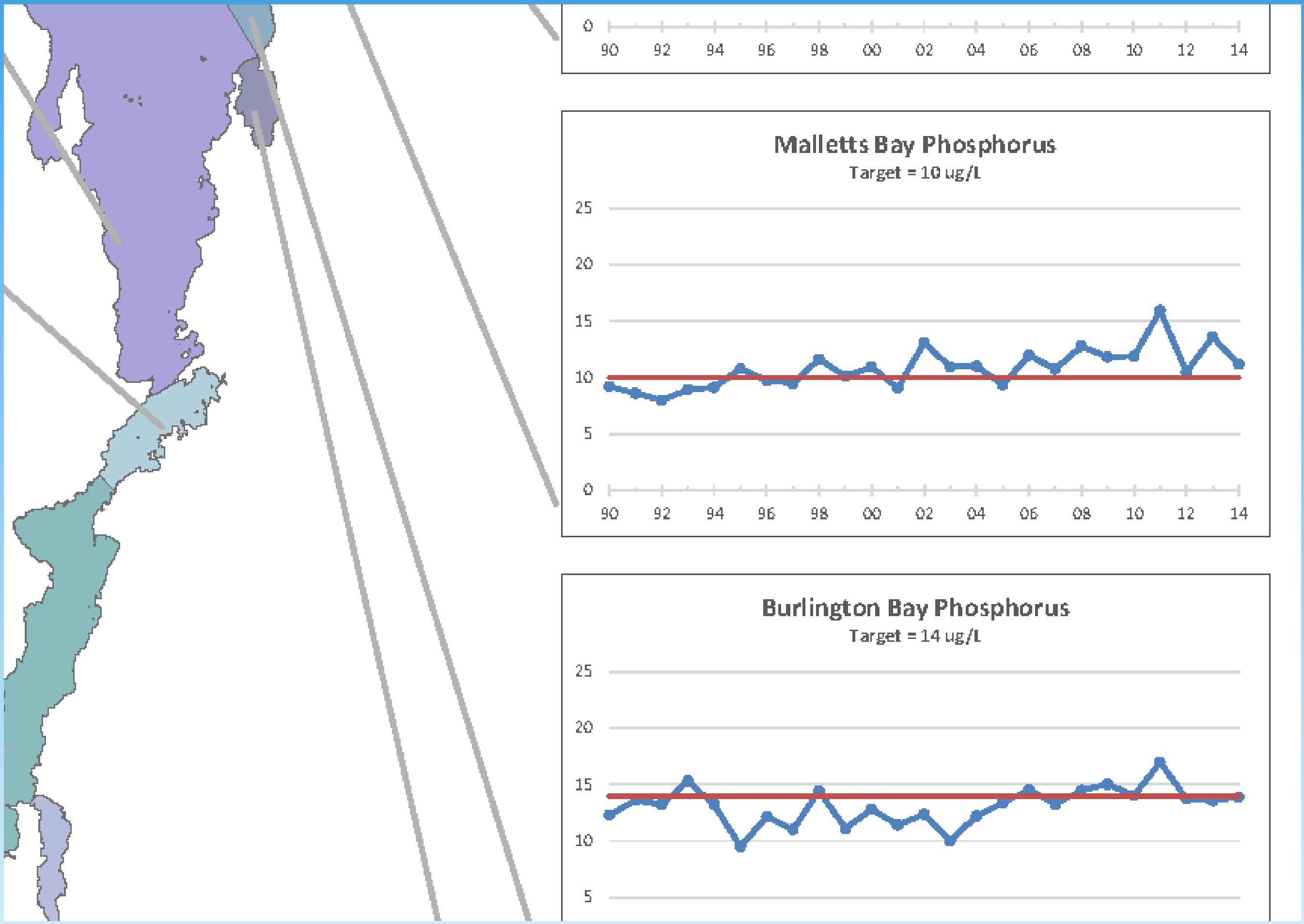

**Figure 4: Vermount sources of phosphorus loading to Lake Champlain segments, by land use; annual average of 2001-2010.**
Data are from TetraTech, 2015c

EPA

Map Tracker ID: 10397.

# Multi-scale policy landscape

**RACC focus on Missisquoi due to severity of the problem, transboundary pollution management setting, & investment of sensing resources**




EPA (2015)

# Multi-scale policy landscape

Table 8. Percent reductions needed to meet TMDL allocations

| Lake Segment | Total Overall | Waste water[1] | CSO | Developed Land[2] | Ag Prod Areas | Forest | Streams | Agriculture |
|---|---|---|---|---|---|---|---|---|
| 01. South Lake B | 43.4% | 0.0% | | 23.7% | 80% | 60.0% | 30.5% | 59.5% |
| 02. South Lake A | 52.7% | 0.0% | | 21.0% | 80% | 5.0% | | 59.5% |
| 03. Port Henry | 15.8% | | | 10.6% | 80% | 5.0% | | 20.0% |
| 04. Otter Creek | 24.7% | 0.0% | | 22.2% | 80% | 5.0% | 40.1% | 46.9% |
| 05. Main Lake | 21.3% | 61.1% | | 23.8% | 80% | 5.0% | 28.9% | 46.9% |
| 06. Shelburne Bay | 12.5% | 64.1% | | 21.3% | 80% | 5.0% | 55.0% | 20.0% |
| 07. Burlington Bay | 30.5% | 66.7% | 10.0% | 38.1% | 0% | 0.0% | | 0.0% |
| 09. Malletts Bay | 17.6% | 0.0% | | 26.3% | 80% | 5.0% | 44.9% | 23.9% |
| 10. Northeast Arm | 13.0% | | | 9.8% | 80% | 5.0% | | 20.0% |
| 11. St. Albans Bay | 24.3% | 59.4% | | 21.8% | 80% | 5.0% | 55.0% | 34.3% |
| 12. Missisquoi Bay | 64.3% | 51.9% | | 30.1% | 80% | 60.0% | 65.3% | 82.8% |
| 13. Isle La Motte | 12.4% | 0.0% | | 12.0% | 80% | 5.0% | | 20.0% |
| **TOTAL** | 33.8% | 42.1% | 10.0% | 24.1% | 80% | 23.4% | 43.4% | 51.5% |

[1] % change from current permitted loads

[2] Includes reductions needed to offset future growth

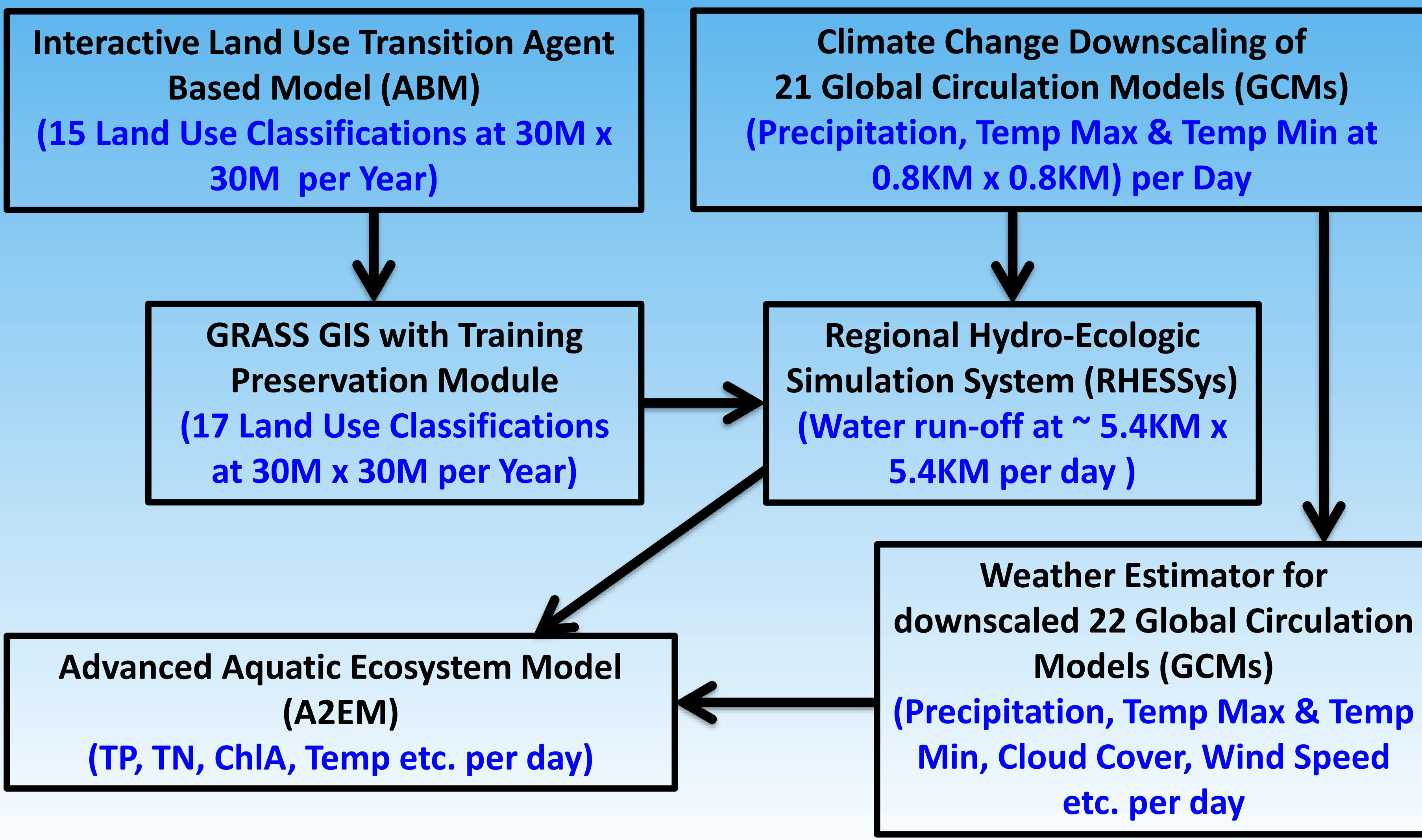
EPA (2015)

# 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**

# V1.0: High Resolution Forecasting of Global Climate Change Impacts on Watersheds and Lakes: Integrating Climate, Land-Use, Hydrological and Limnology Models



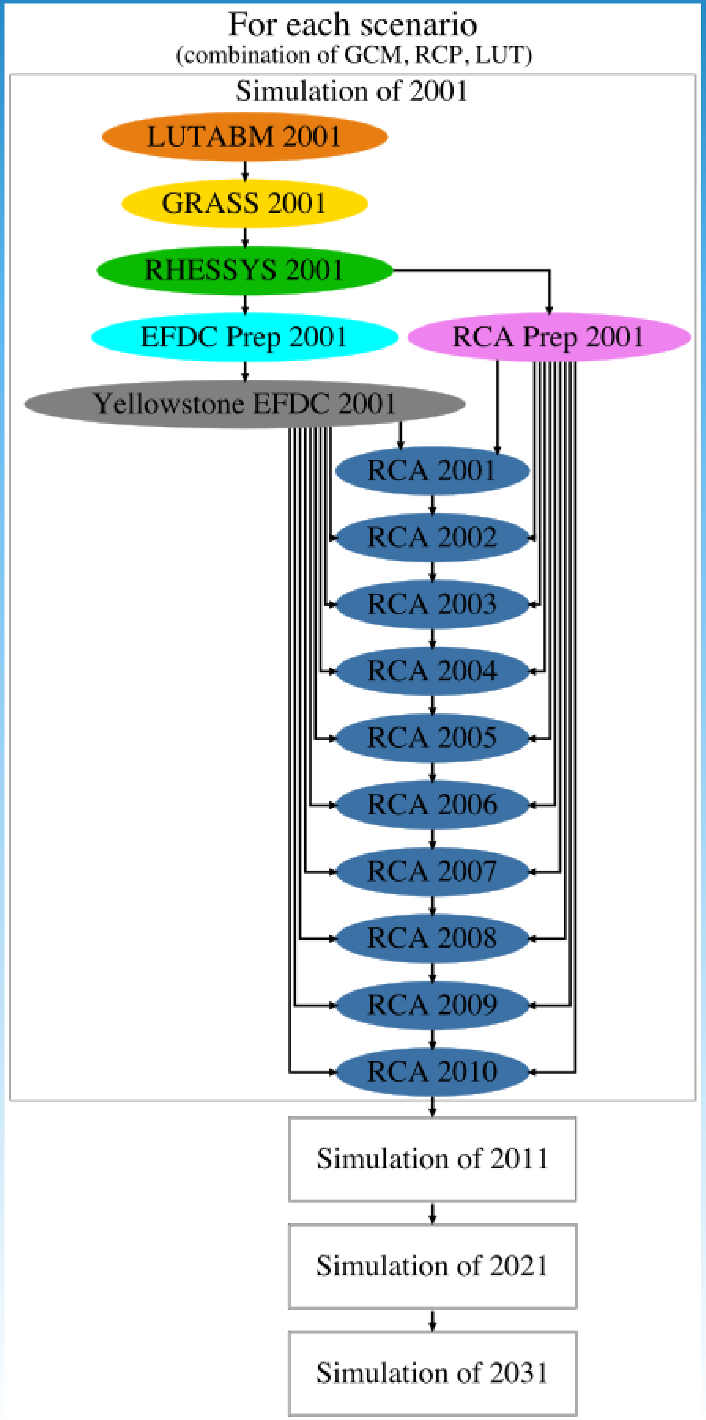
# Cascading IAM development overview

- Cascading IAM
  - Version 1.0 [RACC]
    - V1.0: Feed-forward enabled with 3 RCPs, 4 GCMs and 4 Land Use scenarios for Missisquoi 2000-2040 period [DONE]
    - V1.1: Feed-forward enabled with 3 RCPs, 4 GCMs and 4 refined Land Use scenarios Missisquoi 2000-2100 period [TEST SIMULATIONS IN PROGRESS]
  - Version 2.0 [RACC]
    - V2.0: Feed-forward enabled with 3 RCPs, 4 GCMs and 4 land management scenarios with BMP adoption generated by stakeholders in October 2015 [DEVELOPMENT IN PROGRESS]
    - V2.1: Feedback enabled [DEVELOPMENT IN PROGRESS]
  - Version 3.0 [BREE]

# PEGASUS Workflow Runs on Yellowstone Cluster for High Resolution Forecasting of Global Climate Change Impacts on Fresh Water Lakes

***For each single scenario and each decade:***

- Decadal land use transitions are simulated
- ABM output is converted by programmatic GIS into input for RHESSys
- RHESSys output is processed to inputs for the first bay model
- Data and models are staged to and run from the Yellowstone supercomputer in parallel
- Data are returned from Yellowstone and the second bay model is run in sequence
- The process is repeated each decade



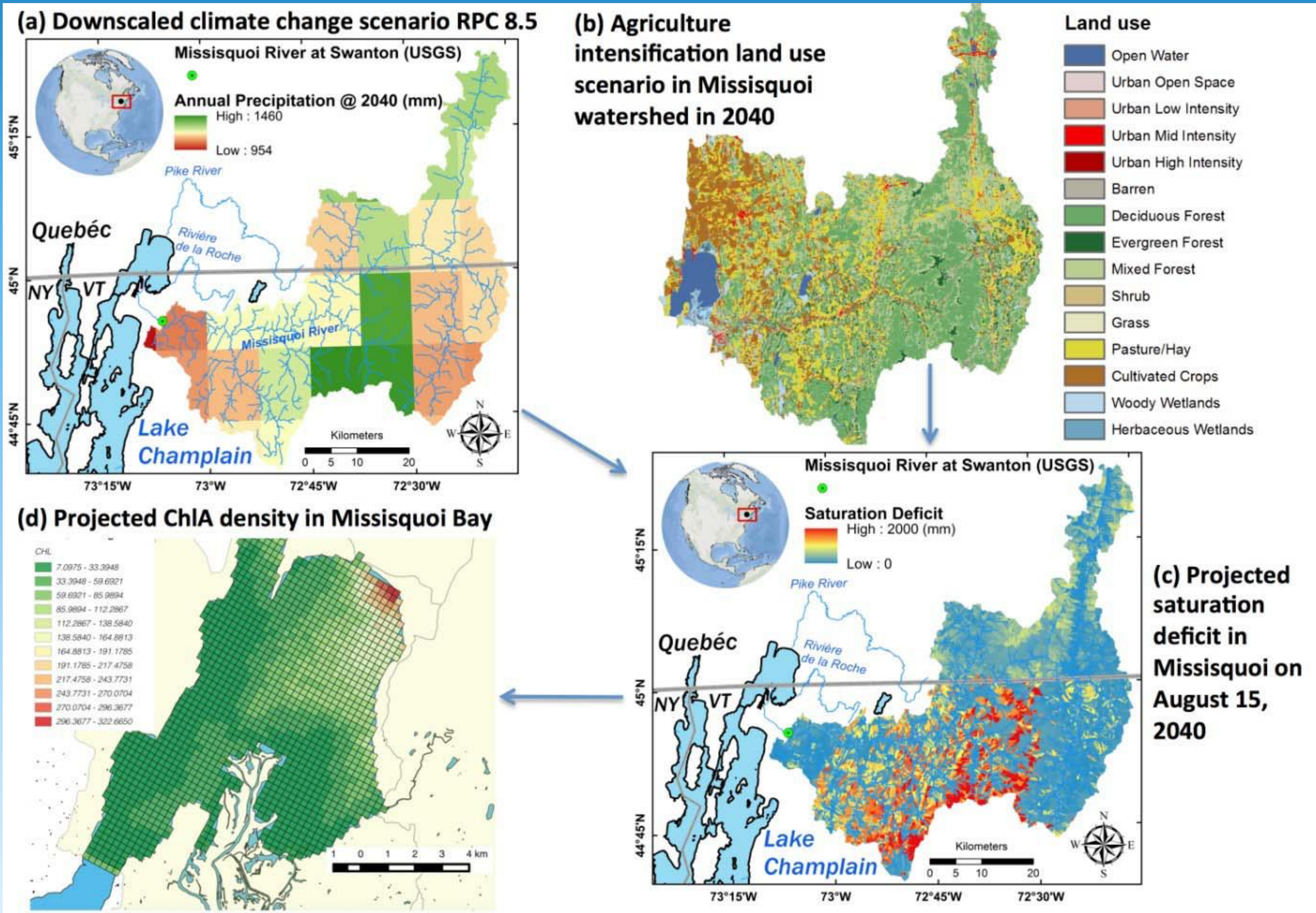


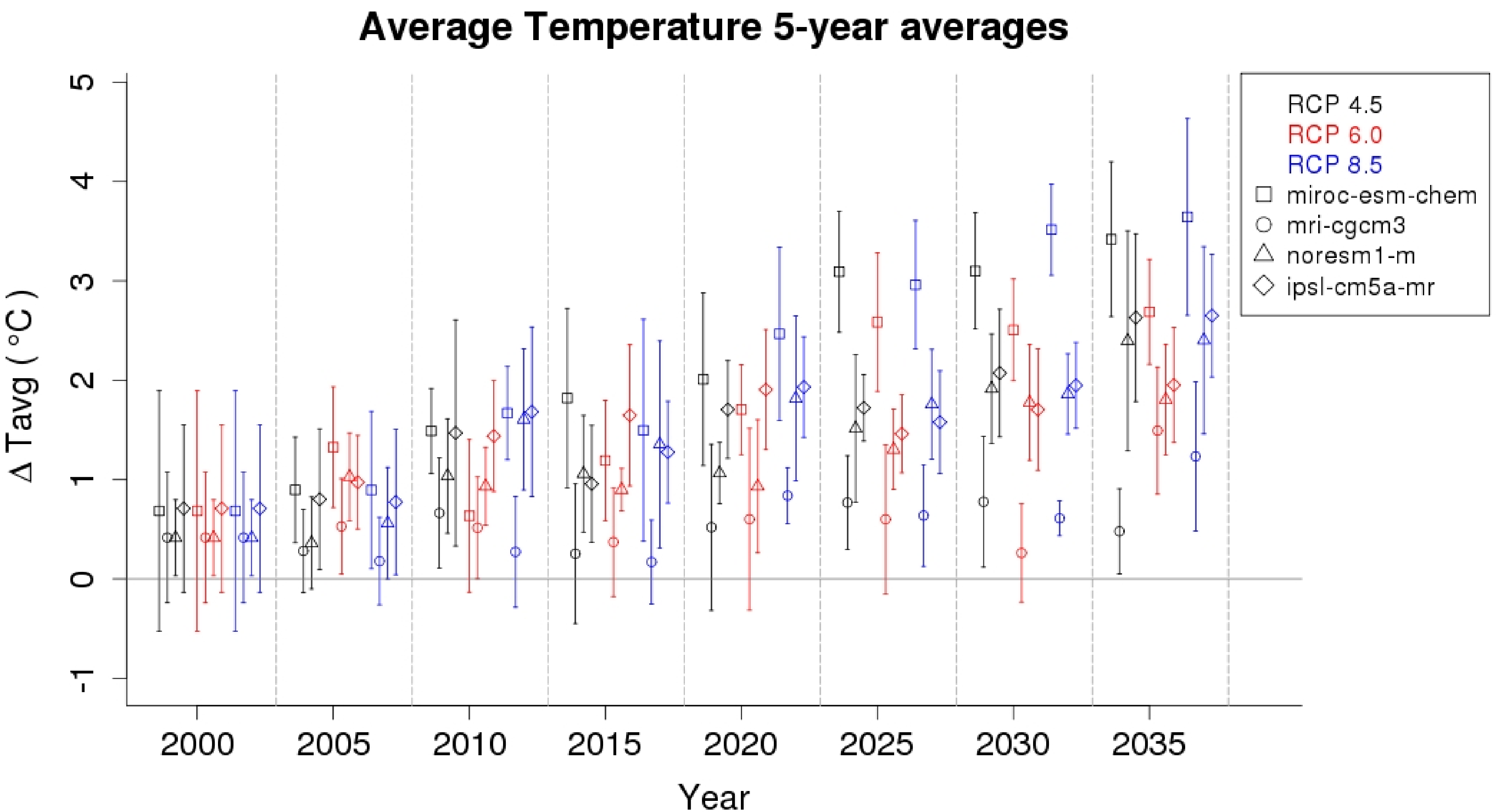

**Figure 8.** Output from cascading current Track-1 IAM that will be replaced by the BREE IAM: Output reveals (a) Projected precipitation by GCM BNU_ESM.1.rcp85 in 2040; (b) Projected Land-Use by Agent Based Model in 2040; (c) Projected hydrological scenario by RHESSys on August 15, 2040; (d) Projected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

# Scenario Settings for Missisquoi for cascading IAM Version 1.0 runs to predict water quality in Missisquoi Bay and response of the watershed hydrology to changing climate and land-use

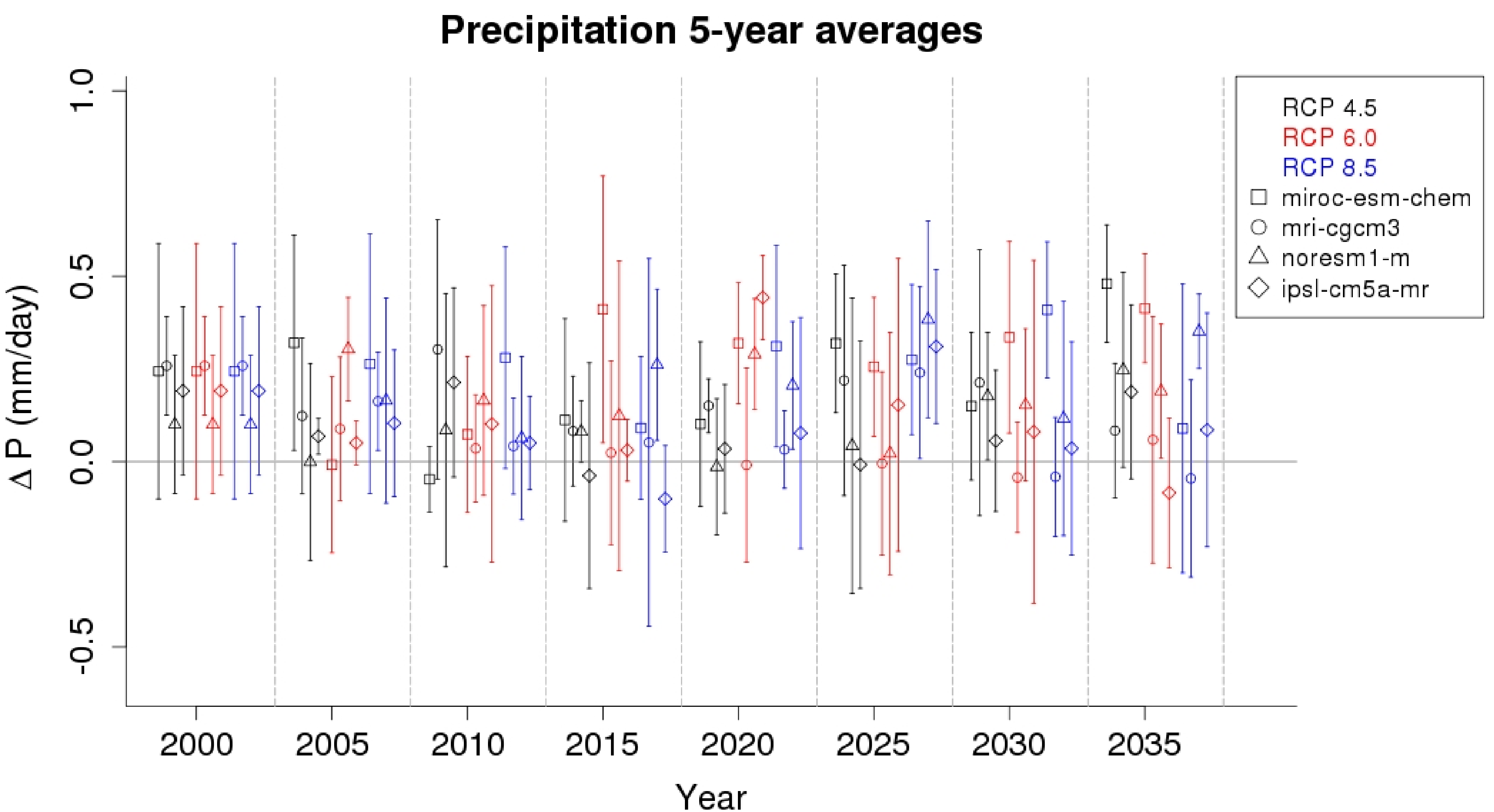
- **THREE Climate Scenarios**: RCP 4.5; RCP 6.0 and RCP 85
  - Four extreme GCMs (Warm: miroc-esm-chem; Cool: mri-cgcm3.1; Wet: noresm1-m.1; Dry: ipsl-cm5a-mr.1) are used for three RCP scenarios.
- **FOUR LULCC ABM Scenarios**: BAU, Pro-forest, Pro-Ag, Urbanization
- Running 2001 through 2041
- We're 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$^{42}$, ….. |

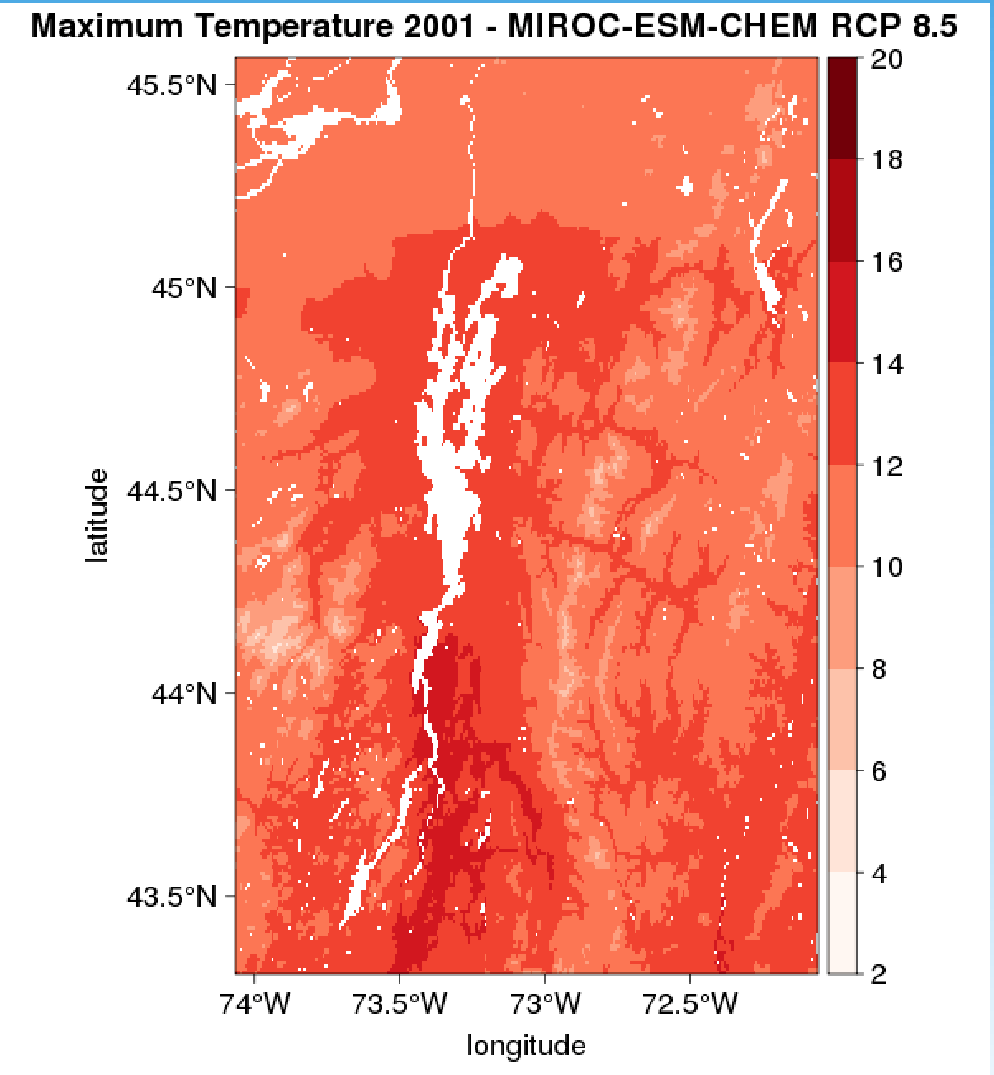
# Large Uncertainty Across Four GCM Projections for Temperature (El Nino effects are not included in these projections)



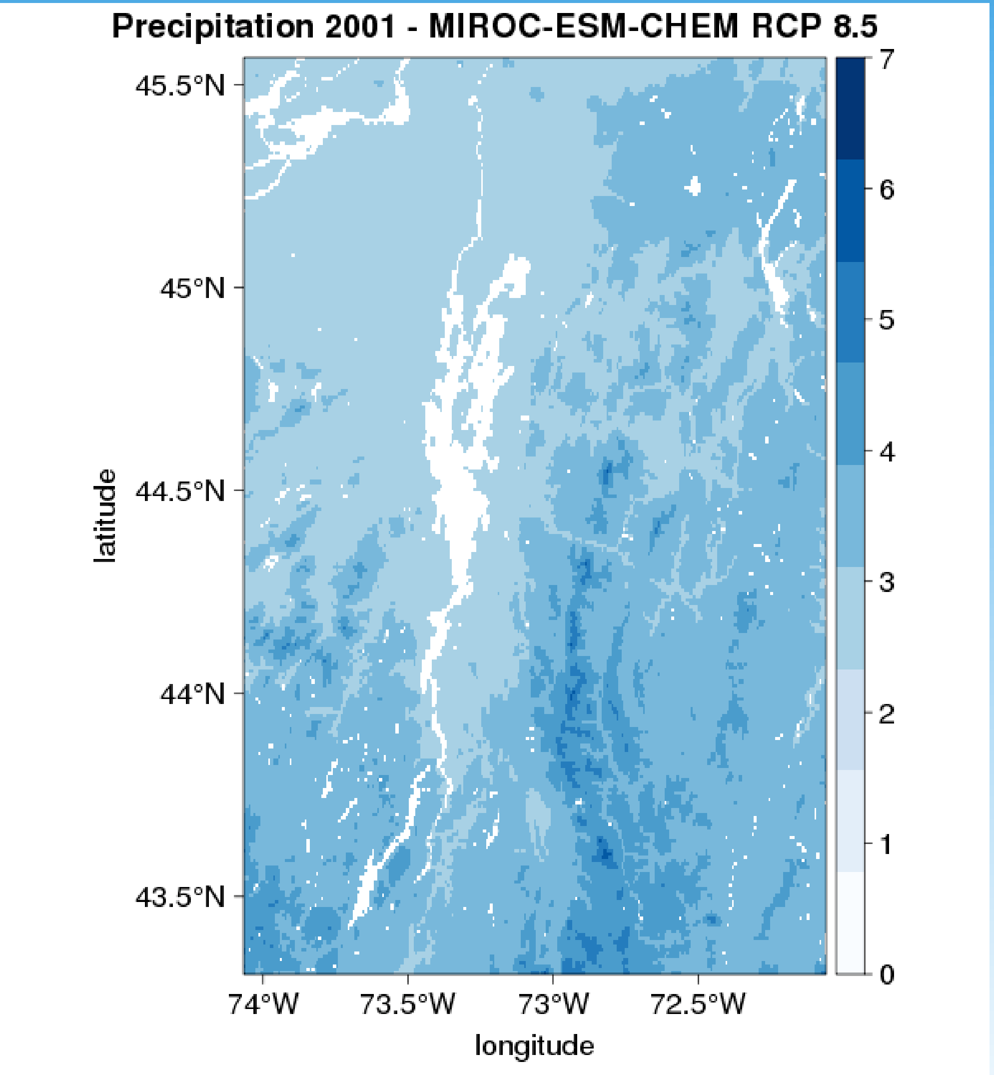
# Large Uncertainty Across Four GCM Projections for Precipitation (Extreme events are not included in such SMOOTHED projections)



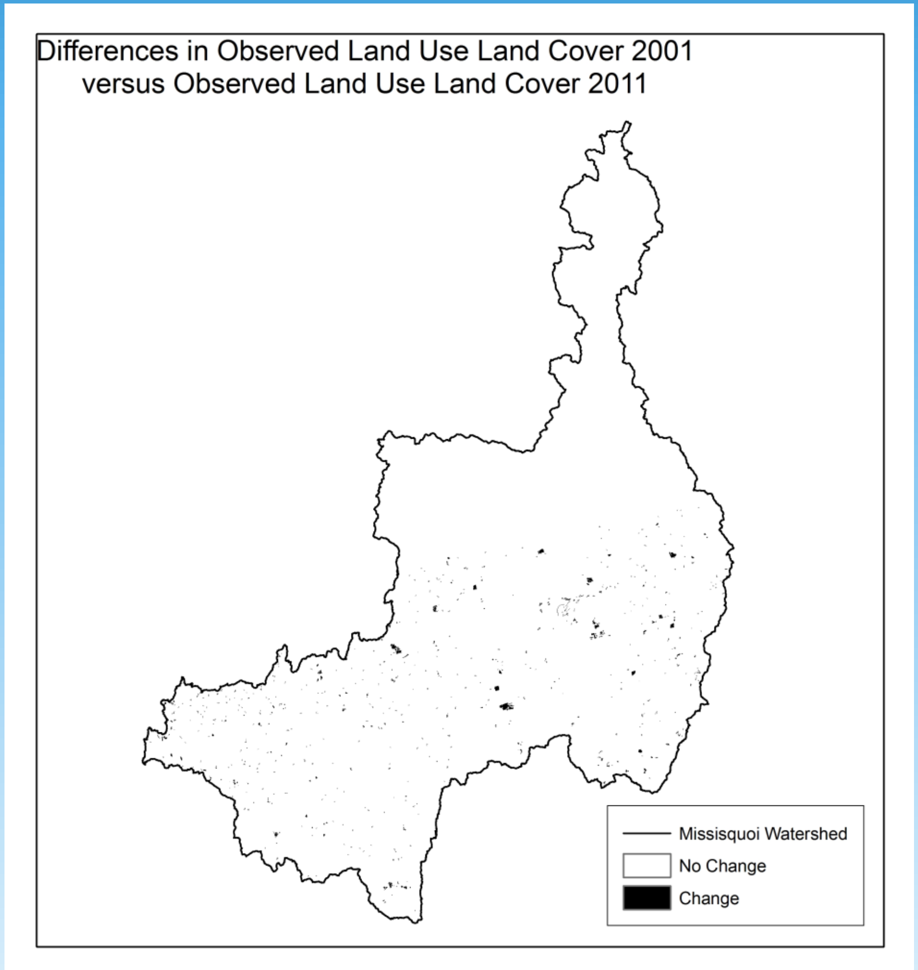
# Cascading IAM can generate high resolution temperature projections for alternate climate scenarios and GCMs for LCB

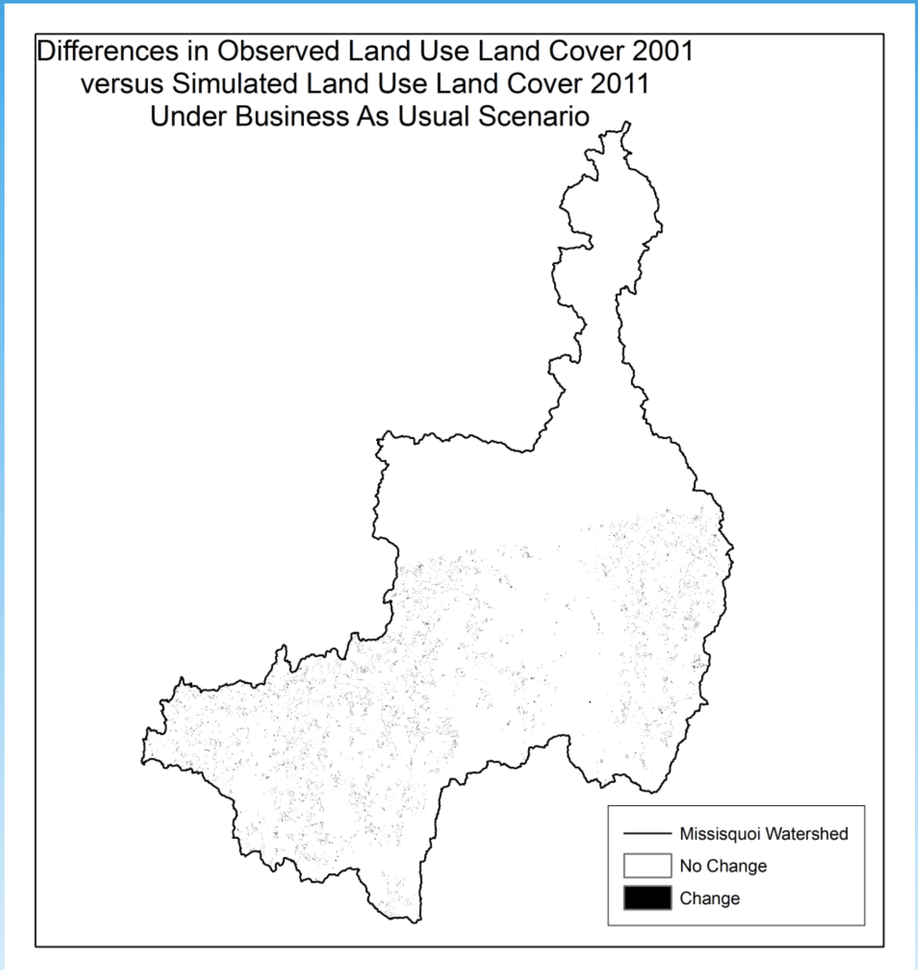


# Cascading IAM can generate high resolution precipitation projections for alternate climate scenarios and GCMs for LCB



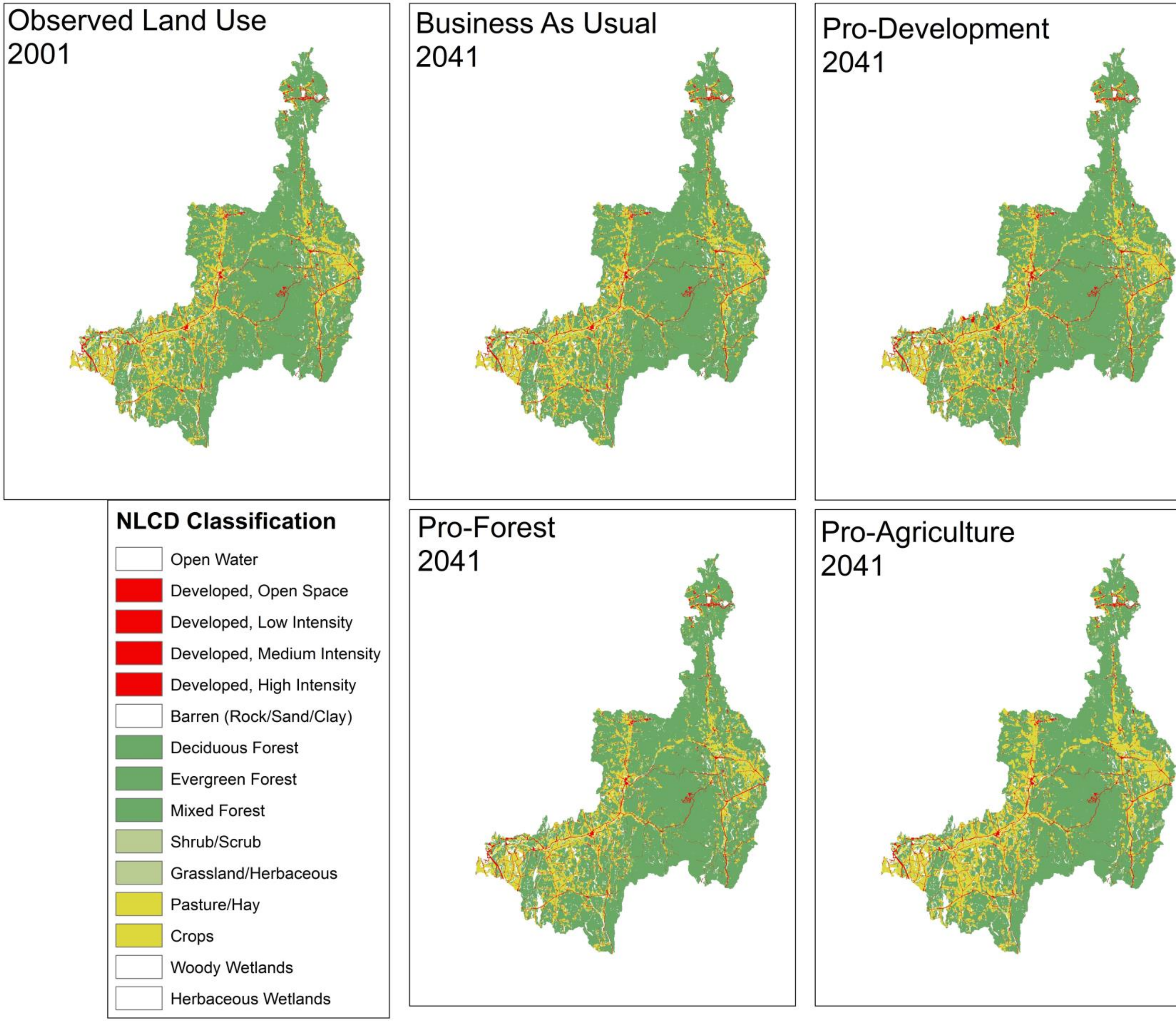
# LULCC Agent Based Model (ABM) calibration for Version 1.0




Current ABM is based on very simple heuristics and accurately predicts only 42.5% of the transitions among 15 land use classifications

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



# Comparison of the simulated Land use fractions in year 2041 given each of the four scenarios versus the observed land-use fractions in year 2001

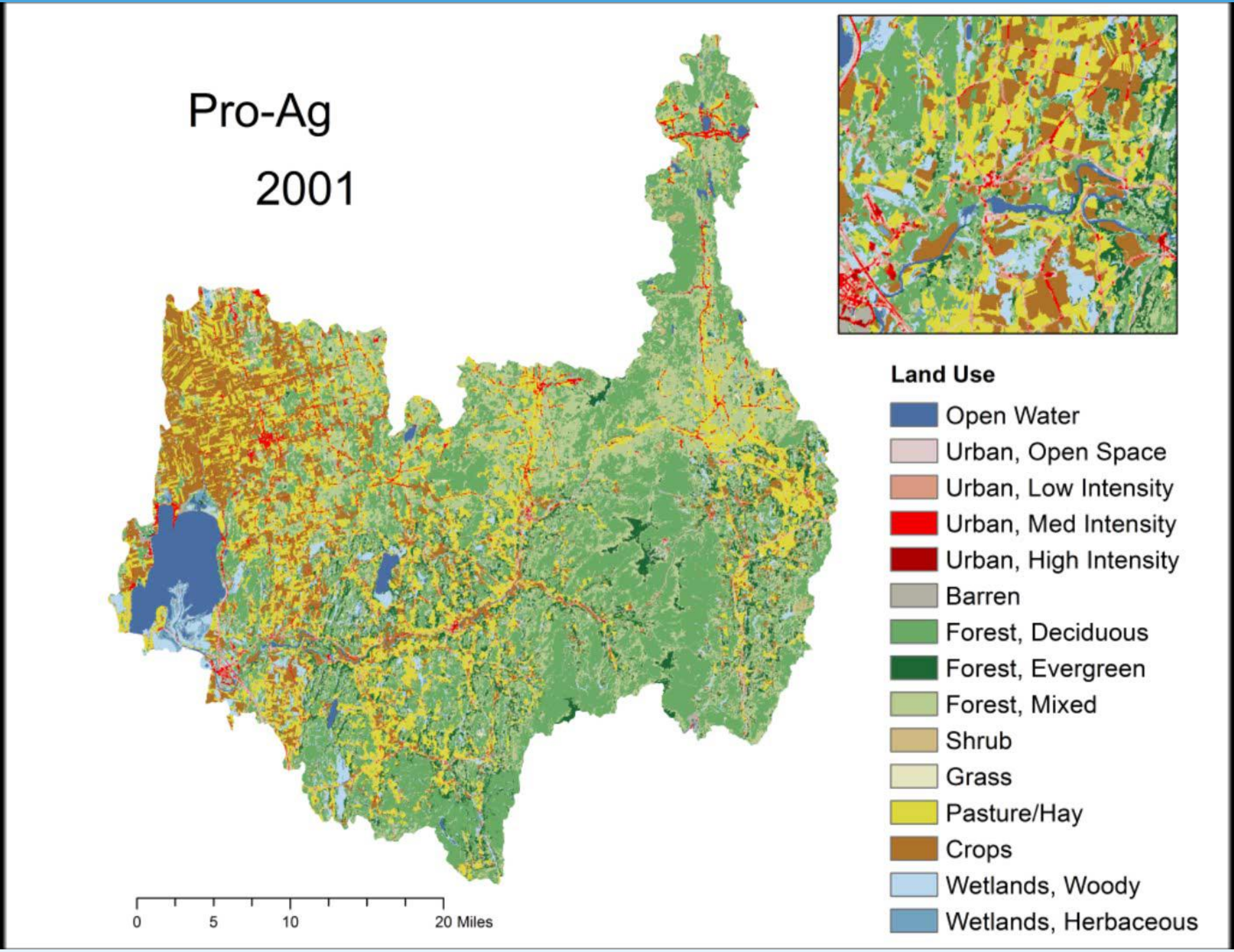
| | Land Use Fractions (%) | | | | |
|---|---|---|---|---|---|
| | Observed Land use In 2001 | Simulated Land Use In 2041 Given LULCC Scenario: | | | |
| Land Use | NLCD 2001 | Business As Usual | Pro-Development | Pro-Forest | Pro-Agriculture |
| Agriculture | 18.73 | 18.32 | 17.81 | 17.22 | 23.15 |
| Forest | 70.85 | 71.15 | 71.26 | 71.56 | 66.52 |
| Urban | 4.16 | 4.23 | 4.54 | 4.16 | 4.16 |

Note: Not much difference in LULCC over the next 25 years under the 4 different scenarios

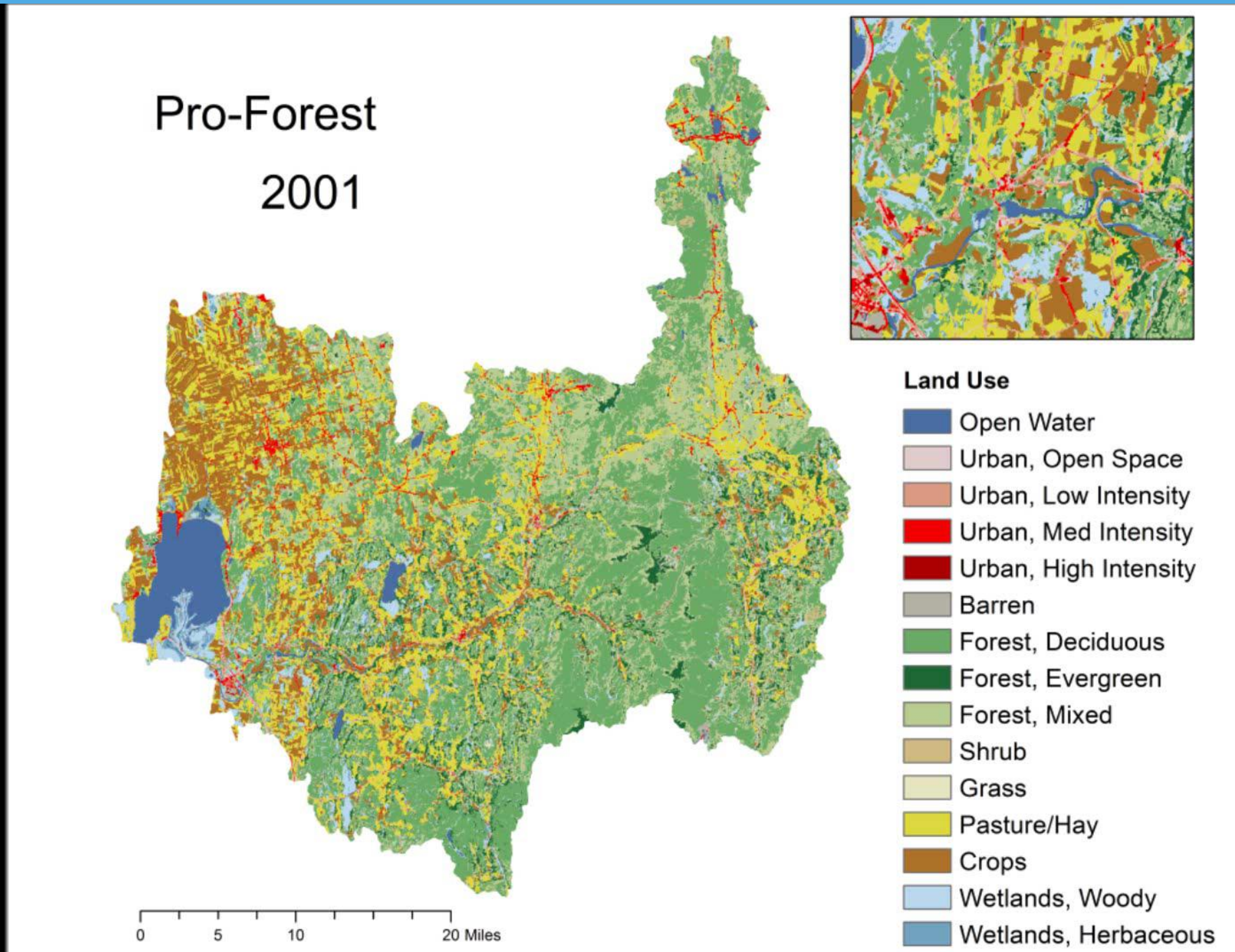
Simple model!

Historically, LULCC doesn't happen faster either!

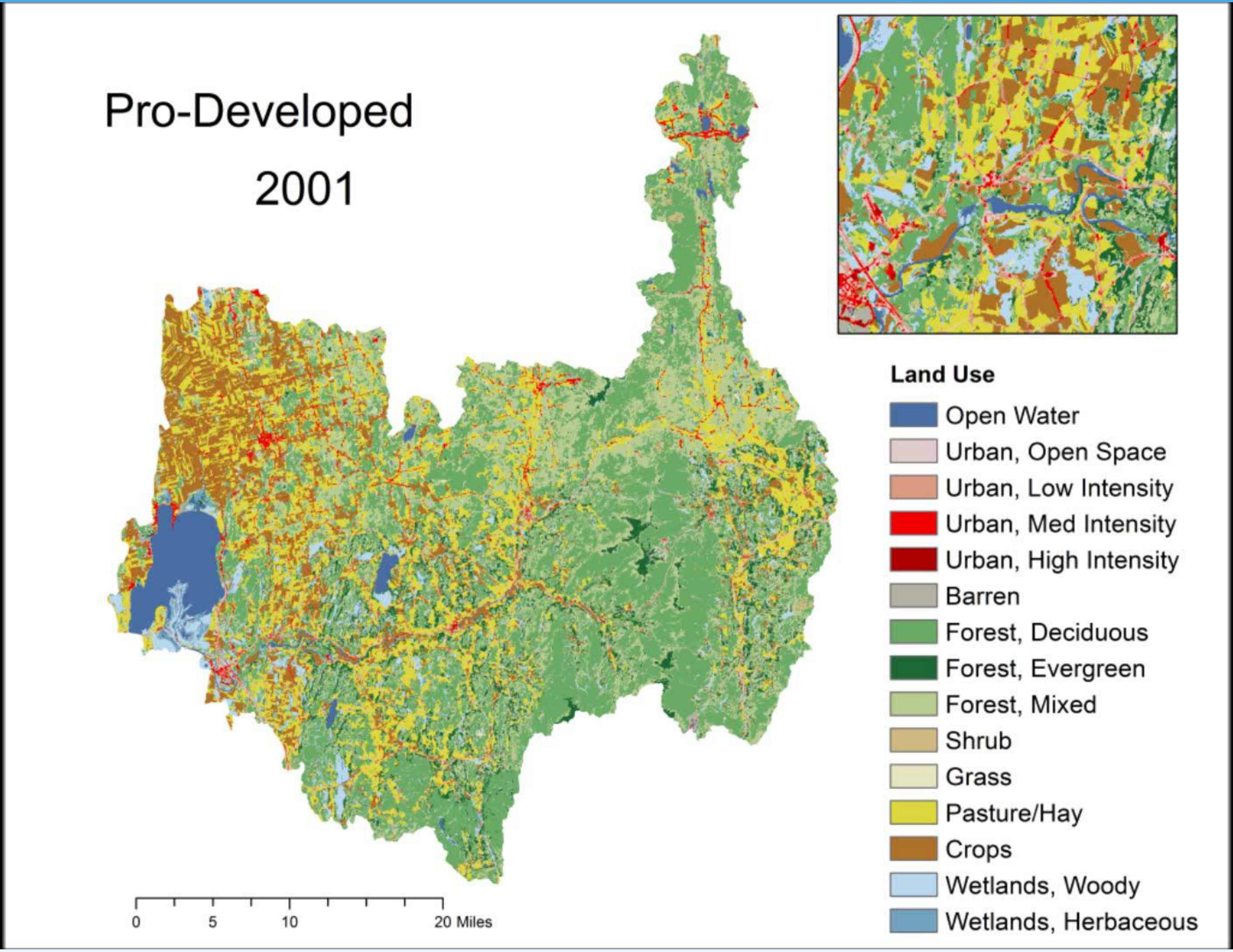
# Agriculturally dominant landscape scenario



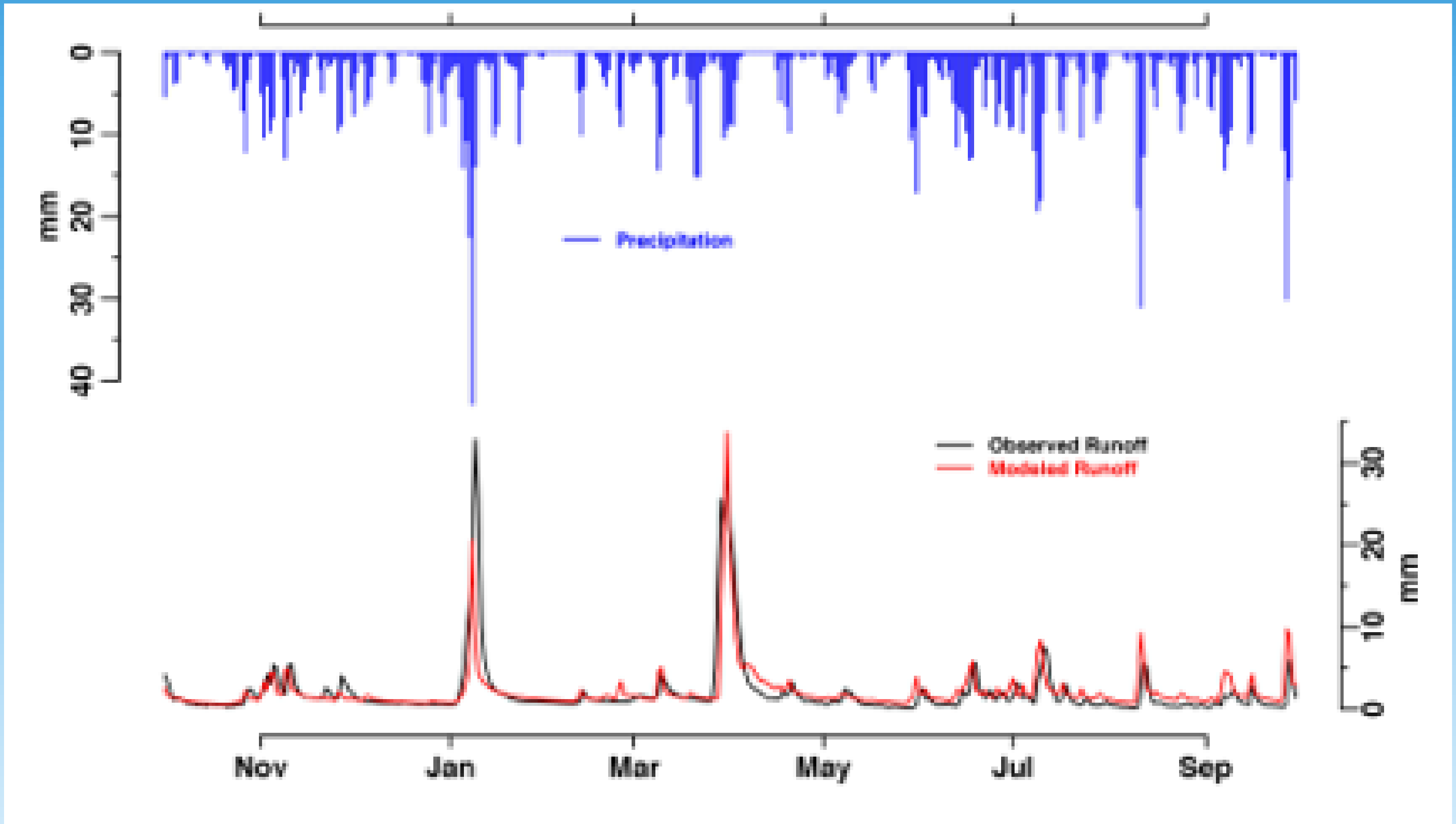
# Forest dominated landscape scenario



# Urbanized landscape scenario

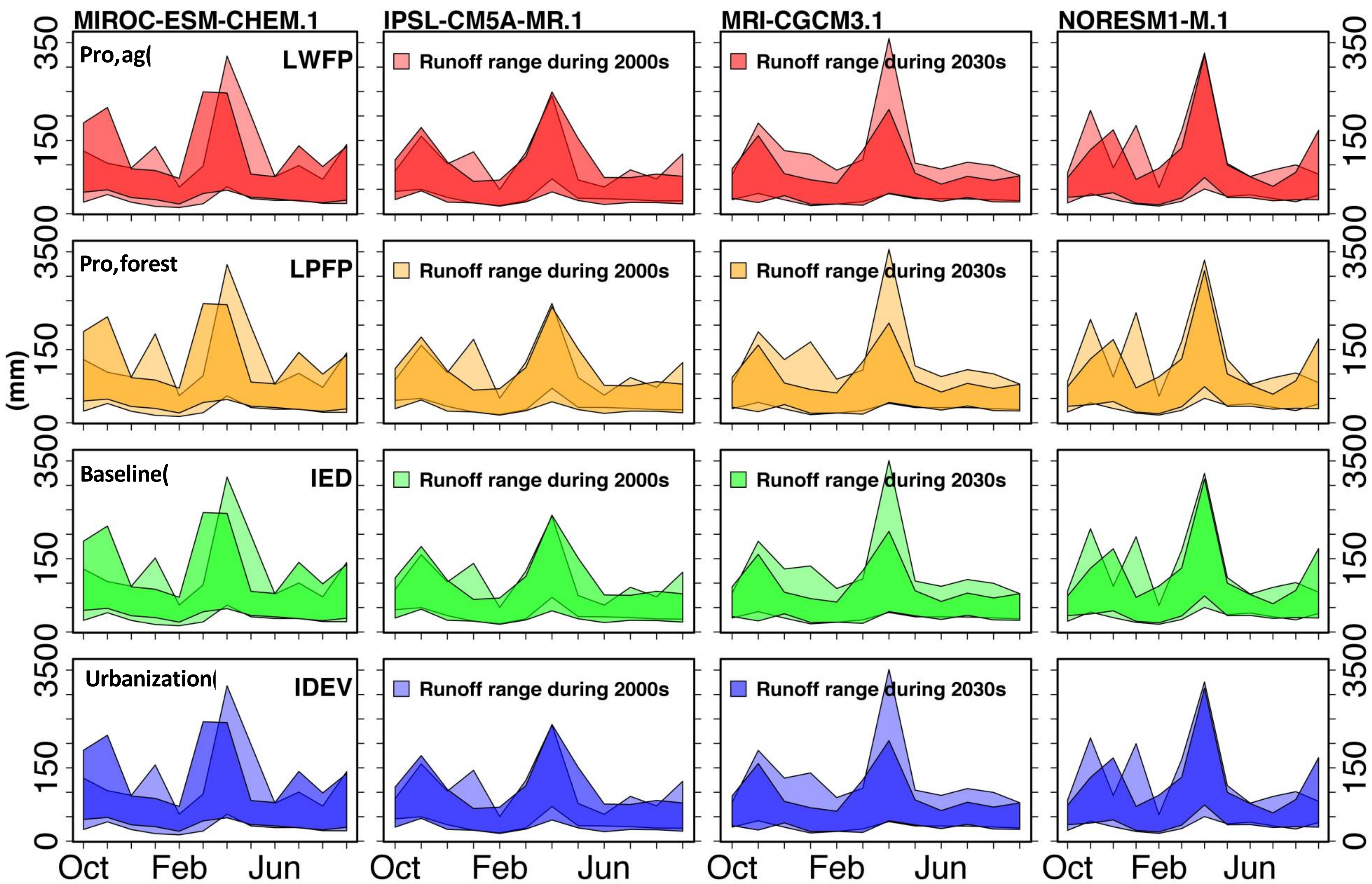


# RHESSys Calibration

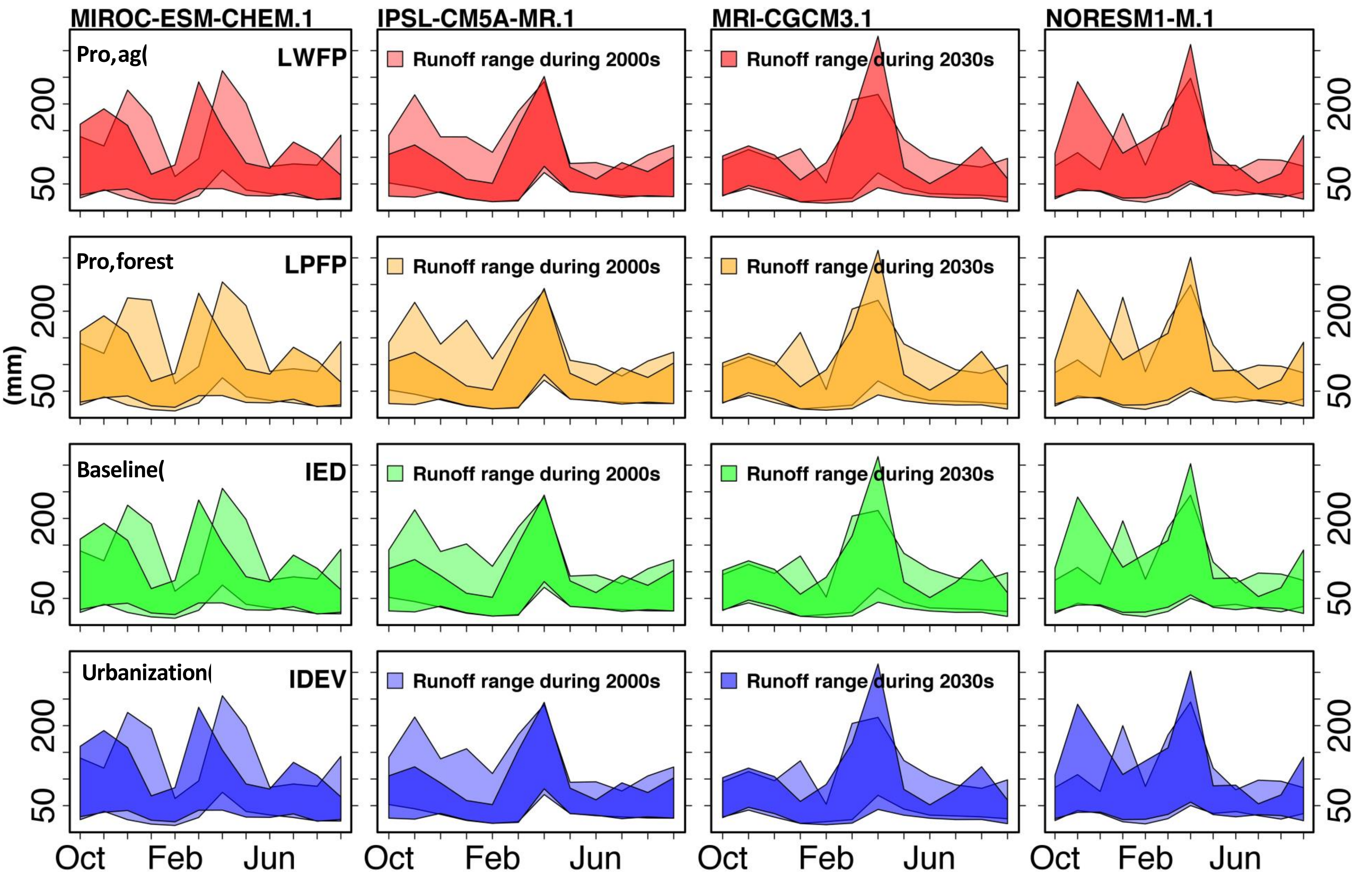


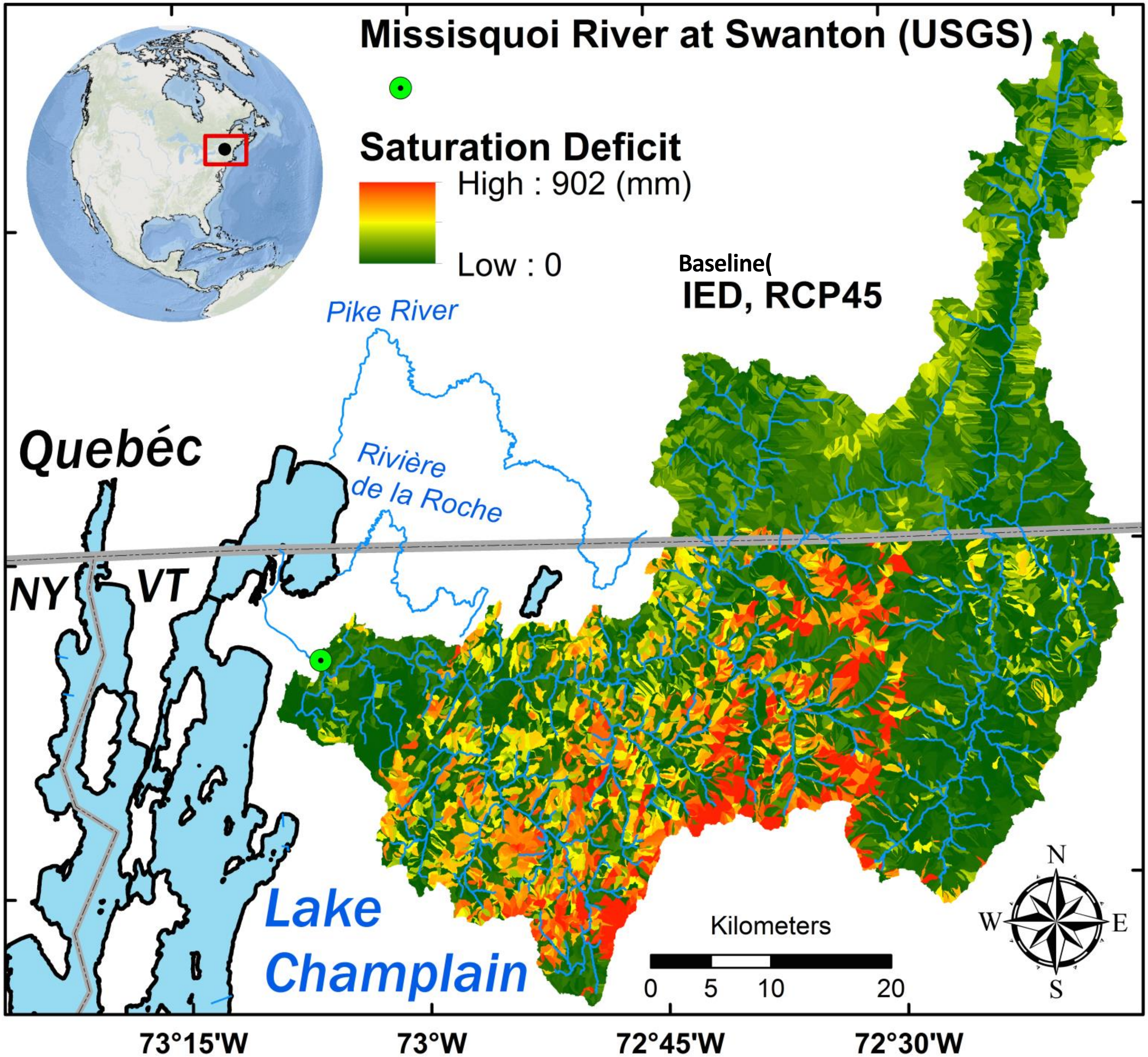

**Daily simulated (red line) and observed (black line) runoff during the 1998 water year (Oct–Sep) for the Missisquoi River watershed at the USGS streamflow gauge # 04294000. Blue lines on the top give daily precipitation values aggregated over the Missisquoi watershed during the 1998 water year.**

# RHESSys Projections for 4 LULCC x 4 GCM scenarios for RCP 6.0

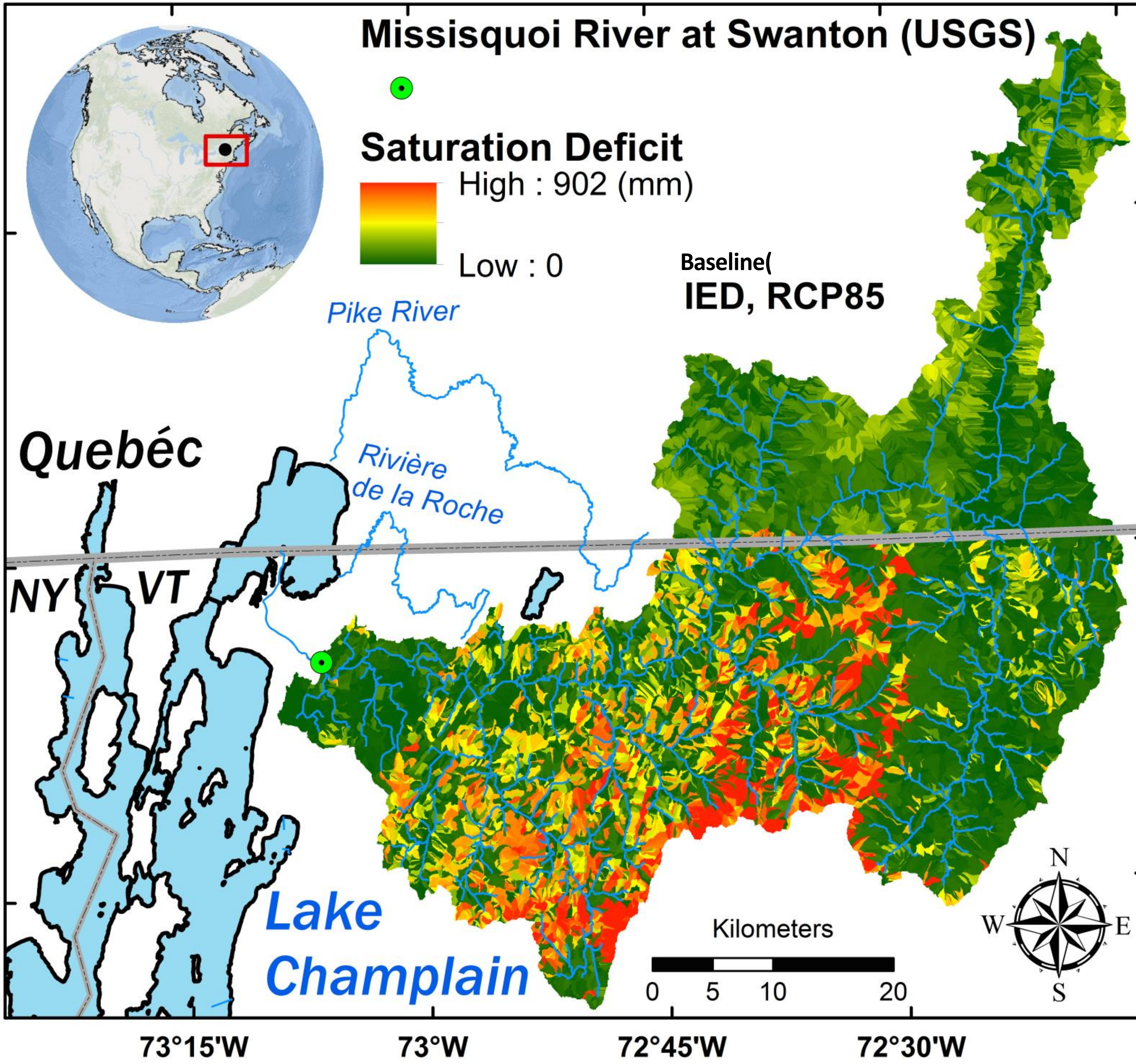


# RHESSys Projections for 4 LULCC x 4 GCM scenarios for RCP 8.5





Missisquoi River at Swanton (USGS)
Saturation Deficit
High : 902 (mm)
Low : 0
Baseline(
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
S
W
E



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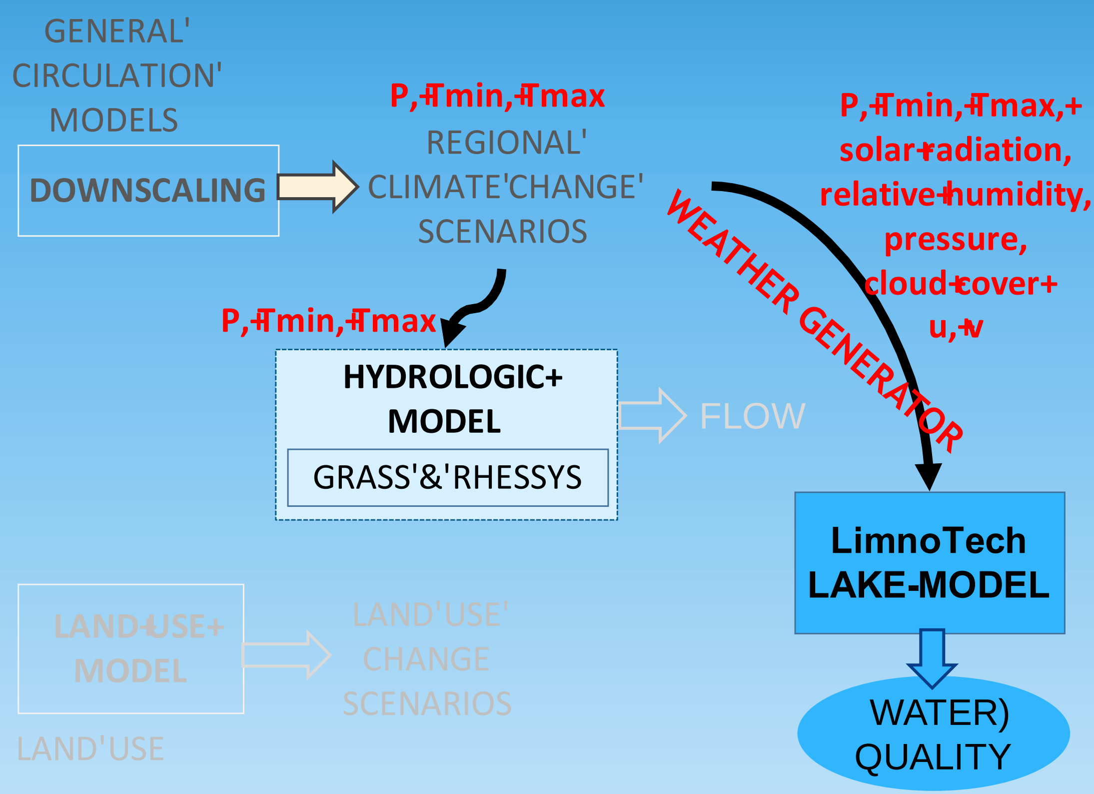
Quebéc
NY
VT
Lake Champlain
Kilometers
0 5 10 20
N
S
W
E
45°15'N
45°N
44°45'N
73°15'W
73°W
72°45'W
72°30'W

# 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

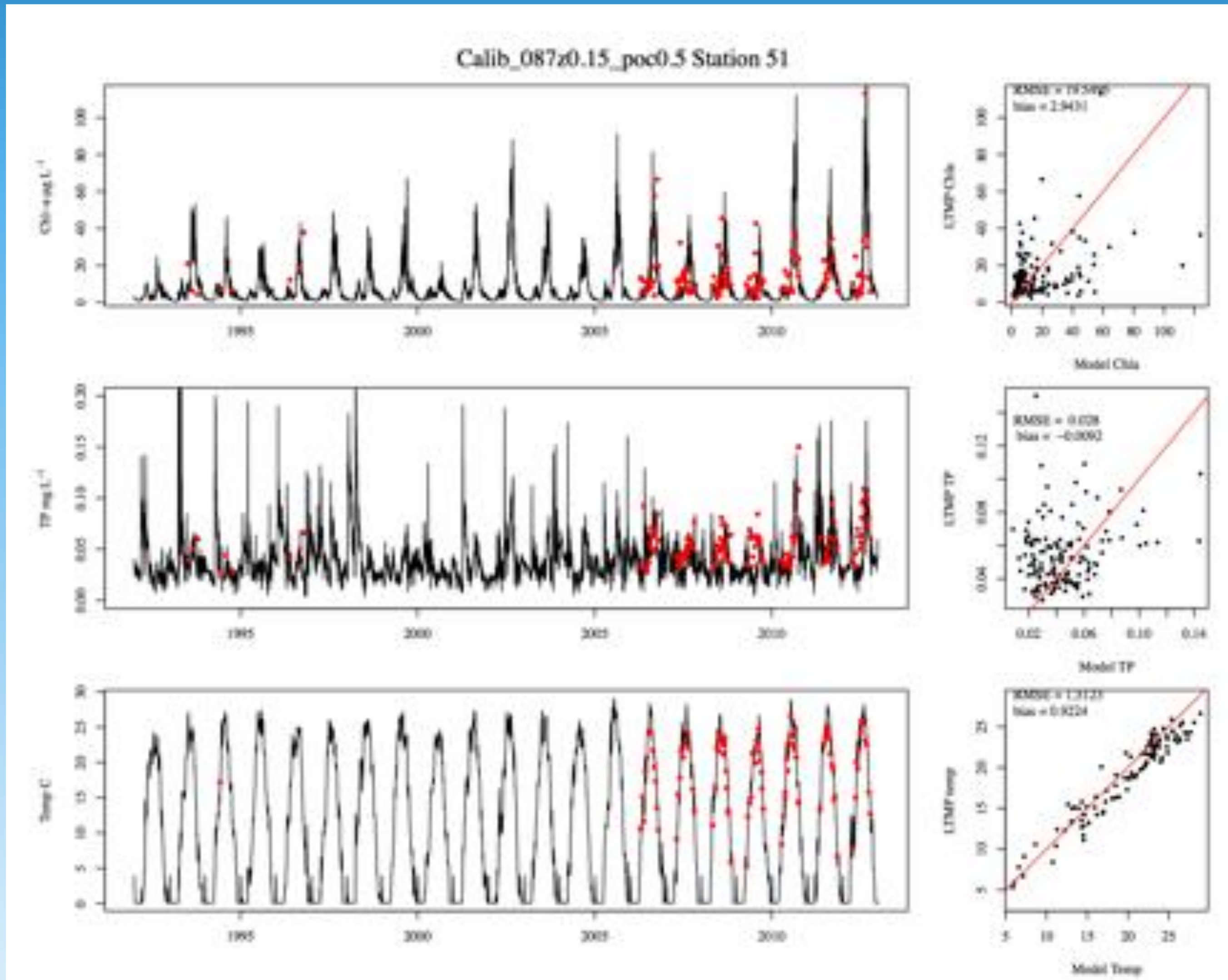
Daily, 1979 - 2014

**North American Regional Reanalysis (NARR)**

32 km grid resolution, daily from 1979 – 2014

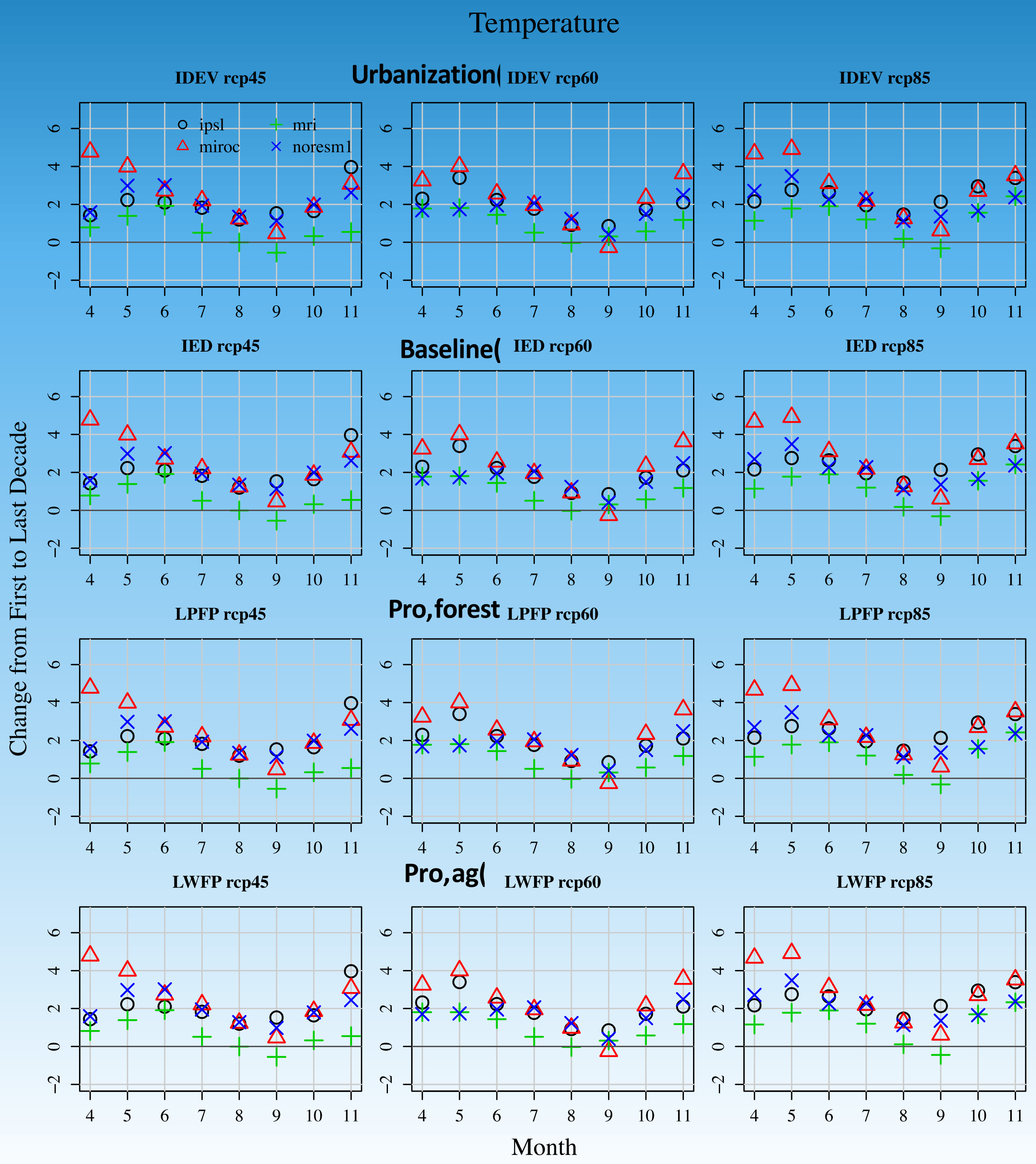
http://www.esrl.noaa.gov/psd/data/gridded/data.narr.html

# Lake model calibration

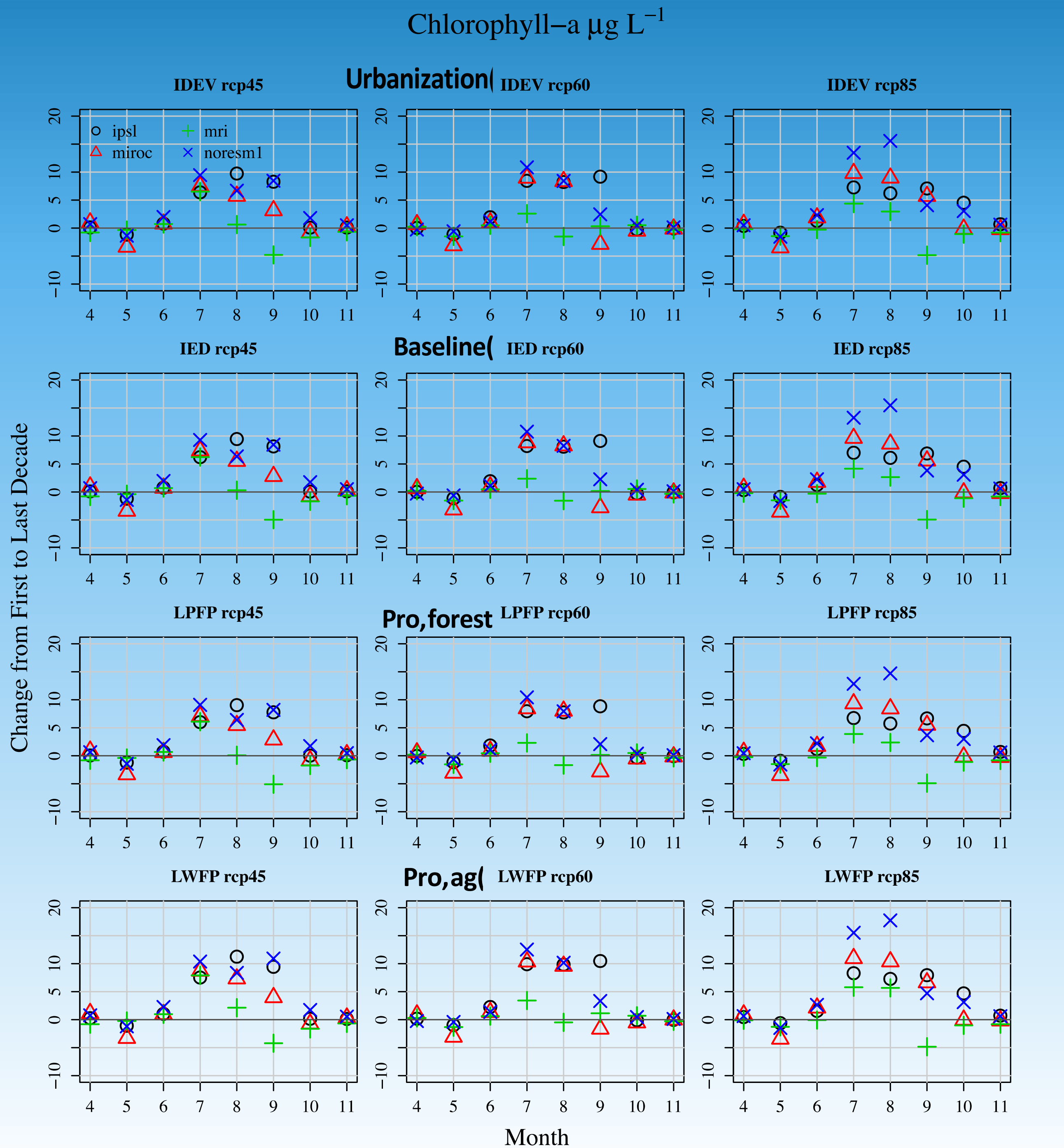



Modeled results (black lines) versus long-term monitoring observations for chlorophyll-a (top), total phosphorus (middle), and water temperature (bottom) at LTMP station 51. On right, scatterplots of modeled v. observed variables matched by date, showing root mean squared error and mean bias. Red line is 1:1.

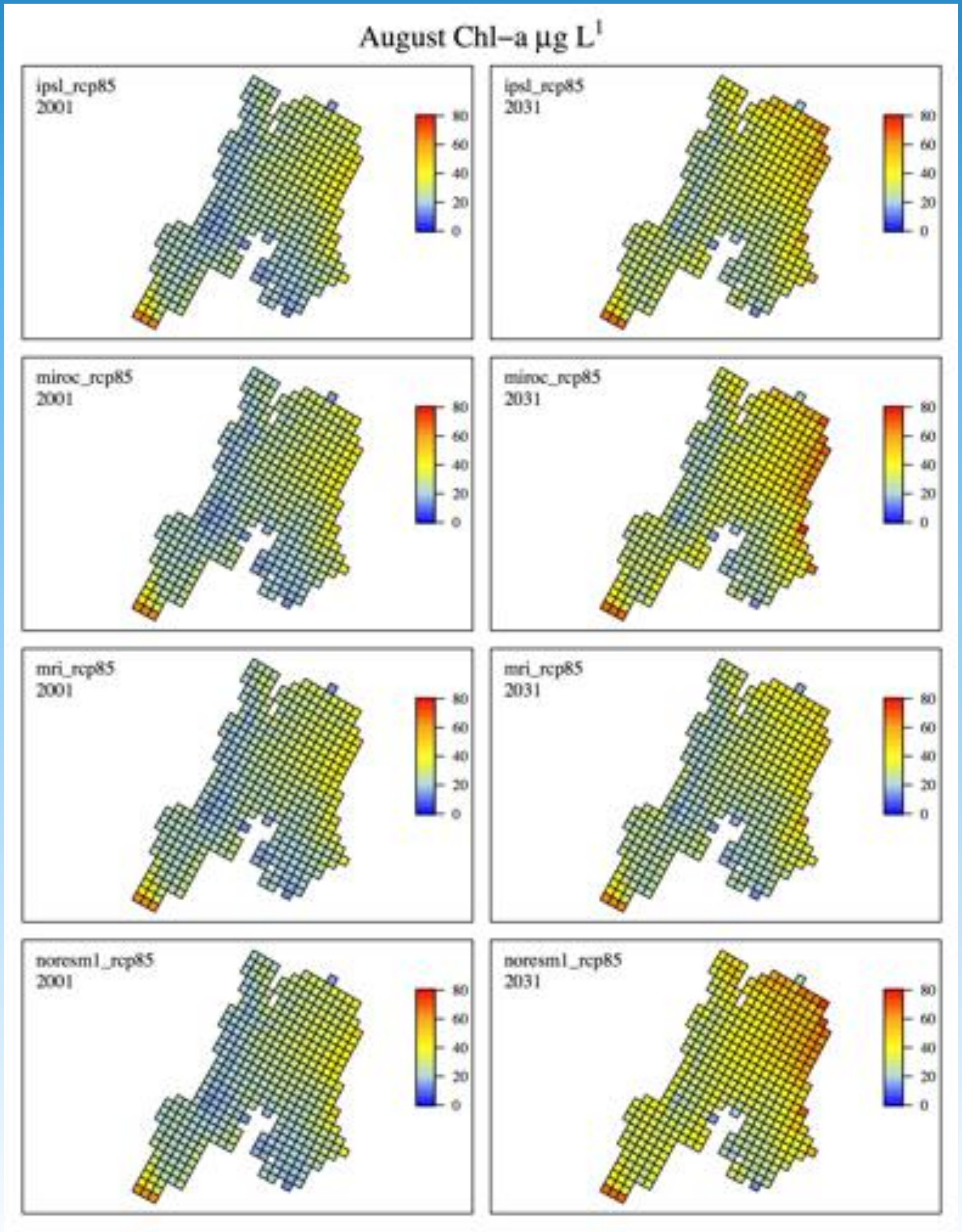
**Projected changes in mean monthly lake temperature (˚C) from the first (2001-2010) to the last (2031-2040) decade of the simulation period. ΔTemperature is shown by month for each LULCC scenario (rows), RCP (columns), and GCM (symbols).**



**Projected changes in ChlA density (μg L[-1]) during the growing season between first (2001-2010) and last (2031-2040) decades of simulation at long term monitoring station 51. ΔChlA is shown by month for each LULCC scenario (rows), RCP (columns), and GCM (symbols)**



**Maps of Missisquoi Bay showing ChlA density (µg $L^{-1}$) averaged for the month of August; comparing first decade (2001-2010) with last decade (2031-2040) projections for four GCMs under Baseline land-use scenario**



# Policy implications from IAM Version 1.0

- Using a large swath of GCMs, set at watershed scale and integrating multiple scale changes in a computational modeling framework, we clearly demonstrate that the usage of one GCM or limited number of land-use change scenarios may misrepresent the embedded uncertainty that drives regime shifts in SESs

- In the most recent TMDL for Missisquoi, for example, EPA (2015: 26) only used one GCM and one RCP scenario (scenario A2 from IPCC's fourth assessment report) to erroneously conclude that "any increases in the phosphorus loads to the lake due to the climate change are likely to be modest (i.e. 15%)."

- We demonstrate that an ensemble of GCM and RCP scenarios is needed for policy design and implementation processes.

# IAM Version 1.1

- V1.1: Feed-forward enabled with 3 RCPs, 4 GCMs and 4 refined Land Use scenarios Missisquoi 2000-2100 period [TEST SIMULATIONS IN PROGRESS]

Foresters'treated'as'farmers:'

| Land'Use' Type' | Land'Use'Fractions'(%)' | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Observed' Land'Use' | Simulated'Land'Use'Given'LULCC'Scenario:' | | | | | | | |
| | NLCD'' | Business'As'Usual' | | ProEDevelopment' | | ProEForest' | | ProEAgriculture' | |
| | 2001' | 2041' | 2101' | 2041' | 2101' | 2041' | 2101' | 2041' | 2101' |
| Agriculture' | 18.73' | 17.70' | 17.69' | 18.82' | 16.60' | 12.90' | 12.85' | 52.80' | 60.67' |
| Forest' | 70.85' | 71.51' | 71.51' | 67.17' | 67.13' | 77.04' | 77.17' | 37.48' | 29.80' |
| Urban' | 4.16' | 4.24' | 4.24' | 7.88' | 10.21' | 4.16' | 4.16' | 4.16' | 4.16' |

'

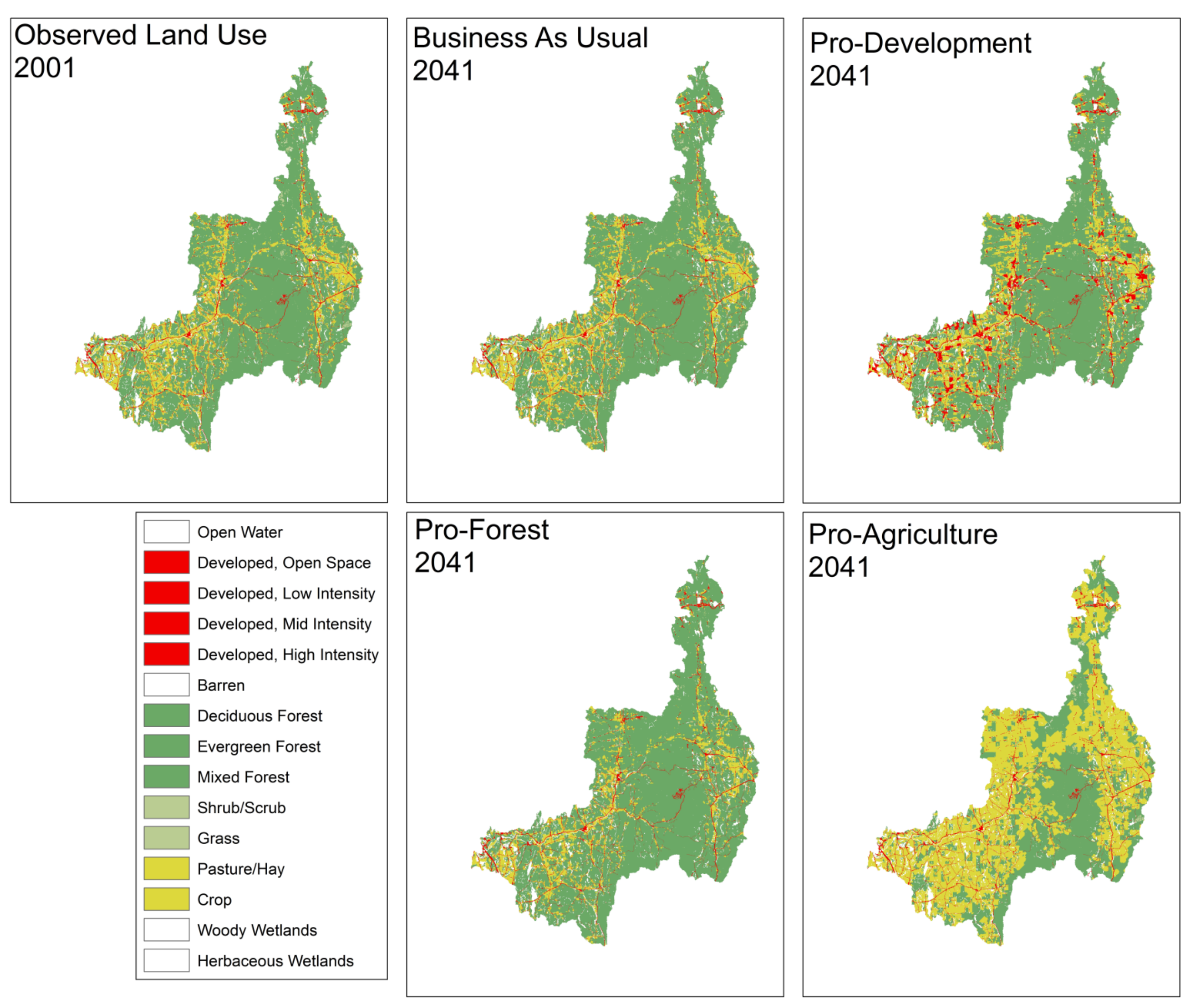
'

Foresters'treated'as'foresters:'

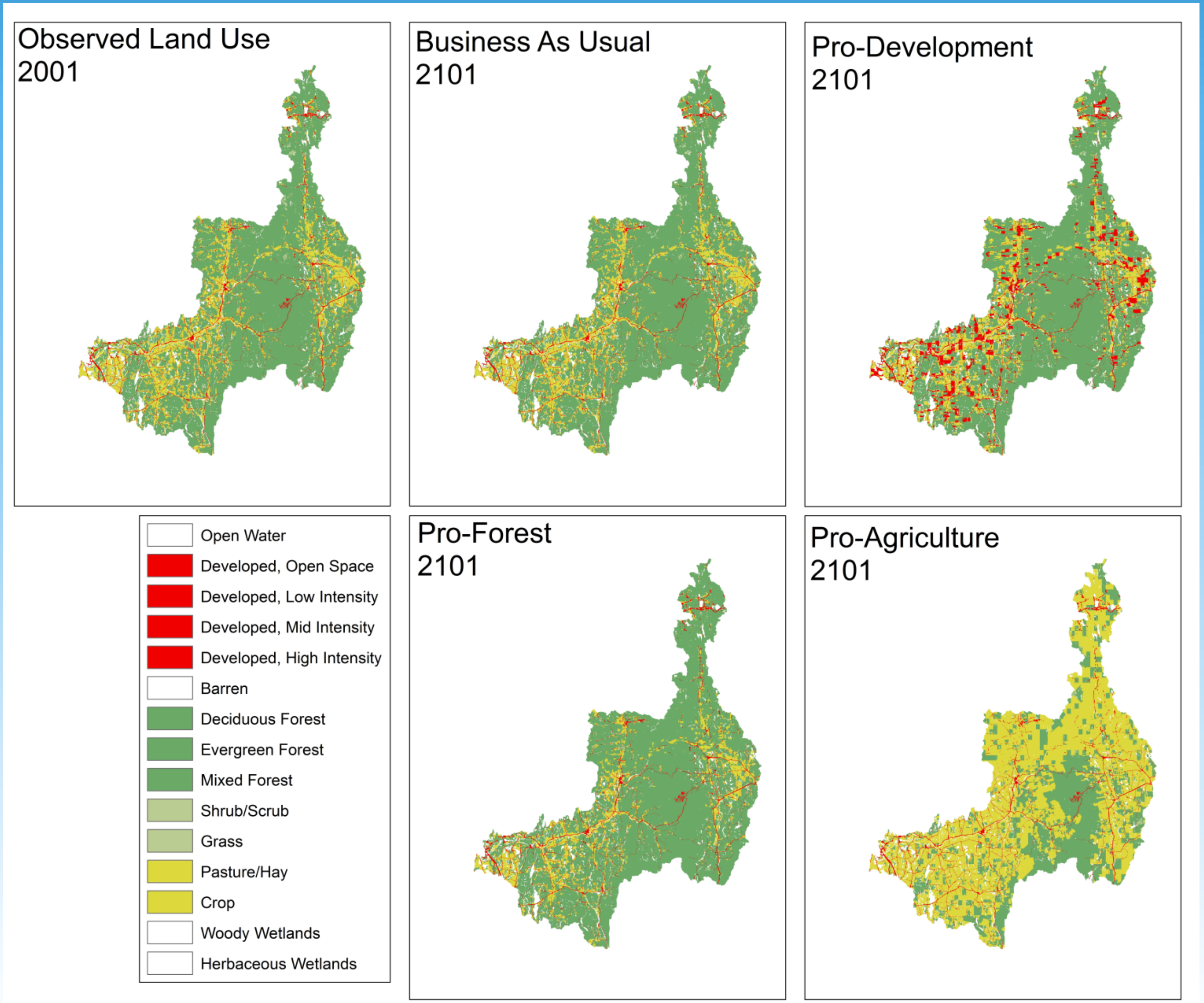
| Land'Use' Type' | Land'Use'Fractions'(%)' | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Observed' Land'Use' | Simulated'Land'Use'Given'LULCC'Scenario:' | | | | | | | |
| | NLCD'' | Business'As'Usual' | | ProEDevelopment' | | ProEForest' | | ProEAgriculture' | |
| | 2001' | 2041' | 2101' | 2041' | 2101' | 2041' | 2101' | 2041' | 2101' |
| Agriculture' | 18.73' | 18.30' | 18.25' | 16.36' | 16.27' | 17.14' | 17.14' | 23.21' | 23.51' |
| Forest' | 70.85' | 71.14' | 71.14' | 71.27' | 71.26' | 71.60' | 71.60' | 66.47' | 66.12' |
| Urban' | 4.16' | 4.24' | 4.30' | 5.96' | 6.07' | 4.16' | 4.16' | 4.16' | 4.22' |

'

# IAM Version 1.1



# IAM Version 1.1



# IAM Version 2.0

V2.0: Feed-forward enabled with 3 RCPs, 4 GCMs and 4 land management scenarios with BMP adoption generated by stakeholders in October 2015 [DEVELOPMENT IN PROGRESS]

V2.1: Feedback enabled [DEVELOPMENT IN PROGRESS]

| Low Political, High Economic Capital | High Political, High Economic Capital |
|---|---|
| • Crop and Land Management: Cover Cropping *for 20% of applicable farms*, Riparian Buffers *for 80% of applicable farms*<br>• Shift to more pasture based dairy<br>• Steer Development Patterns: Divest in floodplain development, Expand conservation easements | • Crop and Land Management: Crop Rotation, Cover Cropping, Reduced Tillage, and Riparian Buffers *for 80% of applicable farms*<br>• Raise taxes on high-P fertilizers and animal feed<br>• Shift to more pasture based dairy<br>• Steer Development Patterns: Maintain Act 250, Prohibit and Divest in floodplain development, Moratorium on development near wetlands, Expand conservation easements |
| **Low Political, Low Economic Capital** | **High Political, Low Economic Capital** |
| • Crop and Land Management: Crop Rotation, Cover Cropping, Reduced Tillage *for 20% of applicable farms* Riparian Buffers *for 80% of applicable farms*<br>• Raise taxes on high-P fertilizers and animal feed<br>• Steer Development Patterns: Prohibit new floodplain development | • Crop and Land Management: Cover Cropping, and Reduced Tillage *for 20% of applicable farms*<br>• Shift to more pasture based dairy<br>• Steer Development Patterns: Integrate Smart Growth, Maintain Act 250, Prohibit new floodplain development |

# IAM Version 3.0 (BREE 2016-2021)

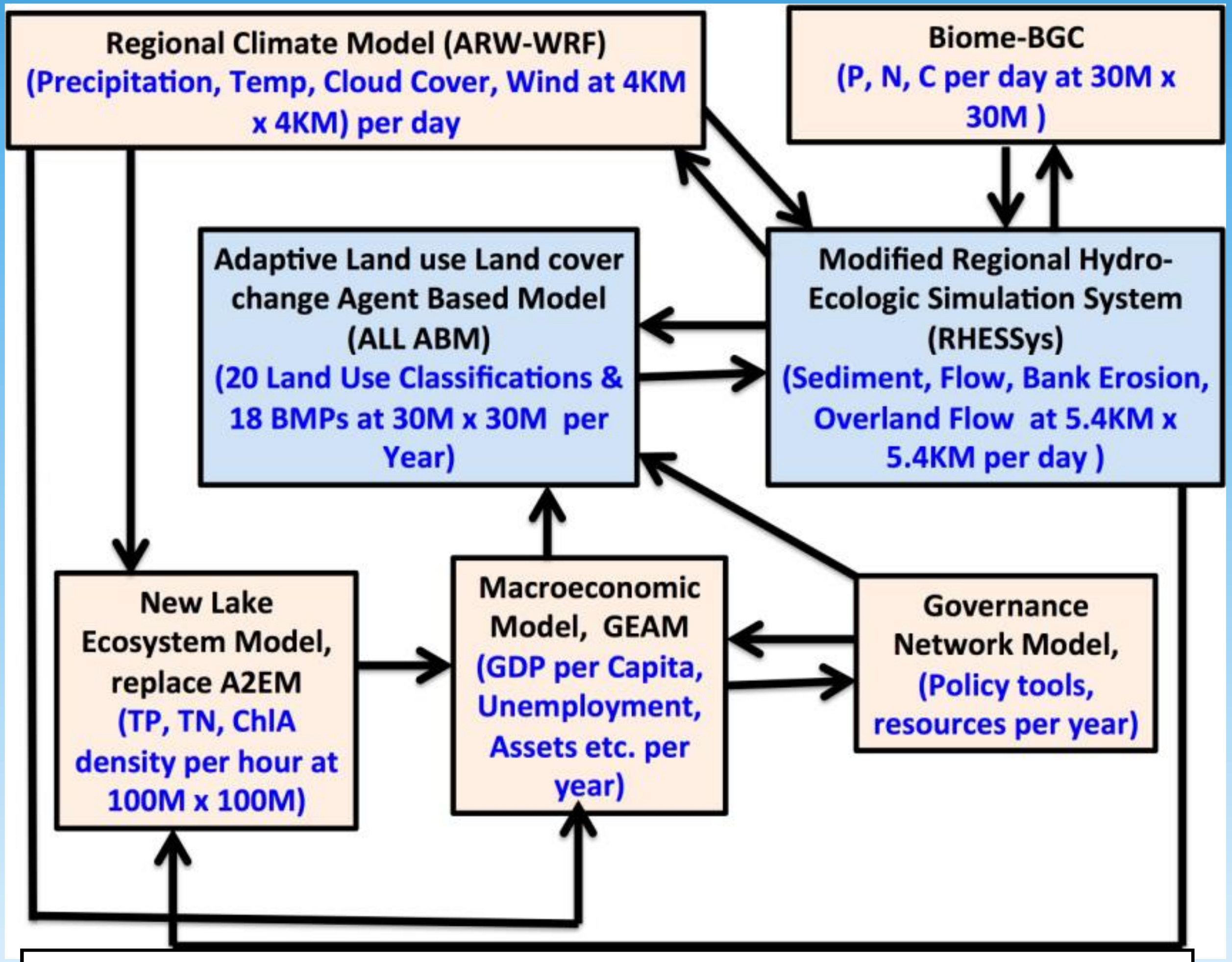



Figure 7: The BREE Integrated Assessment Model (IAM) of coupled social ecological systems for understanding the cascading impacts of climate change induced extreme events at watershed scales; tan = new model; blue = expanded existing model; WRF: Weather Research and Forecasting; ALL: Adaptive Landuse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