WHERE HAVE WE BEEN?

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

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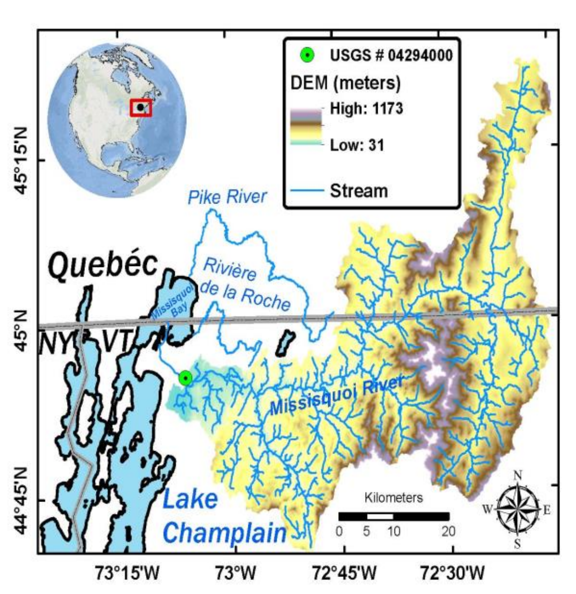


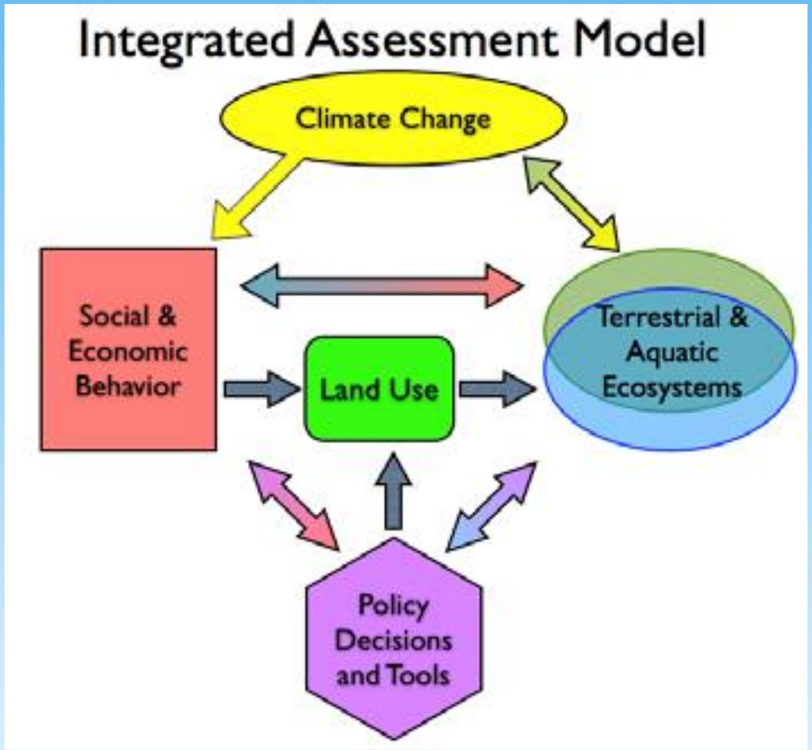
Acknowledgements: NSF-EPSCOR and amazing collaborators – **Patrick Clemins, Scott Turnbull, Morgan Rodgers, Ahmed Hamed,** Chris Koliba, Arne Bomblies, Andrew Schroth, Brian Beckage, Donna Rizzo, Beverley Wemple, Yushiou Tsai, Steve Scheinert, Ibrahim Mohammed, Peter Isles, Justin Guilbert, Yaoyang Xu, Gabriela Bucini, Breck Browden, Sarah Coleman, Stephanie Hurley, Linyuan Shang, Carol Adair, Gillian Galford, Richard Kujawa, Judith Van Houten & **engaged stakeholders**

The Overarching RACC Question (from NSF funded proposal)

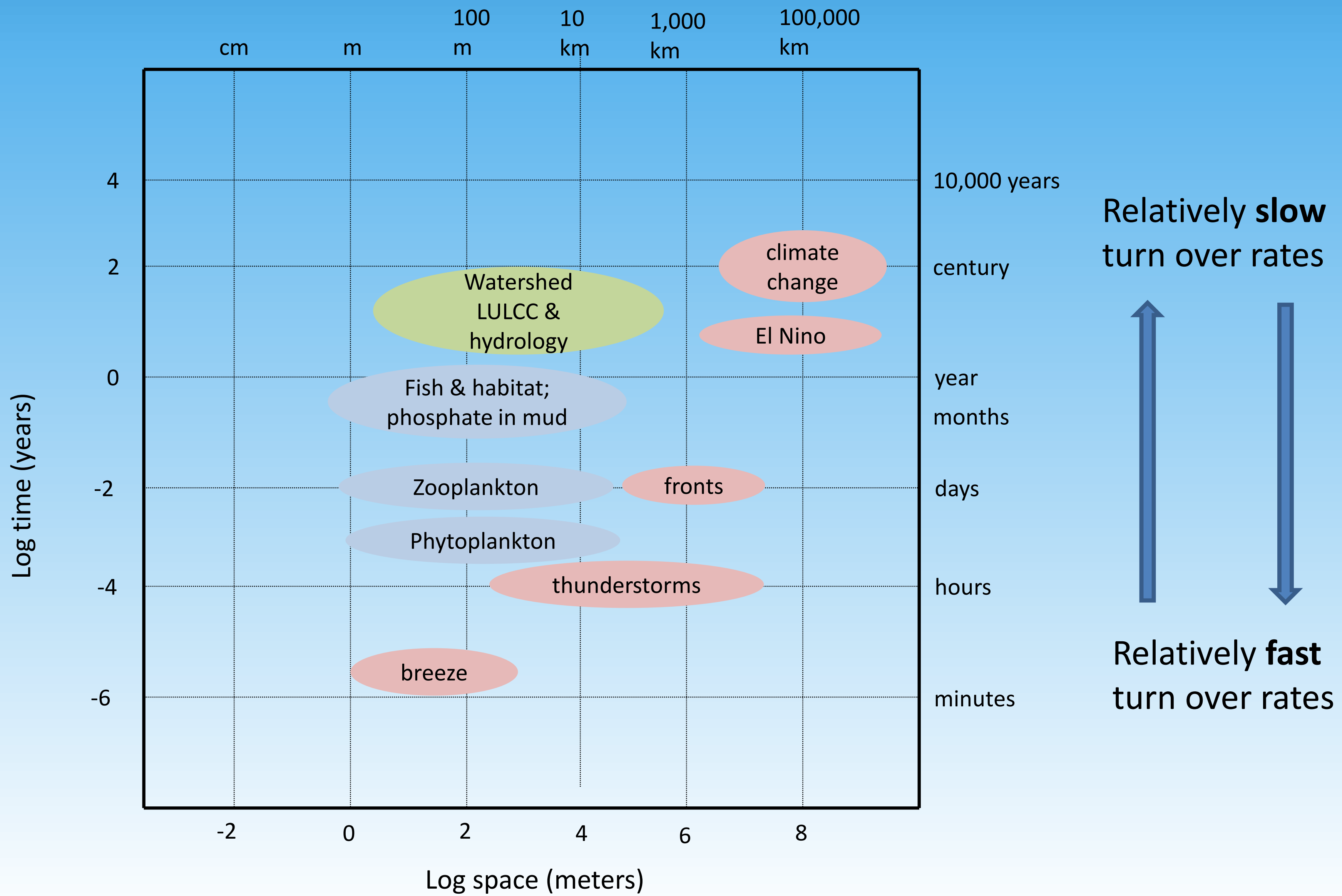
How will the interactions of climate change and land use alter hydrological processes and nutrient transport from the landscape, internal processing and eutrophic state within the lake, and what are the implications for adaptive management strategies?

Social Ecological System (SES) science goals

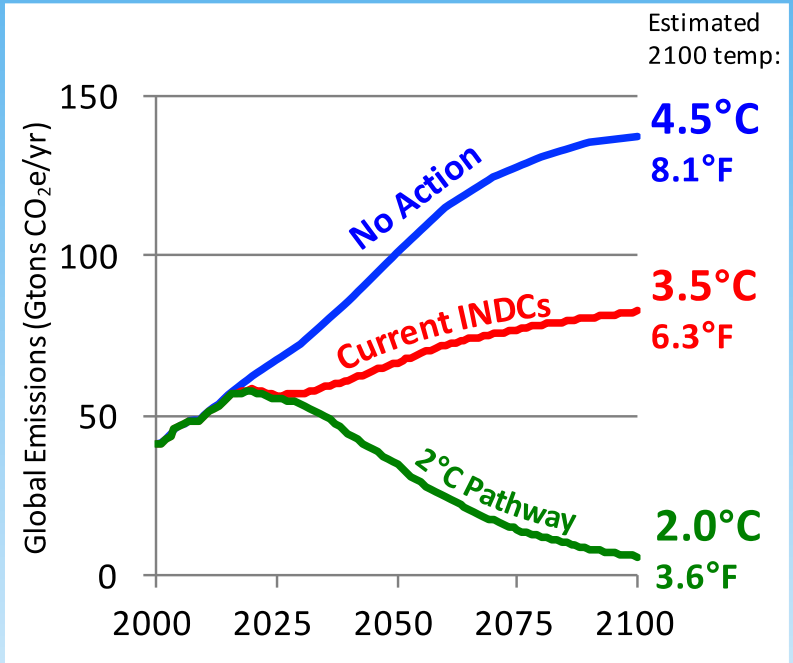
Adaptive management goals



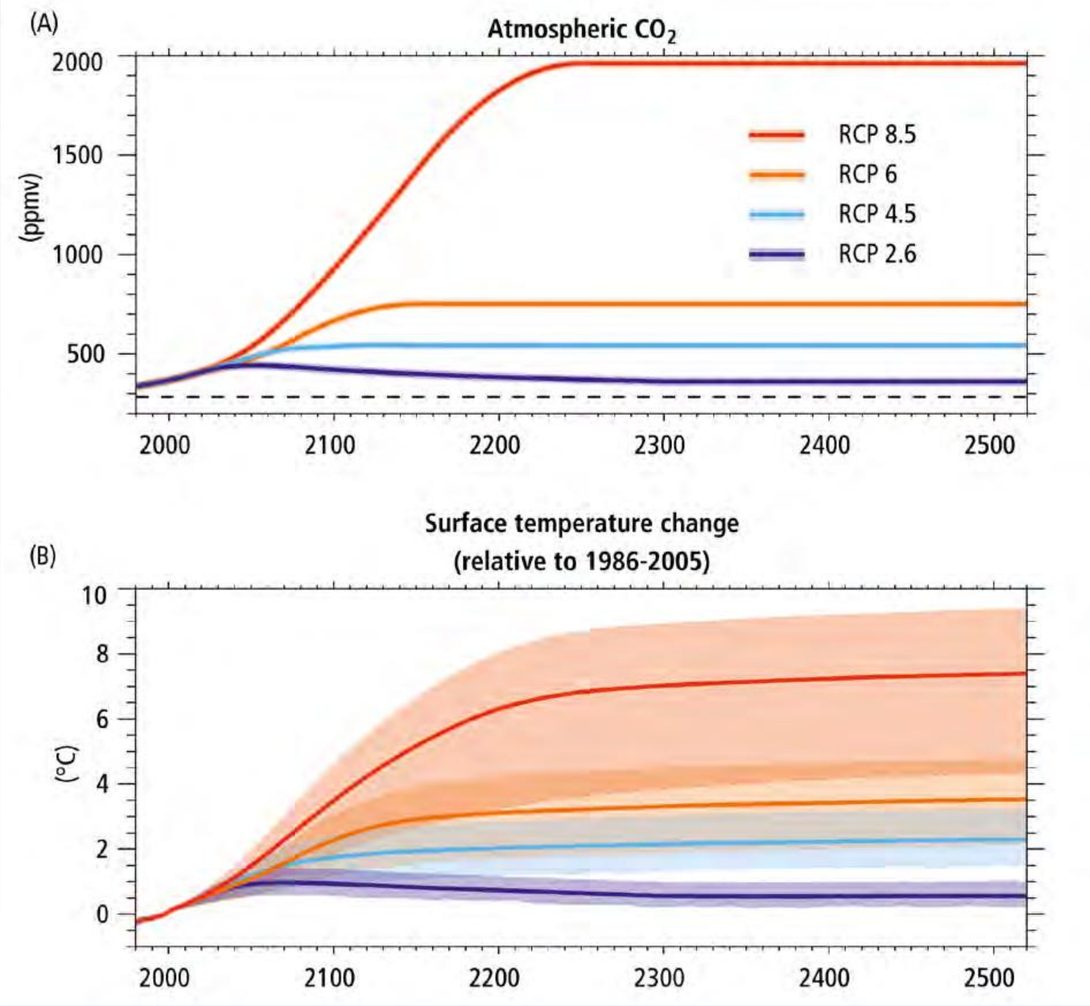
Complexity of modeling cross-scale interactions in Social Ecological Systems (SES)



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



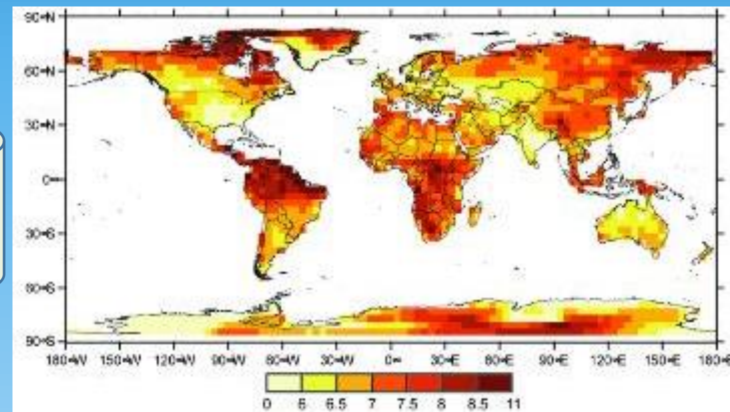
Source: Climate Interactive



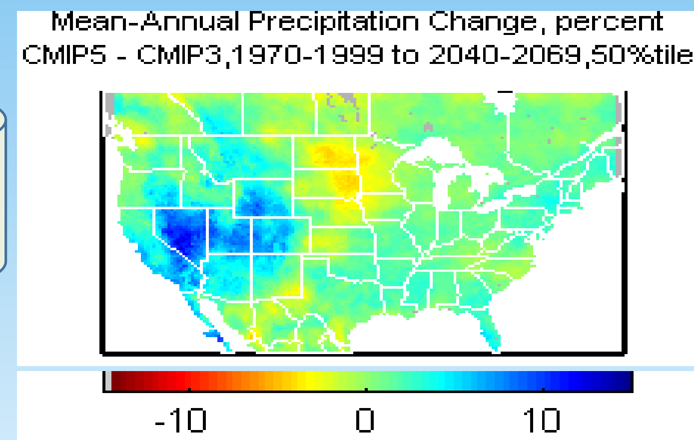
IPCC 2014

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

General Circulation Models → Climate ~100 Km



CMIP5 Intermediate Downscaling → Climate ~12 Km



Fine Downscaling → Climate ~ 1km

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)

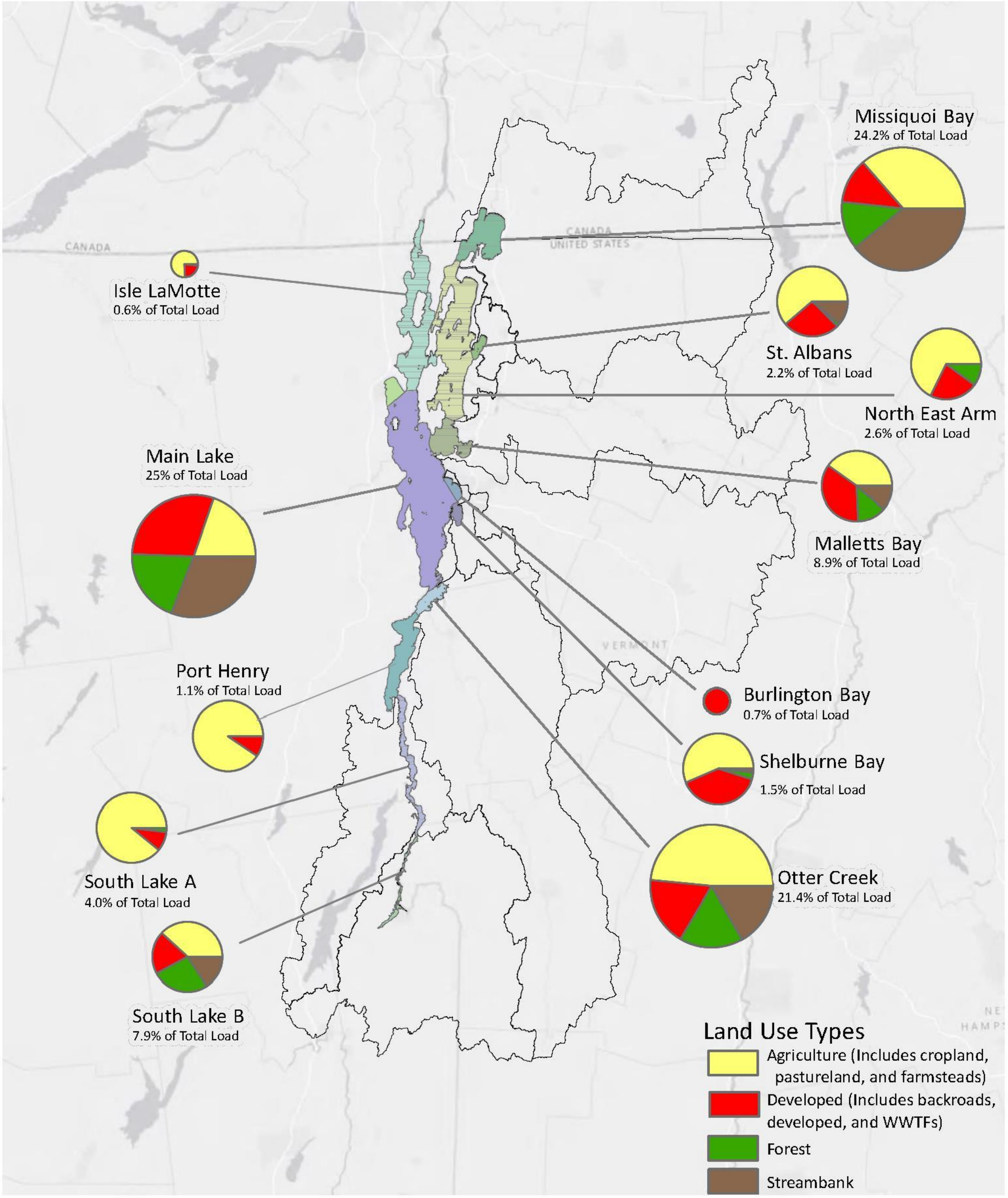
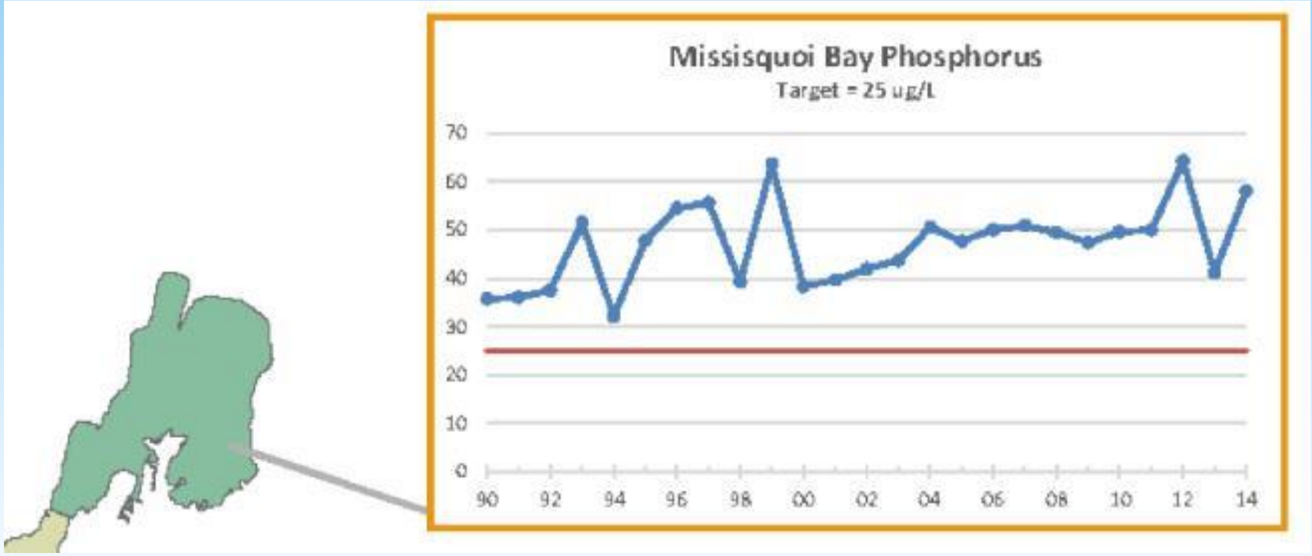


Figure 4: Vermount sources of phosphorus loading to Lake Champlain segments, by land use; annual average of 2001-2010.
Data are from TetraTech, 2015c

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 <u>IN</u> Social Ecological Systems

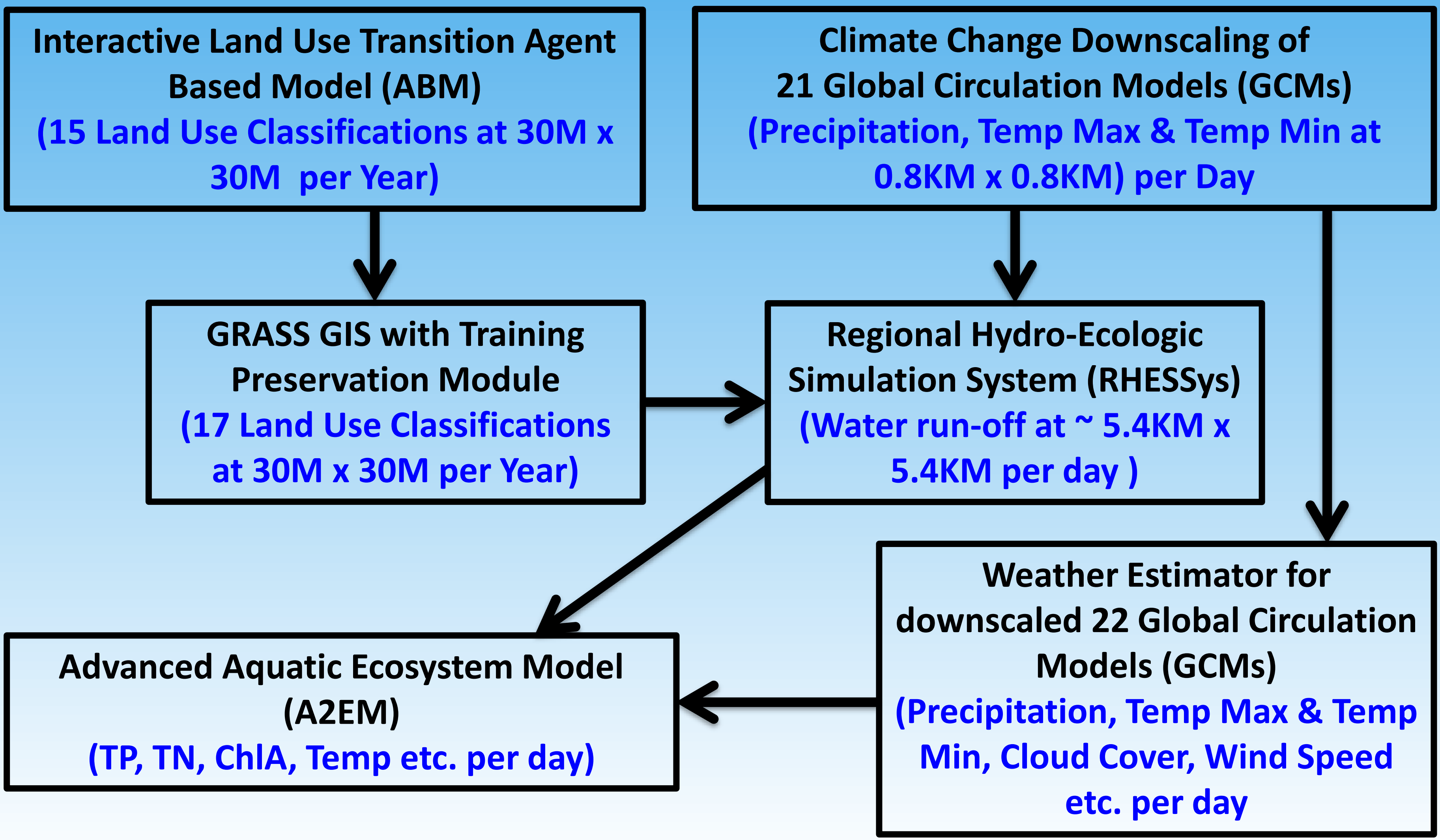
- Social Ecological Systems are characterized by:
  - Cross-scale interactions
  - Uncertainty in behavior across space and time,
  - Non-linearities, thresholds, lags, alternate stable states
  - Cascading interactions
  - Conflicting values and goals

- “Command and Control” 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 (and resilience) to climate change in LCB:
  - FORESIGHT: Incorporating uncertain forecast information in decision making
  - SOCIAL & POLICY LEARNING FROM EXPERIMENTS
  - VALUE PLURALISM

- 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



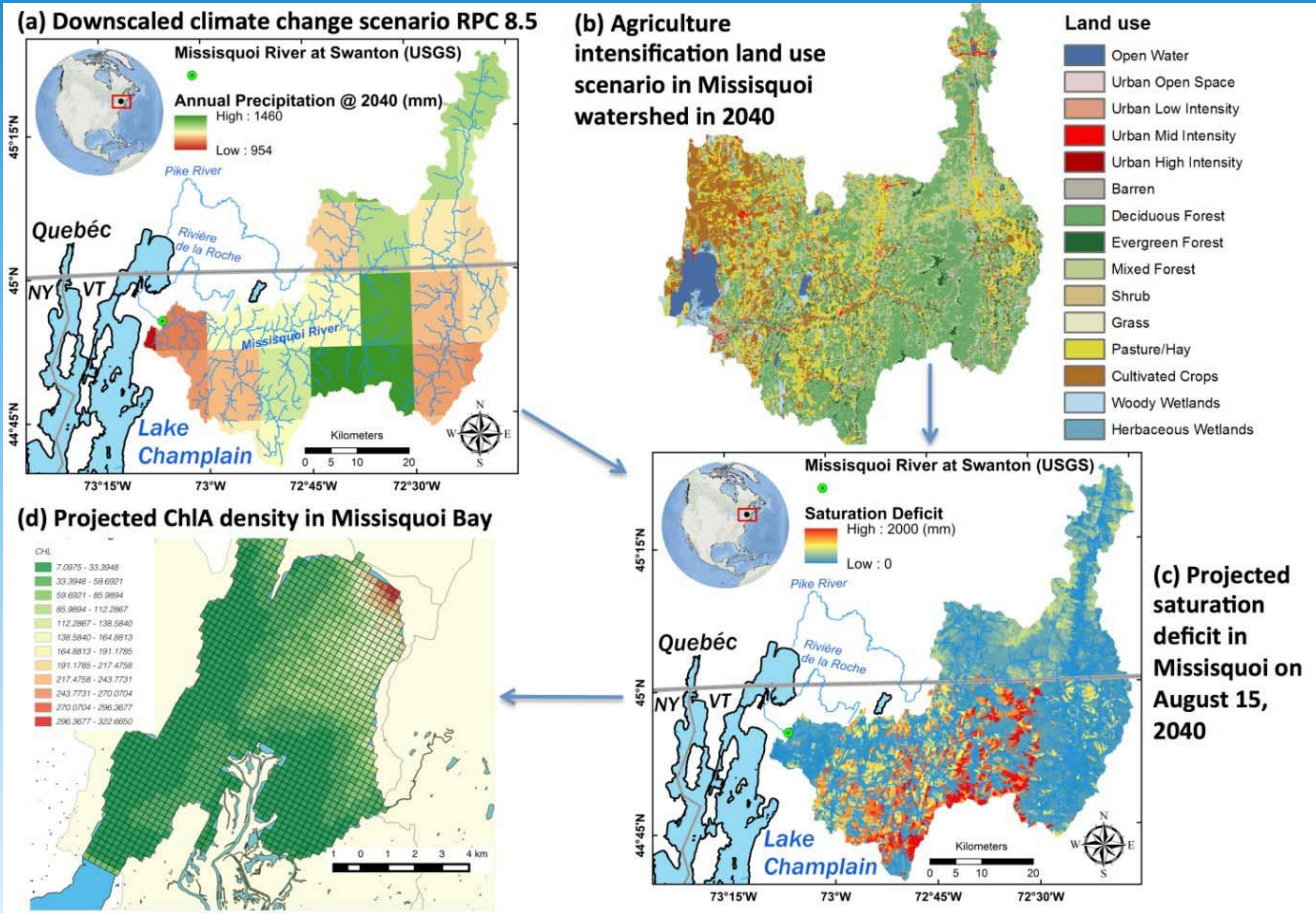


Figure 8. Output from cascading current Track-1 IAM that will be replaced by the BREE IAM: Output reveals (a) Projected precipitation by GCM BNU_ESM.1.rcp85 in 2040; (b) Projected Land-Use by Agent Based Model in 2040; (c) Projected hydrological scenario by RHESSys on August 15, 2040; (d) Projected Chlorophyll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

Cascading IAM Development Overview

- Version 1.0
  - Feed-forward enabled with 3 RCPs, 4 GCMs and 4 Land Use scenarios for Missisquoi 2000-2040 period [Zia et al. 2016]
- Version 1.1
  - Feed-forward enabled with 4 RCPs, 5 GCMs, 4 land management and TP reduction scenarios for Missisquoi 2000-2050 period [Manuscript in Preparation]
- Version 1.2
  - Feed-forward enabled with 3 RCPs, 4 GCMs, 4 refined Land Use scenarios Missisquoi 2000-2100 period [Manuscript in Preparation]

- Version 2.0: See the latter presentation on "where are we going?"

"Extreme Method" of Scenario Settings Used for Cascading IAM Version 1.0 Missisquoi Runs, 2000-2040 (Zia et al. 2016)

- **THREE "extreme" Climate Scenarios**: RCP 4.5; RCP 6.0 and RCP 8.5
  - 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 "extreme" LULCC ABM Scenarios**: BAU, Pro-forest, Pro-Ag, Urbanization

LULCC ABM	RCP 4.5/GCM1	RCP 6.0/GCM1	RCP 8.5/GCM1
Business As Usual	$ChlA^{11}$, TP^{11}, …..	$ChlA^{12}$, TP^{12}, …..	$ChlA^{13}$, TP^{13}, …..
Pro-forest	$ChlA^{21}$, TP^{21}, …..	$ChlA^{22,}$, TP^{22}, …..	$ChlA^{23,}$, TP^{23}, …..
Pro-Ag	$ChlA^{31}$, TP^{31}, …..	$ChlA^{32}$, TP^{32}, …..	$ChlA^{33}$, TP^{33}, …..
Urbanization	$ChlA^{41}$, TP^{41}, …..	$ChlA^{42}$, TP^{42}, …..	$ChlA^{43}$, TP^{43}, …..

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LETTER

Coupled impacts of climate and land use change across a river–lake continuum: insights from an integrated assessment model of Lake Champlain's Missisquoi Basin, 2000–2040

Asim Zia[1,2,3,4], Arne Bomblies[4,5,6], Andrew W Schroth[7], Christopher Koliba[1,4], Peter D F Isles[8], Yushiou Tsai[6], Ibrahim N Mohammed[6], Gabriela Bucini[6], Patrick J Clemins[2,6], Scott Turnbull[6], Morgan Rodgers[6], Ahmed Hamed[6], Brian Beckage[9], Jonathan Winter[10], Carol Adair[8], Gillian L Galford[4,8], Donna Rizzo[4,5] and Judith Van Houten[6,10]

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

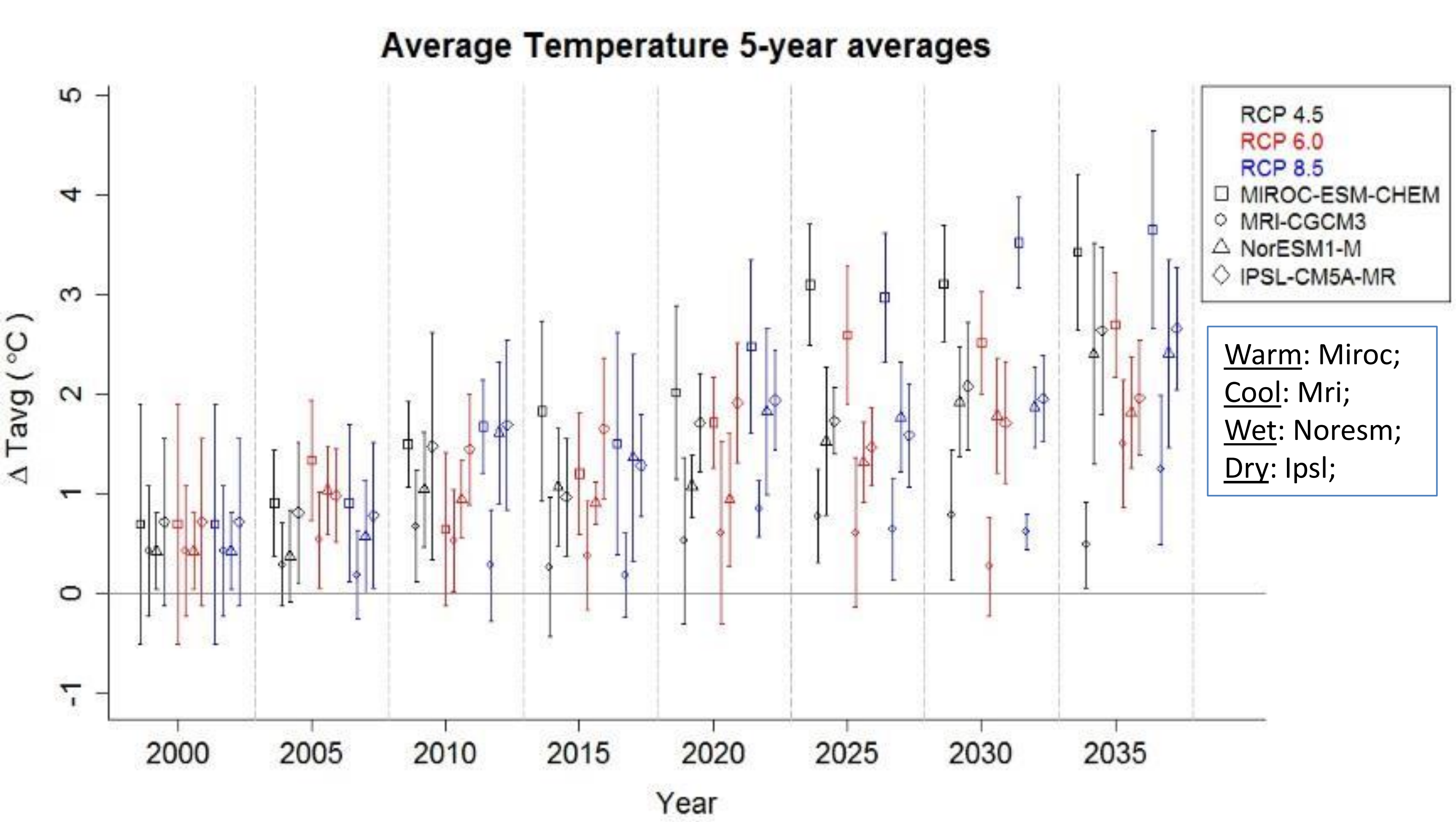


Figure 2a: Four GCM projections for three RCP scenarios of temperature change in the Misssisquoi watershed (baseline =1970-1999).

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

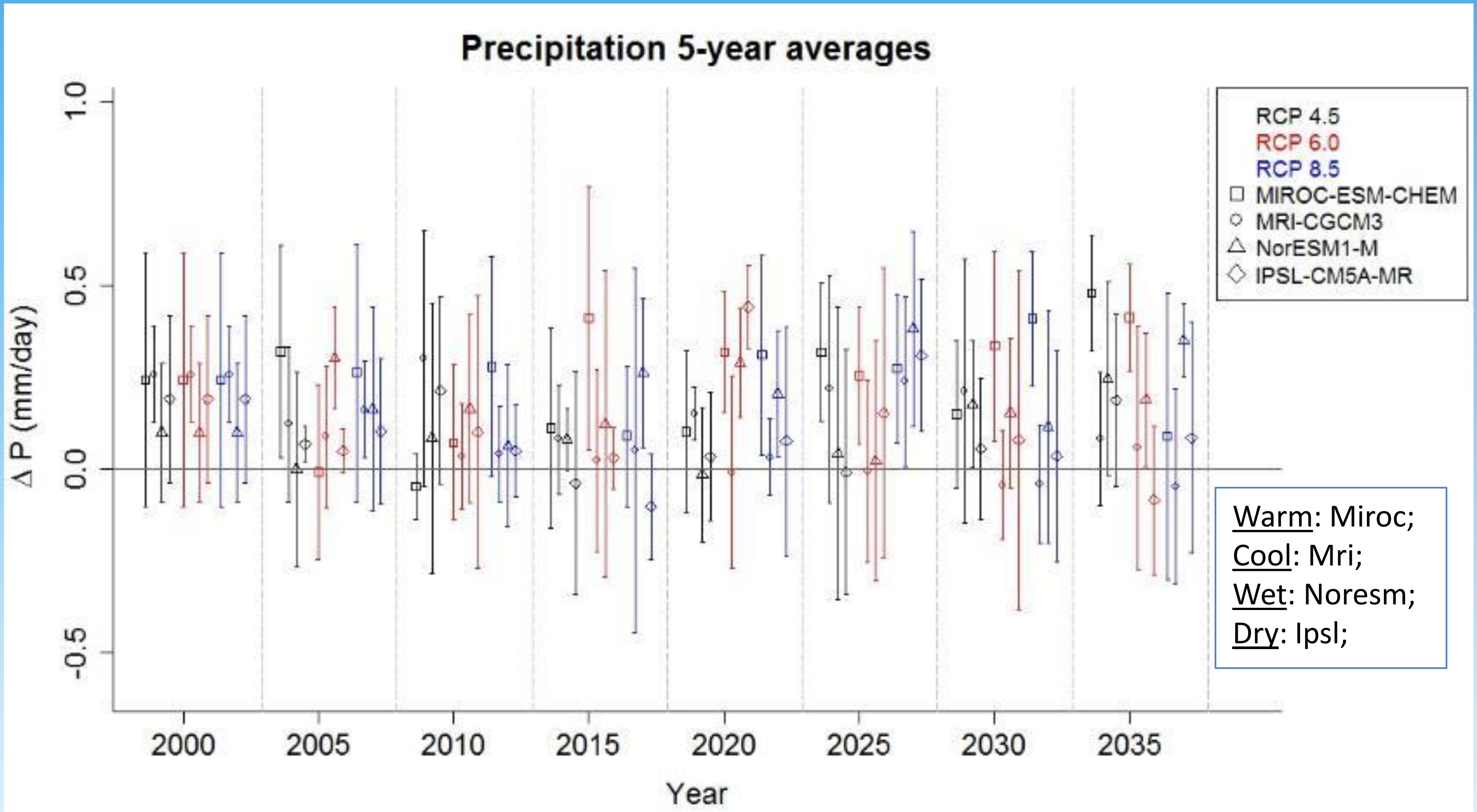
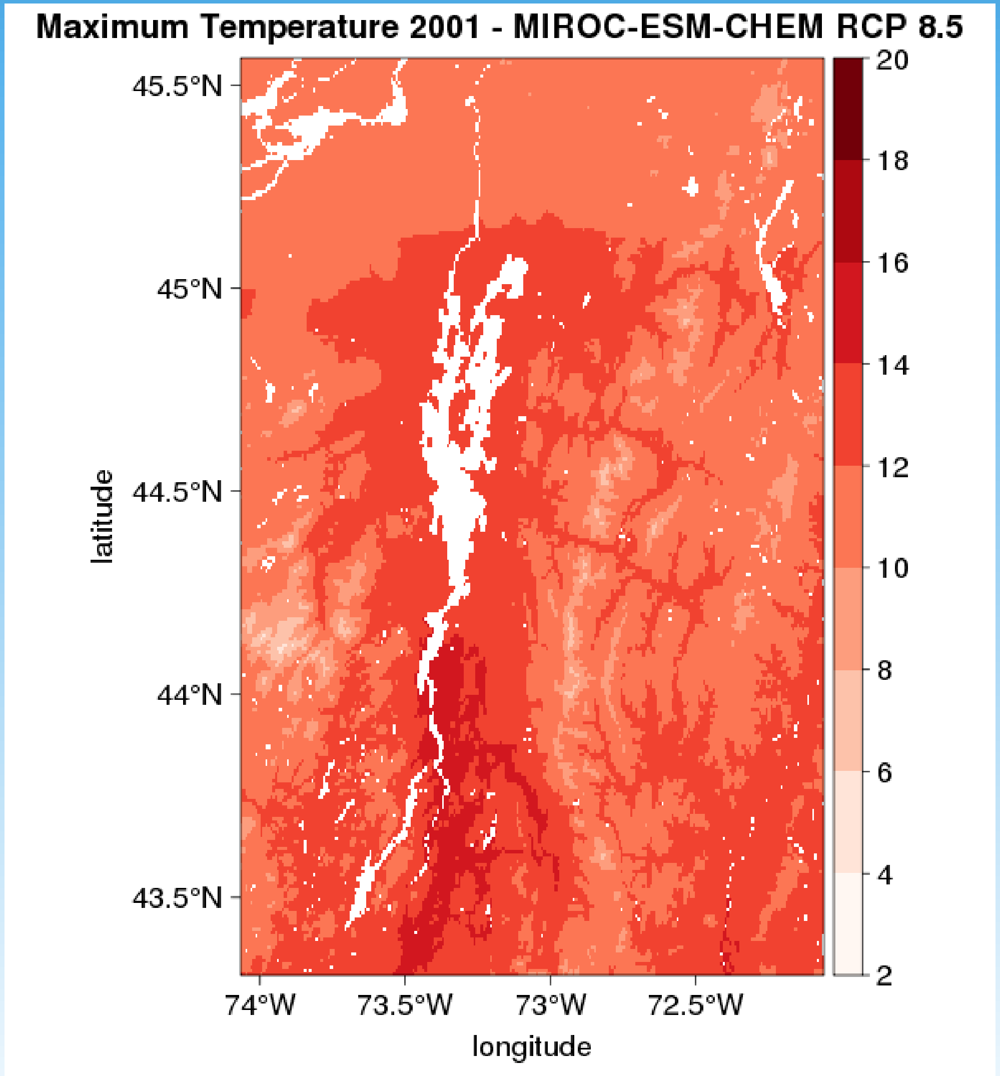


Figure 2b: Four GCM projections for three RCP scenarios of precipitation change in the Missisquoi watershed (baseline = 1970-1999).

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



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

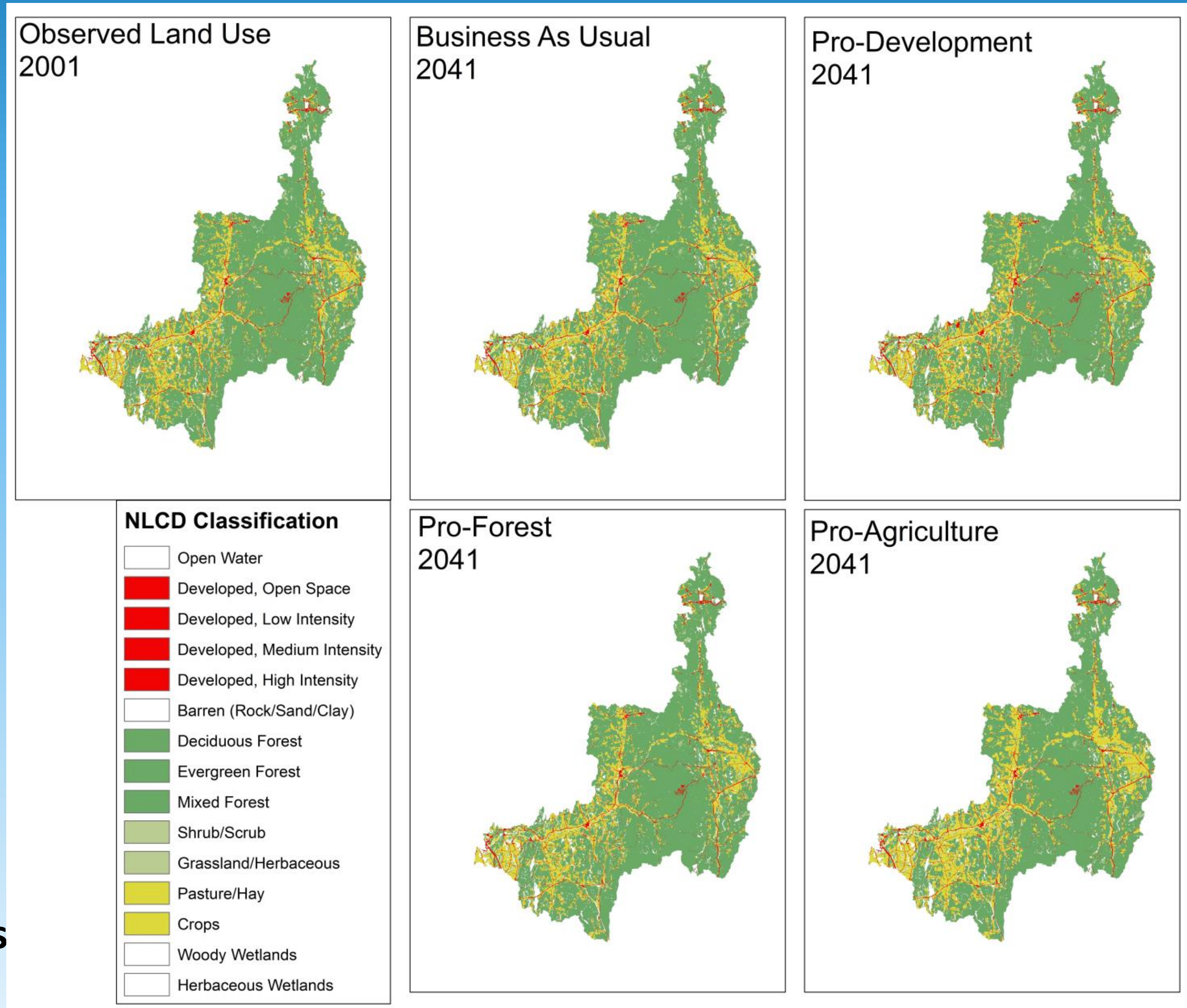
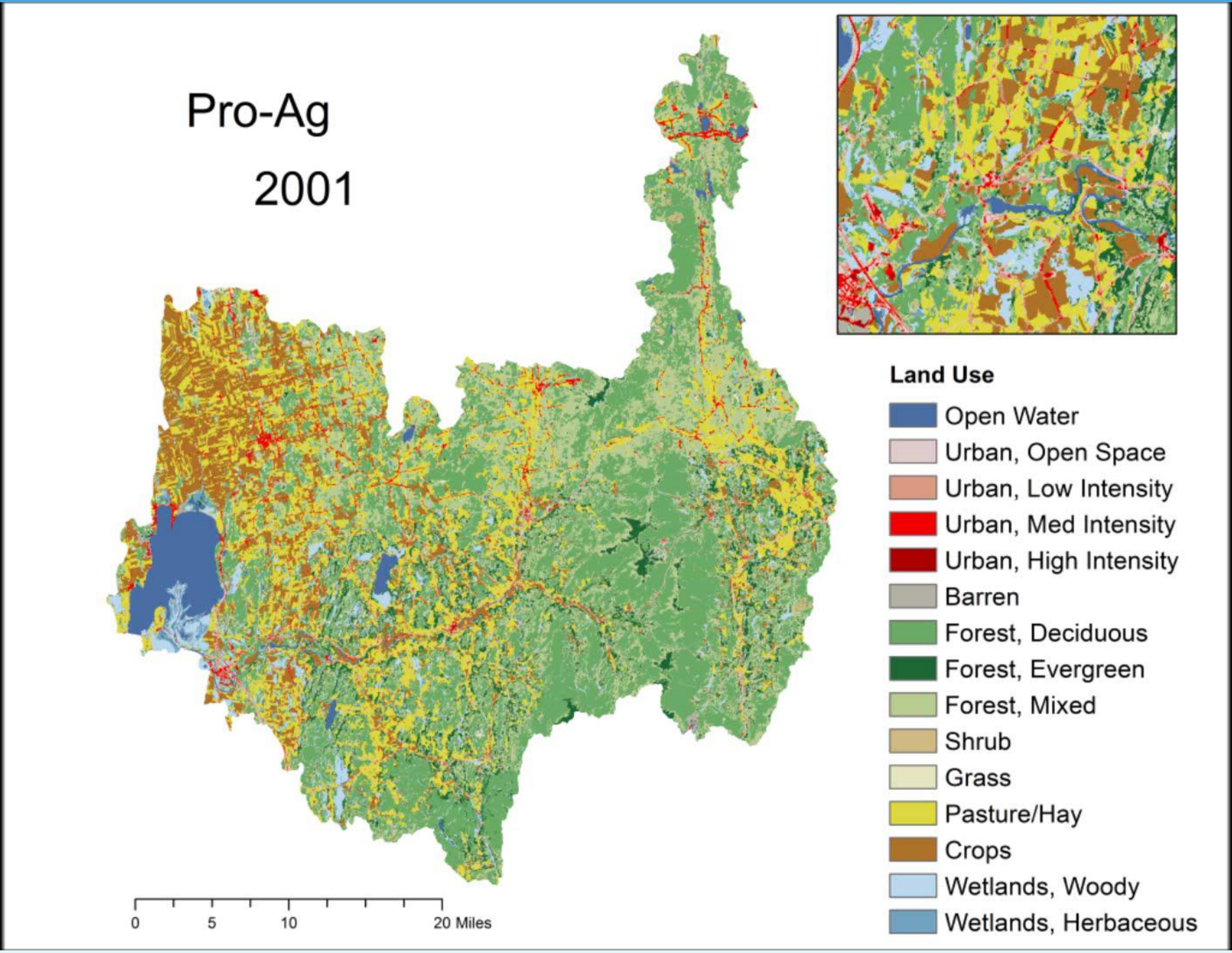
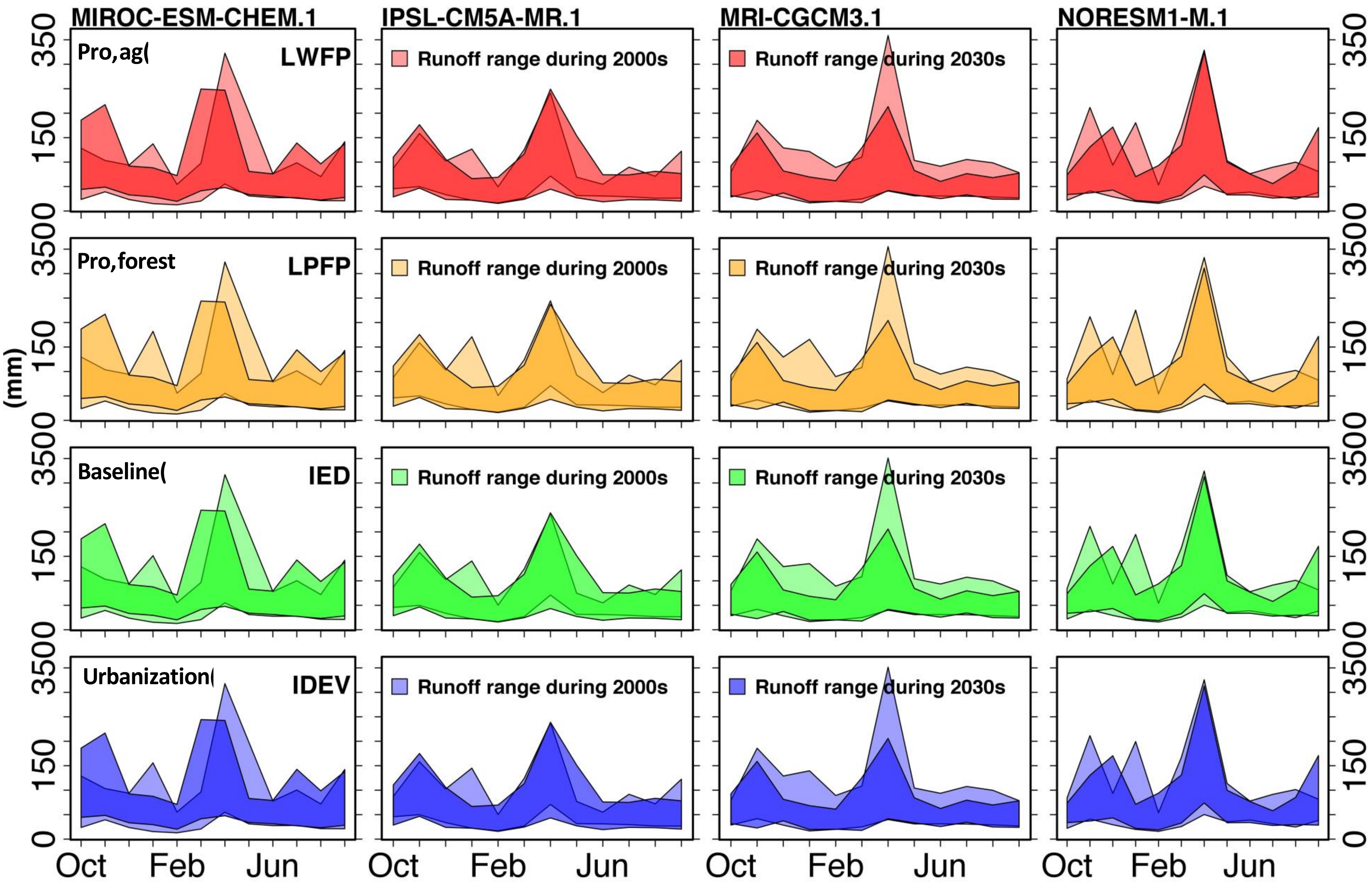


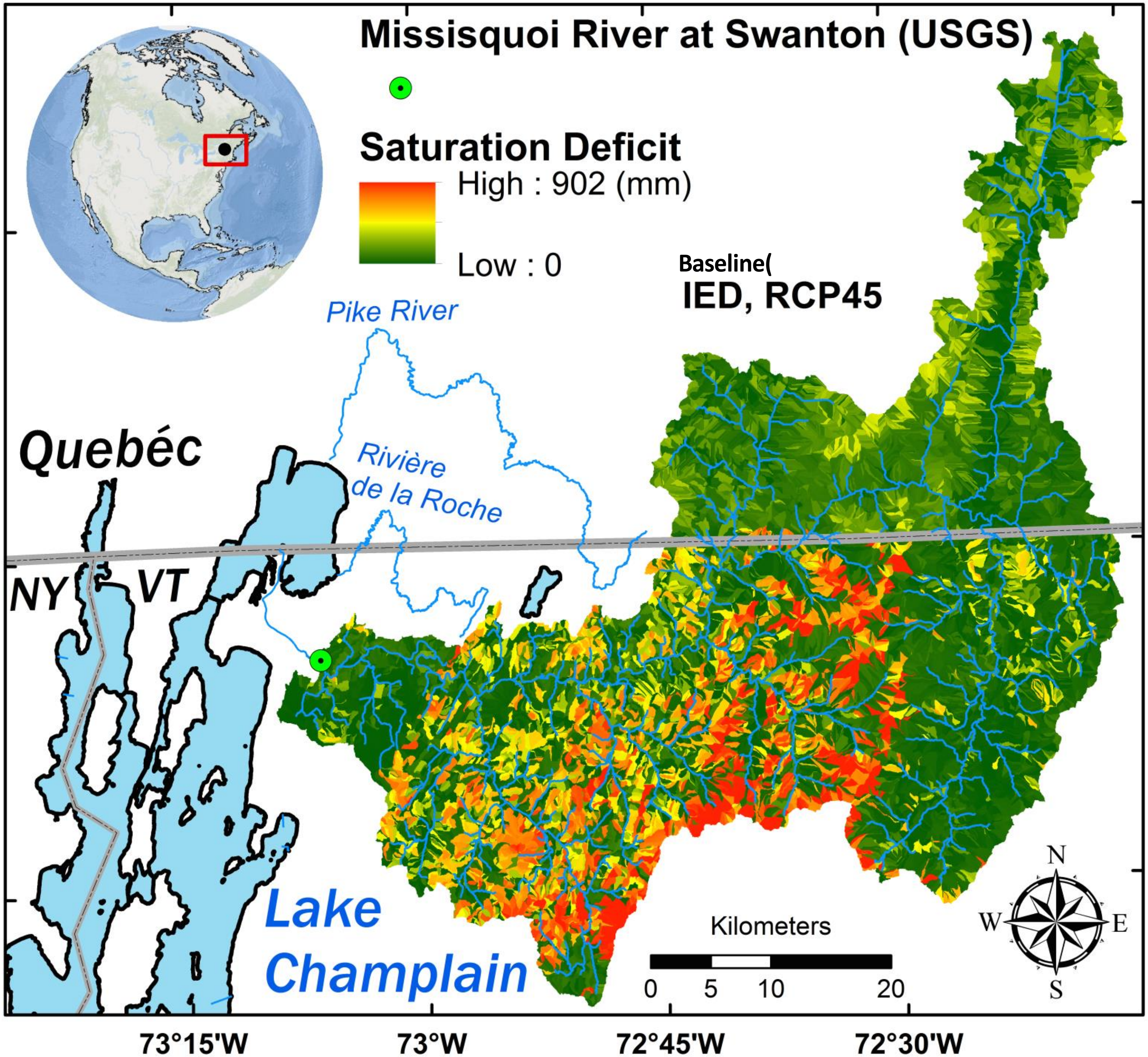
Figure 3: Land-use classifications produced by the LULCC model for four economic and policy scenarios for the final simulation year (2041), also showing initial land-cover at start of simulation.

Agriculturally dominant landscape scenario

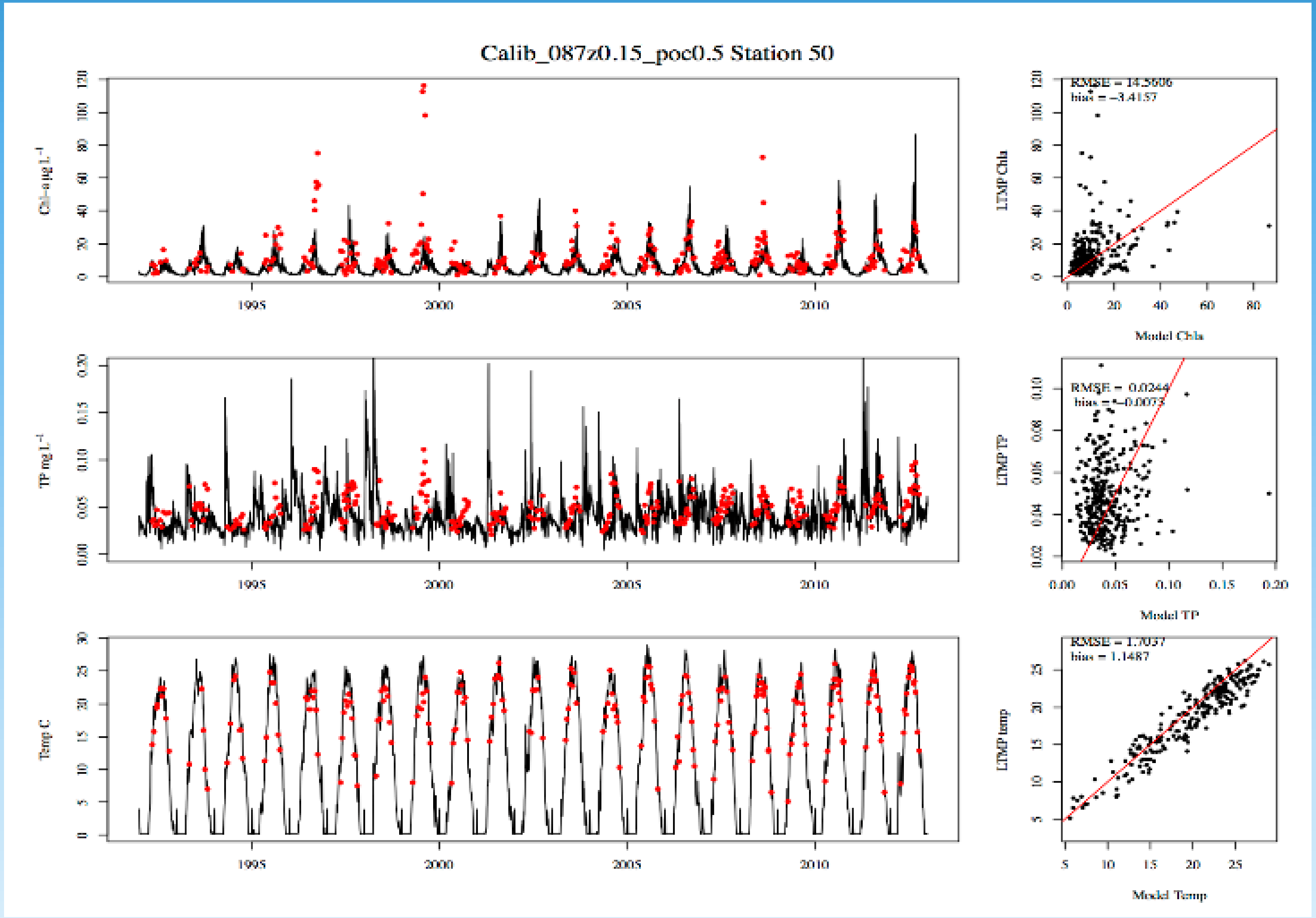


RHESSys Projections for 4 LULCC x 4 GCM scenarios for RCP 6.0



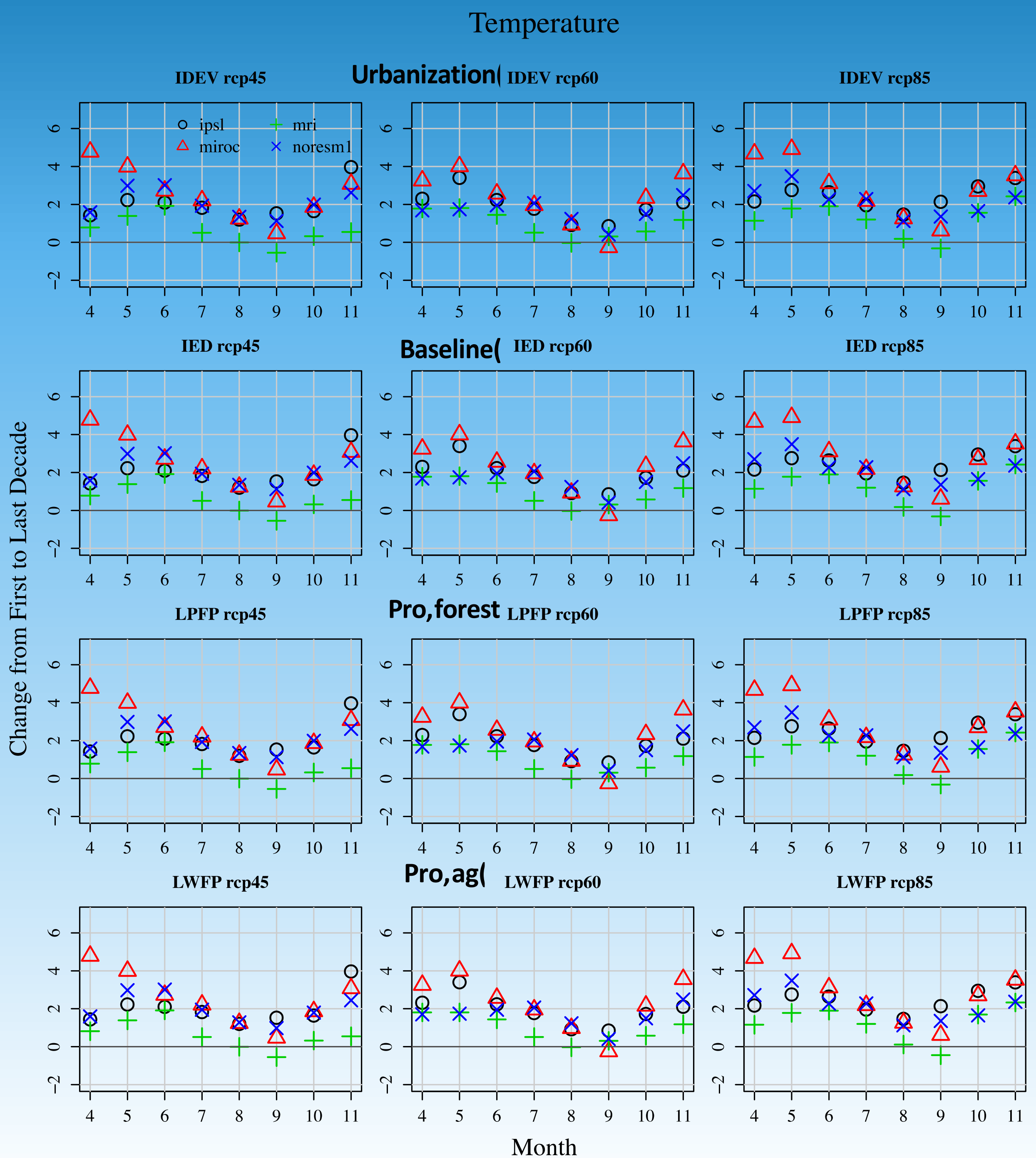

Missisquoi River at Swanton (USGS)
Saturation Deficit
High : 902 (mm)
Low : 0
Baseline(
IED, RCP45
Pike River
Rivière de la Roche
Quebéc
NY
VT
Lake Champlain
Kilometers
0 5 10 20
N
S
W
E
45°15'N
45°N
44°45'N
73°15'W
73°W
72°45'W
72°30'W

Lake model calibration



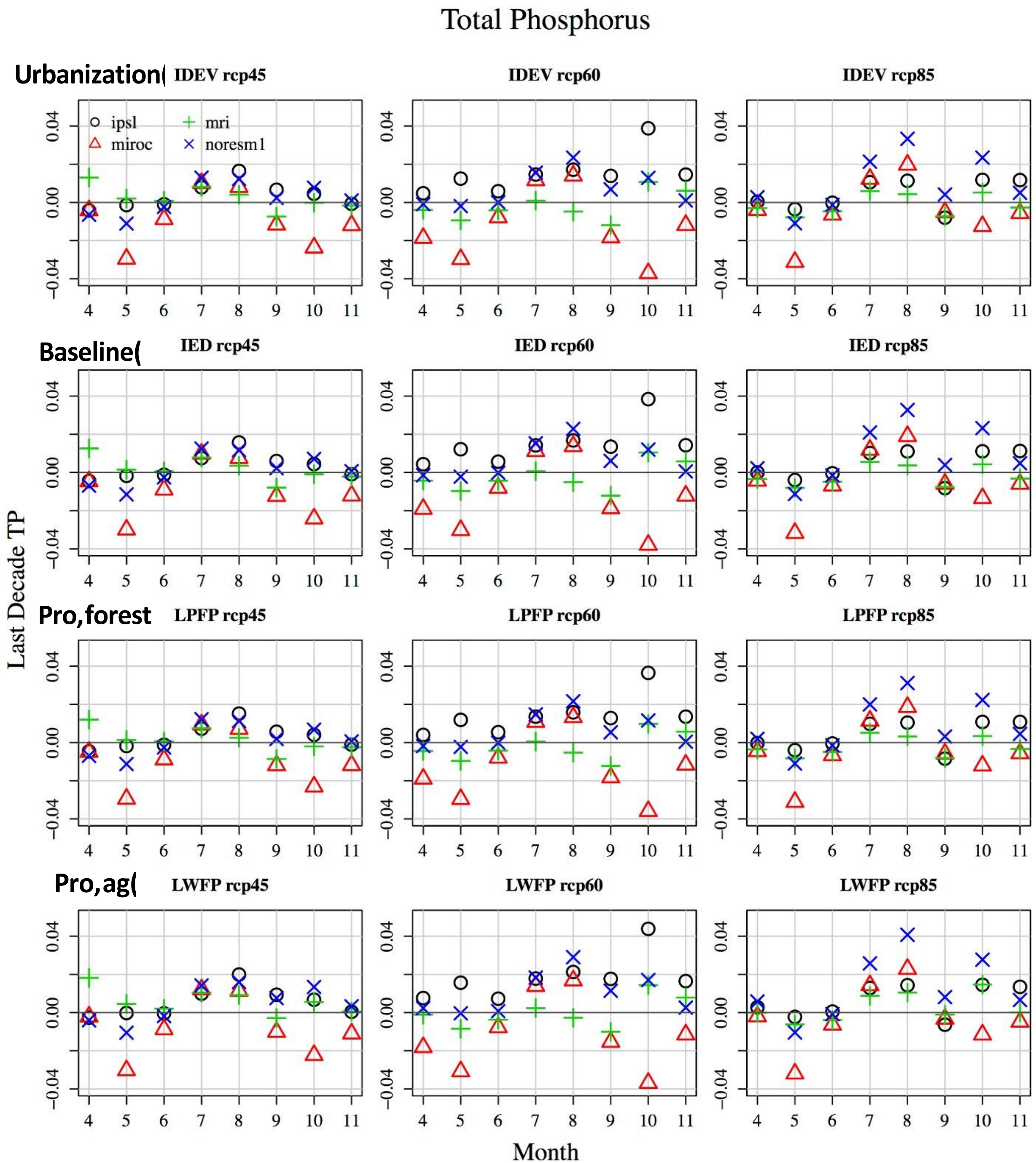
Modeled results (black lines) versus long-term monitoring observations for chlorophyll-a (top), total phosphorus (middle), and water temperature (bottom) at LTMP station 50. On right, scatterplots of modeled v. observed variables matched by date, showing root mean squared error and mean bias. Red line 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).



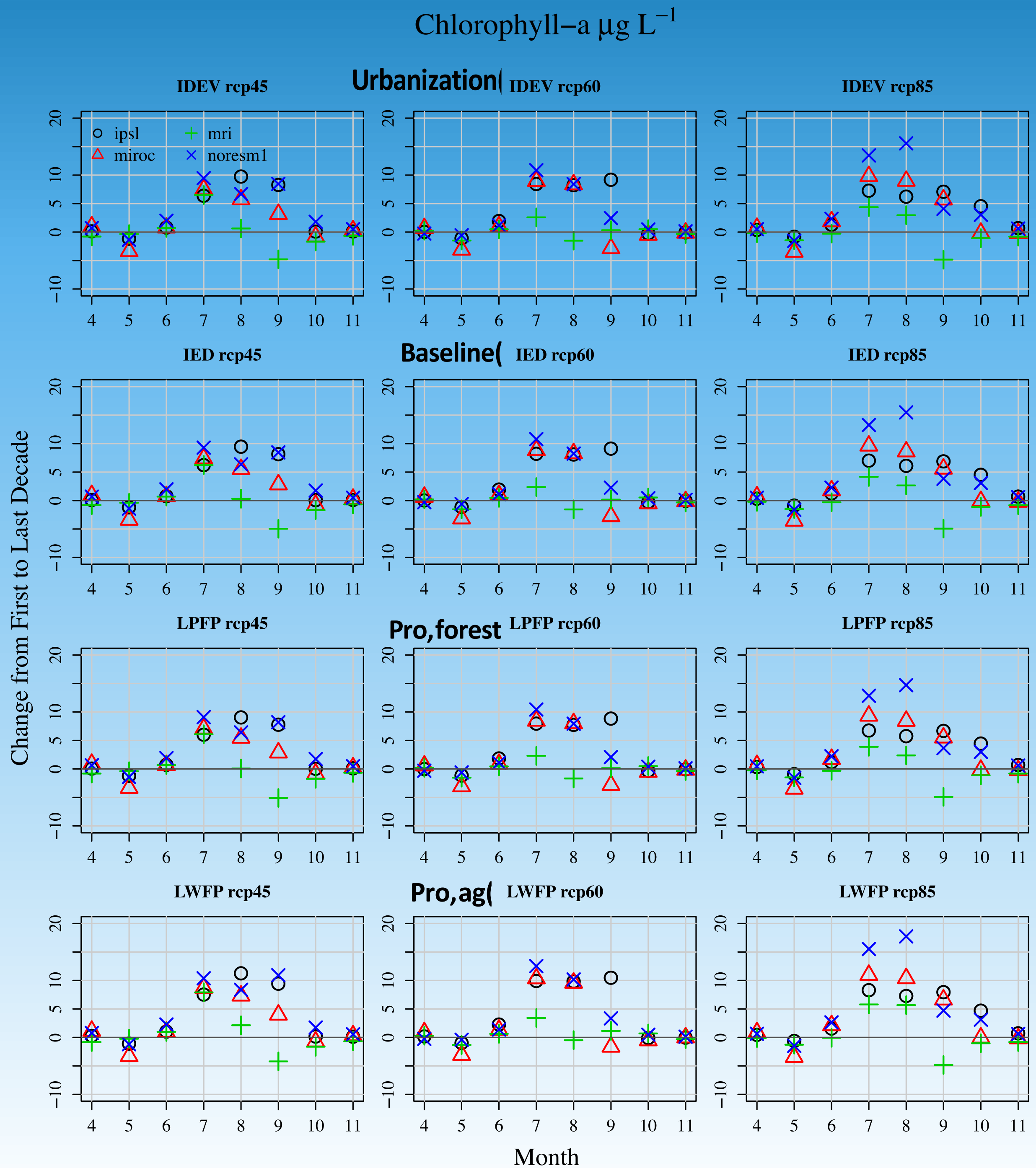
<u>Warm</u>: Miroc;
<u>Cool</u>: Mri;
<u>Wet</u>: Noresm;
<u>Dry</u>: Ipsl;

Projected Difference in TP (mg/L) loading between 2030s and 2010s for 48 scenarios



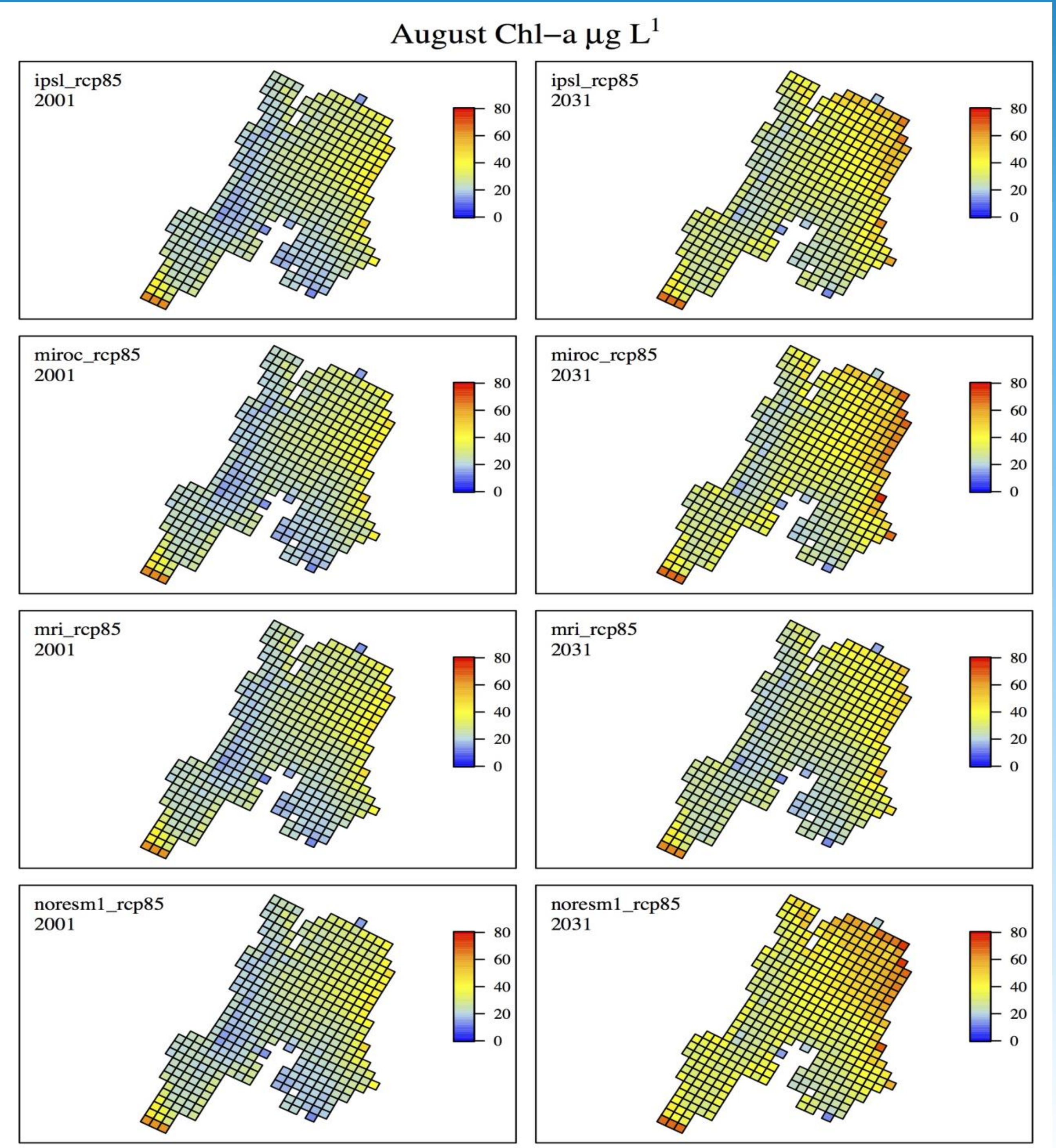
<u>Warm</u>: Miroc;
<u>Cool</u>: Mri;
<u>Wet</u>: Noresm;
<u>Dry</u>: Ipsl;

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)



Warm: Miroc;
Cool: Mri;
Wet: Noresm;
Dry: Ipsl;

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



<u>Warm</u>: Miroc;
<u>Cool</u>: Mri;
<u>Wet</u>: Noresm;
<u>Dry</u>: Ipsl;

IAM Version 1.1

V1.1: Feed-forward enabled with 4 RCPs, 5 GCMs, 4 land management and TP reduction scenarios for Missisquoi, 2000-2050

Accelerating Climate Change Will Limit Adaptation Options for Water Quality Management

Asim Zia[1,2,3,4,*], Andrew W. Schroth[5], Christopher Koliba[1,4], Arne Bomblies[4,6,8], Peter D.F. Isles[7], Yushiou Tsai[8], Ibrahim N. Mohammed[8], Gabriela Bucini[8], Patrick Clemins[2,8], Scott Turnbull[8], Morgan Rodgers[8], Jory Hecht[8], Brian Beckage[9], Jonathan Winter[10], Carol Adair[4,7], Donna Rizzo[4,6], Judith Van Houten[8, 11]

- Target Journals: Nature Climate Change, PNAS, etc.

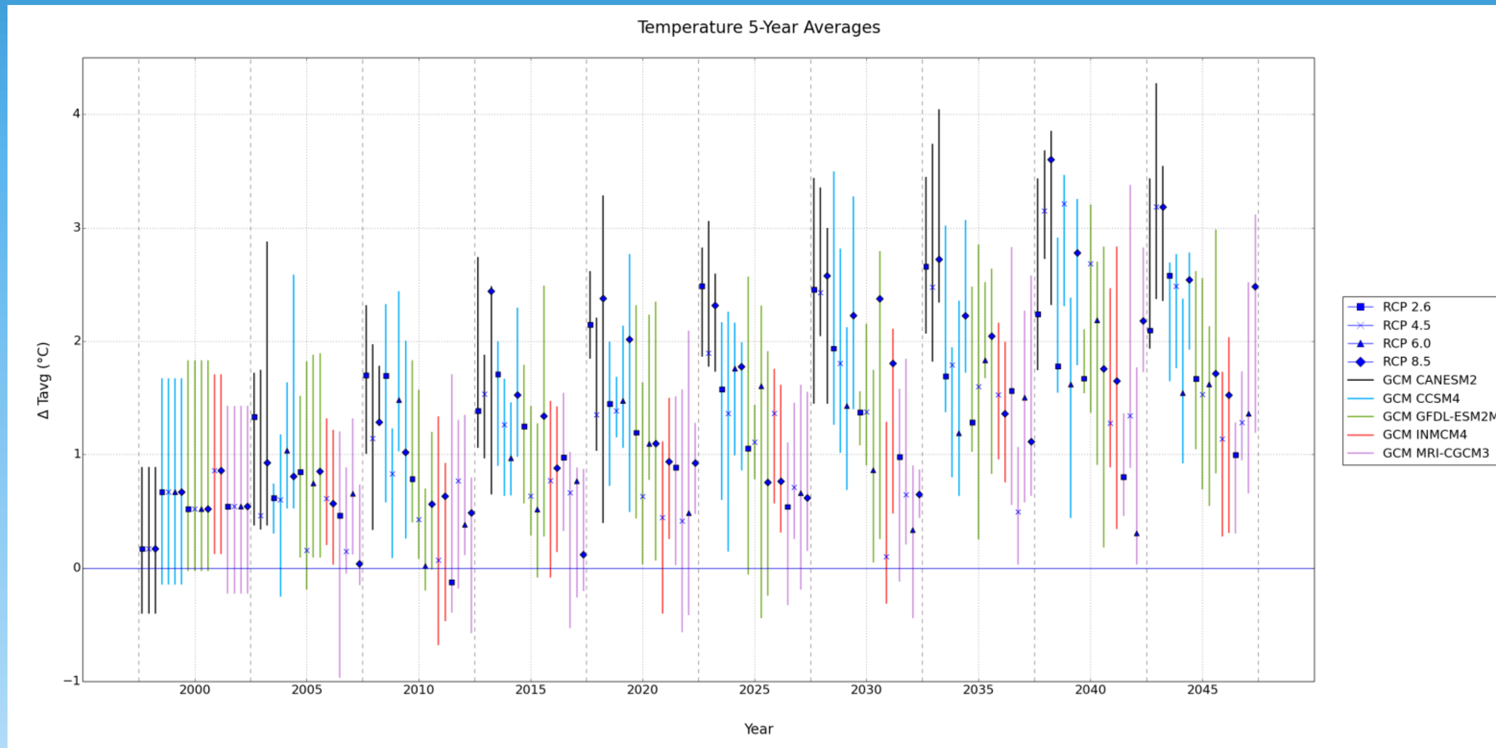
"Ensemble Method" of Scenario Settings Used for Cascading IAM Version 1.1 Missisquoi Runs, 2000-2050

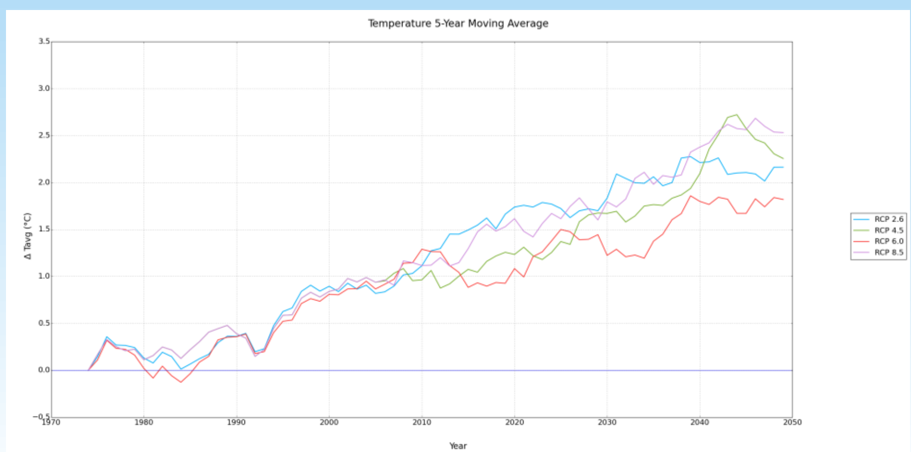
- **Four Climate Scenarios**: RCP 2.6, RCP 4.5; RCP 6.0 and RCP 8.5
  - Ensemble of five GCMs that are among the best to replicate North-Eastern US climatic conditions identified by Thibeault, J.M. and Seth, A., 2015. Toward the credibility of Northeast United States summer precipitation projections in CMIP5 and NARCCAP simulations. *Journal of Geophysical Research: Atmospheres*, *120*(19).

- **FOUR LULCC ABM Scenarios "Refined"**: BAU, Pro-forest, Pro-Ag, Urbanization

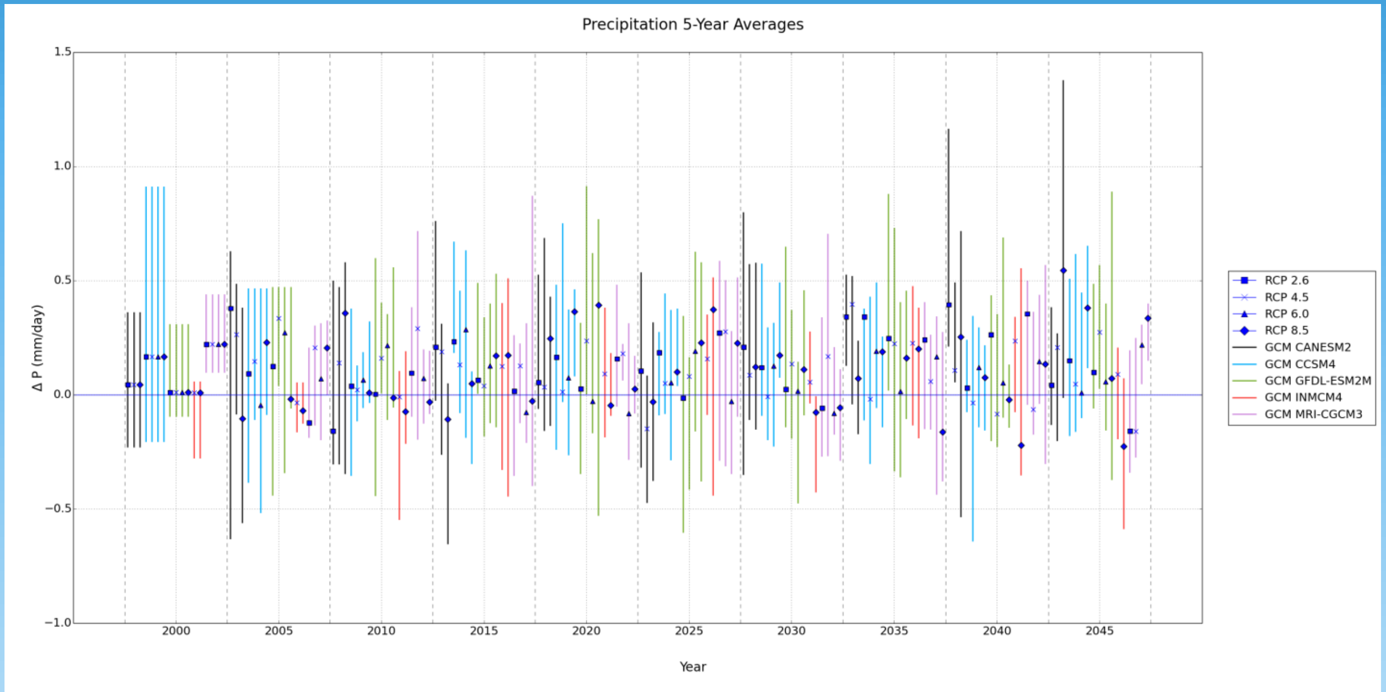
- **Hypothetical TP reduction scenarios**
  - 100% TP reduction from 2016-2050 scenario (ex-Secretary Ag scenario)
  - 90%, 85%, 80%, 70%...0% scenario runs (in progress)
  - Monte Carlo analysis on TP flux regression equations driving the Limnotech Model (in progress)
- **Remaining settings are similar to IAM Version 1.0** (e.g. no additional changes in model settings and calibration)

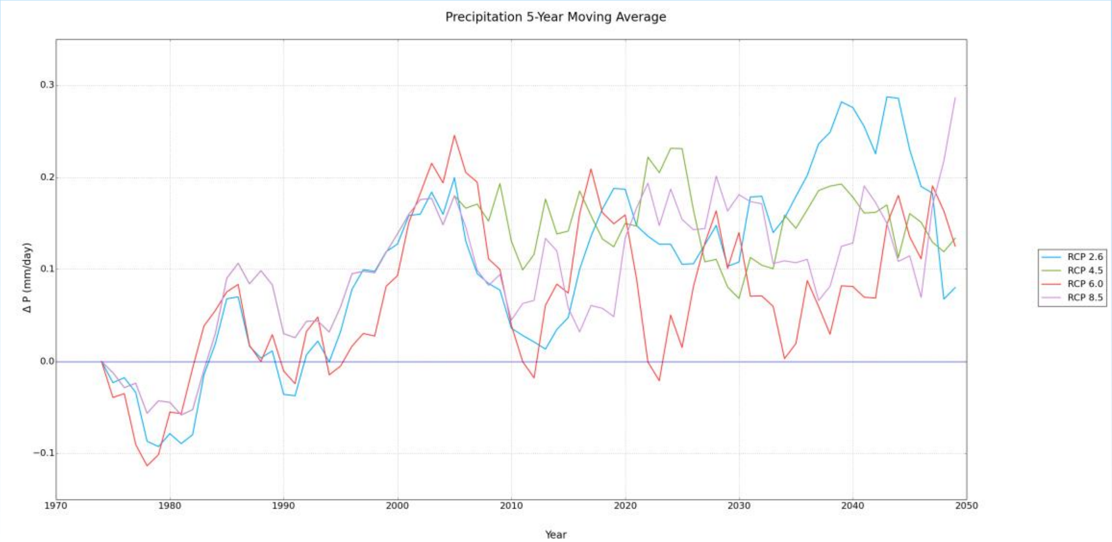
GCM Ensemble Projections, 2000-2050





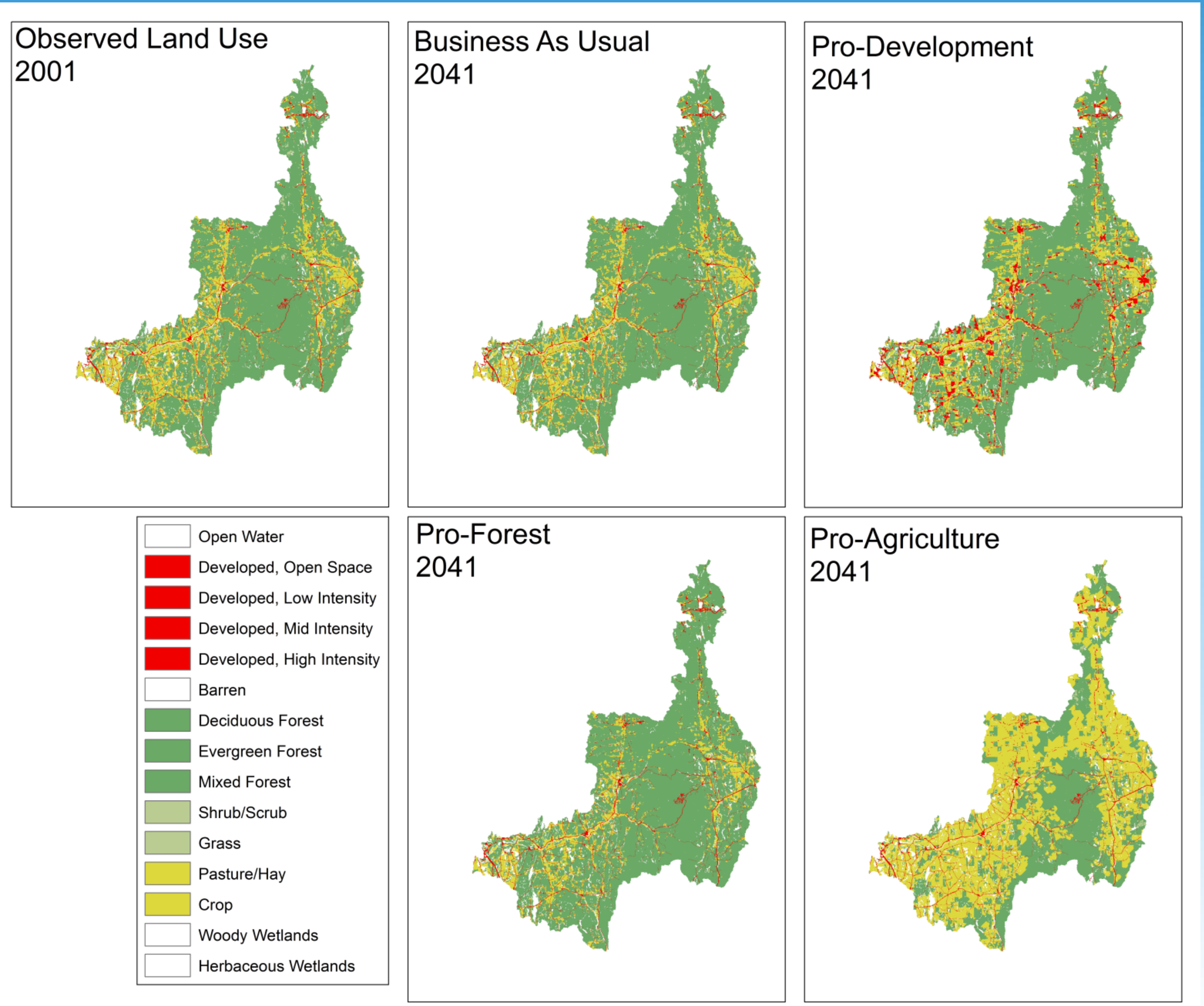
GCM Ensemble Projections, 2000-2050

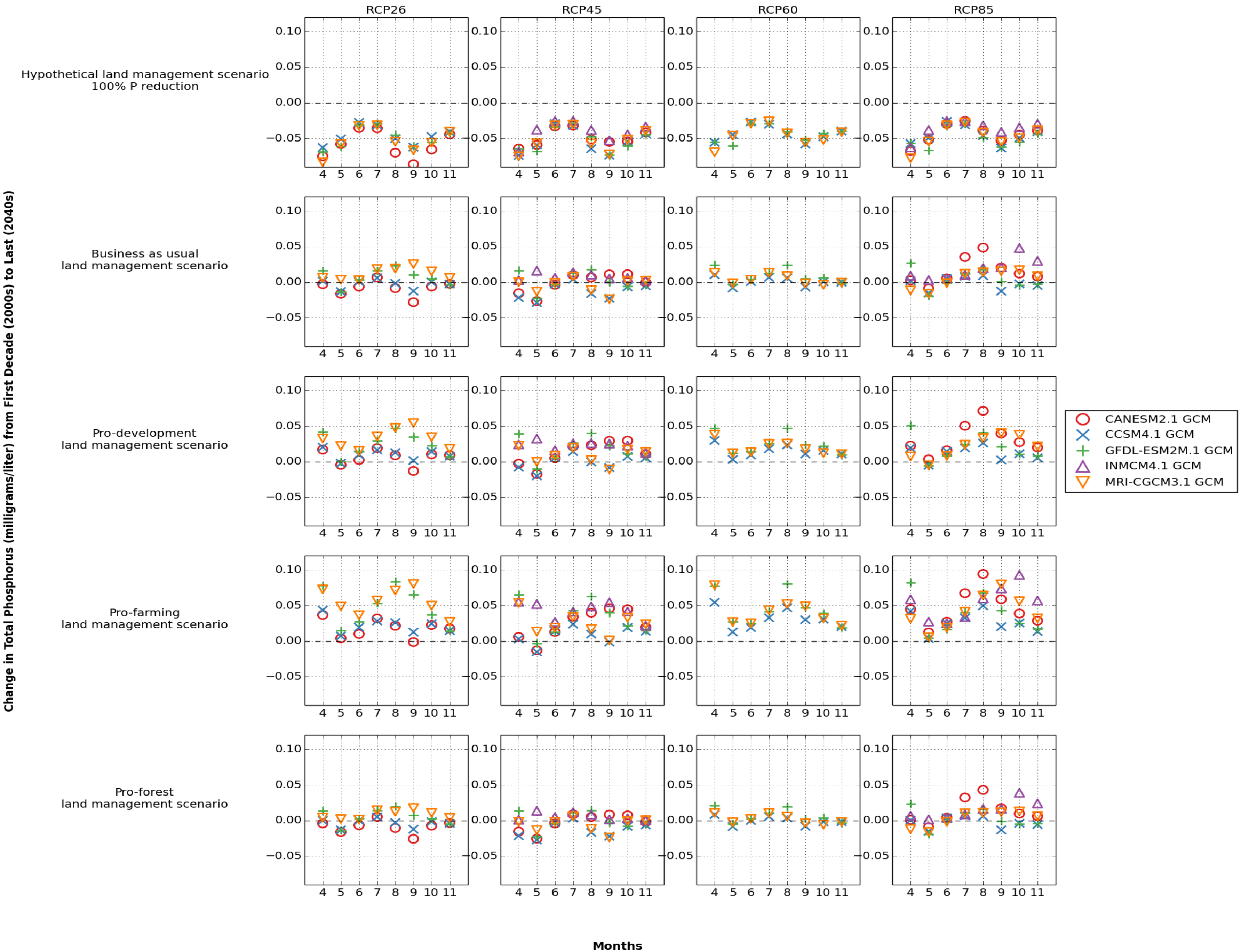




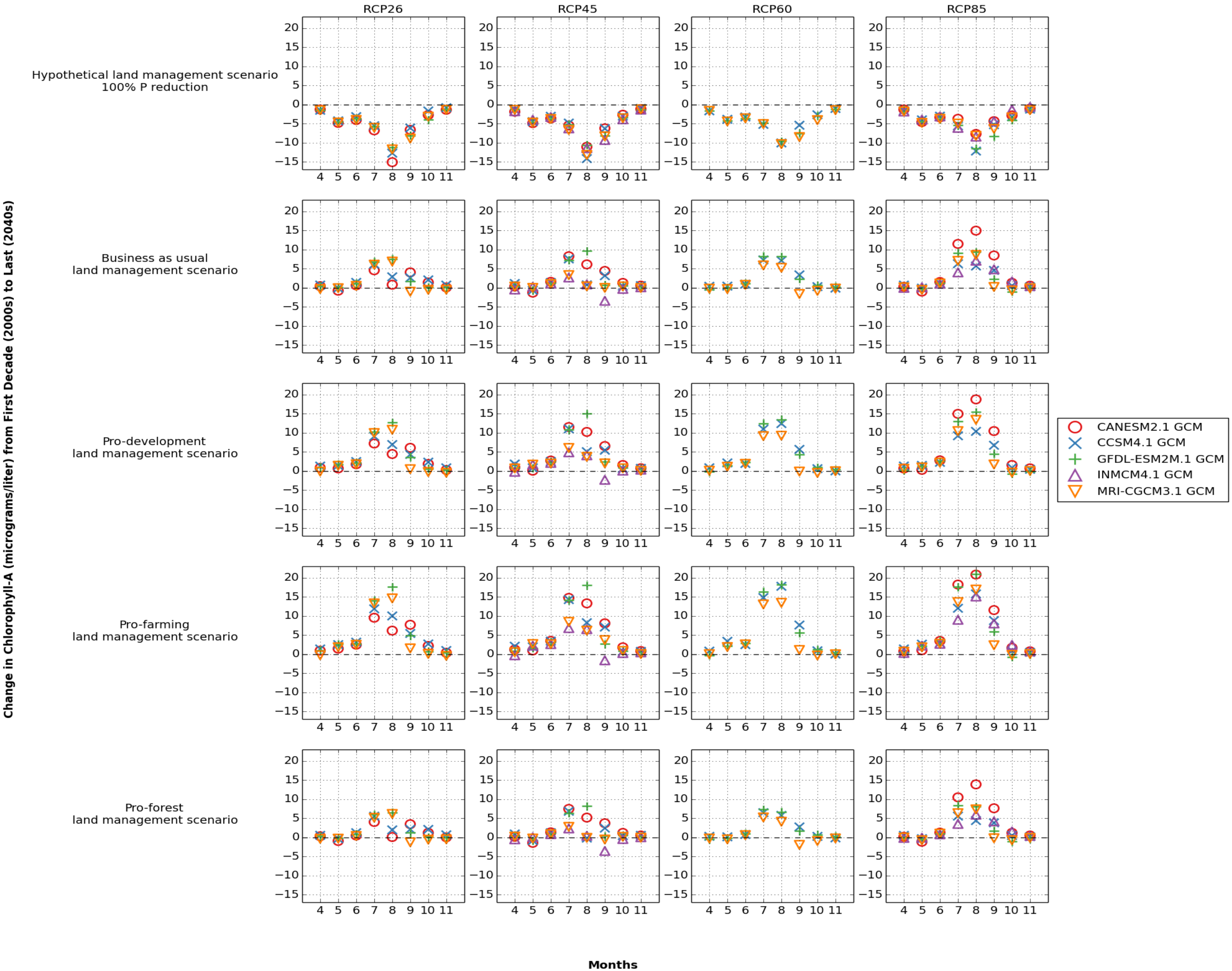
IAM Version 1.1

Projections of 4 "refined" Land Use scenarios Missisquoi, 2000-2041

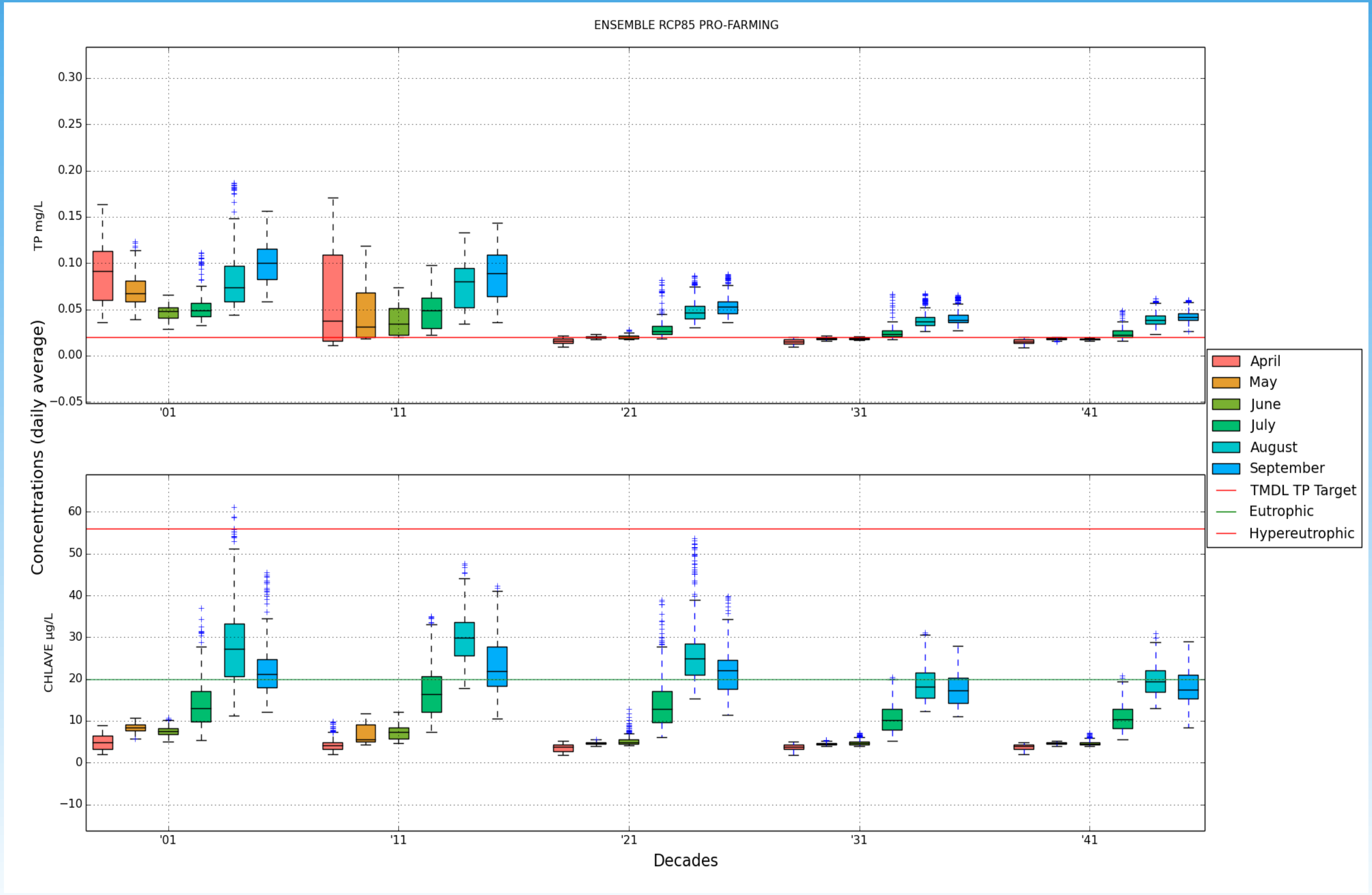




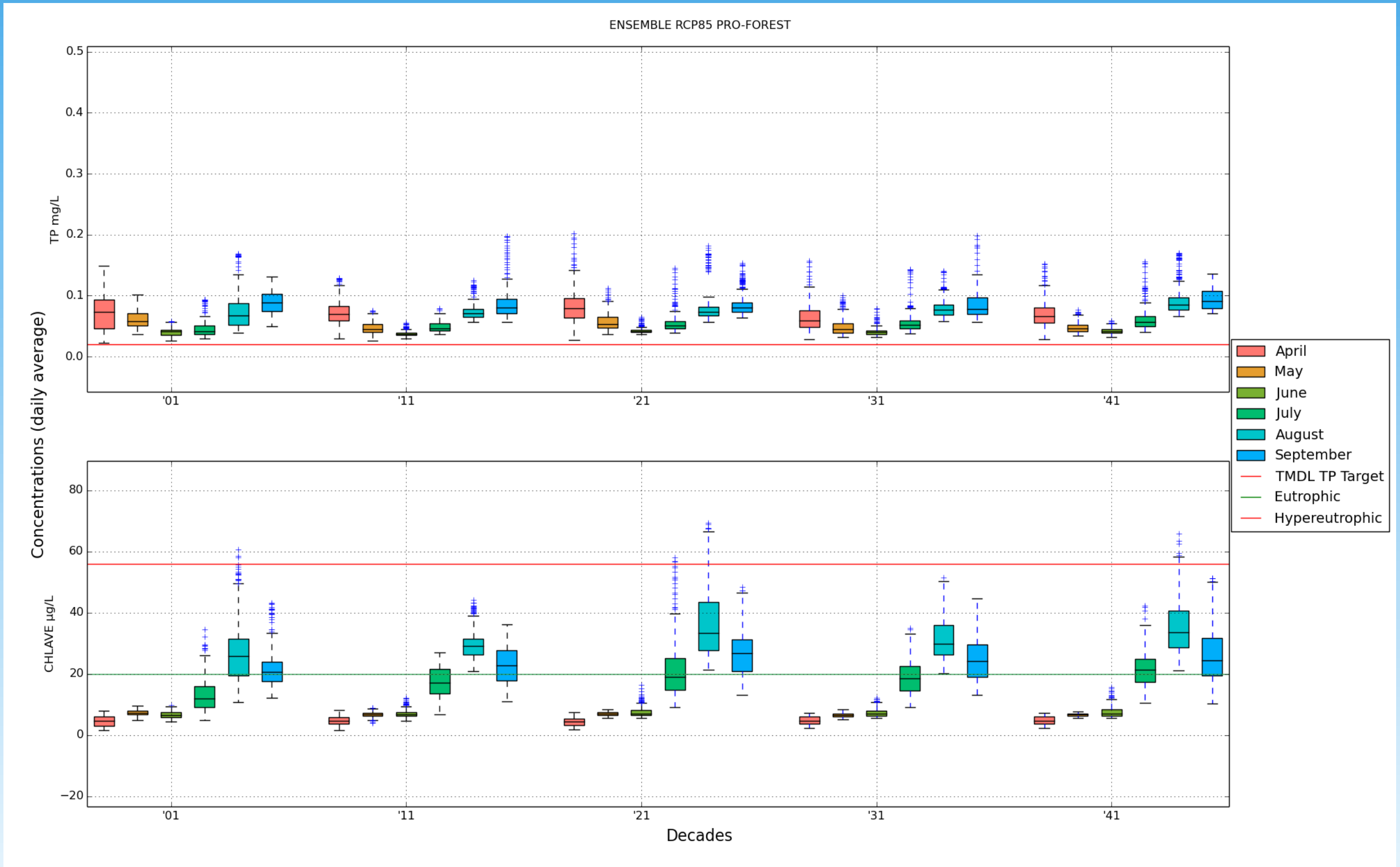
RCP26
RCP45
RCP60
RCP85
Hypothetical land management scenario
100% P reduction
Business as usual
land management scenario
Pro-development
land management scenario
Pro-farming
land management scenario
Pro-forest
land management scenario
Change in Total Phosphorus (milligrams/liter) from First Decade (2000s) to Last (2040s)
Months
CANESM2.1 GCM
CCSM4.1 GCM
GFDL-ESM2M.1 GCM
INMCM4.1 GCM
MRI-CGCM3.1 GCM


RCP26
RCP45
RCP60
RCP85
Hypothetical land management scenario
100% P reduction
Business as usual
land management scenario
Pro-development
land management scenario
Pro-farming
land management scenario
Pro-forest
land management scenario
Change in Chlorophyll-A (micrograms/liter) from First Decade (2000s) to Last (2040s)
Months
CANESM2.1 GCM
CCSM4.1 GCM
GFDL-ESM2M.1 GCM
INMCM4.1 GCM
MRI-CGCM3.1 GCM

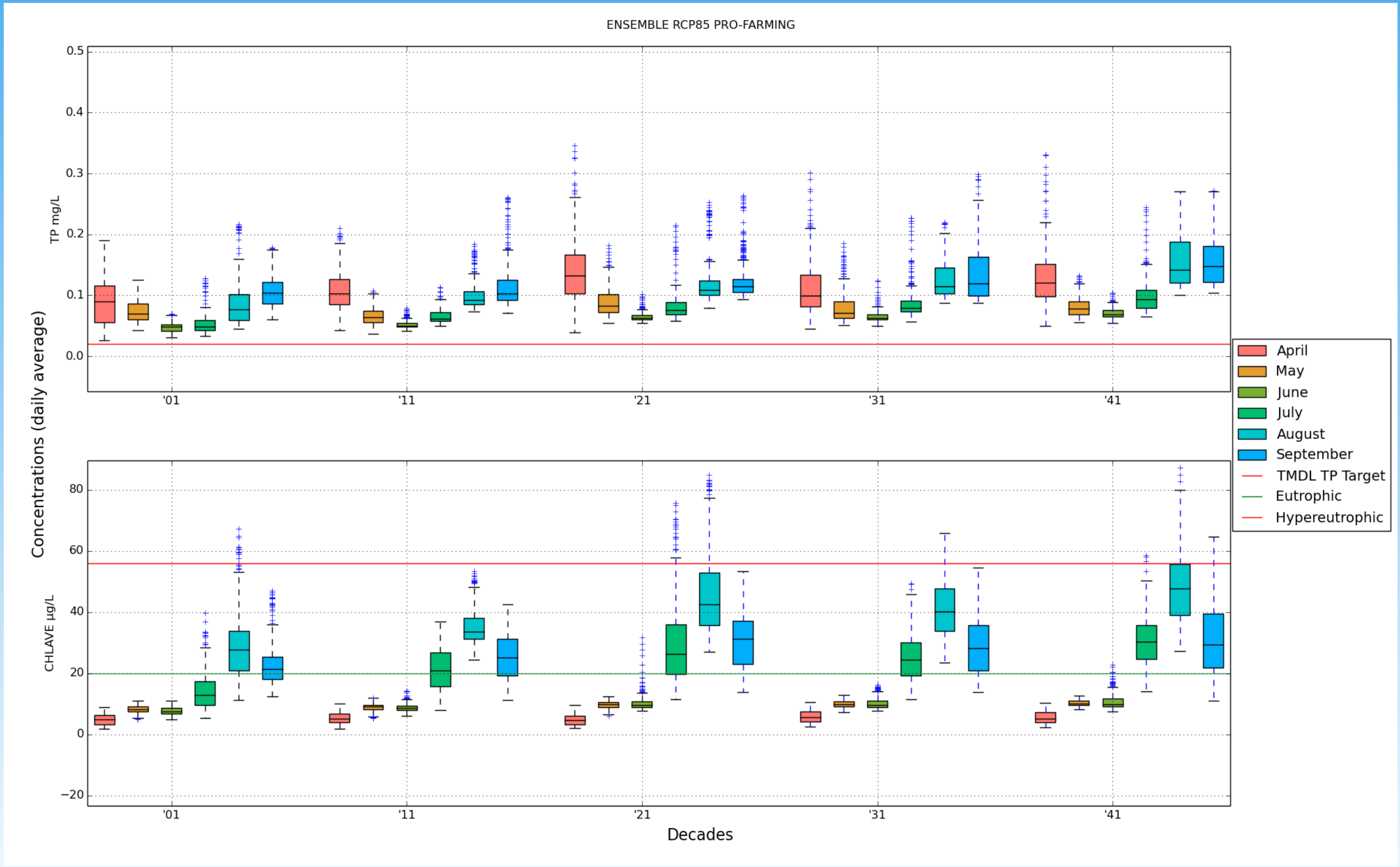
GCM ENSEMBLES FOR RCP85 X 100% P REDUCTION SCENARIO: TP(MG/L) AND CHLA(μG/L) PROJECTIONS



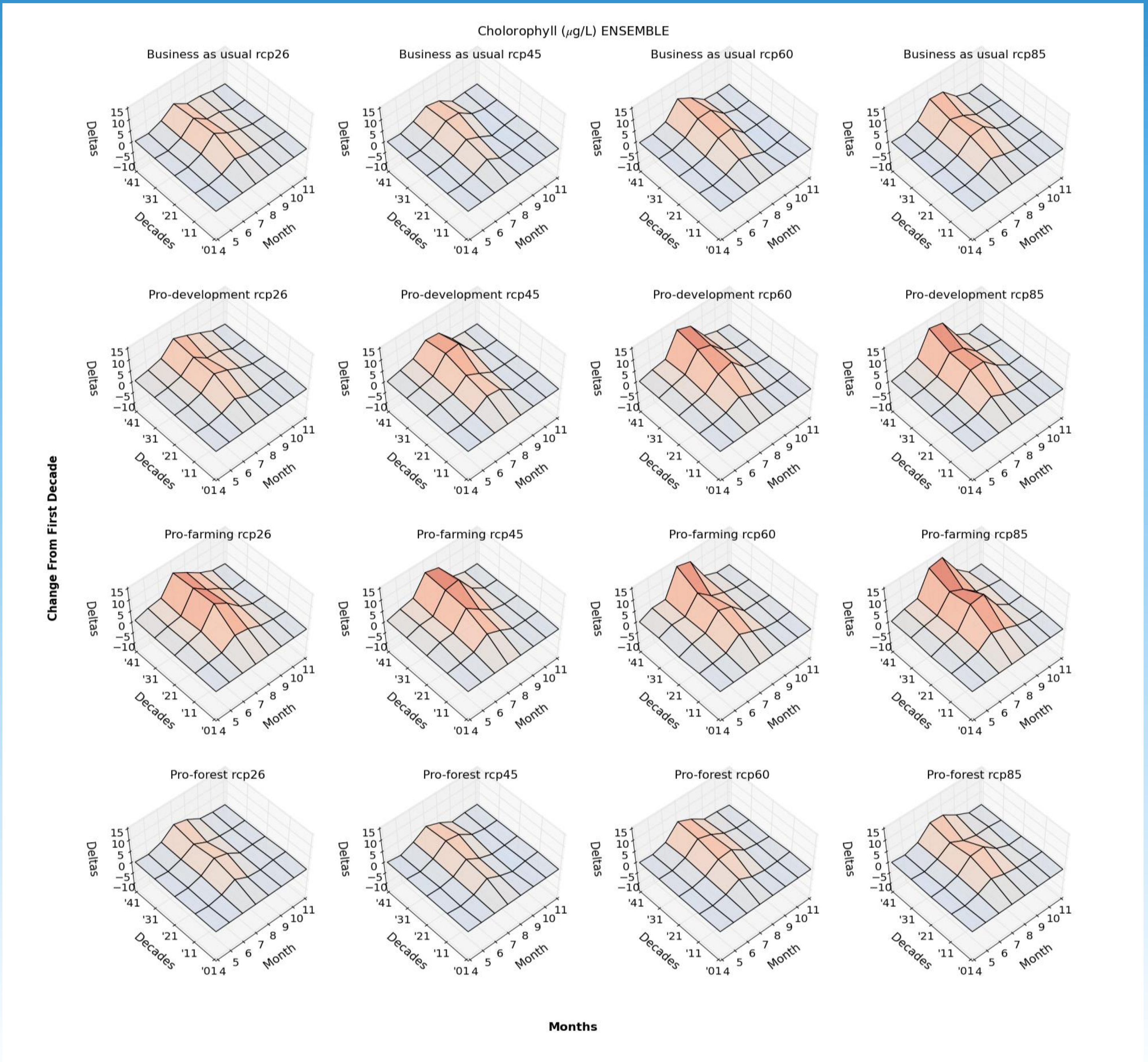
GCM ENSEMBLES FOR RCP85 X PRO-FOREST LAND SCENARIO: TP(MG/L) AND CHLA(μG/L) PROJECTIONS



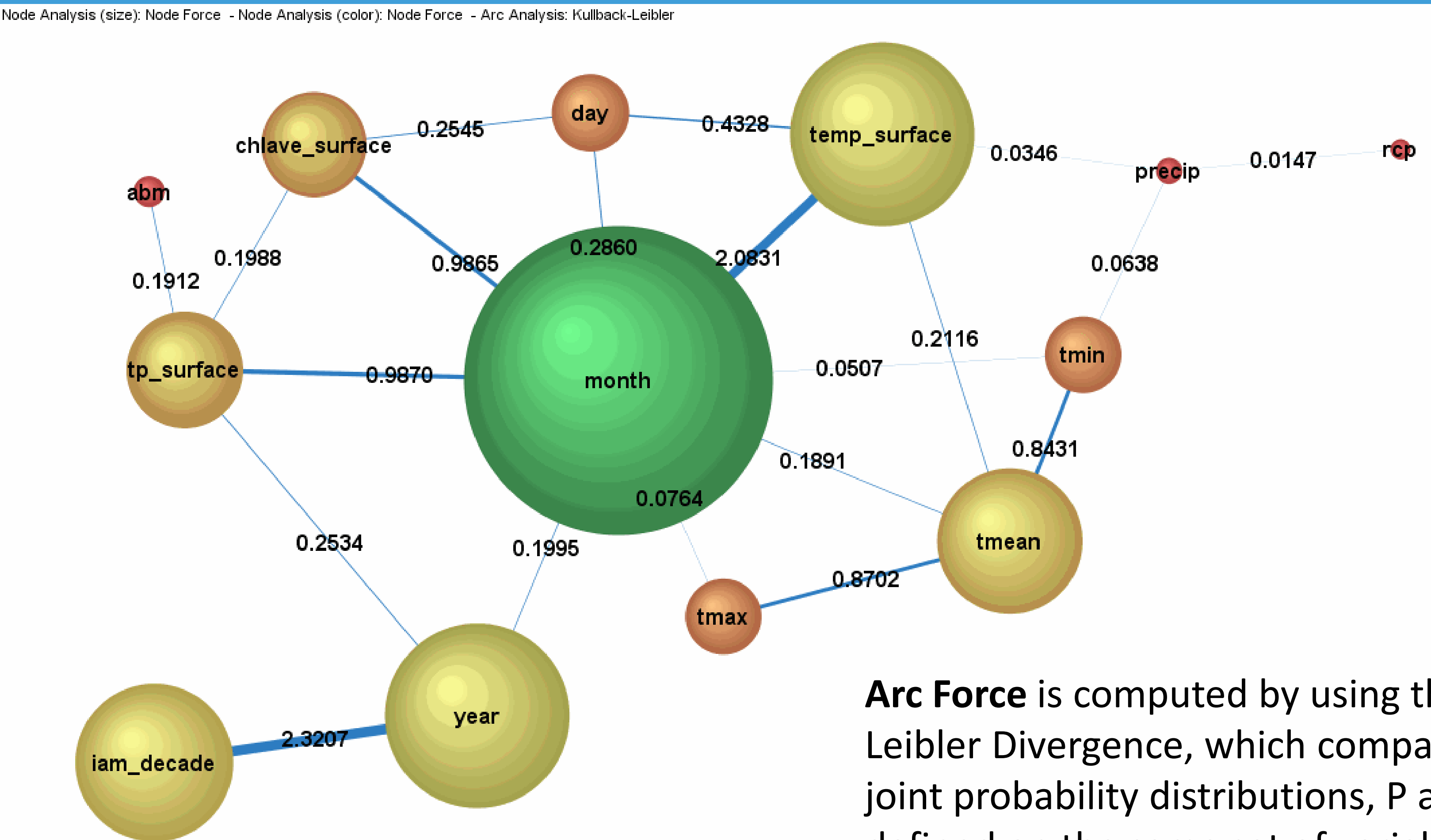
GCM ENSEMBLES FOR RCP85 X PRO-FARMING LAND SCENARIO: TP(MG/L) AND CHLA(μG/L) PROJECTIONS



GCM ENSEMBLES FOR 4 RCPS X 4 LAND SCENARIOS: CHLA(μG/L) PROJECTIONS



Comparing Relative Importance of Climate Vs. Land on the Bay Water Quality: An Information Theory Approach to Quantify System Uncertainties



Arc Force is computed by using the Kullback-Leibler Divergence, which compares two joint probability distributions, P and Q, defined on the same set of variables X , Where P is the current network and Q is the exact same network except that the arc under study is removed.

$$D_{KL}(P(X) \| Q(X)) = \sum_{X} P(X) \log_2 \frac{P(X)}{Q(X)}$$

Node Force is the sum of all incoming and outgoing arc forces from a node

IAM Version 1.2

- V1.2: Feed-forward enabled with 3 RCPs, 4 GCMs and 4 "refined" Land Use scenarios Missisquoi 2000-2100 period

Understanding Lags, Thresholds and Cross Scale Dynamics in Social Ecological Systems: Cascading Impacts of Climate and Land Use Adaptation on Missisiquoi Bay, 2000-2100

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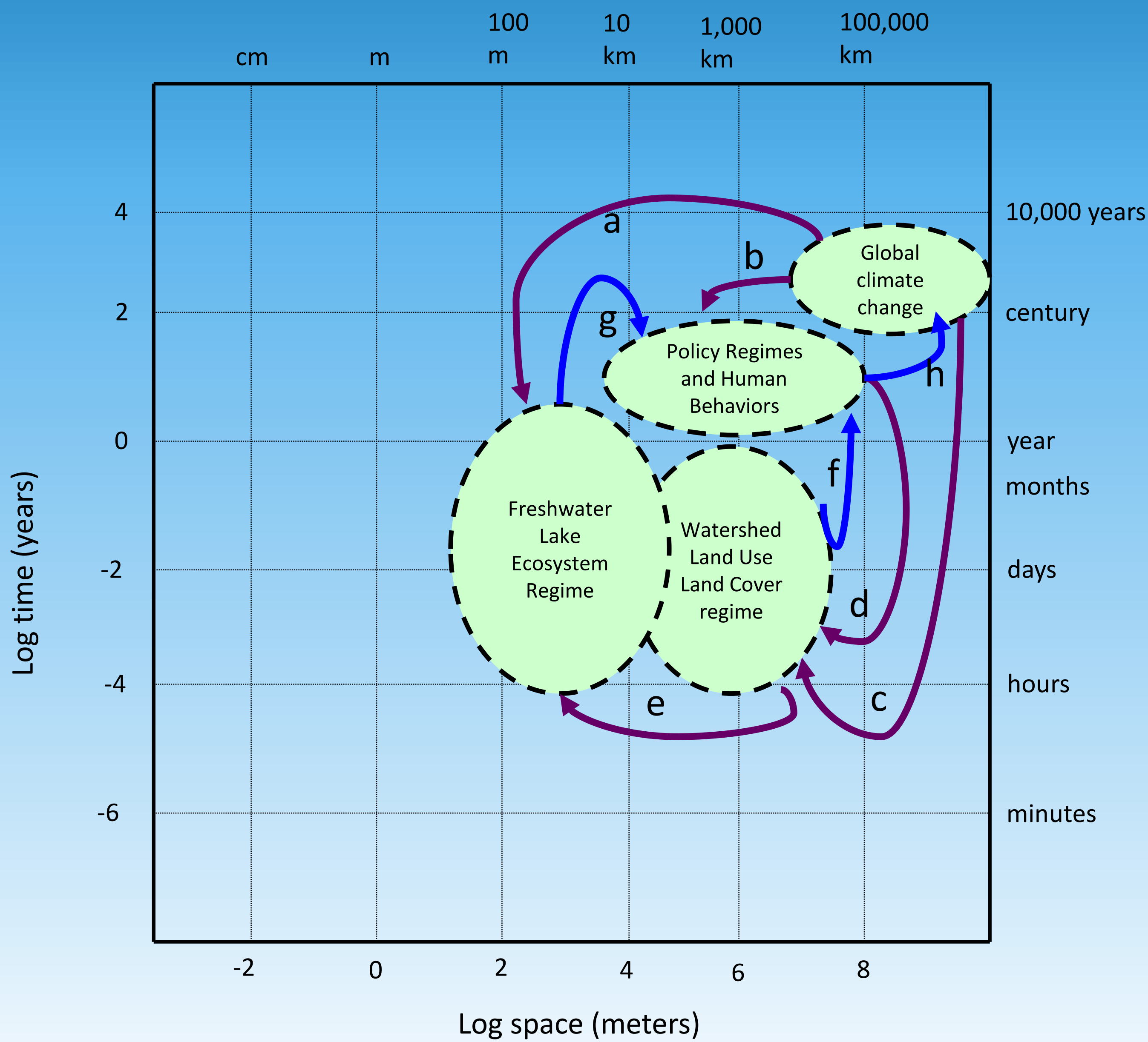
- Target Journals: PNAS, Ecology and Society etc.

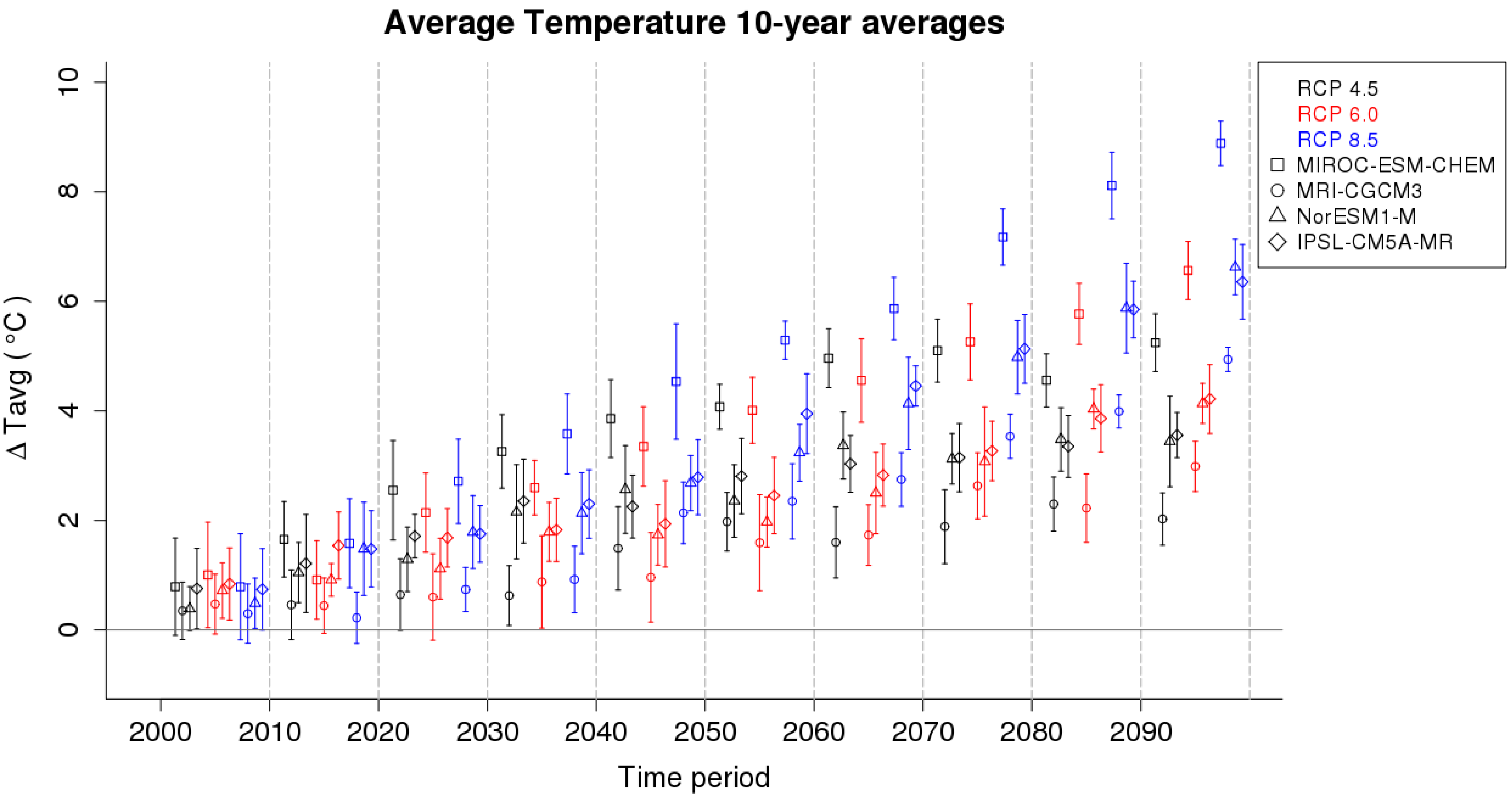
"EXTREME" SCENARIO SETTINGS

- **THREE "extreme" Climate Scenarios**: RCP 4.5; RCP 6.0 and RCP 8.5
  - Four extreme GCMs (<u>Warm</u>: miroc-esm-chem; <u>Cool</u>: mri-cgcm3.1; <u>Wet</u>: noresm1-m.1; <u>Dry</u>: ipsl-cm5a-mr.1) are used for three RCP scenarios.
- **FOUR "extreme" LULCC ABM Scenarios**: BAU, Pro-forest, Pro-Ag, Urbanization

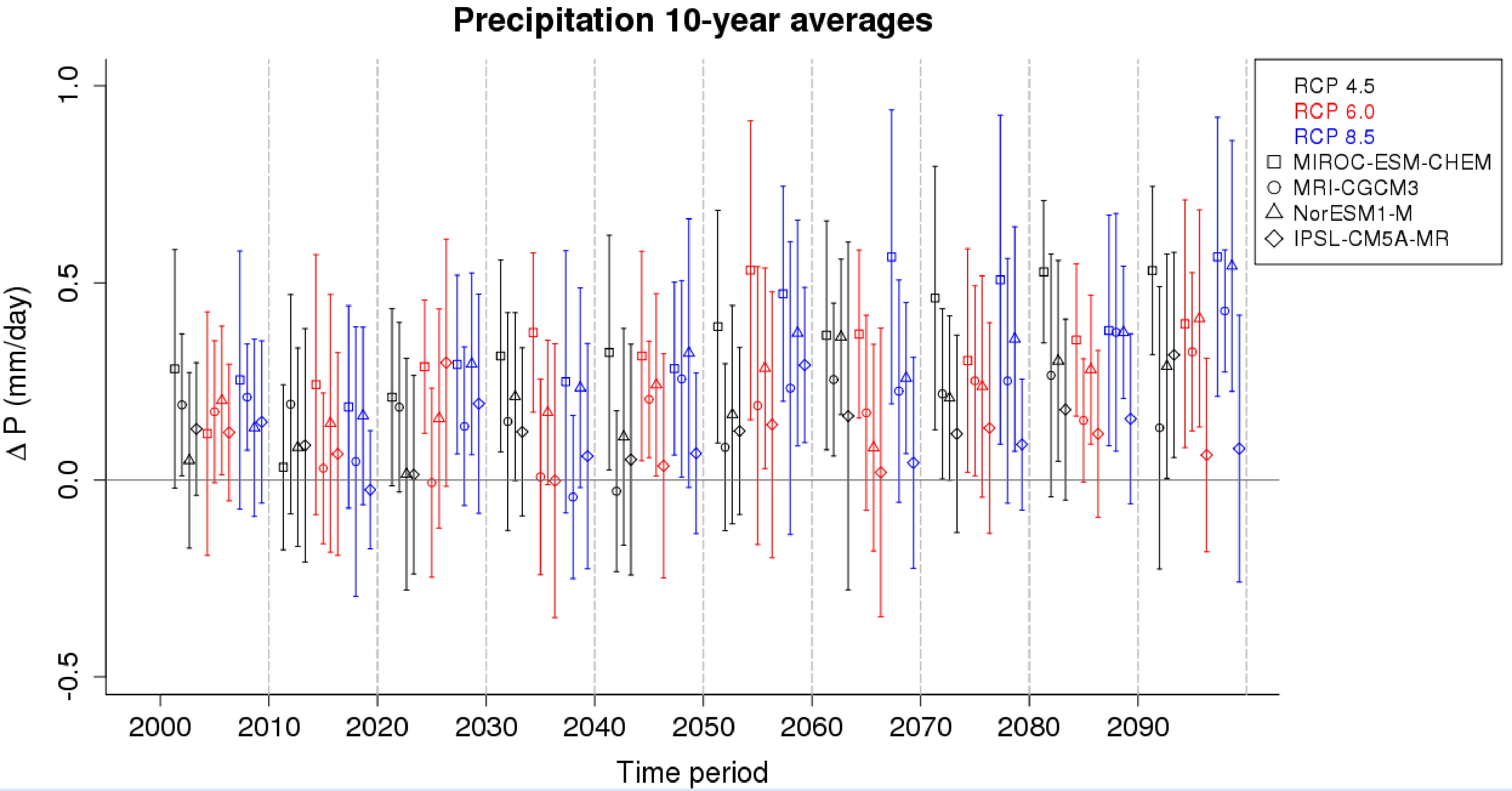
Situated in Social Ecological Systems (SES) theoretical and empirical framework, this paper addresses the following question : **How do lags, inertia and thresholds (phase transitions) affect the evolution of state variables in SES that interact across multiple scales of space and time ?**



Four GCM x Three RCP Projections for Temperature

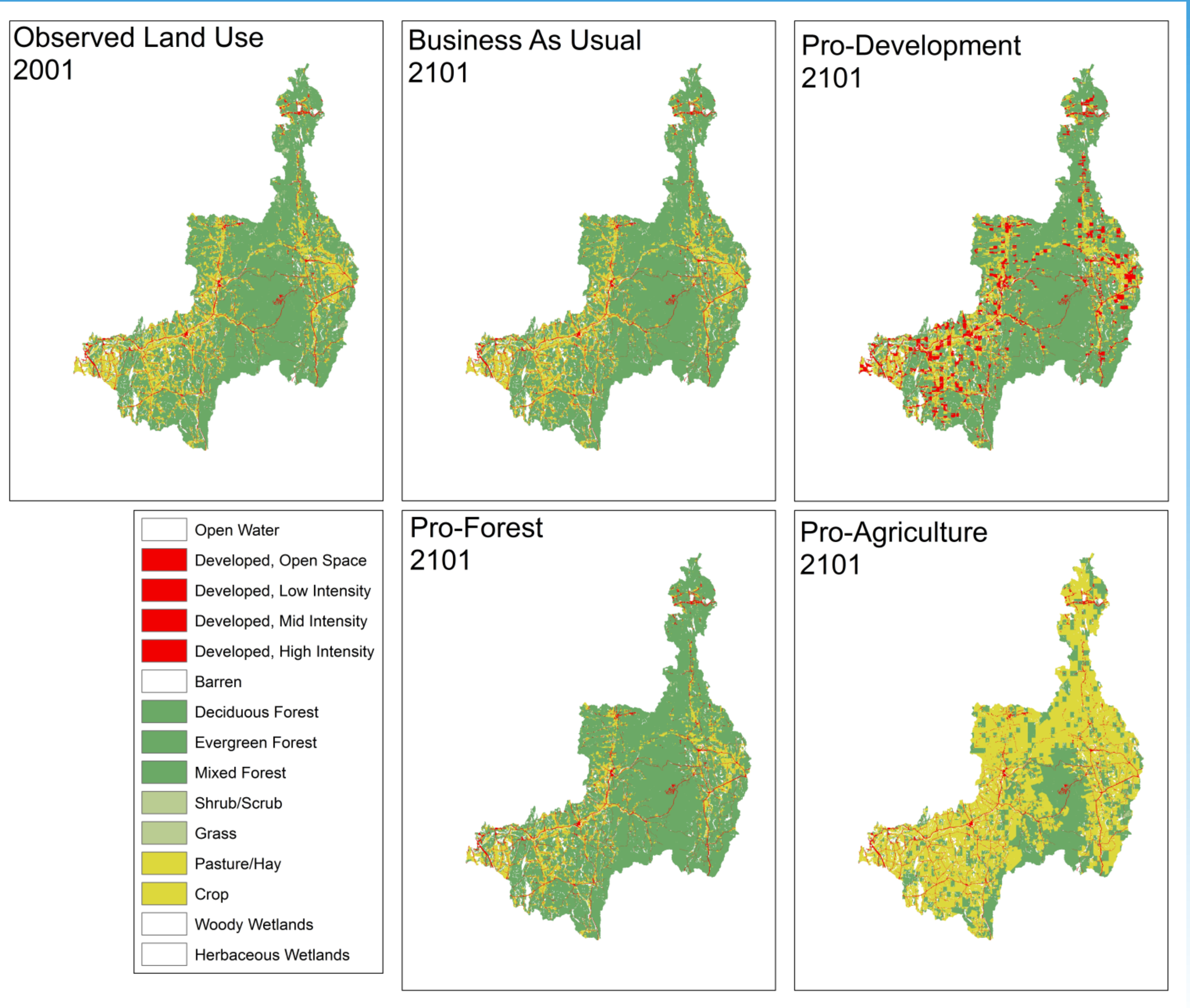


Four GCM x Three RCP Projections for Precipitation

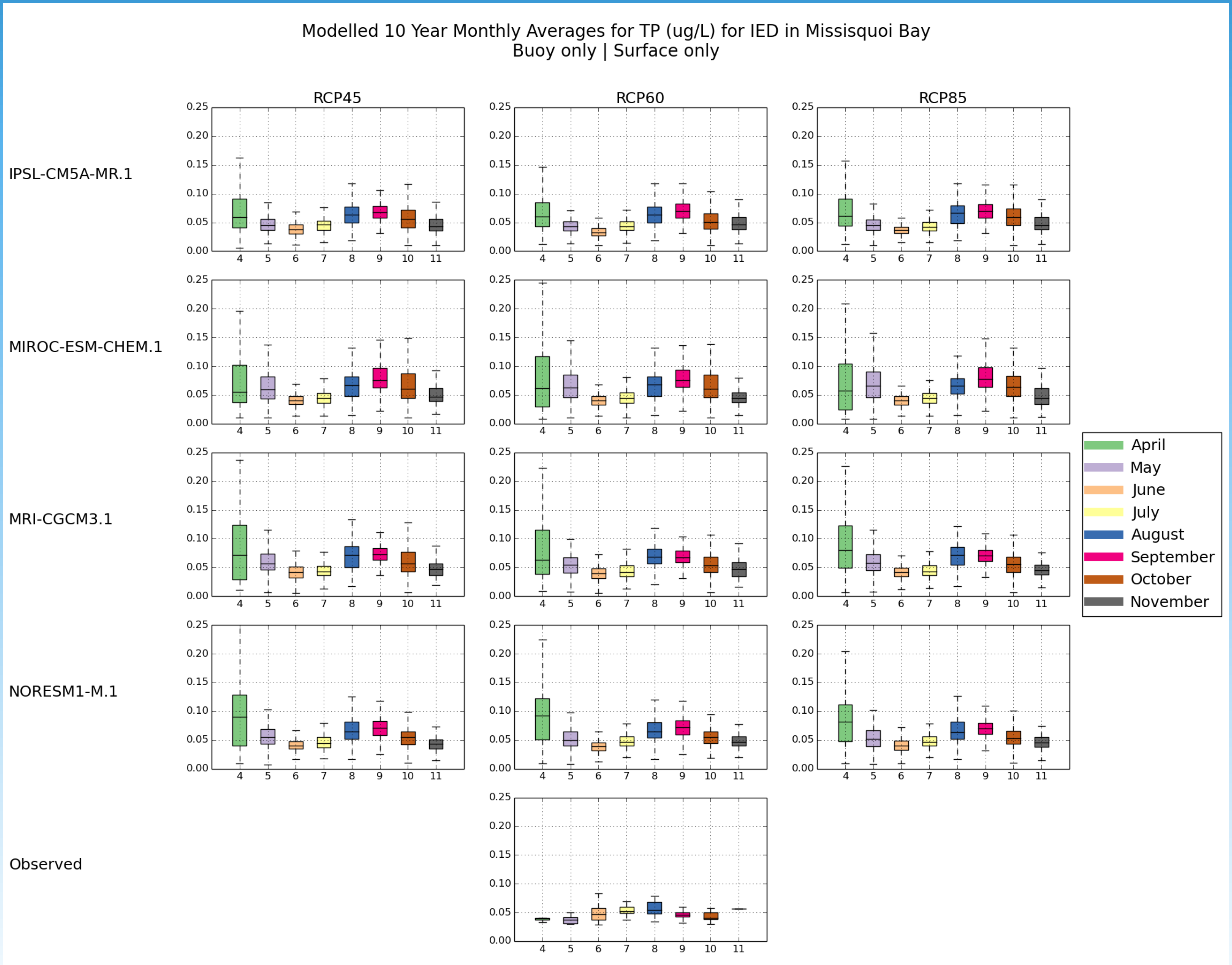


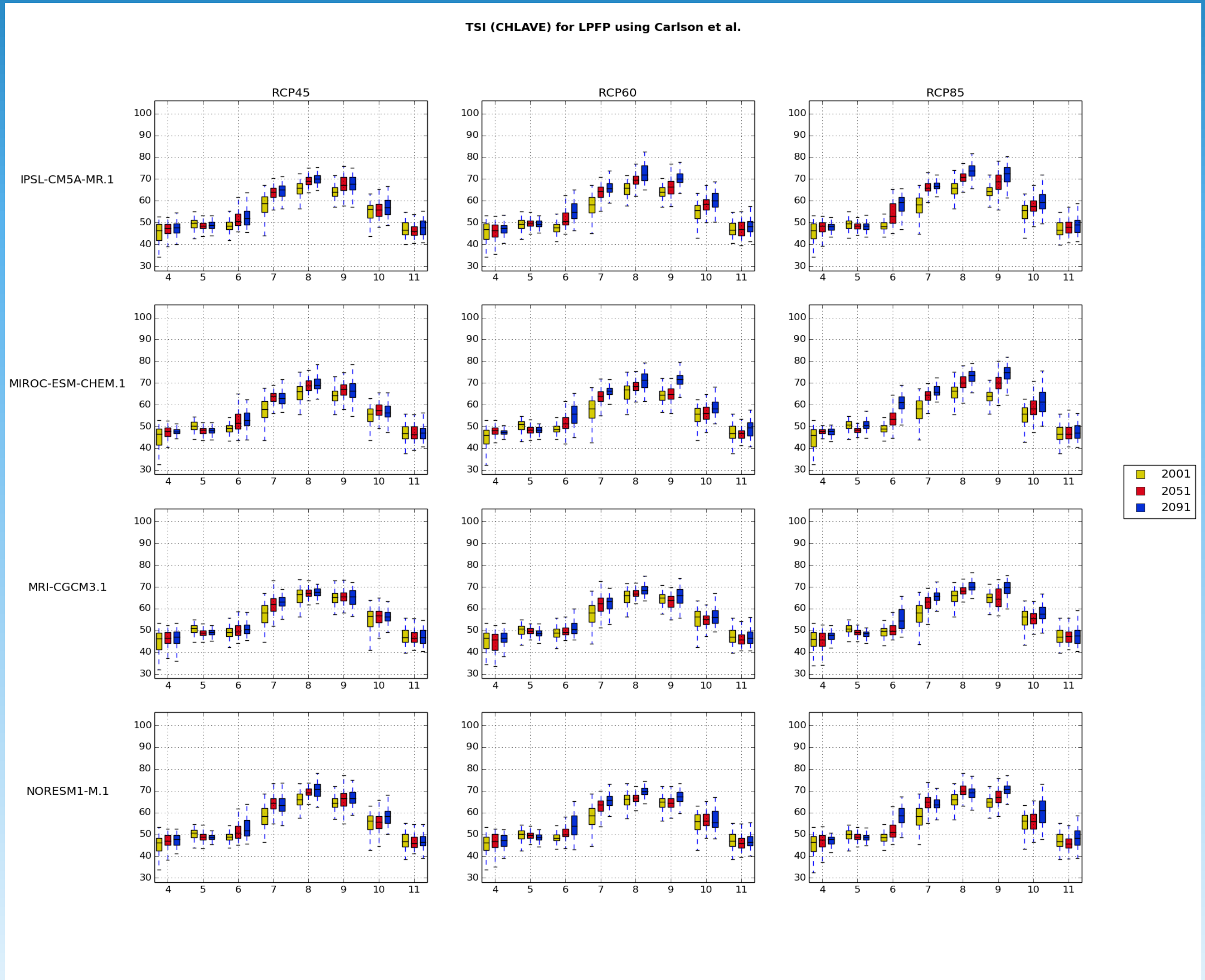
IAM Version 1.1

Projections of 4 "refined" Land Use scenarios, Missisquoi 2000-2041

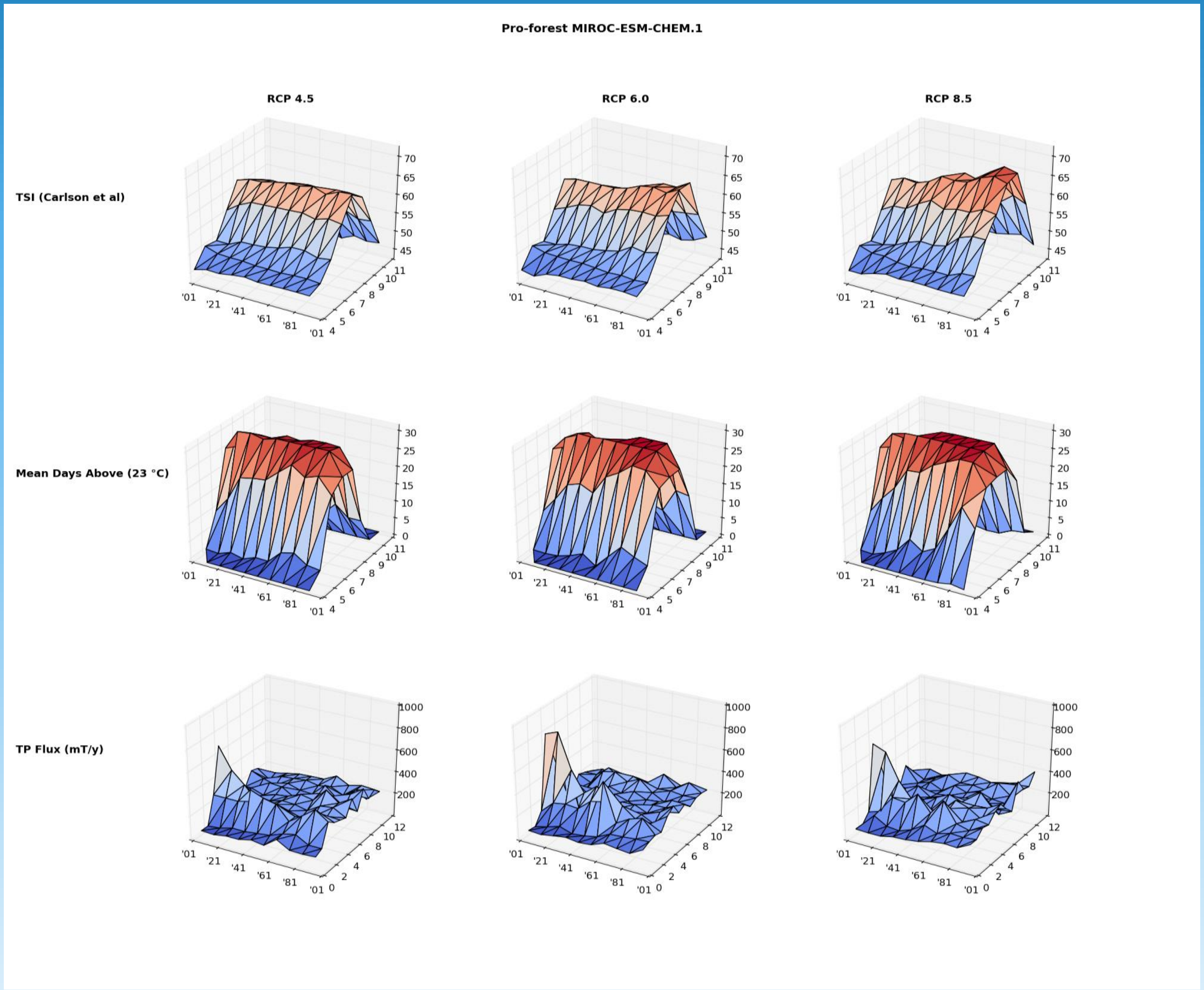


COMARING OBSERVED VS. SIMULATED TP CONCENTRATIONS, 2001-2010

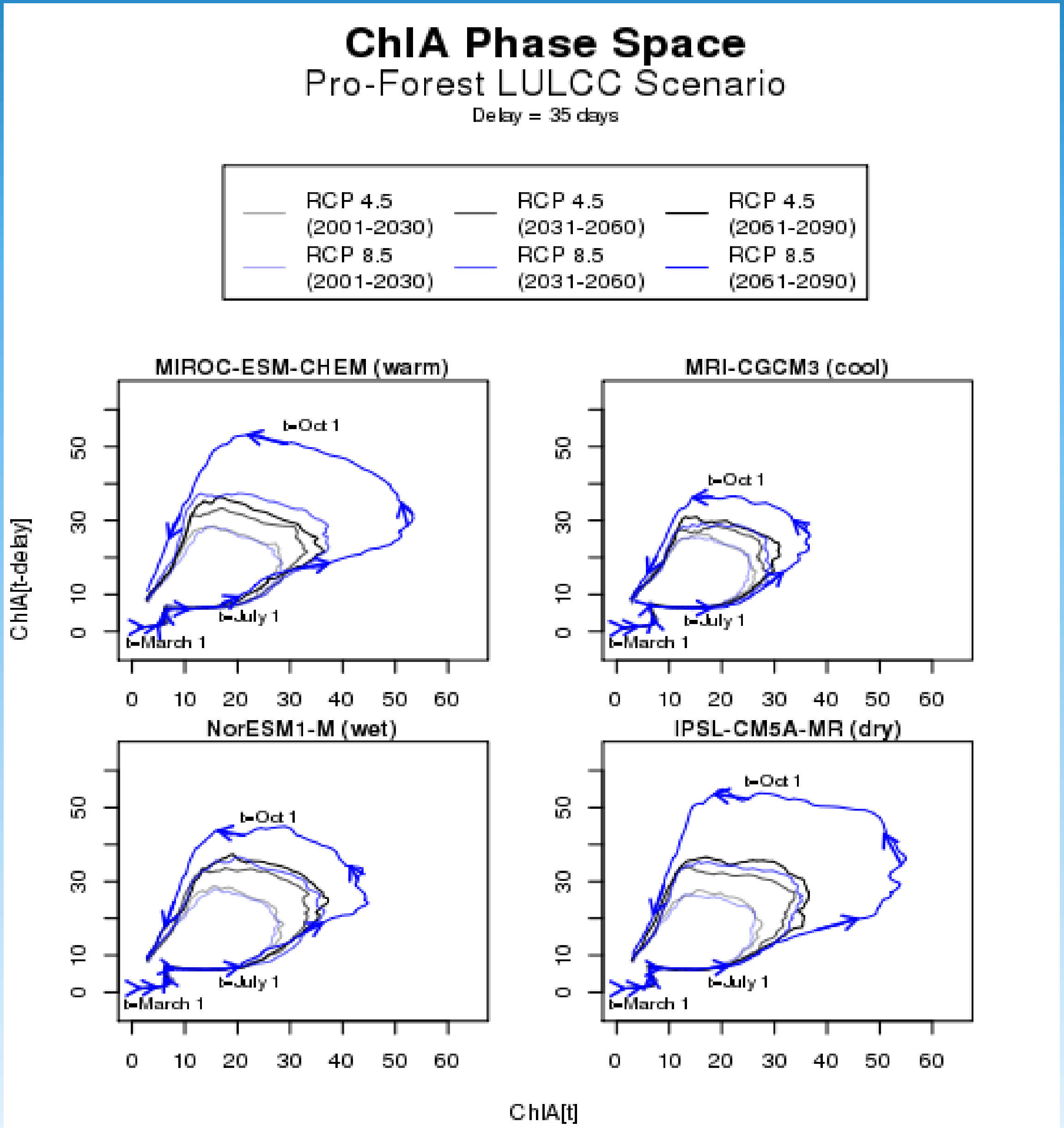




Projected Carlson's tropic state index for decadal averages (2001-11-yellow, 2051-61, 2091-2101) for the 'pro-forest scenario' under warm, wet, dry, and cool GCM ensembles. State transitions from meso to eutrophic occur at TSI 50, and from eutrophic to hypereutrophic conditions at 70 with this metric.



Projected change in TSI (Carlson et al. 1977) under high warming GCM for best case land use adaptation scenario x 3 greenhouse gas emissions scenarios. Mean days above 23C and TP Flux (Mt/Year) are also shown in second and third rows for the same set of GCM and land use scenarios.



Projected Phase Transitions in CHLA Concentrations under four GCMs x 2 RCPs for pro-forest land management scenario

THANK YOU

QUESTIONS?